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THE UNIVERSITY OF NEW SOUTH WALES

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REPORT No. 70

The Collection and Analysis of Rainfall and Stream Level Data

Vol. I

by

J. R. Learmonth

APRIL, 1964

THE COLLECTION AND ANALYSIS OF RAINFALL AND STREAM LEVEL DATA - VOL. I.

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FOREWORD

This report covers the first phase of a current programme of research in hydrologic instrumentation undertaken by the author as a partial requirement for the award of the Degree of Master of Engineering. The succeeding phases include the manufacture, testing and trial installations of the equipment described and the development of other instruments and improved methods of collection and analysis of hydrologic data.

The programme is under the direction of Professor C. H. Munro, Foundation Professor of Civil Engineering.

H. R. Vallentine,
Officer-in-Charge,
The Water Research Laboratory.

ABSTRACT

It is argued that hydrological variates could be economically recorded to the satisfaction of all users by event-timing methods (recording of time at known increments of the variate). New designs are suggested for certain basic instruments, featuring reduced systematic errors and recording by event-timing methods.

A system of telemetering hydrological variates is proposed, using fully transistorized, medium frequency, FM radio equipment, recording being by event-timing of transmitted pulses.

Data processing by digital computers is advocated and a design is proposed for a paper tape punching head suitable for recording a variety of phenomena by event-timing. The tape is suitable for direct input to a digital computer.

ERRATA

p. 41, line 7: for "diametically", read "diametrically".
p.107, line 4: for "dashed", read "fine".
p.155, mid-page: for "signed", read "signal".
p.214, line 7: for "factor", read "ratio".
p.217, 9 lines from bottom: for "factor", read "ratio".

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My thanks are due to many members of the staff of the University of New South Wales and to others in scientific and commercial circles for their assistance in the preparation of this thesis. I wish to thank in particular:

- Professor Munro for his initial suggestion of the broad topic of data-collection, and his help in guiding the work through a number of false starts;
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1. INTRODUCTION

1.1 REASONS FOR THE INVESTIGATION

1.1.1 Inadequacies of Basic Data

The writer has sometimes been forced to make sweeping simplifying assumptions in (or actually to abandon) a hydrological investigation only because the basic data on rainfall and runoff were inadequate for his purposes. Such inadequacies usually took the forms:

(a) scarcity of data
(b) inaccurate data
(c) data lacking sufficient detail.

The frustrations suffered were none the less real for the knowledge that some of the catchments being investigated were in fact adequately instrumented for the purposes of the authority controlling the catchments. The trouble was that the writer's and the authority's purposes differed.

Whilst it is realized that the number of instruments installed in a particular area is limited generally by money available to the controlling authority, it did seem a pity that the instruments which were installed could not have been designed to provide data adequate for all likely users. It was quickly seen that the traditional form of an autographic recorder (giving an analogue record on a constant-speed chart) was the main impediment preventing realization of this ideal, and an endeavour was then made to devise a better method of recording.

As a separate research, the factors which cause systematic errors in the measurement of rainfall and stream level were investigated, and, as far as was possible, methods of reducing such errors were considered.

The final object of the above two researches was to suggest modifications or new designs for the following basic instruments:

(a) the daily-read rain gauge or "hand" gauge,
(b) the storage rain gauge,
(c) the pluviograph or recording rain gauge,
(d) the float-operated stream level recorder
(e) the pressure-operated stream level recorder,
(f) the telemeter, for both rainfall and stream level.

1.1.2 Digital Methods in Hydrology

It was felt that recording and processing by digital methods offered many advantages over the traditional analogue methods. Fortunately, the new designs which were developed for the basic recording instruments were extremely suitable for incorporating in a system of digital recording and processing. Accordingly, a separate project was undertaken in order to develop a tape-punching head which could record basic data, with a sensitivity adequate for all likely users, on paper tape, which could then be input directly to an electronic digital computer. This punching head should be applicable to record both rainfall and stream level, as well as a variety of other phenomena not necessarily of interest to hydrologists.

1.2 SCOPE AND FORMAT OF THIS THESIS

1.2.1 Scope of this Thesis

The title of this thesis uses the words "collecting and analyzing certain hydrological data". Firstly, the data referred to are mainly rainfall and stream level, although some other data (temperature, wind, etc.) are referred to incidentally in the thesis. Snow is specifically excluded, and any designs suggested for rain gauges are quite unsuited for snow measurement.

The word "collecting" is limited in application to the methods of measuring the variate with an instrument, which is presumed to be located so as to avoid errors caused by poor exposure or bad choice of site. In other words, this thesis considers only errors arising at and in the instrument itself.

The methods of analysis which are discussed are confined to the use of digital computers in producing a corrected printout either of the original data or of some other variate dependent on the original data in an intimate way (as, for example, corrected stream flow from recorded data of stream level).

(It was initially intended to design, build, and test a new type of printing pluviograph substantially similar in conception to that described in Appendix E, and to present this work as the main part of this thesis. Although considerable work was done on the pluviograph and an article published thereon (Learmonth, 1959), the prototype was not completed because a suitable clock movement was, until recently, unavailable. Accordingly, the scope of this thesis was widened to cover the design problems associated with all the basic instruments for measuring rainfall and stream level, leaving the construction and testing of the gauges to be tackled in future researches. A brief statement of the work done to date on the printing pluviograph is included as Appendix N.)

1.2.2. Format of this Thesis

After a discussion of the requirements of the various users of data on rainfall and stream level, (Section 2), the main theme of the thesis begins, leading to the suggested designs for the basic instruments. The investigations for the designs are given in Sections 3 to 6 inclusive, the designs themselves appearing as appendices. Section 7 deals with the analysis and presentation of data, and the design for the tape-punch mentioned in this section is given as another appendix.

The thesis is written predominantly for civil engineers, but some use has had to be made of terms from the field of communications. A glossary (Appendix A) explains the meaning of these and other terms.

2. THE USER'S REQUIREMENTS

2.1 DATA CONSIDERED IN THIS THESIS

2.1.1 Rainfall Data

The rainfall data usually collected by investigators are of three main types which may be classified according to the time intervals into which it is possible to dissect the data:

(a) data from storage rain gauges,

(b) data from daily-read rain gauges,

(c) data from pluviographs.

The storage gauge is visited at intervals, usually of more than a week. Thus it can provide data on the mean rate of rainfall only during the period between visits. It is primarily used as a supplementary gauge in a network of other gauges read more frequently.

The daily-read rain gauge is the most common type of gauge, but in spite of its name, there are often days when these gauges are not read. For example, many gauges are located at post offices where it is often inconvenient for a Sunday reading to be taken. Thus a daily-read rain gauge cannot be relied upon to give better information than 2-day totals. On the other hand, some observers (in particular those at the synoptic reporting stations)take more than one reading per day, especially during heavy storms.

When information on rainfall intensities is required in greater detail than can be supplied by a daily-read gauge, it is usual to install some form of pluviograph, which provides data on the variation of rainfall intensity during small time intervals. The type of pluviograph installed depends on how accurately and to what degree of sensitivity the data must be provided. These requirements vary widely with the type of problem being investigated.

2.1.2 Stream Level Data

In a similar fashion to rainfall data, there are various ways in which stream level is usually measured:

(a) irregular readings at long intervals,

(b) daily readings,

(c) readings from stream level recorders.

The first type of data is normally used for a special purpose, such as flood warning. In this thesis, this type of data will not receive special consideration since the instrumentation required to supply type (a) data is the same as that required to supply the more important daily readings of level.

Daily reading of level is the most common way of collecting stream level data, and is usually quite satisfactory when the rate of change of stage is small. However, when the stage is likely to change at a rapid rate, the daily-read stream gauge does not give satisfactory information for many problems. One method of overcoming this is to read the gauge more frequently than once a day during those periods when rapid changes of stage are occurring, but this is usually inconvenient.

The problem is solved by installing an automatic stream level recorder of a type which gives data meeting the requirements of accuracy and sensitivity.

2.1.3 Telemetered Data

There are a number of reasons for telemetering hydrological data, the most important ones being:

(a) the data originate at a place where access is difficult,

(b) the data may sometimes be required for processing more quickly than is possible by the usual methods of data collection described in 2.1.1 and 2.1.2.

It is often sufficient that the data (either rainfall or stream level) be available to the user at certain definite times (such as every six hours), and many telemetry systems are designed to give information in this way. In other cases, it might be necessary for the user to know the current value of the variate at odd times; telemetry systems are available which provide this "call-up" facility. Still other systems are available which provide (within defined limits) the current value of the variate at all times, and it is evident that such systems are especially relevant to the theme of this thesis, stressing as it does methods which are suitable for all users.

This thesis is therefore concerned with the telemetry of both rainfall and stream level, particularly in a form which gives the current value at all times.

2.2 USES OF THE DATA

2.2.1 Preamble.

Hydrological data such as rainfall and stream level can be put to a variety of uses, many of them quite divorced from hydrology. Some of these will be mentioned in Sections 2.2.2 and 2.2.3 to give an idea of the wide scope for using such information. However, these lists do not pretend to be exhaustive; nor is there any need for them to be so, since the standards required of the data are set by the needs of the most demanding user. For example, assuming that the aim is to collect rainfall data suitable for all users, it is feasible to do this by assuming that the data are being obtained for the study of extreme rates of rainfall, and designing an instrument to measure such rates accurately.

2.2.2 Hydrological Uses of Data

Rainfalls and stream levels can be used for solving many hydrological problems concerned with the design and operation of works for the supply and drainage of water. Some of the main problems are contained in the lists of the following paragraphs:

(a) Water Supplies

(i) Estimation of suitable storage capacities for various purposes including domestic supplies for individual houses, farms, towns, cities and districts; stock water supplies from bores, tanks and ponds; irrigation water supplies for farms and districts; water supplies for generation of electric power; water supplies for industrial uses.

(ii) Assessment of the available water yields, and the reliability of these yields from existing reservoirs such as lakes and underground storages.

(iii) Estimation of evapo-transpiration losses from catchments and storages.

(iv) Siltation of reservoirs and stream channels.

(v) Estimation of likely demands on water supplies for the design of reticulation systems (pipes, canals, pumping stations, etc.)

(vi) Assessment of streamflow for legal purposes (distribution of water rights, etc.)

(vii) Measurement of streamflow for publication of hydrological statistics on water resources.

(viii) Operation of a reservoir or system of reservoirs to achieve some goal such as optimum economy or reliability of supply. (The goal being sought might be quite complex, involving optimum operation under conflicting requirements like water supply and flood control.)

(ix) Estimation of snowmelt.

(b) Water Drainage

(i) Estimation of discharges, levels and volumes of floodwaters for the design of drainage structures: house gutters and drain pipes, street gutters, kerb inlets, gully pits, stormwater sewers, drainage canals, agricultural drain pipes, ditches, racelines, recreation fields, airfields, culverts, bridge openings, flood control reservoirs, cofferdams, dam spillways.

(ii) Forecasts of levels, discharges and volumes of floods and the times of occurrence of flood crests at various points along a watercourse, in order that action may be taken to prevent, or decrease, flood damage.

(iii) Hydrological research involving measurements of the components of the runoff cycle.

(iv) Hydrometeorological studies, including storm maximization, storm transposition, and depth-area-duration analyses.

It will be appreciated that some problems relate to both (a) and (b) above. For example, drainage systems can be - and often are - used to catch water to be stored for subsequent use.

2.2.3 Other Uses of Data

Data on rainfall and stream level are also used in a number of problems which are not hydrological, many of which appear in the lists below:

(a) <u>Uses for Stream Level Data</u>

(i) Provision of adequate depth for river navigation.

(ii) Legal problems connected with flood damage and flood insurance.

(iii) Design of water level instruments (limnometers).

(iv) Provision of water for wild life, including fresh-water fisheries.

(v) Provision of water for recreation purposes.

(b) <u>Uses for Rainfall Data</u>

(i) Meteorological research into variations of precipitation with time, area and altitude.

(ii) Meteorological research into storm morphology.

(iii) Meteorological research into theory of precipitation, including studies of raindrop size and size distribution.

(iv) Design of precipitation instruments (pluviometers).

(v) Research into artificial rain-making.

(vi) Corrections to be applied to readings of evaporation pans.

(vii) Legal problems of rain damage and insurance.

(viii) Farm and forest management.

(ix) Problems associated with radio-active fallout.

(x) Climatological uses.

2.3 CRITICAL REQUIREMENTS

2.3.1 Preamble

Any instrument should be designed to satisfy the requirements of its users. Many problems of instrument design are concerned with convenience of use (as for example portability, power consumption, ruggedness and weather-proofing). These problems are in a sense secondary to the main task of designing an instrument which will deliver the data required of it in a form suitable for the data user. The instrument designer must first be aware of the data to be presented, and must then design an instrument to give such data, keeping in mind that the equipment should be convenient to use and preferably quite cheap. It is usually difficult, and sometimes impossible, to satisfy all requirements and many practical instruments are a compromise: some desirable data may have to be sacrificed for convenience or cheapness, for example. However, the designer should keep aiming at the ideal of presenting satisfactory data with convenience and economy.

The problems of convenience and economy will be ignored for the present and attention directed to the qualities required of the data: range of measurement, accuracy and sensitivity.

2.3.1.1 Range of Measurement:

The designer must know the upper and lower limits of the variable being measured. Further, if the instrument provides data from which other variables may be derived (e.g., rainfall intensity may be derived from records of rainfall depth and time), these secondary variables should also have their upper and lower limits specified.

2.3.1.2 Accuracy

Errors which occur in instrumental measurement are of two types: random errors and systematic errors (or bias). Bias is usually the more important, as its effect is cumulative, and every reasonable effort should be made to track down and reduce it. This is often very difficult and it is well known that rainfall measurements in particular are subject to considerable bias (Learmonth, 1960). Random errors, many of them errors of observation, can often be reduced to low values by good design. Wherever feasible, allowable errors of measurement should be specified to guide the designer, although it must be realised that indeterminate factors might make it difficult or impossible to guarantee measurement within a specified overall error. If it is possible to specify certain "partial errors" for sections of the instrument which are unaffected by the indeterminate factors, then this should be done. Errors should be specified for any relevant secondary variables which may be derived from the data. In some cases, the allowable errors may vary with the magnitude of the primary and secondary variables; if so these variations should be specified.

2.3.1.3 Sensitivity

Although often used as a synonym for accuracy, sensitivity is a different concept.[(1)] It may be roughly defined as the instrument's response to unit change in the variate being measured. The designer will usually have no trouble building into the instrument any specified sensitivity, though perhaps at the expense of convenience and economy. Specification of required sensitivity should include any variations of sensitivity with magnitude of the relevant primary and secondary variables.

2.3.2 Universal Instruments

At present, an investigator interested in rainfalls or stream levels is in the position of having dozens of instruments to choose from, some cheap, some expensive, some

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(1) An inaccurate instrument can be quite sensitive: e.g., a microammeter with a calibration factor of 1.5. An insensitive one can be very accurate; e.g., a set of precision gauge blocks, none less than 1 inch long.

suitable, some unsuitable. Let us now suppose that there were available one instrument which provided satisfactory data and was cheaper and more convenient than any other instrument. If, in addition, its data could be used with equal satisfaction by many others investigating different problems, the logical course would be for all users of data to install this universal instrument.

It is evident that this investigator's paradise is unlikely to eventuate, for the reason that any universal instrument would have to use a recording device of some sort. Such a device would almost certainly make the instrument too expensive for those whose requirements are modest. It might be possible however to get half-way to paradise by designing universal recording instruments and universal non-recording instruments. This at least would be a considerable step forward.

The main problem in designing such universal instruments is firstly to determine which users have critical requirements of range, accuracy and sensitivity and then to devise convenient and economical instruments which provide data to the critical specifications. Having done this, another problem might arise: highly sensitive instruments can be quite a nuisance to those who do not require high sensitivity.(1) This problem is not insuperable, nor does it always occur. It can be overcome if necessary by presenting the data in both fine and coarse form. This is relatively easy to do if processing is done by a computer, and this idea is developed in Section 7.5.4.2.

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(1) For example, an observer reading mean current over a period would prefer an insensitive meter (pointer swing = 1^o) to a sensitive one (pointer swing = 10^o).

2.3.3 Critical Data Requirements for Pluviometers

A pluviometer is defined here as any device for the measurement of rainfall, including recording and non-recording gauges. The definition also includes instruments which measure rainfall intensity directly, but these are outside the scope of this thesis.

2.3.3.1 Range

2.3.3.1.1 Range of Depth

The range of depths measurable by any pluviometer goes from zero up to some maximum value which is usually determined by the climate of the gauge site and on the period between visits. The maximum value may be an irrelevant parameter in those instruments which allow rainfall to run to waste after measurement. Assuming that the rainfall must be stored, the maximum rainfall depth to be measured is usually fixed by examining past records.

At this point we should decide which user has the critical requirements for maximum depth. It is indeed difficult to make a case for anybody but the climatologist. His main function is to collect data so that it may be available for use by any interested person. If he fails to collect at least some data on extreme depths of rain because his instruments overflow, he will have failed in his job. It is appropriate then to consider the extreme depths which have been recorded. Attention will be confined to Australian falls.

The highest recorded falls for various durations are:

1 day	- - 35.7 inches	1 month	- - 118 inches
3 days	- - 71.7 inches	1 year	- - 311 inches

These can be used as a guide in selecting suitable storage capacities for gauges; to be specific, let us consider the capacity of a daily-read rain gauge.

Several arguments can be raised for adopting, as the design storage capacity, a value greater than 35.7 inches:

(a) higher falls have probably occurred, or will probably occur, at the site of the recorded fall, or at other sites;

(b) the measured 35.7 inches is probably negatively biased;

(c) some "daily-read" gauges must perforce be read occasionally at intervals of 2 or 3 days;

(d) extreme depths may be readings for a 24-hour period ending at 9 a.m., and might have been greater if read at another hour;

Other arguments suggest that a smaller value should be used:

(e) during heavy rains, observers become interested in rainfall and may take intermediate readings;

(f) it is not economical to design every instrument for the worst conditions;

(g) very heavy falls can often be estimated by using other information (rises in tanks, buckets, etc.).

It is felt that arguments (e) and (g) should not be taken too seriously. Some observers will take intermediate readings but many will allow the gauge to overflow; and the main purpose of an accurate instrument is defeated if we must rely on other "instruments" to supply data.

But the other arguments are valid, and this makes the climatologist's problem of collecting satisfactory information quite complex. One solution would be to have all daily-read gauges store a very large quantity of water, enough to account for the increase caused by bias, the 3-day period of operation, plus a factor of safety. However, this would be an expensive solution. A better method would take account of the facts:

that not all gauges are likely to be left unattended for three days, that the rainfall climate varies throughout the continent, and that the general windiness of the site will determine the magnitude of the bias effect. A suitable network of gauges could then be arranged, in which judgment was used in selecting the appropriate capacity of each gauge, but with a certain number of high-capacity gauges deliberately installed to collect information on extreme depths.

A logical outcome of this attack on the problem is the design of a universal daily-read gauge which is standardized except for the storage capacity; this characteristic can be specified to suit particular conditions. However, there should be a minimum storage capacity below which it will be uneconomical to make special gauges. The present Australian standard daily-read gauge (10 inches capacity) appears reasonably satisfactory.

Similarly, a universal storage rain gauge, standardized except for the storage capacity seems a logical solution to the problems of long-term depth measurement. In this case, the storage capacity provided would normally depend on climate and period between visits. Some gauges might have storage capacity deliberately increased to collect at least some information on extreme depths.

Such daily-read and storage gauges do not appear impracticable, and the ideas are developed further in Section 5.2 and Appendices C and D.

A universal pluviograph no doubt could be designed using a system involving storage of the measured water, but it seems preferable to adopt the technique of allowing the measured water to run to waste. This plan has been followed in designing the universal pluviograph described in Appendix E, making it unnecessary to consider range of depth as a design criterion except as it affects the capacity of the magazine for the recording medium and the size of the power supply.

2.3.3.1.2 Range of Intensity

The range of intensities to be recorded by a universal pluviograph must - as with range of depths - be decided from a study of past records. The highest intensities recorded in Australia can be used as a guide in deciding the upper limit to be used for design, but the question then arises as to whether one should aim at recording greater intensities.

The solution to the problem in the case of depths was the relatively simple one of designing a standard instrument whose capacity could be varied to specification. For intensities an analogous simple solution is not available because several important design criteria (upper limit of intensity, accuracy, and sensitivities of depth and time) are all inter-related in any practical pluviograph mechanism. A specified upper limit must be set and the pluviograph designed to operate (not necessarily with high accuracy) at all intensities below this limit.

Once again, the climatologist becomes our guide, since he is extremely interested in statistics on high intensities and seems to be the only one who is prepared to quote figures on limits. Engineers doing research on small catchments, and interested in the drainage of houses and urban areas, are also concerned with high intensities, but seem hesitant about giving upper limits which might aid the instrument designer. In unofficial communications to the writer, the Commonwealth Bureau of Meteorology has indicated interest in rates of rainfall up to 25 inches per hour, although the Bureau's specification for a radio reporting pluviograph (Commonwealth of Australia, Bureau of Meteorology, 1961) is less demanding, stating that the instrument "shall be capable of withstanding, and operating satisfactorily under the following climatic conditions:.....Maximum rainfall rate - 12 in/hr".

The maximum intensity recorded at branch offices of the Bureau is about 9 inches per hour (for a period of 5 minutes at Brisbane), but there is ample evidence that as the period considered decreases, the expected maximum intensities continue to increase. The world-record rainfall intensity, for a period of 1 minute, is about 60 inches per hour (Opids Camp, California, U.S.A.).

2.3.3.1.3 Range of Time

The maximum unattended period is a trivial consideration in designing a daily-read rain gauge, but must be seriously considered for all other gauges. If a gauge must be located at a site where access is difficult or inconvenient, one must usually decide on the relative economics of many trips to a short-period instrument compared with few visits to a long-period gauge.

Storage gauges, pluviographs and telemetry transmitters for use in Australia need seldom be unattended for periods greater than six months because no reasonable site for a pluviometer (snow measurement is not being considered here) is inaccessible for more than a few months, for example during the wet season in the northern parts of Australia. Trips to the gauge would normally be timed for the dry season. However, it is always possible for unseasonable wet weather to make the scheduled visit impossible, and a safety margin above the six months period would be an advantage.

2.3.3.2 Accuracy

2.3.3.2.1 Accuracy of Depth

Few authorities collecting rainfall data seem prepared to specify allowable errors for rainfall depths. Such an attitude is not completely unreasonable and may be defended by the argument that rainfall is extremely difficult to measure without bias. There is in fact no rain gauge which is universally recognised as completely bias-free, thus it is impossible to state the absolute error in any rainfall measurement. However, although certain errors might be difficult to estimate because their causes are variable and uncontrollable, other errors arise from known causes which are under the control of the instrument designer. It should be possible to write a specification to ensure that the latter errors are within certain limits. It will then be the designer's job to satisfy this specification, and in addition to reduce the other errors as much as possible, consistent with economy and convenience of use.

The climatologist once again seems to be most demanding in his need for accuracy. In fact, from the writer's inquiries, he seems to be the only one to specify requirements for accuracy. For example, in specifying for the supply of instruments, the Bureau requires accuracies as in the following paragraphs:

(a) Radio Reporting Rain Gauges

"The accuracy of measurement of one increment of rainfall shall be ±.005" and the accuracy of measurement of the total of a number of increments shall be at least ±8%, where the rainfall rate does not exceed 12 inches per hour."[1]

(Commonwealth of Australia, Bureau of Meteorology, 1961)

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(1) One increment = .01 inch. Taken literally, this specification means that the percentage error in measuring one increment can be as high as 50% (sic). There seems to be some confusion between accuracy and sensitivity.

The same Reference also states:

"If required,.....the gauge shall also provide a permanent record.....of the rainfall.....If a recording system is provided, it shall meet the following requirements:.....Accuracy of increments of rainfall and of total rainfall measurements to be ±5 hundredths of an inch or ±5% whichever is the greater."

(b) Recording Rain Gauges (Pluviographs) for Six Months Unattended Operation

(Commonwealth of Australia, Bureau of Meteorology, 1958)

"Accuracy of increments of rainfall and of total rainfall measurements to be ±5 points or ±5% whichever is the greater."

It is not stated whether the "accuracy of measurement" of depths represents an overall accuracy or what one might call an internal instrumental accuracy. Overall accuracy arises from comparing the measured depth with the true value; internal instrumental accuracy from comparing the measured depth with the depth of the catch. (See Appendix A for a definition of catch.) The writer presumes that it is internal instrumental accuracy which is being specified. If one were to include possible errors which arise prior to the catching of the rain, these figures for allowable error might have to be increased considerably.

It appears to the writer that specifications for the supply of instruments are too often written with this question in mind: "What must we be satisfied with?", where the more appropriate question should be: "What would we really like to have?" The former approach makes it relatively easy for the manufacturer to supply instruments but does little to stimulate fresh ideas in design. Perhaps the solution is to present two specifications, one ideal and one acceptable. Those manufacturers who are keen enough might then be stimulated to produce more satisfactory designs.

Specifications for the required accuracy of universal pluviometers in measuring depths can be estimated by examining the best existing instruments (daily-read gauges, storage gauges, pluviographs) which are standard equipment at first - order climatological stations.

Internal instrumental errors in the Australian daily-read gauge appear to be 0.005 inch for small falls, and about 1% to 2% for large falls, including errors introduced by a careful observer when taking a single reading. Careful design, proper observation techniques, and good maintenance should reduce these instrumental errors for large falls to about 0.5%.

Storage gauges are not usually installed at first order climatological stations. For these gauges a lower accuracy than that adopted for daily-read gauges is usually permitted. The gauges are mainly used for engineering, not climatological purposes and internal instrumental errors of less than 3% would generally be acceptable.

2.3.3.2.2 Accuracy of Intensity

Pluviographs installed at first-order stations generally have limits of reading of about $\frac{1}{4}$ point of rainfall and about 3 minutes of time, leading to instrumental errors of about 60%, 30%, 10% and 5% in measuring reasonably high average rainfall intensities for time periods of 5, 10, 30 and 60 minutes respectively. With siphoning or tipping bucket instruments, such accuracies are attainable only if allowance is made for unmeasured rainfall during the periods of siphoning or tipping.

The writer finds it hard to believe that the climatologist is satisfied with such poor accuracy in measuring the intensity of short bursts of rainfall. Certainly the data are not very satisfactory for an engineer interested in flooding of urban drainage systems, where storms of 10 to 30 minutes' duration are often critical. A case seems to exist for an instrument to supply more accurate data on rainfall intensities for short storms. (About 10% error is suggested for 5-minute periods.)

2.3.3.2.3. Accuracy of Time

The accuracy of time measurement in pluviographs appears to be quite easily obtained with normal clocks. Many timing errors can be corrected (often however with much labour) by noting the correct times of starting and finishing of the record. The specifications for Australian pluviographs (Commonwealth of Australia, Bureau of Meteorology, 1958) call for a timing error of less than 5 minutes per day. Although time is used in deriving intensities, it is not inaccuracies of timing which usually cause high errors in intensities, but the difficulty of reading times (i.e. the insensitivity of the time scale.)

2.3.3.3 Sensitivity

2.3.3.3.1 Sensitivity of Depth

There appears to be ample evidence that rainfall depths are practically never required more sensitively than to the nearest point. For climatological purposes, smaller depths than this are simply recorded as a "trace" of rain; tipping bucket mechanisms are usually designed to operate at each point of rainfall; pluviograph charts seldom have least counts less than 1 point.

The overall errors of rainfall measurement are so large that for storms greater than about 20 points in depth, the least count of 1 point is already becoming submerged in errors. Therefore, if any investigator is interested in sensitivity better than 1 point, he will probably be dealing with small storms. These storms may occasionally be studied by engineers for research purposes and, in fact, one special instrument has been developed for road research (the Road Research Laboratory combined total-rainfall and rate-of-rainfall recorder) which gives greater sensitivity than standard climatological instruments. This instrument is capable of an effective least count of 0.1 point, obtained however with the drawback of having a collector which is 30 inches in diameter. Such a sensitivity is in the writer's opinion unwarranted for any except very special purposes such as measurement of dewfall or fog drip. In fact, the internal instrumental errors of the Road Research pluviograph are likely to be 1% or more (Lewis and Watkins, 1955), meaning that a 0.1 point sensitivity is being submerged in internal instrumental errors alone after 10 points of rain have fallen.

Gauges which measure only fairly high depths (such as storage gauges) need not measure as sensitively as 1 point, if this is inconvenient. For such gauges, the accuracy requirements will usually be critical, and the least count will be submerged in instrumental errors for any reasonable fall of rain.

2.3.3.3.2 Sensitivity of Intensity

The sensitivity to which intensity can be measured is strictly dependent on the sensitivity with which the primary variables, depth and time, can be read. Therefore, if specifications are given for the sensitivity of depth and time it is not possible to specify independent sensitivity for intensities. A little thought will show, moreover, that the percentage least count of intensity is obtained by adding the percentage least counts of the primary variables; since the latter vary with the storm duration and depth, the percentage least count (and the actual least count) of intensity will be different for different portions of the pluviograph record. For short, intense storms the least count of time will control the least count of intensity, and for long periods of drizzle, the least count of depth will control.

It will be assumed that primary variables will have sensitivities specified, making specification of intensity redundant.

2.3.3.3.3 Sensitivity of Time

Pluviographs and telemeters are the only instruments which may require timing devices, and the sensitivity to which time must be measured is controlled by the accuracy required in measuring high rates of rainfall.

Engineers seldom are interested in time periods less than 5 minutes for general work, although research work may call for measurements to periods of 1 minute. There is evidence that intensity varies rapidly during some storms; recent studies on high intensity bursts associated with lightning flashes (Moore et al., 1962) have shown intensities varying from zero to about 4 in/hr, in a period of about 20 seconds and for this, a gauge reading in seconds might be required. Such research is quite specialized and it is felt that special equipment should be used (in fact Moore used radar). For normal engineering and climatological stations, where it may occasionally be necessary to measure rainfall intensities for 5-minute storms to 10% (see Section 2.3.3.2.2), a least count of 1/2 minute should be satisfactory.

2.3.4 Critical Data Requirements for Limnometers

A limnometer is any instrument which measures the level of water in a watercourse. The definition includes staff gauges, level recorders and level telemeters. Recording limnometers shall be called limnographs.

2.3.4.1 Range

2.3.4.1.1 Range of Depth

Limnometers in general are set up to measure a range of depths from zero (this is usually slightly below the level at which the stream ceases to flow) up to some estimated peak flood level. The maximum depth to be recorded is usually judged on past flood levels for the stream or for similar streams. If no records exist for the stream, local knowledge of past flood heights is often used. Failing this information, synthetic unitgraphs and estimated stage-discharge relations may be used to give rough estimates of the level of some rare flood. However the maximum depth be obtained, the instrument must be installed so that the full range of depth is measurable. As a guide, depth ranges in Australia seldom exceed 100 ft for streams, but may be several times this value for reservoirs.

Limnographs can be designed so that the range of depth is an irrelevant design criterion, by arranging for the depth scale (or register) to be traversed an unlimited number of times in succession. In designing a universal limnograph, this idea might prove useful.

A stream surface moves up and down and the total surface movement in any given time is in some cases an important design criterion for a limnograph. The critical case will evidently be a flashy stream which is subject to many storms during the year. Data are hard to obtain, but figures have been suggested (for flashy streams on the Queensland coast) of 1,000 ft in six months and 1,500 ft in one year (Mortley, 1960, p.3).

It is not considered worthwhile to investigate maximum surface movements for shorter periods. Surface movement is important only in unattended limnographs and telemetry transmitters, and any such universal instruments should be designed for at least six months of unattended operation.

2.3.4.1.2 Range of Vertical Velocities

The rate of rise or fall of a stream (the vertical velocity of the surface) is an important criterion for design of a limnograph. The storm hydrograph rises more rapidly than it falls, so that highest vertical velocities occur with a rising stream. The rate of rise can, in certain cases such as a flash flood in a dry stream bed, or a bore, be extremely large. In fact, the front of such waves may be almost vertical.

It is not considered necessary for limnographs to measure such high rates or rise since better instruments (e.g. cine cameras) are available for such specialized measurements. Further, if such phenomena are likely to occur, it is usually possible to predict this likelihood and, if required, to install special instruments designed to cope with the conditions.

Ideally, even if a limnograph did not measure extreme rates of rise, at least it should not be put out of action by such events, and it should return to correct registration after the wave has passed.

Apart from bores and flash floods, streams generally rise and fall in a fairly gentle, well-behaved manner. It has been estimated (Mortley, 1960, p.4) that for Queensland streams of a flashy nature an extreme rate of rise would be 30 ft/hr.

It does not necessarily follow that a limnograph designed for a certain rate of rise should also be designed for that rate of fall. In certain cases it might be advantageous to take account of the fact that rate of fall is less than rate of rise.

2.3.4.1.3 Range of Time

The periods at which limnometers are visited vary from one day (often less during floods) to many months. The period depends on the use to which the data are put, the accessibility of the site and often on the design of gauge. The comments of Section 2.3.3.1.3 apply where they are relevant to limnometers.

2.3.4.2 Accuracy

2.3.4.2.1 Accuracy of Depth

The most important reason for taking measurements of stream level is to enable stream discharge to be computed (using a derived relation between stream level and discharge). For first-order stream gauging stations with well-defined stable controls, measurements of annual discharge have an accuracy of about 3%. Readings of depth should be accurate enough to ensure that discharge can be estimated to this accuracy, preferably over the whole range of flows. This latter requirement is difficult to fulfill at very low flows where the percentage error of discharge is even greater than that of level.

Some figures which can be used as a guide to the accuracy attainable at low flows are given in the following paragraph.

According to Stevens (c. 1940, p.29), small depths should without difficulty be measurable with an error of about 0.02 ft. This gives percentage errors of 20% and 2% in measuring depths of 0.1 ft and 1 ft respectively. Conversion to discharge would increase these errors to about 40% and 5% respectively, allowing for some uncertainty in the value of the conversion constant.

It is apparent that satisfactory accuracy can normally be obtained for streams which deliver the bulk of runoff at depths greater than about 1 ft. For streams which do not meet this requirement special limnographs of higher accuracy might be required. However, a better solution, which is usually adopted if feasible, is to make the low-water control more sensitive; i.e. for small flows the rate of change of discharge with level is increased. With this solution usually available, there is little need for limnometers to measure more accurately than to the nearest 0.01 ft, and frequently 0.05 ft is satisfactory.

Limnometers are used for other purposes (flood forecasting, calculation of reservoir contents) as well as estimation of discharge. However, these other uses would normally require lower accuracy than discharge measurements.

2.3.4.2.2 Accuracy of Vertical Velocity

Although a limnograph must respond to fast rises and falls, the measurement of such vertical velocities is not usual. Therefore the accuracy of measurement of such velocities need not be considered in designing any universal limnometer.

2.3.4.2.3 Accuracy of Time

The comments of Section 2.3.3.2.3 apply here also.

2.3.4.3 Sensitivity

2.3.4.3.1 Sensitivity of Depth

Since most streams are well-behaved, without abrupt changes in their rise and fall, a time-sampling technique is usually adequate to describe stream behaviour. It is assumed that smooth curves may be drawn between the sampled measurements. When extremely low flows occur, with stream level below the limit of registration of the limnometer, it is not possible to estimate the flows very accurately. However, when flow is in this region, the hydrograph is generally in recession and a reasonably reliable equation can be fitted to the recession curve. Discharges can be computed from this equation without the need for measurement.

It is the writer's opinion that extreme sensitivity is not required in limnometers, and 0.1 ft is suggested as a reasonable depth sensitivity.

2.3.4.3.2 Sensitivity of Vertical Velocity

As discussed in Section 2.3.4.2.2, vertical velocity is not normally measured and no sensitivity requirements need be specified.

2.3.4.3.3 Sensitivity of Time

In Section 2.3.4.3.1 it was pointed out that most hydrographs are well-behaved and that smooth curves drawn between the sampled points are satisfactory. However, it is essential that enough samples are taken to ensure that all relevant information in the hydrograph is presented. Even if the hydrograph is sampled continuously, errors will arise if the time scale is not sensitive enough to allow the rising and falling limbs of the hydrograph to be separated. In this case the effective sampling rate is too small.

The least increment of time measurable controls the effective sampling rate, which must be sufficient to define the critical parts of the hydrograph, which are the steeply sloped rising limbs. As previously explained, it is not intended that the near-vertical slopes of flash floods and bores should be recorded, only the well-behaved rises and falls. For very small experimental catchments, appreciable rises are to be expected in periods of about 1 or 2 minutes.

2.3.5 Tentative Specifications for Universal Instruments based on Critical Requirements

2.3.5.1 Daily-Read Gauge

Storage capacity : 10 inches minimum

Internal instrumental accuracy: 1 point for falls up to 1 inch;
1% for falls over 1 inch

Sensitivity : ½ point for falls up to 5 points;
1 point for falls over 5 points.

2.3.5.2 Storage Rain Gauge

Storage capacity : to specification. (Gauges will normally be made in several sizes for unattended operation for periods up to 1 year.)

Internal instrumental accuracy : 3% for large falls.

Sensitivity : sufficient to ensure that specified accuracy is achieved; it may vary with stored contents.

2.3.5.3 Pluviograph

Maximum depth measurable: limited only by supply of recording medium and power

Maximum intensity measurable: 30 in/hr

Maximum period between visits: 1 year

Instrumental accuracy of depth: 1 point for falls up to 1 inch; 1% for falls over 1 inch.

Instrumental accuracy of intensity: 10% over measurable range for 5 minute burst.

Accuracy of time: 3 minutes per day

Sensitivity of depth: 1 point

Sensitivity of time: 0.5 minute

2.3.5.4 Rainfall Telemeter

Specifications as for pluviograph, current data to be available at all times at receiving station.

2.3.5.5 Limnograph

Range of level: preferably unlimited, but 100 ft satisfactory.

Maximum vertical velocity: instrument must record velocities up to 30 ft/hr and must resume proper operation after the passage of near-vertical wave fronts.

Maximum total vertical movement: 1,500 ft

Maximum period between visits: 1 year

Accuracy of level: 0.02 ft up to 4 ft; ½% above 4 ft

Accuracy of time: 3 minutes per day

Sensitivity of level: 0.1 ft

Sensitivity of time: 1 minute

2.3.5.6 Stream Level Telemeter

Specifications as for limnograph, current data to be available at all times at receiving station.

3. TIME-SAMPLING OF HYDROLOGICAL VARIATES

3.1 PREAMBLE

Hydrological variates observed at a point may be measured by taking intermittent sample readings or continuous readings. It might be thought that continuous recording always gives better information [1] than intermittent recording. However this is not the case. When the sampling rate is low (i.e., long periods between sample readings)some information is lost. By increasing the sampling rate, more and more information is recovered, and eventually a state is reached when the sampled record contains all the information of the original. It is interesting to note that this occurs before the sampling rate becomes infinite: if the hydrograph is considered as a segment of a repeating wave form and analysed harmonically into a Fourier series, then a sampling rate slightly higher than twice the frequency of the term of highest order in the series will ensure that all information is recorded. This is the well-known "sampling theorem" of information theory (Goldman, 1953 p.67).

In many, if not all, problems which use hydrological data it is not necessary to recover all the information contained in the original fluctuations of the variates. In such cases, an adequate sampling rate would be less than half the highest frequency contained in the original.

The taking of a sample reading can be initiated by some process which is more or less random, but this system is not used, and has no apparent advantage, in measuring rainfall or stream level. The only systems which have been generally adopted are clock-controlled and event-controlled systems.

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(1) The word information is used in its technical sense. See definition in Appendix A.

In the first system readings are taken in a definite sequence which is determined by a clock. Readings may be at regular or irregular intervals, and may be initiated automatically by the clock or else an observer may take a reading after referring to the clock.

The event-controlled system, on the other hand, depends on a change in some variate to initiate the taking of a sample. Most frequently, the event which triggers the sampling is a change in the variate being measured; e.g. if stream level is being measured, a stream rise or fall of known magnitude is the event used as a trigger. It is possible to use other events (i.e. changes of atmospheric pressure or temperature) to trigger the sampling but this is very rarely done.

Occasionally both clock- and event-controlled systems may be used together, the sampling rate (clock-control) varying with the magnitude of the variate or with its rate-of-change (event-control).

Section 3 deals with various systems of time-sampling, discussing their relative advantages and disadvantages. Continuous sampling is also treated in this section, since it may be considered as a system of time-sampling with theoretically infinite sampling rate. Random or semi-random control of sampling will not be treated.

3.2 CLOCK-CONTROLLED SAMPLING

3.2.1 Irregular Clock-Control

Variates which show intermittent but predictably cyclic activity can be measured adequately by irregular clock-controlled sampling by arranging for frequent readings to be taken when the variate is most active and less frequent readings when the variate is quiescent. Hydrological variates are not cyclic nor, in general, are their periods of activity predictable, and irregular clock-controlled sampling is little used.

However, occasionally we do find the system used, but only to provide some extra information not provided by an existing regular clock-controlled system. For example the system used for sampling rainfall depth at daily intervals (with readings usually at 9 a.m.) provides fairly meagre information and some stations supplement this by taking an additional reading at 3 p.m. The time intervals between readings then follow the irregular sequence:

Even this can, if desired, be considered as two superimposed regular clock-controlled systems:

In some cases, the record produced by a time-sampling system might appear to indicate irregular clock-control, but it is almost certain that further investigation will show that the system is in fact event-controlled; irregular clock-control is rare in hydrological work.

3.2.2 Regular Clock-Control

This is the most widely used of all systems of intermittent sampling.

For variates with more or less continuous activity, the method is quite suitable, especially if the frequency (f_{max}) of the highest-order term of the Fourier series can be estimated. The sampling rate then depends on the amount of information required, and need never be higher than $2f_{max}$. Higher rates simply waste money by wasting time, energy and paper. However, for sampling rates just above $2f_{max}$, it is often difficult to recover all the information which is on the record, because no redundant data are present. (An analogous situation exists when trying to follow a concisely written mathematical discussion: it is made more easily understandable by a few words of explanation). When deciding to use sampling rates less than $2f_{max}$, the money saved must be balanced against the information lost in recording.

When regular clock-controlled sampling is applied to variates of an intermittent nature which have periods of little or no activity followed by periods of high activity, some disadvantages become evident. In order to record the high activity satisfactorily, one must adopt a high sampling rate. This results in waste of money when the variable is inactive; the record here is simply a long list of repeated identical readings. If it is decided to save money by adopting a low sampling rate, then one is forced to throw away most of the information when recording the high activity of the variate. Hydrological variates are of course extremely variable, intermittent and unpredictable, and the argument of this paragraph applies with special force.

A solution to the problem of economically recording the whole of the fluctuations of hydrological variates is to retain the system of regular clock-controlled sampling, but to arrange for the sampling rate to be changed as the variate changes. As an example, storm flow in an ephemeral stream or sewer could conceivably be recorded satisfactorily and economically as follows:

(a) When flow is zero, the equipment does not operate, i.e. sampling rate is zero.

(b) When the stream starts to rise, the equipment is switched on with high sampling rate in order to record the steep rise of the hydrograph and any rapid fluctuations near and after the crest.

(c) When flow has decreased to some pre-determined low value the sampling rate is suddenly decreased in order to record economically the slowly falling recession curve.

(d) When flow practically ceases, the equipment is switched off; sampling rate returns to zero.

Variations on this theme are many: the sampling rate can be made to vary with the magnitude of the variate, with its rate-of-change, or according to some pre-arranged time-sequence (clock-controlled). The sampling rate may change suddenly from one value to another or may change progressively. One factor common to all these methods is that extra equipment is necessary to vary the clock-controlled sampling rate.

3.3 EVENT-CONTROLLED SAMPLING (EVENT TIMING)

In the common time-controlled system of sampling, the variate is measured at certain increments of time. It is worthwhile examining the alternative method: recording the time of occurrence of certain increments (or decrements) of the variate. Such a system might be called an event-controlled time-sampling system, but to avoid frequent use of such a cumbersome title, the system will henceforth be referred to as "event timing."

The event which has to be timed is the occurrence of some predetermined value of, or change in, a variate. This variate is normally the variate being measured, but under certain circumstances it might be convenient to sample one variate at times which are controlled by the behaviour of another variate.

The simplest method of event timing is to record the times of occurrence of successive equal increments of the measured variate, which is assumed to be capable of only increasing, decreases not being possible (e.g. cumulative rainfall depth). It will be appreciated that the actual value of the variate need not be recorded; provided one knows its initial value, the current value at any moment can be deduced by counting the number of events (or increments) which have been recorded since the initial time. All that is really necessary is a record of the time at which each event occurred.

A slight complication exists when the variate shows bi-directional behaviour, decreasing as well as increasing (e.g., stream level). In this case one must be able to distinguish between a rising event and a falling event; in other words, the record must show not only the time of occurrence but also the polarity of each event. This is necessary and sufficient to allow all the information in the original fluctuations to be recovered from the record. However, if convenient, a cumulative count may also be kept of the events, taking account of differences in polarity, and this provides, in effect, a reading of the current value of the variate.

Event timing need not be regular. It is possible to note the time of occurrence of any predetermined sequence of increments, regular or irregular, and this would still be a valid system of recording. In practice there might be some advantage in adopting such a system (e.g. uniform accuracy of measurement over a wide range of the variate), but other disadvantages would almost certainly occur (e.g. more complex and more expensive equipment in order to trigger at unequal increments).

The event timing system of time-sampling seems particularly well suited to measuring variates which are likely to have long quiescent periods, with occasional periods of feverish activity. This aptly describes the behaviour of many phenomena, of which rainfall depth and stream level are only two. Among others behaving in this way may be listed many meteorological phenomena (wind velocity and direction, temperature, pressure), wave heights, volume of road traffic, earthquake tremors, and cosmic ray showers. It is suggested that event timing methods might be used in recording such variates more satisfactorily than methods at present employed.

The most important advantages gained from the event timing method in measuring such sporadic variates are:

(a) When little or no activity is evident, little or no recording takes place, saving time, energy, paper and money.

(b) When the variate is active, its very activity ensures that many samples are taken; if the sample is taken at regular increments of the variate, the sampling rate is in fact proportional to the activity of the variate, as represented by its rate-of-change. (A corollary of this is that rates-of-change of a variate are measurable with practically constant accuracy. For the error in each increment (dx) of the variate x will be approximately constant, and the error in the time interval (dt) between successive samples will usually be negligible; the percentage error in the rate-of-change dx/dt will then be governed only by the constant error in dx. Hence the percentage error in dx/dt is reasonably constant except when dt becomes small and its error becomes appreciable; this will occur at high values of dx/dt.)

(c) When the event timing system is used in a telemeter, the equipment at the field station can be made relatively simpler than for clock-controlled systems. In fact, no clock is needed at the transmitter; the events to be timed are themselves used to send signals to the receiver of the telemeter, the actual timing of each event being done by a clock at the receiver. Clocks in field equipment have the reputation of being relatively unreliable components and if they can be eliminated from the field completely, the general quality of records should be improved.

However, most systems have some disadvantages and the event timing system has two important ones:

(a) During prolonged periods when the variate is quiescent no records will be produced. Hence one cannot be sure that the instrument is in working order.

(b) If no independent record is kept of the value of the variate, then an event which is missed because of faulty equipment, or a spurious event which might get recorded, will cause any subsequent calculation of the value of the variate to be erroneous. This error will continue to exist until an independent check is made of the value of the variate.

These two disadvantages are of particular importance in a telemeter installed at a remote location, and it is felt that some extra expense and instrumental complexity is worth while if these disadvantages can be overcome. This is discussed more fully in Section 6.

3.4 CONTINUOUS SAMPLING

Continuous sampling is an extremely common method of recording a variate. The record is presented as a graph of the variate against time, this form of record being frequently termed an analogue record. The system is clock-controlled, the recording medium (usually a paper chart) being moved past the stylus at a known, and usually constant rate.

The stylus, controlled by the variate, moves across the chart, either in a straight line or in an arc, depending on the design of the instrument. The coordinates can thus be rectangular or curvilinear; the coordinate system can be cartesian or polar, the latter case corresponding to the disc-type chart.

Whilst time is almost always recorded to a uniform scale, it is possible for the variate to be recorded non-linearly. This is sometimes no disadvantage, but linearity is helpful if the record has to be analyzed graphically. The rate-of-change of the variate corresponds to the slope of the graphical record, and if rate-of-change is important, then instruments which record the variate linearly on rectangular cartesian coordinates have this definite advantage over others using polar or curvilinear cartesian coordinates: that a given rate-of-change always corresponds to the same slope of the graph.

The theoretically infinite sampling rate of the continuous sampling method is a finite rate for all practical purposes. The thickness of the trace drawn by the stylus, and the speed of the chart, together set a limit to the smallest increment of time which can be used in analysing the record. It is this smallest interval which in fact determines the effective rate of sampling. The only ways to increase the effective sampling rate are to increase the chart speed and/or decrease the width of the trace drawn by the stylus. It will be evident that a continuous record made with a slow chart speed and a thick trace may contain less information than an intermittent record.

Just as regular clock-controlled time-sampling is quite satisfactory for variates showing continuous activity, so can constant-speed continuous sampling record such variates satisfactorily. However, when the variate displays erratic and intermittent activity (as do most hydrological variates), then constant-speed continuous sampling displays the same fundamental disadvantage which regular clock-controlled sampling displays: a balance must be struck between good economy (which demands a slow chart speed) and sensitivity in recording the high activity of the variate (demanding a fast chart speed). Since the demands are diametically opposed, a compromise must be made; one cannot have both sensitivity and economy.

This problem can be overcome in the case of intermittent sampling by increasing the sampling rate when the variate becomes active, as described in the last two paragraphs of Section 3.2.2. The same method is available for continuous recording by changing the chart speed with the activity of the variate; this is rarely done however, probably because of the mechanical complications which would occur in the clock gearing.

3.5 SUMMARY

Hydrological variates quite naturally behave sporadically with relatively long periods of little or no change, interspersed with periods of higher activity. The times of occurrence of high activity cannot be predicted in advance. These variates, and others which behave in a similar way, can be recorded by a clock-controlled system, either continuously or intermittently. However, economy of operation and sensitivity to high rates-of-change of the variate cannot both be obtained with such a system, unless the system is complicated by introducing some way of varying the sampling rate or the chart speed.

On the other hand, if an event-timing system be used economy and sensitivity can easily be obtained together, the equipment remaining fairly simple. This is especially true in telemetering applications, where the field transmitters contain no clocks and hence should be considerably cheaper and more reliable than those using a clock-controlled system.

Event-timing methods have a few major disadvantages, but these can be overcome, albeit at the cost of complication of the equipment.

4. ERRORS IN MEASURING HYDROLOGICAL VARIATES

4.1 PREAMBLE

Whenever a quantity is measured, or estimated from measurements, errors are introduced. Such errors may be classified as sampling errors, instrumental errors and observational errors.

Sampling errors occur whenever the variate is not measured continuously (in both time and space), and thus they increase as fewer measurements are taken. Poor experimental technique can also cause large sampling errors (for instance, when using a non-representative sample or poorly located instruments). It is not intended in this work to discuss the problems of representative sampling in space, and the problems of time sampling have already been discussed in Section 3. Accordingly sampling errors will not be further treated.

The instrument used for measurement introduces errors which are inherent in its design. These errors are of two kinds, classified in this thesis as internal and external instrumental errors. The internal errors arise because of physical limitations of the instrument which make it incapable of measuring exactly what is presented to it; the external errors come from the distortion of the variate caused by the very presence of the instrument, so that even an instrument with no internal errors would be incapable of making a true measurement. Many instruments have negligible external errors but it is difficult to design rain gauges so that these errors are small. Section 4 is mainly a discussion of these external and internal instrumental errors in rainfall and stream level measurement.

Recording instruments have their own peculiar troubles associated with the recording gear. Typical of these are clock stoppages, tearing of paper, paper-feed failures, effects of humidity on the chart and consequently on the trace, ink-feed failures and so on. The frequency with which these troubles occur seems to depend mainly on the thought which has gone into design and development of the instrument. It is not intended that such recording problems be discussed in this thesis.

Observational errors are introduced by the observer when he reads the instrument. They are often caused by carelessness or lack of knowledge of observational techniques. They can be made less likely to occur by good instrumental design, the designer paying attention to the details which make it easy for the observer to take a reading. Such aspects of instrument design will receive brief attention in Sections 4.2.3 and 4.3.3.

4.2 ERRORS IN RAINFALL MEASUREMENT

4.2.1 External Instrumental Errors

Pluviometers, in general, give indications of rainfall which are influenced by the instrument itself: by its shape and size, by its position relative to the ground and by its position relative to surrounding objects. The position relative to other objects is usually referred to as the exposure of the instrument. Errors arising from the presence of the surroundings (poor exposure) are not instrumental in origin but are space-sampling errors. Therefore they will not be treated in this section, nor do they come within the scope of this thesis.

4.2.1.1 Aerodynamic Errors

Errors caused by the shape, size and elevation of the pluviometer arise from the geometry of the installation and are instrumental in origin. They are caused by the fact that the vector field of raindrop trajectories is disturbed by the gauge itself, this disturbance increasing as wind velocity increases and as drop size decreases. For standard rain gauges, this disturbance causes the catch to be less than the true rainfall (i.e., the depth which would have fallen in the absence of the gauge). In other words, standard gauges have a negative error from this cause. Such errors are usually called aerodynamic errors since they are wind-dependent, and a gauge with no such error would be described as aerodynamically neutral.

Aerodynamic errors have been extensively studied experimentally but little theoretical work has been done. One theoretical approach (Moss, 1960) has shown that air in a converging wind field possesses a longitudinal acceleration and the effect of this is to force the drop trajectories progressively farther apart as one moves along a streamline towards the convergence zone; in a diverging field, the drop trajectories converge because of the deceleration of the air. Experiments by Moss indicate that in the region above a standard gauge the wind field is convergent, hence the drops will separate and the catch will be less than the true catch. Further, rough quantitative estimates showed that "the rain-gauge convergence zone will seriously affect all sizes of raindrops but particularly those of smaller diameters than the median drop."

The above conclusions, theoretically derived, have been verified by experiments by many observers. It has been shown (Warnick, 1953) using sawdust to simulate snow precipitation, and a wind tunnel to provide controlled wind velocities, that a U.S. standard gauge caught only 27% of the true catch in a 15 m.p.h. wind. A summary of such experiments has been published (Handcock, 1960).

4.2.1.2 Splash

If, instead of a pluviometer, only a thin bodyless collector orifice existed at the gauge site, one would expect that any splash from the ground which entered the orifice from above would be exactly balanced by splash from the ground entering the orifice from below; the nett effect would be zero. Further this would remain true for all wind velocities and for all heights of orifice.

The presence of the body of the gauge and the catchment funnel distort the "splash field" in the following ways. Firstly the body of the gauge effectively prevents ground splash moving upwards through the orifice, and secondly the collector funnel provides extra splash upwards through the orifice. It is practically impossible to ensure that the upward splash from the funnel equals the upward splash from the ground which it replaces, hence there is usually some nett error caused by splash.

One would expect, since collectors are normally placed at least 12 inches above ground, that outsplash from the funnel would be greater than insplash from the ground, giving an overall negative error.

The magnitude of the error is difficult to determine since it cannot normally be separated from other errors. However, tests have been done using gauges which were identical except for the vertical position of the funnel (Mani, 1957) (Glasspoole, 1931) (Kadel, 1930). The results as a whole were statistically rather inconclusive, but Kadel's experiments seemed to show that with strong winds, negative errors exist for gauges with highly-placed funnels.

4.2.2 Internal Instrumental Errors

Many factors exist in rain gauges and pluviographs which lead to incorrect measurement of the nett catch which reaches the funnel of the instrument. Some of these factors act in a random fashion, producing errors which in some gauges might be positive, in others negative. Examples are tolerances in manufactures, some types of accidental damage and inaccurate adjustment. Other factors tend to produce a bias (either positive or negative) in the measurement. In this thesis random errors will not be treated but errors which cause bias will be discussed fairly fully.

4.2.2.1 Evaporation from the Gauge

When rain falls into a dry pluviometer, some of the rain may be retained as a surface film on the rim, funnel and other parts of the instrument. This water, or an amount equal to it, will eventually evaporate. The error from this cause may be appreciable, especially where rain falls as a series of short, light showers well separated in time. As far as is known, no measurements of such evaporative losses have been made.

Evaporation also occurs from water which is in storage in the measuring device. Experimental work (Carter, 1929) in Nebraska U.S.A. indicates that evaporation from a standard U.S. rain gauge, kept reasonably full, was of the order of 0.01 to 0.02 inches per day under fairly severe conditions of exposure (corresponding to a pan evaporation of 6 to 9 inches per month, which is equivalent to about 0.25 inches per day).

Most gauges which are read daily would not be subjected to such extreme conditions. The water is removed from the gauge in the early morning (usually) before conditions are favourable to high evaporation. Therefore water is not in the gauge continuously and the abovementioned figures could be reduced appreciably. A more reasonable figure for evaporation, averaged over winter and summer, would be about .005 inches per day, and this would occur only on rainy days.

Assuming one day in five to be a rainy day, one arrives at a rough estimate of .001 inches per calendar day for evaporation loss from a daily-read rain gauge. This corresponds to about 0.4 inches per annum. (It must be emphasized that this figure is largely guesswork; nevertheless the writer thinks it is probably an overestimate for temperate regions).

Gauges which are attended infrequently could have a quite appreciable error (several inches per annum) because of evaporation of the catch. This is not usually the case, however, because it is standard practice to use some evaporation preventative with these gauges.

One would expect the magnitude of the evaporation losses to depend on the insolation and insulation of the gauge and on its ability to reflect incident heat energy. The characteristics of the wetted surfaces (slopes, materials, surface treatments) will all be important in determining the amount of water retained. The general design of the instrument (with reference to such factors as area of exposed water surfaces and orifices which might restrict flow of water vapour) will also appreciably affect the evaporation from the stored catch.

Although in some designs of pluviograph, evaporation from the storage chamber is detectable and can be allowed for, evaporated water normally goes unmeasured. Errors from this cause thus introduce a negative bias to the measurement, meaning that the true amount of rainfall is under-estimated.

4.2.2.2 Effect of Size of Collector Orifice

Experiments show (Huff, 1955) (Puri, 1929) that very small orifices introduce a negative bias, but that the size of the collector orifice has little effect if its dimension exceeds 3 inches. The position is summarized by Handcock (1960) as follows:

"It would appear that for the collector areas usually used for rain gauges (collector diameters from 5 in. to 12 in.) there are no large errors introduced by the use of areas of different sizes."

4.2.2.3 Admission of Extraneous Matter

Any insoluble solids which enter the measuring device displace some precipitation. The volume of precipitation then appears to be higher than it should be if volumetric methods are being used. If measurement is by gravimetric means, then the solids are weighed in addition to the precipitation, again leading to an apparent increase in the catch.

If soluble solids are added, and if these actually have time to dissolve, then a volumetric instrument will show little or no error, since the volume of water is not appreciably changed by the dissolved matter. However, a gravimetric instrument will be affected and will over-register.

Addition of extraneous liquids, whether miscible or immiscible with water, will cause an apparent increase in volume and mass of the rainfall catch, hence both volumetric and gravimetric instruments will over-register.

The positive error usually resulting from adding extraneous matter is normally small provided the matter is measured once only. For example, the small amount of dust and dirt caught in a daily rain gauge is normally read at the end of each day and discarded when the measuring glass is rinsed out. However if such matter settles and is allowed to harden in the bottom of the measuring vessel it gives every subsequent measurement a positive bias. Likewise, such deposits of solid matter in the float chamber of a siphoning pluviograph, or in the measuring buckets of a tipping-bucket pluviograph, introduce a positive error at each operation of the measuring device. These errors could conceivably have an appreciable cumulative effect, although no experiments seem to have been done on this.

4.2.2.4 Effect of Sloping Collector Orifice

The standard installation for a pluviometer is with its collector orifice in a horizontal plane. Tilt of the orifice causes an alteration in the catch proportional to the cosine of the tilt angle for vertical raindrop trajectories; this leads to an error of under-registration. This error is practically negligible, requiring a tilt of about 6 degrees to produce a 1% reduction of catch.

If rain is not falling vertically, a tilted gauge might collect more or less than a horizontal gauge, depending on the orientation of the tilt axis relative to the raindrop trajectories, on the angle of tilt, and on the angle of the trajectories. The problem has been studied from a theoretical viewpoint (Serra, 1953) but unfortunately Serra's treatment ignores the separation of the drop trajectories in the convergent wind field above the gauge. Serra makes it clear that the hydrologist and the meteorologist are in fact trying to measure two different things: the meteorologist wants to know the precipitation falling through the atmosphere in order to study storms as rainfall generators, whilst the hydrologist wants to know how much rain reaches the ground in order to study runoff. The latter (the ground rainfall) depends on ground slope, the windward slope normally receiving more rain than the leeward. Although pluviometers with sloping orifices have been considered as indicators of ground rainfall, no general agreement has been reached on the best type of gauge. The problem is in fact quite complicated, as has been shown by Serra. In fact, a solution which is satisfactory under all conditions might not be possible. It is generally considered that there is little to be gained by replacing the standard horizontal gauge by a non-standard tilted gauge when ground slopes are, say, less than 10 degrees, and the problem will not be considered further in this thesis.

4.2.2.5 Leaks

Leaks in a gauge obviously lead to an under-estimate of the catch, and can be eliminated by proper maintenance or replacement of faulty equipment.

4.2.2.6 Clogging of Apertures

Dirt, leaves, bird droppings, spider webs and insect nests are frequently found in pluviometer funnels. Such obstructions increase the area of wetted surface and hence increase evaporation errors. Bad clogging can make the gauge useless by preventing water inflow altogether or by reducing the flow to such an extent that water banks up in the funnel and overflows. In pluviographs, clogging can so restrict the rate of inflow that short-period intensities are under-estimated. (See Appendix M for an example of this effect.)

4.2.2.7 Friction and Backlash in Linkage Mechanism

Some types of pluviograph incorporate mechanical linkages and floats between the measuring container and the recording device, the mechanism being so arranged that errors can be introduced when it operates. Ideally (unless a step-by-step movement is being used), any increase in the water level in the container should be immediately apparent as a movement at the recorder. This does not happen in practice because friction in the mechanism means that work must be done to drive the recording stylus. Therefore the mechanism is subject to loads which introduce elastic deformations. Further, any looseness or backlash in the connexions of the mechanism causes a delayed response in the recorder. If a float is being used, there must be some extra submergence of the float to provide the force which loads the mechanism; this submergence will vary if the friction in the mechanism changes. Float submergence has the same effect as backlash, causing a delayed response.

For most designs of pluviographs, the errors arising from backlash and friction are negative. They can be quite appreciable and in bad cases can cause the instrument to become inoperative.

4.2.2.8 Off-Duty Error

Pluviographs which operate using a repeating cycle (i.e. instruments using siphons, tipping buckets, or stepped cams) may introduce errors when proceeding from the end of one cycle to the beginning of the next. During the period between cycles the instrument is, so to speak, off-duty and the error introduced will be called the off-duty error.

4.2.2.8.1 Off-Duty Error in Siphon Pluviographs

The action of siphon pluviograph is that water in the measuring chamber is siphoned out automatically whenever the chamber becomes full. When the water level has fallen to a predetermined point, the siphon is broken and the chamber once again can begin measuring.

An error arises from the fact that the chamber takes some seconds to empty through the siphon, and water which enters the collector during this period is fed into the chamber and is siphoned out; accordingly it is not measured by the recording device, operated by a float in the measuring chamber. This off-duty error is evidently negative, since the instrument under-registers. It is also, to a first approximation, proportional to rainfall intensity, because the amount of water entering during the off-duty period is proportional to rainfall intensity, provided one assumes an off-duty period of constant length. (In practice the off-duty period increases slightly with rainfall intensity.)

Siphon pluviographs are usually adjusted so that a specified amount (usually 0.20 or 0.40 inch) of rain is siphoned out of the chamber when the rainfall intensity is infinitesimal. However, the actual amount can be altered by adjustments provided. It is therefore possible to adjust the instrument to read correctly for any specified intensity (p) compensating for the rain which is siphoned out during the off-duty period. An instrument so adjusted will have a negative error for intensities greater than p and a positive error for intensities less than p.

The magnitude of the off-duty error can be estimated fairly easily by measuring the time of siphoning and computing the wasted rainfall for various rainfall intensities. For typical gauges the error is of the order of - 3% for each 1 in/hr of rainfall intensity (Lewis and Watkins, 1955), (Handcock, 1960). Any denting or clogging of the siphon will increase the error.

By collecting the discharged water (or by comparison with a nearby rain gauge) the total error over a period can be found and the wasted water can be roughly distributed among the off-duty periods; this is standard technique with siphon pluviographs.

4.2.2.8.2 Off-Duty Error in Tipping Bucket Pluviographs

The tipping bucket is a bi-stable balance beam which is provided with two buckets A and B, only one of which can receive water at any one time (Fig. 4.1).

The pivot, C is mounted directly below the outlet from the collector and the stops D and E are normally adjusted so that when a specified amount of rain (usually 0.01 inch) has been collected in one bucket, the beam overbalances. This causes the second bucket to be brought into the receiving position and allows the rain in the first bucket to be discharged.

Error is introduced because the bucket takes some time to tip. This time is quoted as about 0.2 sec (Middleton and Spilhaus, 1953, p.124) for a Canadian instrument. If one imagines the stops to be adjusted so that the beam tips when just 0.01 inch has entered a bucket, then the instrument should have no off-duty error when rain falling at less than some threshold intensity. At the threshold intensity, drops of rain will be emerging from the collector outlet at such a rate that the period between drops will just be equal to the time taken for the beam to move from rest to its horizontal mid-position (the lag time). If this threshold intensity is exceeded, then one or more extra drops will fall into the first bucket (instead of into the second, where they belong) and this rain will be discharged unmeasured. The error from this cause will be negative and will increase as rainfall intensity increases above the threshold value.

The threshold intensity will obviously vary with the design of gauge, but assuming a typical gauge with an 8-inch collector diameter, a drop diameter of 0.1 inch, a bucket tipping every 0.01 inch, and a lag time of 0.2 sec, the threshold intensity may be computed to be about 0.2 in/hr.

At high rates of rainfall (greater than about 1 in/hr) the effect of the threshold becomes insignificant and the percentage error in measurement may be considered proportional to rainfall intensity, the constant of proportionality depending on the lag time. For a gauge with a lag time of 0.2 sec, the error can be computed as -0.55% for each 1 in/hr of rainfall intensity.[1] This computation is confirmed by experiments on the Canadian gauge mentioned above (Middleton & Spilhaus, 1953), which has an error of - 0.6% for each 1 in/hr (see Fig. 5.7). The magnitude of the error will evidently increase as the pivot friction increases or if the action of associated equipment (e.g. electrical switches) becomes sticky.

Since the stops D and E (Fig. 4.1) are adjustable, it is possible so to adjust them that the instrument reads correctly at some intensity (p) above the threshold intensity. If this be done, the gauge will have a negative error for intensities greater than p, and a positive error for intensities less than p.

Errors could theoretically be corrected by separately measuring the total rainfall volume and distributing the difference through the record in proportion to rainfall intensity. However, this is seldom if ever done because of the tedium involved.

4.2.2.8.3 Off-Duty Error in Stepped-Cam Pluviographs

A stepped-cam is used in some designs of pluviograph in order to return the stylus to the beginning of the chart at the end of each cycle. With few exceptions, these instruments are float-operated, non-siphoning gauges, intended to operate with a continuously rising float until the design capacity is reached. Since it is inconvenient to have the

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(1) At 1 in/hr there are 100 tips/hr or 1 tip every 36 sec. The off-duty/on-duty ratio is therefore 0.2/36 or 0.55%. Since the error arises from wastage of water during the off-duty period, the error must also be 0.55%.

full capacity of the instrument represented by the width of the chart, the scale is effectively expanded by allowing multiple traverses of the stylus across the chart. This gives greater sensitivity and keeps the chart to a manageable width. During the time when the stylus is returning to zero, the instrument, though not actually recording, is not strictly off-duty, because water entering to float chamber at this time is not thrown to waste. This water causes a rise in the float which will be indicated by the stylus when it has returned to zero. Strictly speaking, the stylus will not return quite to zero, but to some higher value, representing the water added during the off-duty period. The only effect of the off-duty period is to cause a slight break in the record; this is practically of no importance since the period is quite short, usually of the order of 1 second, whilst the on-duty period is usually many minutes.

4.2.2.9 Freezing of the Catch

When water freezes in the measuring chamber, that part which turns to ice increases in volume by about 10%. If this ice breaks up and floats on the surface of the remaining water, it is easily shown that the water level does not change (neglecting thermal expansion of the water). A reading of rainfall depth, either by dipstick or by graduated measuring cylinder, will not be in error from this cause. Further, a float pluviograph will not be affected provided the ice is broken up and floating in the water surrounding the float. However, since the water annulus around the float is generally quite small (and the ice therefore sticks to the float), it is quite usual for the float to be pushed upwards by even moderate amounts of ice. When the ice melts, the float returns to its original position. This makes the error detectable and correctable.

Other errors may be caused by the presence of ice in siphon pluviographs, ranging from over-registration because of repeated measurement of solid ice (see Section 4.2.2.3) to complete breakdown of the instrument by bursting. Such errors are rare in stepped-cam pluviographs, which have more capacious float chambers, but if the float in these gauges sticks because of freezing and rain occurs when the gauge is so frozen, then portion of the intensity record will be missed. However heavy rain in such freezing conditions is unlikely in most locations. If certain sites are prone to these conditions, steps should be taken to heat the gauge.

Gravimetric instruments do not usually suffer from errors caused by freezing of the catch. Some exceptions might occur with tipping bucket gauges; freezing of water in a bucket which is on the point of tipping might cause the centre of gravity to shift because of lateral expansion, and sticking of ice in a bucket might cause over-registration (see Section 4.2.2.3). However, such occurrences would be rare.

4.2.2.10 Failures during the Off-Duty Period

It occasionally happens that the mechanism which operates during the off-duty period fails to function properly. This usually results in a complete loss of part of the record.

Siphon instruments appear to be particularly susceptible to this fault, and it appears that the tilting siphon gauge (which starts the siphon action positively) was specifically developed because of the unreliability of the "natural siphon" gauge. Both are described in reference books (Middleton and Spilhaus, 1953, pp.121-2). Failure of the siphon to operate results in a trace which remains at the upper edge of the chart, caused by the fact that the float has remained at the top of the chamber while water dribbles out of the siphon tube.

Stepped-cam instruments occasionally give faulty records because the stylus fails to return or returns only part of the way. Friction is usually the cause of this. Once again, part or all of the record is lost.

Tipping bucket instruments can also suffer from failure to tip at the measured weight of water. If failure is complete, the bucket will overflow and the whole record will be lost; with a pivot which is not jammed but only slightly sticky, some extra water might cause the beam to tip, and this will cause under-registration.

4.2.2.11 Vibration

A pluviograph which uses a repeating cycle (siphon, stepped-cam or tipping bucket types) can give erroneous readings when subject to vibration from wind, earth tremors, accidental knocks or other causes. Such vibrations have the effect of prematurely causing the off-duty mechanism to operate. The gauge then registers a certain precipitation when in fact that amount has not been reached. Hence a positive error exists from this cause. As far as is known, no measurements of this error have been made.

4.2.3 Observation Errors

Errors arising during observation are many and varied. They occur from a number of causes, the most important ones being carelessness on the part of the observer and/or his lack of knowledge of the proper techniques of observation.

Apart from random errors associated with the limit of reading of any instrument (and which will not be discussed in this thesis), the only other observation errors arise from unforeseeable contingencies which occur only rarely. Occurrences such as sickness or absence of the observer, continuous rainfall which makes observations difficult, breakage or loss of measuring equipment, unexpected heavy falls which cause overflow of the gauge, all come under the heading of contingencies.

Many of the errors of observation can be overcome, or materially reduced, by paying attention to the design of the instrument. An instrument should be so constructed that observation is simple, and this is especially important when one might be relying on untrained observers.

A list of observation errors appears below. In every one of these errors there can be detected some element of carelessness and/or faulty technique of observation. The brief comments after each type of error will be confined to explaining any effect of unforeseen contingencies, or indicating how improved instrumental design might lessen the tendency to error.

4.2.3.1 Neglect in Measuring Small Amounts

Possibly a more suitable design of rain gauge might make it more obvious to the observer that rain has fallen. Error is negative.

4.2.3.2 Spill during Measurement

Gauges might be redesigned so that spill is unlikely. Error is negative.

4.2.3.3 Wet Measuring Vessel

If moisture is present in the measuring vessel before the catch is introduced the catch will be spuriously increased. Suitable water-repellent treatment of the vessel should reduce or eliminate this error. Error is positive.

4.2.3.4 Observation during Rainy Period

This is a contingency effect which may be unavoidable.

Some rain may go unmeasured, giving a negative error. Design changes which automatically eliminate this error are feasible, but might entail appreciable complication of equipment. The best answer seems to lie in the use of an extra container and good techniques of observation.

4.2.3.5 Gauge Read Less Frequently than Once a Day

Gauges which are intended to be read daily occasionally have to be read less frequently. Contingencies such as the observer's illness make this always liable to happen to any gauge. However with some locations, the position is worse and missed readings are frequent. Gauges located at schools and post offices are particularly affected in this way, with readings on Saturday and/or Sunday regularly omitted and there seems little possibility of improvement in this regard. The error caused is negative, brought about by evaporation of the stored catch. In extreme cases heavy rainfall may cause overflow, again a negative error.

4.2.3.6 Use of Dipstick

Australian standard rain gauges are designed to be read by decanting into a measuring glass. A contingency such as loss or breakage of this glass might force the observer to use a dipstick for measurement. Three errors, all positive, may arise:

(a) the dipstick displaces water, which rises to a spuriously high level,

(b) if the dipstick surface is favourable to the effect, water will move upwards along the stick by capillary action,

(c) the stick is held at an angle to the vertical, the immersed length will be greater than it should be.

Even if a gauge is designed for measurement by dipstick the above errors can occur if a non-standard dipstick is used carelessly. Thought in designing the instrument can eliminate the errors.

4.2.3.7 Overflow

Both contingencies and poor design of instrument may be responsible for overflow. An interested observer is useful in preventing it. Where it is a frequent source of trouble, steps should be taken to replace the gauge with one of larger capacity. Error is negative.

4.2.3.8 Evaporation Preventative not Used

This is usually a contingency effect caused by loss of the liquid which should have been added. Error is negative.

4.2.3.9 Computation Errors when Using a Necked Gauge

If a storage gauge with a narrow neck is used and measurement is by dipstick, an allowance must be made if the water level is in the necked part of the gauge. The errors can be made less likely if the gauges are of sufficient capacity to ensure that rain rarely reaches the necked portion. Error is positive, and is detectable and correctable.

4.2.3.10 Failure to Empty Gauge after Reading

When a pluviometer is visited for the purpose of taking a reading, it is normal practice to empty the gauge of water before leaving it in order to provide the maximum storage for subsequent rainfall. If any water is mistakenly left in the gauge this will be measured again when the gauge is next visited. The error, which is positive, can be avoided by designing the gauge so that it must be emptied in order to measure the catch.

4.2.4 Miscellaneous Errors

A few errors do not conveniently fit into the three classifications so far dealt with. These are listed below, with brief comment.

4.2.4.1 Vandalism

Abuse of an instrument by vandals usually results in damage and loss of record. However, this is not always the case: water may merely be tipped out or extraneous matter introduced into the gauge, the latter being usually detectable. Vandalism is very much a contingency effect and is difficult to guard against. Bullet proof cases are a help against certain types of abuse, and it has occurred to the writer that prominent, and quite untruthful signs saying "DANGER - HIGH VOLTAGE EQUIPMENT" might deter the would-be meddler. If such deceit is distasteful, an unpleasant but harmless shocking coil could be incorporated operated by a trembling contact, so that the instrument, if disturbed, could prove that the sign means what it says. Error from vandalism can be positive or negative.

4.2.4.2 Non-Standard Measuring Vessel

Daily rain gauges are avilable in various diameters, the most used ones being 5 in and 8 in. The contingency of loss or breakage of a measuring vessel might give rise to the thoughtless purchase of a replacement of the wrong size. Error can be positive or negative.

4.3 ERRORS IN STREAM LEVEL MEASUREMENT

4.3.1 External Instrumental Errors

The introduction of a level measuring device (limnometer) into a stream does not usually cause much disturbance to the stream flow. However, there are instances where appreciable variation from the true piezometric head can be observed. These are caused by the disturbance of the flow pattern by the limnometer itself and result in the whole or part of the velocity head being added to (or occasionally subtracted from) the piezometric head. Such variations seldom matter, since the measured stage is normally converted to discharge by correlation. Whether the measured stage truly represents the piezometric head is of no consequence as long as the measurement is repeatable in the same set of circumstances.

However, errors of appreciable magnitude can be introduced if the limnometer causes a disturbance which is characterized by a fluctuating or very turbulent water surface. This makes a staff gauge hard to read, but with recording instruments the effect is usually negligible because inertia damps out the rapid fluctuations.

4.3.2 Internal Instrumental Errors

Errors which usually arise in limnometers used for measuring stream level are not nearly so great as similar errors in pluviometers. One of the important reasons for this is that limnometers can use a large area of water surface if necessary to provide ample force to overcome instrument friction and lag.

As explained in Section 4.2.2, some internal errors produce random effects and some bias the measurement: biassing errors only will be considered.

In float-operated instruments, such errors are usually small or can be reduced to negligible proportions by techniques which are well known. A good discussion on the internal errors of float-operated instruments, and on methods of lessening such errors is available (Stevens, c.1940, pp. 18-38). This reference also discusses the use of the float well and inlet pipe to damp out waves which would tend to make the record needlessly complex. Internal errors in float-operated gauges will be but briefly treated in this thesis.

Pressure-operated instruments used for sensing liquid level are of two main types, which will be referred to as the closed system and the open system. Each type is subject to internal errors which can be appreciable. These errors have not been so easy to decrease as errors in float-operated equipment, and they will accordingly be dealt with in more detail.

The internal errors which can occur in limnometers can be classified in various ways, but the scheme adopted here groups them according to the type of limnometer employed.

4.3.2.1 Errors in Staff Gauges

4.3.2.1.1 Staff at Incorrect Slope

Normally, staff gauges are set vertically and any deviation of the staff from the vertical will cause a positive error in the measurement. Some gauges however, are intended to be installed in an inclined position, and employ a suitably expanded scale; deviation from the correct angle of installation can bias the measurement either positively or negatively.

The causes of these errors are usually obvious and the errors would not occur with careful workmen and observers.

4.3.2.1.2 Vertical Displacement of Staff

By accidental knocking or gradual slip, a staff gauge may move vertically, usually downwards. Such downward movement will obviously cause a positive error. These errors can be quite serious and regular surveys are required if movements are likely.

4.3.2.2 Errors in Peak Level Indicators

A peak level indicator is a staff gauge or similar device installed to show the maximum flood stage reached between inspections. They are usually designed to measure discontinuously with a relatively low sensitivity (least count of several inches) although some instruments give continuous readings. In addition to the two errors listed in 4.3.2.1 above, the following errors can occur:

4.3.2.2.1 Wave Action

If waves are not damped out, for example by some inertial device, then a continuous indicator will read the peak level of the highest wave crest. With discontinuous indicators the reading will increase by one or more increments only if the waves are sufficiently large; small waves may produce no effect.

4.3.2.2.2 Capillary Creep

Continuous indicators normally depend for their operation on a change in condition of the indicator after wetting. Any capillary rise will give a spuriously high indication, and the indicator should be designed so that this effect is negligible.

4.3.2.3 Errors in Float Limnometers

Only brief discussions of these errors are given here. Further information is available in detail in the literature, (Stevens, c.1940, pp. 18-38).

4.3.2.3.1 Float Lag

The mechanism operated by the float will have friction and perhaps unbalanced rotating parts, which impose a load on the transmitting mechanism. This "operational" load must be supplied by hydrostatic forces acting on the float, and the float submergence must therefore change to supply this load. It is possible then for the liquid level to vary by a small amount without a corresponding change at the indicator. The maximum variation (peak to trough) for which no response occurs is called the float lag, and it is similar in effect to instrumental backlash (see 4.2.2.7 above). The error is proportional to the operational load and inversely proportional to the area of the float. With floats greater than about 1 ft diameter the error is small, provided the instrument is well designed and lubricated.

4.3.2.3.2 Line Shift

A continuously rising stream causes more and more of the float line to pass from the float side of the pulley to the counterweight side. The effect of this is the same as if weight were being continuously added to the counterweight, leading to a progressively increasing error of over-registration (assuming the indication to be correct at low stages). Conversely, if the gauge reads correctly at high stages, it will have a negative error at low stages. The error is proportional to the heaviness of the line (weight per unit length)and to the change in stage from that corresponding to zero error; it is inversely proportional to the area of the float. With well-designed instruments, line shift is negligible unless the change of stage exceeds about 100 ft, and if desired, the error can be compensated by calibration. Alternatively the error can be eliminated by using an extra pulley at the bottom of the well with an endless loop of line. With this arrangement greater friction can be expected, hence greater float lag.

4.3.2.3.3 Submergence of Counterweight

If the counterweight becomes submerged at high stages, its effectiveness decreases and a greater submergence of the float is then required to overcome friction. This leads to a positive error in registration, proportional to the mass of the counterweight and inversely proportional to (a) its density and (b) the float area. The error is negligible in well-designed equipment and can be allowed for by calibration.

4.3.2.3.4 Line Shift of Submerged Line

After submergence of the counterweight, some of the float line also becomes submerged. The line shift error, compared with the error for unsubmerged line, decreases slightly. This decrease is practically negligible but can be allowed for in calibration.

4.3.2.3.5 Temperature Errors

Since both float line and well structure expand with increase in temperature, the effects tend to compensate one another. Accordingly thermal errors are proportional to the difference between the coefficients of expansion of line and structure. They are negligible except for very large ranges of stage (over 100 ft).

4.3.2.3.6 Backlash in Step-by-Step Systems

Step-by-step float-operated systems are designed to give signals at certain defined stream levels, and ideally the signals should occur at the same stream levels on both rising and falling streams.

The effects of float lag and backlash as discussed in 4.3.2.3.1 are usually relatively large in step-by-step systems because the device which initiates the signal is in most designs, spring loaded. The extra load on the spring varies in direction as the stream rises and falls, causing larger than normal float lag errors. The instrument can be set to read correctly on either a rising or falling stream but when the stream reverses, the signals will be delayed. Typical lag errors from this cause (for the Ott impulse transmitter) are about $\frac{1}{4}$ inch. These errors are correctable.

4.3.2.3.7 Insufficient Damping

It is usually not necessary to record all fluctuations in stream level and it is standard practice to use the inlet pipe resistance, the inertia of the water in the pipe, and the storage in the well to damp out minor waves. If this damping is not sufficient, there can occur two important defects in the record.

(a) the continual movement of the stylus across the chart causes an apparent thickening of the trace, leading to uncertainties in estimating levels, and

(b) the stylus may eventually cease recording, the ink supply having been exhausted in recording all the minor waves.

Rules-of-thumb are given (Stevens, c.1940, pp. 3-7) for proportioning the well and inlet tube to give adequate damping.

4.3.2.3.8 Silting Up

Accumulations of silt in the well can cause defects in the record by preventing descent of the float. Similar deposits in the inlet pipe can prevent the water level in the well following the changes in level of the stream. Methods of preventing silt deposits, and of removing them after they form, are well known (Stevens, c.1940, pp. 9-11).

4.3.2.4 Errors in Pressure Limnometers

Closed and open type pressure limnometers are illustrated in Fig. 4.2(a) and 4.2(b). Each type has its own peculiar errors, and other errors are common to both.

4.3.2.4.1 Gas Compression in Closed Systems

In closed systems, the gas transmitting the pressure variations from the bell to the transducer is subject to variations in volume as the pressure changes. The variation in volume results in a vertical movement of water level inside the bell, causing measurements of water level to be too low by an amount equal to the rise of water in the bell. (A further error exists arising from the static head of gas in the piezometer tube; this is treated in Section 4.3.2.4.13.)

Fig. 4.3 is a definition sketch for the analysis which follows. It is assumed that there is no water rise in the bell when the pressure in the system is atmospheric.

Let S = area of bell

B = area of transducer element

x = rise of water in bell

y = displacement of transducer element, relative to position when $x = 0$

V_0 = volume of gas when $x = 0$

L_0 = effective length of system at bell $= \dfrac{V_0}{S}$

w = specific weight of water

p_0 = atmospheric pressure

p = pressure in system

h = height of water surface above lowest point of bell

$$\mu = \frac{dy}{dh} \quad \text{(assumed constant)}$$

Equating pressures at base of bell,

$$p_o + wh = p + wx \qquad (4.1)$$

Initially, when $h = o$, the conditions are that

$$p = p_o \ , \quad x = 0 \ , \quad \text{and} \quad y = o .$$

Finally, after the stream rise, the volume of gas in the system is

$$V_o - Sx + By$$

and Boyle's Law gives

$$p(V_o - Sx + By) = p_o V_o \qquad (4.2)$$

From (4.1), $\qquad p = p_o + w(h - x)$

and (4.2) becomes

$$\left[p_o + w(h-x)\right].\left[V_o - Sx + By\right] = p_o V_o$$

which reduces to the following quadratic equation, after putting $y = \mu h$:

$$x^2 - x\left[\frac{p_o}{w} + L_o + h\left(1 + \mu\frac{B}{S}\right)\right] + \left[L_o + \mu\frac{B}{S}\left(\frac{p_o}{w} + h\right)\right]h = 0$$

The solution is (taking the negative sign before the radical),

$$x = \frac{1}{2}\left[\frac{p_o}{w} + L_o + h\left(1 + \mu\frac{B}{S}\right)\right] - \frac{1}{2}\sqrt{\left[\frac{p_o}{w} + L_o + h\left(1 + \mu\frac{B}{S}\right)\right]^2 - 4h\left[L_o + \mu\frac{B}{S}\left(\frac{p_o}{w} + h\right)\right]} \qquad (4.3)$$

Since the second term of the radical is considerably smaller than the first, the radical may be expanded by the binomial theorem and terms of high order neglected. The expansion is

$$\left[\frac{p_o}{w} + L_o + h\left(1 + \mu\frac{B}{S}\right)\right] - \frac{2h\left[L_o + \mu\frac{B}{S}\left(\frac{p_o}{w} + h\right)\right]}{\frac{p_o}{w} + L_o + h\left(1 + \mu\frac{B}{S}\right)}$$

Therefore

$$x = \frac{1}{2}\left[\frac{p_o}{w} + L_o + h\left(1+\mu\frac{B}{S}\right)\right] - \frac{1}{2}\left[\frac{p_o}{w} + L_o + h\left(1+\mu\frac{B}{S}\right)\right]$$

$$+ \frac{h\left[L_o + \mu\frac{B}{S}\left(\frac{p_o}{w} + h\right)\right]}{\frac{p_o}{w} + L_o + h\left(1+\mu\frac{B}{S}\right)}$$

In any practical instrument, L_o is negligible compared with $\frac{p_o}{w}$, and the equation simplifies to

$$x = \frac{h\left[L_o + \mu\frac{B}{S}\left(\frac{p_o}{w} + h\right)\right]}{\frac{p_o}{w} + h\left(1+\mu\frac{B}{S}\right)} \qquad \text{———— (4.4)}$$

Since $\mu\frac{B}{S}$ is much less than unity, further simplification gives

$$x = \frac{h}{\frac{p_o}{w} + h}\left[L_o + \mu\frac{B}{S}\left(\frac{p_o}{w} + h\right)\right] \qquad \text{———— (4.5)}$$

For those cases where volumetric change in the transducer can be neglected, the expression is yet again simplified.

$$x = h\left[\frac{L_o}{\frac{p_o}{w} + h}\right] \qquad \text{———— (4.6)}$$

Expressions (4.4), (4.5), and (4.6) assume that x is small, and this will no longer be true if water is permitted to reach the piezometer tube. It is therefore essential that the maximum value of x is less than the physical length of the bell (not the effective length L_o). Putting $n = \frac{L}{L_o}$, we have the condition $x_{max} \leqslant n L_o$. ———— (4.7)

But from (4.5),

$$x_{max} = \frac{h_{max}\left[L_o + \mu\frac{B}{S}\left(\frac{p_o}{w} + h_{max}\right)\right]}{\frac{p_o}{w} + h_{max}} \qquad (4.8)$$

Substituting (4.8) in (4.7),

$$n \geqslant \frac{h_{max}}{\frac{p_o}{w} + h_{max}}\left[1 + \mu\frac{B}{S}\left(\frac{\frac{p_o}{w} + h_{max}}{L_o}\right)\right] \qquad (4.9)$$

which represents the limitations on n so that gross errors are prevented. It will be noted that when volume changes in the transducer are negligible, the condition specifies that

$$n \geqslant \frac{h_{max}}{\frac{p_o}{w} + h_{max}} \qquad (4.10)$$

4.3.2.4.2 Leakage of Gas from Closed Systems

Since the closed system limnometer is normally at higher pressure than atmospheric, any leak will allow gas to escape, and if leakage is not prevented the system will reach equilibrium at atmospheric pressure. This results in complete failure of the equipment and closed systems must therefore be hermetically sealed.

4.3.2.4.3 Temperature Errors in Closed Systems

Any change in temperature of the gas in the closed system, without variation in stream level, will cause pressure changes in the gas, resulting in errors of measurement. The volume will also change and therefore, x, the rise of water on the bell, will change. In the analysis which follows, it is assumed that the stream level stays constant while the temperature of the gas changes from T_1 to T_2. The variation of x will be assumed small, so the pressure variations will be small enough to be negligible, meaning that Charles's Law can be used.

By Charles's Law,

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

$$\frac{V_2 - V_1}{V_1} = \frac{T_2 - T_1}{T_1}$$

Using obvious notation,

$$\frac{\Delta V}{V_1} = \frac{\Delta T}{T_1} \qquad (4.11)$$

Provided the water never gets into the tube, and noting that an increase in V corresponds to a decrease in x, Eq. (4.11) becomes

$$-\frac{\Delta x . S}{(L_o - x_1)S} = \frac{\Delta T}{T_1}$$

$$\text{or} \quad -\frac{\Delta x}{L_o - x_1} = \frac{\Delta T}{T_1} \qquad (4.12)$$

A decrease in x is associated with an equal increase in measured pressure head (p/w).

Hence,

$$\frac{\Delta (p/w)}{L_o - x_1} = \frac{\Delta T}{T_1} \qquad (4.13)$$

The thermal error Δ(p/w) is greatest when $(L_o - x_1)$ is greatest, i.e., when $x_1 = 0$. This corresponds to the lowest measurable stage, when $h = 0$. Assuming that the instrument reads correctly at 65^{o}F (525^{o}A), and a likely temperature rise of 40^{o}F, we have, for $x_1 = 0$,

$$\frac{\Delta(p/w)}{L_o} = \frac{40}{525} = 0.076 \qquad (4.14)$$

In practical closed systems, L_o is very unlikely to exceed 1 ft, so that thermal errors in stage should be less than about 0.1 ft. Further, the assumption of a 40^{o}F rise in temperature is very conservative, since by far the largest part of the gas is in the bell, where one would expect much smaller temperature variations.

The error can be decreased by:

(a) reducing ΔT by insulation

(b) reducing L_o, by a decrease in V_o and/or an increase in S.

The analysis leading to Eq. (4.13) does not consider the effect of leakage of gas out of the bottom of the bell if the temperature continues rising after x has become zero. Whilst this is not possible if a flexible diaphragm is fitted, it can occur when the bell is open at the bottom. In the latter case, the thermal error will be limited to the value reached when gas just starts to escape, and will not increase with a further rise in temperature. When the gas cools again to T_1, the water will have risen in the bell to a height somewhat greater than x_1. In effect, the instrument will thereafter read correctly at some temperature greater than T_1. Such effects are practically insignificant.

Temperature errors affecting the transducer will be discussed in Section 4.3.2.4.9.

4.3.2.4.4 Insufficient Flow of Gas in Open Systems

The open-type pressure system can be used (usually with an hand-operated pump) to give a registration whenever the observer desires, but this arrangement is rare in stream level measurement. More commonly, the system is used with an automatic recorder or telemeter, and with this arrangement a continuous flow of gas is usually supplied from a storage cylinder through a regulator and metering valve. When the stream level is steady or falling, the rate of gas flow is of little or no consequence, and in fact could be practically zero at these times. However, when the stream is rising, the flow of gas should be sufficient to maintain bubbles at the outlet at all times. If the stream rises very rapidly, a negative error can arise caused by movement of water upwards into the gas feed line. We shall find the conditions necessary to eliminate this error.

Referring to Fig. 4.4, and using the previous notation, it is assumed that when the stream is at level h and x = 0, the gas flow is stopped. If the stream rises by an amount Δh, then a corresponding rise Δx will occur in the line, and corresponding changes in the gas volume and pressure (ΔV_o and Δp). Boyle's Law gives

$$pV_o = (p + \Delta p)(V_o + \Delta V_o) \qquad (4.15)$$

Equating pressures at the datum, we have

$$\frac{p_o}{w} + h + \Delta h = \frac{p + \Delta p}{w} + \Delta x \qquad (4.16)$$

From (4.16)

$$\Delta x = \frac{p_o}{w} + h + \Delta h - \frac{p + \Delta p}{w} \qquad (4.17)$$

From (4.15)

$$p + \Delta p = \frac{pV_o}{V_o + \Delta V_o} \qquad (4.18)$$

Substitute (4.18) in (4.17)

$$\Delta x = \frac{p_o}{w} + (h + \Delta h) - \frac{pV_o}{w(V_o + \Delta V_o)} \qquad (4.19)$$

Now

$$\Delta V_o = -S \cdot \Delta x,$$

So (4.19) becomes

$$\Delta x = \frac{p_o}{w} + (h + \Delta h) - \frac{p V_o}{w(V_o - S.\Delta x)}$$

This reduces to a quadratic,

$$(\Delta x)^2 - \left[\frac{V_o}{S} + \frac{p_o}{w} + (h+\Delta h)\right]\Delta x - \frac{V_o}{S}\left[\frac{p-p_o}{w} - (h+\Delta h)\right] = 0$$

Noting that $\frac{p-p_o}{w}$ is equal to h, and putting the effective length L_o for $\frac{V_o}{S}$, we have

$$(\Delta x)^2 - \left[L_o + \frac{p_o}{w} + (h+\Delta h)\right]\Delta x + L_o.\Delta h = 0$$

The solution, taking the negative sign before the radical, is

$$\Delta x = \tfrac{1}{2}\left[L_o + \frac{p_o}{w} + (h+\Delta h)\right] - \tfrac{1}{2}\sqrt{\left[L_o + \frac{p_o}{w} + (h+\Delta h)\right]^2 - 4L_o.\Delta h}$$

An amount of gas ΔV must now be allowed through the valve for bubbling to begin.

$$\Delta V = -\Delta V_o = S.\Delta x$$

$$\therefore \quad \Delta V = \frac{S}{2}\left[L_o + \frac{p_o}{w} + (h+\Delta h)\right] - \frac{S}{2}\sqrt{\left[L_o + \frac{p_o}{w} + (h+\Delta h)\right]^2 - 4L_o.\Delta h}$$

Since the second term of the radical is much smaller than the first, the radical may be expanded by the binomial theorem and high-order terms neglected. The expansion is

$$\left[L_o + \frac{p_o}{w} + (h+\Delta h)\right] - \frac{2L_o.\Delta h}{L_o + \frac{p_o}{w} + (h+\Delta h)}$$

Therefore

$$\Delta V = \frac{S}{2}\left[L_o + \frac{p_o}{w} + (h+\Delta h)\right] - \frac{S}{2}\left[L_o + \frac{p_o}{w} + (h+\Delta h)\right] + \frac{S L_o.\Delta h}{L_o + \frac{p_o}{w} + (h+\Delta h)}$$

As Δh is negligible compared with $\left[L_o + \frac{p_o}{w} + h\right]$, the equation simplifies to

$$\Delta V = \frac{S L_o.\Delta h}{L_o + \frac{p_o}{w} + h} = \frac{V_o.\Delta h}{L_o + \frac{p_o}{w}(1+m)} \qquad (4.20)$$

where $$m = \frac{h}{\frac{p_o}{w}}$$

Let λ be the specific weight of gas at atmospheric pressure p_o. Then $\lambda(1 + m)$ is the specific weight under a superimposed water pressure equal to m atmospheres, (corresponding to an absolute head of $\frac{p_o}{w} + h$). Let ΔW be the weight of gas released.

Then $$\Delta W = \lambda(1+m)\,\Delta V$$

and $$\frac{dW}{dt} = \lambda(1+m)\frac{dV}{dt}$$

or $$\frac{dW}{dt} = \frac{\lambda(1+m)V_o}{L_o + \frac{p_o}{w}(1+m)} \cdot \frac{dh}{dt} \qquad (4.21)$$

Eq. (4.21) gives the relation between the gas consumption necessary to keep the apparatus bubbling for any given rate-of-rise of stream level. Evidently low gas consumption requires that the volume of the system be small and the effective length large. These requirements are satisfied by keeping the diameter of the feed line small, especially where it opens into the stream; that is, a bell should not be used. It is true that a bell makes gross errors in registration unlikely when the stream rises quickly enough to cause bubbling to stop (for the reason that the deficit in gas corresponds to only a small rise in the bell). However, if no bell had existed, even greater rates of stream rise could have been followed accurately with the same (or less) gas consumption. There seems to be no argument in favour of the use of a bell in continuously bubbling open systems, although they have been recommended in text books (Addison, 1946).

4.3.2.4.5 Friction Loss in Feed Line in Open Systems

Referring to Fig. 4.4, it will be noted that gas flow in the feed line must cause some pressure drop. If the feed line is tapped at a distance c, measured along the line from its end, then the pressure drop in this length will be subtracted from the true pressure, giving a negative error in the measurement.

The error can be reduced by any method which decreases the head loss through c, viz:

(a) decrease length c

(b) increase area of this portion of the feed line

(c) decrease gas flow.

Method (a) can eliminate the error if c = 0. Methods (a) and (b) each cause an increase in V_o which, from Eq.(4.21) of the previous section results in poorer performance. Final design will be a compromise, but no difficulty is usually experienced in providing satisfactory performance.

4.3.2.4.6 Temperature Errors in Open Systems

If the gas temperature in an open system suffers a sudden decrease, the volumetric contraction can cause water to rise by an amount Δx in the feed line if the gas flow is insufficient. In the following analysis it will be assumed that the gas flow is stopped just before the temperature changes.

Putting $x_1 = 0$ in Eq. (4.12) of Section 4.3.2.4.3, we have

$$\Delta x = -L_o \frac{\Delta T}{T_1}$$

A volume of gas $\Delta V = S.\Delta x$, if now released from the valve, will just cause bubbling.

$$\Delta V = -S L_o \frac{\Delta T}{T_1}$$

$$= -V_o \frac{\Delta T}{T_1}$$

Hence the gas flow which just prevents this temperature error is given by

$$\frac{dV}{dt} = -\frac{V_o}{T_1} \cdot \frac{dT}{dt} \qquad (4.22)$$

The error is most likely to occur in installations where the line is above ground and gas flow is very low. In practice, there is no problem in eliminating the error.

Temperature errors affecting the transducer will be discussed in Section 4.3.2.4.9.

4.3.2.4.7 Regulator Setting in Open System

The function of the regulator is to accept gas at high pressure from the storage vessel and to deliver it at a controllable low pressure to the metering valve. If the regulator were not used, a high pressure drop would exist across the valve, making control difficult; also, if permanent complete blockage at the base of the feed line ever occurred, the full pressure in the storage vessel could be applied to the system, resulting in probable damage to the transducer.

The delivery pressure of the regulator must exceed the highest likely back pressure in the gas system, otherwise flow of gas would be reduced to zero. In practical instruments the regulator delivery pressure must exceed the maximum back pressure by a sufficient amount to ensure that fast stream rises are followed.

4.3.2.4.8 Blockages

Blockage in any tube of a pressure limnometer can cause the instrument to give wrong measurements. These blockages can be caused by accidental damage, dirt, or condensed liquid. They may be permanent or temporary, partial or complete. (A complete blockage is here defined as one in which a small pressure change on one side of the blockage causes no corresponding change on the other.)

Complete blockage of any tube in a closed system will put the instrument out of action. If the complete blockage occurs in the gas feed line of an open system, there is a chance of its being cleared as the line pressure behind it builds up. There is a limit (set by the regulator) to the pressure which can occur in the line, and if the blockage has not been cleared when this pressure has been reached, there is a high probability that it will not be cleared. The instrument will of course give spurious readings until the line is clear.

Partial blockage of the feed line in an open system causes a decrease in the flow of gas, making the instrument less able to follow rapid rises in level, more liable to errors caused by sudden falls in temperature, but decreasing the error caused by friction loss. Blockage of piezometer lines by condensed liquid can cause negative errors since some force is required to move the liquid drops along the line. This effect has been investigated (Duncan and Whitehouse, 1959) and found to be small. However, it is a sensible precaution to fill the lines with dry gas and to ensure that the lines do not lie with bends to which condensed water may drain. Partial blockages in a piezometer line caused by dirt or crimping usually have little effect, since gas movement in such lines is very slight, and pressure drops across the blockage are negligible.

4.3.2.4.9 Leaks in Open Systems

If a leak develops in the piezometer line of an open system, gas must flow along the piezometer line to make good the loss. There must therefore be a head loss in this section of the line resulting in a negative error in the reading. The magnitude of the error can be appreciable, depending on the amount of gas leaking out and the dimensions of the line.

A leak in the gas supply line above the piezometer connection, whilst wasteful of gas, has no effect on the reading as long as gas still bubbles from the end of the tube.

4.3.2.4.10 Temperature Errors in Transducers

The function of the transducer is to convert the changes of pressure in the piezometer line to observable movements which may be measured by eye or recorded automatically. The transducer may be a manometer or some type of elastic element such as a bellows, Bourdon tube, or spring-loaded piston.

The only practical manometer liquid is mercury, any other requiring very high tubes in order to record the likely changes in stream level. Unfortunately, mercury has a higher coefficient of cubical expansion than any material likely to be used as a container for it and, as a result, temperature effects can be troublesome. However, the expansion of the mercury may be partly corrected by expansion of the other parts of the instrument (including the measuring scales) depending on the details of the instrument's design. Good discussions are available, (Middleton and Spilhaus, 1953, Chap. 2), (Mortley, 1960, pp. 11-12), (Gould, 1923, p. 152).

Mortley points out that there are two methods of dealing with the thermal error: compensation (using bi-metallic elements or bellows filled with, for example, ether) or insulation. After considering the relative merits, he favours insulation and describes an experiment with a manometer buried in a hole some 6 feet deep; with atmospheric temperatures varying through 78°F, the corresponding range in the hole was 17°F.

Bourdon tubes and bellows are also sensitive to temperature changes, and an excellent analysis of this effect has been done (Duncan and Whitehouse, 1959). They point out that in a typical transducer (as used in the "Bristol" pressure recorders) errors are caused by:

(a) differential movement of the instrument parts caused by differences in coefficients of expansion of the materials of which the parts are made;

(b) changes in the compliance of the elastic system, brought about by variation of Young's modulus with temperature, and by changes in geometry of the system as pressure is applied.

They further investigate methods of compensation for these errors and develop a particularly simple bi-metallic compensator which can be connected to the pen arm of the recorder. This compensator can be adjusted to correct for the error classified under (a) above. Complete correction with a simple compensator is not possible, but metals are available whose Young's Modulus does not vary with temperature. With such a metal in the elastic element, and with a simple compensator fitted, the only thermal effects would be second-order movements caused by variation of compliance of the elastic element as it moves with change of temperature.

A discussion of some temperature effects on manometers follows, in which the volume of the connecting link between the manometer tubes will be assumed negligible. Further, the tubes are assumed to be made of the same material.

In Fig. 4.5 (a) the initial conditions are shown, before temperature rise ΔT. Atmospheric pressure is p_0, β is the cubical expansion coefficient of the liquid, α the linear expansion coefficient of the tube material. Fig. 4.5 (b) represents the final state after a temperature change ΔT.

$$V = V_0 (1 + \beta . \Delta T) = j V_0$$

$$A = A_0 (1 + 2\alpha . \Delta T) = k A_0$$

$$B = B_o(1+2\alpha.\Delta T) = k B_o \qquad (4.25)$$

$$\text{where} \begin{cases} j = 1+\beta.\Delta T \\ k = 1+2\alpha.\Delta T \end{cases}$$

$$\frac{\gamma}{\gamma_o} = \frac{v_o}{v} = \frac{v_o}{j v_o}$$

$$\therefore \quad \gamma = \frac{\gamma_o}{j} \qquad (4.26)$$

Since p and p_o do not change, the pressure difference (γz) in the manometer must be the same as its initial value ($\gamma_o z_o$). Therefore

$$z = \frac{\gamma_o}{\gamma} z_o = j z_o \qquad (4.27)$$

Equation (4.27) states that if the measurement taken is the difference between the elevations in the legs, then a positive error exists for temperature rises, the error being proportional to the temperature rise and to the measured pressure difference. With cistern type manometers, where $A \gg B$, it is usual to measure only one leg of the manometer, and the error is not the same. Expanding Eq. (4.23), we have,

$$Aa + Bb = j[A_o a_o + B_o b_o]$$

$$A(b-z) + Bb = j[A_o(b_o - z_o) + B_o b_o]$$

from which

$$b = \frac{j[b_o(A_o+B_o) - A_o z_o] + Az}{A+B}$$

Substituting for z, A and B in terms of z_o, A_o and B_o,

$$b = \frac{j[b_o(A_o+B_o) - A_o z_o] + jk A_o z_o}{k(A_o+B_o)}$$

$$= \frac{j}{k}\left[b_o + z_o(k-1)\frac{A_o}{A_o+B_o}\right]$$

The error in measurement is $(b - b_o)$, which can be simplified to

$$(b - b_o) = b_o\left[\frac{j - k + qj(k-1)}{k}\right] - a_o\,\frac{qj(k-1)}{k}$$

where
$$q = \frac{A_o}{A_o + B_o}$$

For cistern manometers, $q \doteqdot 1$ and

$$(b - b_o) \doteqdot b_o(j-1) - a_o\,\frac{j(k-1)}{k}$$

$$\doteqdot b_o\beta\,\Delta T - a_o\left[\frac{1 + \beta\Delta T}{1 + 2\alpha\Delta T}\right]2\alpha\Delta T \quad \text{———} (4.29)$$

The expression in brackets is approximately unity for reasonable temperature changes, so

$$(b - b_o) \doteqdot (b_o\beta - 2a_o\alpha)\Delta T \quad \text{——————} \quad (4.30)$$

For mercury, in glass or steel tubes, $\alpha \doteqdot \frac{\beta}{20}$

$$\therefore\ (b - b_o) \doteqdot \left(b_o - \frac{a_o}{10}\right)\beta\,\Delta T \quad \text{——————} \quad (4.31)$$

and to a first approximation, even $\frac{a_o}{10}$ may be neglected, except for very low stream levels.

This gives the error in height of mercury as

$$(b - b_o) \doteqdot \beta\, b_o\,\Delta T \quad \text{——————} (4.32)$$

or, expressed as an error in stream level,

$$\Delta h \doteqdot 13.6\,\beta\, b_o\,\Delta T \quad \text{——————} \quad (4.33)$$

since the specific gravity of mercury is 13.6.

Thus, when the pressure in the system is detected by linear measurement of the manometer (either a U-tube or cistern type), it may be assumed that thermal errors are proportional to Δ T and also (at least approximately) to the pressure measured by the manometer.

Assuming stream levels of 100 ft, the likely thermal errors can be estimated. These are about $\pm$ 1 inch for a buried manometer (temperature change : $\pm$ 10°F) and about $\pm$ 4 inches for an exposed instrument (temperature change: $\pm$ 40°F.)

4.3.2.4.11 Meniscus Errors in Manometer Transducers

It might at first be thought that "surface tension errors" would better describe these errors. However, the more general term "meniscus errors" is used because some of the effects are caused by variations in meniscus shape even without change in surface tension.

The errors can be evaluated by first considering an ideal case in which the manometer liquid has no surface tension; the menisci are therefore flat and horizontal with zero pressure difference across them. This is illustrated in Fig. 4.6(a).

The actual case shown in Fig. 4.6(b) involves a surface tension τ which causes pressure differences across the menisci in the tubes. Let p_a, p_b be the pressures below the menisci in the left and right tubes respectively. It is easily shown that the pressure difference is related to the downward forces on the liquid surface:

$$p_a = \frac{2\pi r_a \tau \cos\theta_a}{\pi r_a^2} + p$$

$$p_a = \frac{2\tau\cos\theta_a}{r_a} + p \qquad (4.34)$$

Likewise

$$p_b = \frac{2\tau\cos\theta_b}{r_b} + p_o \qquad (4.35)$$

Equating pressures at the bases of columns

$$p + \gamma a_o = p_o + \gamma b_o \qquad (4.36)$$

and

$$p_a + \gamma a = p_b + \gamma b \qquad (4.37)$$

Since v, the volume of mercury, remains constant,

$$A a_o + B b_o = A a + B b \qquad (4.38)$$

From (4.38),

$$b = \frac{A}{B}(a_o - a) + b_o \qquad (4.39)$$

From (4.37),

$$a = \frac{p_b - p_a}{\gamma} + b \qquad (4.40)$$

Substituting (4.39) in (4.40) and simplifying,

$$b = \frac{A}{A+B}\left[a_o - \frac{p_b - p_a}{\gamma}\right] + b_o \frac{B}{A+B}$$

Putting $q = \dfrac{A}{A+B}$ and $(1-q) = \dfrac{B}{A+B}$

$$b = q\left[a_o - \frac{p_b - p_a}{\gamma}\right] + b_o(1-q) \qquad (4.41)$$

The error in measurement is

$$b - b_o = \frac{q}{\gamma}\left[\gamma(a_o - b_o) - (p_b - p_a)\right]$$

$$= \frac{q}{\gamma}\left[-(p - p_o) - (p_b - p_a)\right]$$

Subtracting (4.34) from (4.35),

$$p_b - p_a = 2\tau\left[\frac{\cos\theta_b}{r_b} - \frac{\cos\theta_a}{r_a}\right] - (p - p_o) \qquad (4.42)$$

Therefore

$$b - b_o = \frac{q}{\gamma}\left[-(p-p_o) + (p-p_o) - 2\tau\left\{\frac{\cos\theta_b}{r_b} - \frac{\cos\theta_a}{r_a}\right\}\right]$$

$$= -\frac{2\tau q}{\gamma}\left[\frac{\cos\theta_b}{r_b} - \frac{\cos\theta_a}{r_a}\right] \qquad (4.43)$$

From (4.40), $z = b - a = -\dfrac{p_b - p_a}{\gamma}$ ——— (4.44)

Substituting (4.42) in (4.44),

$$z = -\frac{2\tau}{\gamma}\left[\frac{\cos\theta_b}{r_b} - \frac{\cos\theta_a}{r_a}\right] + \frac{p - p_o}{\gamma}$$

From (4.36) $\dfrac{p - p_o}{\gamma} = z_o$

Therefore

$$z - z_o = -\frac{2\tau}{\gamma}\left[\frac{\cos\theta_b}{r_b} - \frac{\cos\theta_a}{r_a}\right] \text{ ——— } (4.45)$$

Assuming that pressures are detected by linear measurement of the manometer, Eq. (4.45) gives the error in a U-tube manometer, and Eq. (4.43) the error in a cistern manometer. Bearing in mind that q $\doteqdot$ 1 for cistern types, it is seen that for either manometer type we may assume the same formula giving the depression error (Δz) as:

$$\Delta z = -\frac{2\tau}{\gamma}\left[\frac{\cos\theta_b}{r_b} - \frac{\cos\theta_a}{r_a}\right] \text{ ——— } (4.46)$$

Assuming that $\theta_a = \theta_b$, Equation (4.46) shows that equal-arm manometers have no mean error from meniscus depression, and that in cistern manometers, where $1/r_a$ is small, the depression error is almost entirely equal to the depression in the measuring tube:

$$\Delta z = -\frac{2\tau\cos\theta_b}{\gamma\, r_b} \text{ ——— } (4.47)$$

The corresponding error in water level (Δh) is

$$\Delta h = -\frac{2\tau\cos\theta_b}{w\, r_b} \text{ ——— } (4.48)$$

The meniscus depression error does not depend on applied pressure and a mean correction can be made by calibration, the error behaving as a zero error. However, the depression error does depend on the angles of contact, which vary in ways which cannot be exactly predicted. The angles tend to be large in a falling, and small in a rising column but they also vary considerably with the cleanliness of the materials and the composition of the gases above the menisci. In particularly bad cases, the menisci may be almost flat. Approximate ranges of meniscus depression in normal usage have been given (Gould, 1923, p. 159) as functions of the tube diameter, with a vacuum above the meniscus. Doubling these ranges to make rough allowance for variable gas composition, one obtains ± 0.004 inch and ± 0.016 inch for tubes with diameters of 0.4 inch and 0.2 inch respectively. These depression errors correspond to water level errors of about ± 1/16 inch and ± 1/4 inch respectively in cistern manometers. Equal-arm manometers might have these errors doubled.

4.3.2.4.12 Friction and Backlash.

Like pluviographs and float limnographs, pressure limnographs may possess lag errors resulting from friction and backlash in the mechanical parts of the transducer, or of the indicating or recording device. The effects are similar to those described in Sections 4.2.2.7 and 4.3.2.3.1.

4.3.2.4.13 Static Head of Gas in Piezometer Tube

Both open and closed systems are subject to an error arising from the fact that the static head of gas in the piezometer tube differs from the static head of atmosphere between the stream surface and the transducer. There are two reasons for this difference: the gas densities are not identical, nor are the two vertical distances over which the pressures are applied.

In Fig. 4.7, H is the height of the transducer above the lowest point of the system and ρ is the specific weight of the atmosphere. It is assumed that rise of water into the pressure system is negligible, and that the mean specific weight of gas in the system can be expressed as $\lambda(1 + m)$, where λ is the specific weight of the gas at atmospheric pressure and m is the stream rise in atmospheres.

Equating pressures at the base of the system,

$$p + \lambda(1+m)H = p_o + \rho(H-h) + wh \quad (4.49)$$

The gauge pressure sensed by the transducer is

$$p - p_o = wh + \rho(H-h) - \lambda(1+m)H$$

instead of the desired value, wh.

The error in pressure is therefore

$$\Delta p = \rho(H-h) - \lambda(1+m)H$$

and the corresponding error in stream level is

$$\Delta h = \frac{\rho(H-h) - \lambda(1+m)H}{w}$$

Putting $m = \frac{h}{p_o/w}$, the equation becomes

$$\Delta h = -\frac{H}{w}(\lambda-\rho) - \frac{h}{w}\left(\rho + \frac{\lambda H}{p_o/w}\right) \quad (4.50)$$

For any given installation, w, H, λ, ρ, and p_o may be taken as constant. The error represented by Eq. (4.50) can thus be split up into a constant term

$-\frac{H}{w}(\lambda-\rho)$ and a term, $-\frac{h}{w}\left(\rho + \frac{\lambda H}{p_o/w}\right)$ which is proportional to h. Such errors are fairly easy to compensate in the instrument itself by a zero adjustment and an adjustment which changes the scale of measurement.

If the gas used is air ($\lambda = \rho$) or nitrogen ($\lambda = \rho$ very approximately), Eq. (4.50) reduces to

$$\Delta h = -\frac{h\rho}{w}\left(1 + \frac{H}{p_o/w}\right) \quad (4.51)$$

Since Δh is in this case strictly proportional to h, only the scale adjustment is necessary for compensation of the error.

The magnitude of the error is relatively small, as may be shown by adopting some extreme values for the constants:

$$\rho = 0.08 \text{ lb/ft}^3 \; ; \quad H = 110 \text{ ft} \; ; \quad \lambda = 0.12 \text{ lb/ft}^3 \text{ (for } CO_2\text{)}$$

Eq. (4.50) gives $\Delta h = -(0.070 + 0.0075\, h)$, representing a zero error of 0.07 ft together with an under-registration of 0.75% in scale.

For systems using air or nitrogen, Eq. (4.51) gives, for the same values of ρ and H,

$$h = -0.0054\, h,$$

which is approximately 0.5% error over the whole range of heights.

It would seem quite feasible to build into an instrument zero and scale adjustments to compensate automatically for these small errors.

4.3.3 Observation Errors

Reading a limnometer is considerably simpler than reading a rain gauge, and the types of observation error are not so diverse. Nevertheless, two types are of importance.

4.3.3.1 Confusion between Decimal and Duodecimal Scales

Many observers are scientifically untrained and confuse the readings of decimal and duodecimal scales. For example, a level of 5.7 ft will be recorded as 5 ft 7 in. This sort of confusion can also occur with trained but careless observers, especially when reading in the lower half of the foot-interval. When reading in the upper half, a trained observer will tend to notice his mistake when he sees no graduations for 10 and 11 inches, but the untrained observer may still read 5.95 ft as 5 ft 9.5 in. There seems to be no easy way of overcoming this difficulty.

4.3.3.2 Turbulence of Surface

Water waves and hydraulic jumps make it difficult to spot the true mean level. The error evidently increases with the amplitude of the disturbance. Whilst no experimental evidence on this has been discovered, the writer feels that most untrained observers would tend to read the crest level, causing positive errors.

5. DESIGN CONSIDERATIONS AND METHODS FOR REDUCING CERTAIN ERRORS

5.1 PREAMBLE

Section 5 of this thesis has two concurrent and complementary aims:

(a) to introduce ideas which may lead to the design of universal instruments to meet the specifications of Section 2.3.5 (the designs themselves are presented in the appendices);

(b) to suggest ways of reducing some of the more important errors which have been discussed in Section 4.

No serious attempt has been made to keep these aims separate, and the discussion proceeds with both of them in mind. In this section, mention is also made of methods of error-reduction which are not in fact incorporated in the instruments suggested in the appendices, where it is felt that these methods are of general interest.

To restrict the scope of the investigations, it was decided not to investigate a number of minor errors (for example, those arising from manufacturing tolerances and faulty observation); only the important errors, in particular those which give a bias to the measurements, are treated.

5.2 DESIGN CONSIDERATIONS AND REDUCTION OF ERRORS IN RAINFALL MEASUREMENT

5.2.1 External Instrumental Errors

The two important external errors in rainfall measurement are aerodynamic errors and splash errors. It will be shown that these errors are inter-related, and they will then be discussed together.

Since aerodynamic errors are dependent on wind patterns around the gauge itself, an obvious way of eliminating them is to sink the gauge in the ground, as in Fig. 5.1. This has the effect of removing the physical body of the gauge from the wind field, and the field should therefore be identical with the field which would exist without a gauge. Unfortunately such a simple solution involves practical objections:

(a) it becomes difficult in many installations to drain the hole in which the gauge is placed;

(b) splash from the ground into the gauge orifice is relatively large, and this is not nearly compensated by splash out of the gauge;

(c) wind-blown debris tends to collect in the gauge.

Therefore, one would expect a sunken gauge to have a positive error.

If the gauge orifice be raised above ground, negative aerodynamic errors tend to compensate the positive splash errors but the degree of compensation (for any given orifice height) depends on wind velocity and raindrop size. With large drops and low wind velocities, the error will tend to be positive; small drops and high velocities will tend to give negative errors. It is not possible to achieve perfect compensation, under all conditions, with a standard unshielded gauge. In order to solve this problem, a variety of approaches has been used.

(a) Pits

The gauge is sunk in a pit (Fig. 5.2) with the orifice level with the surrounding ground. The depth of the pit and the material at the pit bottom are chosen to make splash into the gauge negligible. It is assumed that the wind field above the pit is identical with the wind field without a pit. However, a drainage problem still exists. Further, it is probable that the pit itself influences the wind field in the pit, and hence the field around the gauge.

Whilst it is not possible to state that pit gauges measure true rainfall, they do show increased catches when compared with standard exposed gauges (Brooks, 1938 - 1).

(b) Fences

Obstructions to the wind are erected around the gauge (Fig. 5.3) presumably with the intention of reducing the wind velocity over the gauge. Whilst they probably do this they also introduce incalculable effects on the wind field within the fence, and therefore also over the gauge. They appear inferior to pits (Brooks, 1938 - 1).

(c) Shields

The original type of rain gauge shield (Nipher, 1879) was presumably designed with the idea of introducing, at the same level as the gauge orifice, an artificial ground plane, the aim of which is to prevent any large vertical components of wind velocity over the gauge orifice (See Fig. 5.4). If eddies caused by the shield are negligible, it seems evident that the shield will do this by deflecting downwards the streamlines below A-A. However, it is probable that eddies do exist in the space between the shield and the gauge and these may affect the catch. Further, splash from the shield can still cause positive errors. To reduce these effects, it is sometimes the practice to put wire or brush screens across this space. These screens indeed should minimize eddies in the space whilst at the same time reducing, but not eliminating splash.

The effectiveness of shields has been demonstrated by many writers (Brooks, 1938 - 2), (Warnick, 1953) without proving (in fact it might be impossible to prove this) that a shielded gauge catches the true rainfall. Warnick's experiments with simulated snow seem to show that shields are still far from perfect. A good summary has been presented by Handcock (1960).

A solution to the problems of wind and splash might lie in the development of shields designed so as to ensure that

(a) large-scale convergence in the wind field around the gauge cannot exist and

(b) the splash field over the gauge is the same as the splash field surrounding the gauge.

It seems to the writer that these requirements would be satisfied by the shield illustrated in Fig. 5.5. The cellular construction of the shield should prevent large scale convergence over the gauge orifice whilst at the same time allowing free drainage into the gauge orifice. The continuity of the shield over the orifice should ensure a uniform splash field (in other words, insplash should compensate for out-splash). The only disadvantages which seem to exist in the use of such a shield are:

(a) retention of rain on the shield over the gauge orifice, such rain being lost by evaporation;

(b) air pressures are not the same at A and B; this might make the splash field non-uniform.

The first of these objections should be overcome by using water repellent material (or surface treatments) for the shield and the second by using throttling orifices in each cell. However, throttling orifices might tend to retain more rainfall and the solutions are conflicting. It is initially suggested that the shield of Fig. 5.5 be tried as a solution to the problems of wind and splash.

5.2.2 Internal Instrumental Errors

Fig 5.6 illustrates a proposed pluviograph incorporating several design features aimed at reducing or eliminating some internal instrumental errors; these are discussed in the following sections, together with problems associated with non-recording gauges.

5.2.2.1 Evaporation from the Gauge

Adequate methods of preventing evaporation from the storage vessel are at present in use, involving a layer of light oil or similar liquid which seals the water surface. The only disadvantage of this method appears to be that a positive error is introduced when reading by dipstick. However, since very little oil is required, this error can be made negligible.

Not enough thought appears to have been given to methods of reducing the evaporative loss from wetted surfaces above the storage vessel. Water repellent materials (plastics perhaps) or water repellent surface treatments should help materially, and any surfaces liable to wetting should be designed without sharp re-entrant angles in an endeavour to eliminate capillary retention.

Pluviographs for long-term operation are sometimes so designed that an oil seal can be used to prevent evaporation (weighing bucket and float types), but this method is not applicable in tipping bucket designs. With these, any rain remaining in a bucket after a storm is available for evaporation; the cumulative effect may be serious over a long period. A possible way of reducing this loss is to ensure that the space above the water surface is saturated.

Fig. 5.6 illustrates a method by which this might be done. An oil seal in the catchment funnel prevents evaporation from the water surface of the upper liquid trap. The stored water in the lower part of the container should ensure that the space is saturated most of the time. A porous plug acts as an outlet for water when the level in the base rises sufficiently; it also offers some resistance to flow of water vapour under the rather low pressure gradients which may exist. The behaviour of such a system would probably involve a daily cycle of evaporation and condensation of the water in the bucket with little nett gain or loss.

5.2.2.2 Admission of Extraneous Matter

Large solid materials (leaves, twigs) will be retained on the cellular shield over the gauge orifice (Fig. 5.6). Fine solids will pass into the liquid trap and will be retained in the filter bowl.

5.2.2.3 Clogging of Apertures

The activities of spiders and insects will be discouraged if the surfaces of the gauge are smooth without re-entrant angles. In Fig. 5.6, the oil seal in the funnel should positively prevent entry of the pests through the top of the instrument, and the likelihood of infestation in the funnel and on the shield might be reduced by using an insect repellent, either in the oil or as a surface treatment or both. Insect entry through the porous plug is impossible.

5.2.2.4 Friction and Backlash

Errors from friction and backlash may be substantial in certain types of pluviograph, but tipping bucket instruments are usually fairly free from such errors if the mechanism is well designed. This is in no small measure a consequence of using a separate electrical energy source to operate the recording apparatus.

5.2.2.5 Off-Duty Error

The off-duty error in pluviographs, as explained in Section 4.2.2.8, is usually negative and tends to increase with rainfall intensity; it is generally possible so to adjust the instrument that it gives correct measurements for one value of rainfall intensity, errors being positive at lower intensities and negative at higher intensities. The error could be eliminated if one could design an instrument so that water was always fed to the measuring device at a constant rate, whatever the intensity of rainfall.

The mechanism shown in Fig. 5.6 represents an attempt to realize this ideal. The upper bucket (X) is smaller than the lower (Y) and discharges its contents in spasms into Y, thereby making bucket Y receive water in a way which is approximately standardized, although not at the constant rate ideally necessary. This double bucket system was developed by A.G. Barker and Associates of Melbourne, and has been described by the makers (Survey Equipment, c.1960). Tests made by the writer have shown that the internal instrumental errors of such a gauge can be within about $\pm$ 2% over the range of intensities from zero to 20 in/hr, and the average error over this range is about 1%. Fig. 5.7 shows the actual calibration curve for the instrument as received (Curve 1) and the calibration curve which should be possible by making small adjustments to obtain lowest overall error at the most common intensities (Curve 2). Also shown for comparison is a calibration curve (Middleton and Spilhaus, 1953, p. 124) for a typical single-bucket instrument (Curve 3). A description of the writer's tests is given in Appendix M.

Some comment seems necessary on the peculiar shape of the curves for the double-bucket gauge, and the following seems to the writer to be a reasonable explanation. It will be assumed that the gauge has been adjusted to read correctly at very low intensities, so that this description fits Curve 2. Further, it will be assumed that rain starts to fall at a very low intensity and that the intensity steadily increases.

(a) Region AB of the curve corresponds to rain entering the bucket X drop-by-drop, the time between drops being less than the lag time of X (i.e., the time it takes for X to move from rest to its mid-position). At these low intensities, X will always discharge the same amount (1 point) when it tips, and this holds true until the threshold intensity is reached (Point B), when the time between drops becomes equal to the lag time of X. If we assume that the bucket Y is adjusted so that it has received the full discharge from X before Y reaches its mid-position, then Y will always receive - and discharge - 1 point for intensities below threshold level. Thus for such intensities, Y will measure correctly.

(b) In region BC of the curve, as the rainfall intensity increases above the threshold, more and more drops of rain fall into bucket X during its lag time, and hence the water discharged into Y steadily increases. However, Y is still receiving the whole discharge from X before Y reaches its mid-position, and therefore a steadily increasing amount is being discharged by Y. The extra water above 1 point is being discharged unmeasured, so that the error is getting more and more negative. Eventually the duration of flow into Y will increase to the point where the flow just ceases as Y reaches its mid-position (Point C).

(c) Just after C has been reached, a small amount of water (the carry-over) will flow into the up-and-coming half of Y after Y has passed its mid-position, and this water will not be thrown to waste but will be measured at the next tip. Accordingly one would expect the downward trend of the curve to be arrested. In fact it may easily be shown that the amount of water saved from waste progressively increases as the rainfall intensity increases, giving the curve an upward trend. In explanation of this, the carry-over decreases the stability of Y, and when it is next about to receive a spasm which will cause it to tip, the tip will commence - and therefore the bucket will reach mid-position - earlier than usual. Since it reaches mid-position earlier, there will be an increase in the carry-over, and as the cycle repeats, the amount of carry-over in the up-and-coming half of Y will increase. Eventually, after a number of tips, there will be sufficient carry-over to give (in effect) a bonus tip, and as rainfall rate increases, the frequency of these bonus tips will increase. Since the bonus tips tend towards over-registration, the effect is to cause the curve to rise after C has been reached, and the error becomes positive after D.

(d) The bucket X will eventually discharge so frequently that water will be reaching Y in an unbroken stream, and the average rate of flow into Y will continue to increase as rainfall intensity increases. Evidently the system has at this stage become in effect a single-bucket system and its calibration curve must begin to show the falling characteristic of Curve 3. This is apparent in region EF.

5.3 DESIGN CONSIDERATIONS AND REDUCTION OF ERRORS IN STREAM LEVEL MEASUREMENT

5.3.1 External Instrumental Errors

As explained in Section 4.3.1, the only serious errors likely are when the introduction of the limnometer into the stream causes rapid fluctuations of the stream surface. The remedy is of course to place the gauge in fairly calm water, even if this has to be provided by a well or breakwater.

5.3.2 Internal Instrumental Errors

Since internal errors in float-operated gauges can be made negligible by well known methods, the discussion in this section will be confined to the reduction of certain errors in pressure-operated limnometers.

5.3.2.1 Gas Compression in Closed Systems

As shown in Section 4.3.2.4.1, the effect of gas compression in closed systems is expressible approximately by Eq. (4.5), repeated here as (5.1):

$$x = \frac{h}{\frac{p_o}{w} + h}\left[L_o + \mu \frac{B}{S}\left(\frac{p_o}{w} + h\right)\right] \qquad (5.1)$$

where x = error in stream level = water rise in bell

h = stream height

p_o = atmospheric pressure

w = specific weight of water

L_o = effective length of system at bell

μ = ratio of transducer movement to stream movement

B = area of transducer element

S = area of bell

The only variables under the control of the designer are L_o, μ, B, and S.

The simplest case to investigate is the one in which volume changes in the transducer are negligible, implying that μ is approaching zero.

In this case

$$x = \frac{h}{h + \frac{p_o}{w}} \cdot L_o \qquad (5.2)$$

For any given instrument (L_o fixed) the error increases from zero at h = 0 to a maximum at h = h_{max}. It can be reduced only by decreasing L_o , which implies that the gas volume V_o be small and that the bell area S be large.

Section 2.3.5.5 specifies that a stream rise of 4 ft be measured to 0.02 ft. Substituting in (5.2) and transposing, we have

$$L_o = \frac{4 + 34}{4} (0.02)$$

$$= 0.19 \text{ ft}$$

and L, the actual length of the bell, must be less than this value. Using Eq. (4.10), it is found that the actual length of the bell must exceed nL_o where

$$n = \frac{h_{max}}{\frac{P_o}{w} + h_{max}} = \frac{100}{134} = 0.746$$

To measure stream rises of 100 ft (see Section 2.3.4.1) this means

$$L \geqslant 0.746 \times 0.19 \geqslant 0.14 \text{ ft}$$

Therefore a bell whose actual length was 0.14 ft would cover the specified range of levels to the specified accuracy, provided the remainder of the system had an effective length less than 0.05 ft. The four variables which affect this length are the length (D) and bore (δ) of the piezometer tube, the initial volume (U) of the transducer and the diameter of the bell (σ). Fig. 5.8 shows the relations which must exist among the four variables in order that the effective length above the bell will be 0.05 ft. Systems which satisfy our specifications of accuracy and range of depth can in fact be designed using Fig. 5.8.

In the case where volumetric changes in the transducer are important, it is seen from Eq. (5.1), and from the condition that a height of 4 ft must be measurable to 0.02 ft, that

$$\frac{4}{34+4}\left[L_o + \mu \frac{B}{S}(38)\right] \leq 0.02$$

i.e.,

$$\frac{4}{38} L_o + 4\mu \frac{B}{S} \leq 0.02$$

from which

$$L_o \leq 0.190 - 38\mu \frac{B}{S} \qquad (5.3)$$

Important volume changes are likely in mercury manometer transducers, where the ratio of change in manometer head to change in water level is fixed at 1/13.6 or 0.0735. Now the transducer movement in a U-tube manometer is only half of the manometric head, but is equal to that head in a cistern manometer. It can easily be shown that, for U-tube manometers,

$$\mu = 0.0368$$

and for cistern manometers,

$$\mu = 0.0735$$

The following argument applies to cistern manometers only: Eq. (5.3) becomes

$$L_o \leq 0.190 - 2.80 \frac{B}{S} \qquad (5.4)$$

Let us adopt the upper limit for L_o; this will just give the required 0.02 ft error at h = 4 ft.

When water rises in the bell, the greatest rise (x_{max}) must not exceed L, the length of the bell in order to prevent gross errors. Putting $L = n L_o$

$$x_{max} \leq n L_o \qquad (5.5)$$

Assuming that a stage of 100 ft is to be measured, we put hmax = 100 in eq. (4.8), which becomes

$$x_{max} = \frac{100}{134}\left[L_o + \mu \frac{B}{S}(134)\right] \qquad (5.6)$$

Expressions (5.5) and (5.6) may be combined to give the condition under which a stage of 100 ft can be measured with the specified accuracy of 0.02 ft when h = 4 ft. The condition is:

$$nL_o \geqslant \frac{100}{134}\left[L_o + 134\mu\frac{B}{S}\right]$$

or, putting $\mu = 0.0735$

$$n \geqslant 0.745 + \frac{7.35\ B/S}{0.190 - 2.80\ B/S} \qquad (5.7)$$

It is thus seen that for values of B/S approaching zero, the specified conditions can be met with $n \geqslant 0.745$. As B/S increases, the minimum value of n also increases, until when B/S is large enough, the minimum n exceeds unity.

Now it is a clearly impossible condition for n to be greater than unity, since this would call for a negative volume of gas above the bell. When (5.7) calls for this condition it simply means that the specification cannot be met with such a high value of B/S.

Since n cannot exceed unity, it is evident from (5.7) that

$$\frac{7.35\ B/S}{0.190 - 2.80\ B/S} \leqslant 1 - 0.745 \leqslant 0.255$$

making $$B/S \leqslant 0.0060$$

From (5.4) and (5.7) we can specify actual figures for L_o and L, depending on the value of B/S, which in fact controls the design.

(a) $B/S = 0$ (lower limit)

(5.4) gives $L_o \leqslant 0.190$ ft

(5.7) gives $n \geqslant 0.745$

from which $L \geqslant 0.745 \times 0.190 \geqslant 0.142$ ft.

(b) $B/S = 0.0060$ (upper limit)

(5.4) gives $L_o \leqslant 0.190 - 0.017 \leqslant 0.173$ ft

(5.7) gives $n \geqslant 1$

from which $L \geqslant 0.173$ ft.

The whole of Section 5.3.2.1 may be summarized thus:

Specification: Error from gas compression is to be 0.02 ft at 4 ft stream level, and a maximum level of 100 ft is to be measured. Gross errors are not allowed, so water must never enter the piezometer tube.

(a) If we adopt a transducer with negligible change of volume under pressure, then

(i) $L_o \leqslant 0.190$ ft

(ii) $L \geqslant 0.142$ ft

(b) If a cistern type mercury manometer is used (area of manometer tube = B) then the design is controlled by the ratio B/S, which must be less than 0.0060. After selecting B/S, the values of L_o and L can be computed from (5.4) and (5.7).

(c) If an equal-arm U-tube manometer is used, the maximum B/S becomes 0.0120, and Eq. (5.4) and (5.7) become respectively

$$L_o \leqslant 0.190 - 1.40\ B/S \qquad \text{(5.4 a)}$$

$$n \geqslant 0.745 + \frac{3.68\ B/S}{0.190 - 1.40\ B/S} \qquad \text{(5.7 a)}$$

The volume of gas (V') above the bell may be found, once n is known, from the equation.

$$\frac{V'}{S} = L_o - L \qquad (5.8)$$

In cases where μ is important, the problem is too complex for simple graphical treatment. Instead, an example of a design is presented below:

<u>Example</u>:

(a) Adopt a cistern manometer with leg diameter of 0.2 in and cistern diameter of 2 in (respective areas are 0.000218 ft^2 and 0.0218 ft^2

(b) Adopt B/S = 0.001, making S = 0.218 ft^2 with corresponding bell diameter = 6.3 in

From (5.4); (c) $L_o \leq 0.190 - 0.003$; Adopt $L_o = 0.187$ ft

From (5.7); (d) $n \geq 0.745 + \frac{7.35 \times 0.001}{0.187} \geq 0.786$

Adopt $n = 0.786$

(e) $L_o - L = 0.214 L_o = 0.214 \times 0.187 = 0.040$ ft

From (5.8); (f) $V' = S(L_o - L) = 0.218 \times 0.040 = 0.00872$ ft^3

(g) Adopt a clearance of 0.005 ft between top mercury level and roof of cistern. Hence initial volume in cistern = 0.005 x 0.0218

= 0.000109 ft^3

(h) Volume available for piezometer line

= 0.00872 - 0.00011 = 0.00861 ft^3

(i) Adopt 1/16 in bore tubing with area = 2.13×10^{-5} ft^2

(j) Tube length = $\frac{861}{2.13}$ = 404 ft

(Compare with 500 ft read off Fig. (5.8) for comparable equipment with a stiff transducer.)

The above computation can also be done using the rather complex nomogram of Fig. 5.9. The dashed lines show the method of use.

In designs which become very difficult from a practical standpoint, it is always possible to relax the specification governing the allowable error at low stream heights. Equation (5.1) shows that an increase in allowable x gives a corresponding increase in L_o and this results in a general increase in freedom for design. The larger errors which must result can be compensated by calibrating the instrument. However, because x is not proportional to h, this calibration is not a simple multiplication by a constant factor. It might also prove difficult to design into the instrument's mechanism some automatic correction for this error.

5.3.2.2 Temperature Errors in Closed Systems

In the discussion in Section 4.3.2.4.3, it was shown that the greatest error in stream level caused by a temperature rise of 40°F is 0.076 L_o where L_o is the effective length of the system at the bell. The feasible ways of reducing this error are either to decrease the temperature rise (by shading or insulating) and/or to decrease L_o.

Adopting a value of 0.01 ft for the allowable thermal error (being rather less than the total error specified in 2.3.5.5) we can state that

$$L_o \leqslant \frac{0.01}{0.076} \leqslant 0.13 \text{ ft}$$

By burying the tube about 1 ft, it may be assumed (Mortley, 1960, p. 11) that the temperature change in the tubing can be reduced to ± 15°F. Assuming that the water temperature also has this variation, the minimum value for L_o

can be increased to

$$L_o \leqslant \frac{0.01}{0.076} \cdot \frac{40}{15} \leqslant 0.35 \text{ ft}$$

It appears then that the system designed as an example in Section 5.3.2.1 should have a thermal error of less than 0.005 ft if installed with a buried tube.

5.3.2.3 Flow of Gas in Open Systems

The flow of gas in an open system must be sufficient to keep bubbles appearing during fast stream rises. Eq. (4.21), repeated here as Eq. (5.9), gives the minimum weight flow of gas to maintain bubbling, the symbols being as defined in Section 4.3.2.4.4.

$$\frac{dW}{dt} = \frac{\lambda(1+m)V_o}{L_o + \frac{p_o}{w}(1+m)} \cdot \frac{dh}{dt} \qquad (5.9)$$

The value of dW/dt will now be computed for a design example for which:

(a) $dh/dt = 30$ ft/hr (See Section 2.3.5.5)

(b) $\lambda = 0.12$ lb/ft^3 (Carbon dioxide)

(c) Piezometer tube and gas feed line are each 300 ft long and have a bore of 1/16 in (Area, $S = 0.000021$ft^2)

(d) Transducer has a gas-filled volume of 0.001 ft^3.

Thus

$$V_o = 0.001 + 600(0.000021) = 0.0136 \text{ ft}^3$$

and

$$L_o = V_o/S = 650 \text{ ft}$$

$$\frac{dW}{dt} = \frac{(0.12)(0.0136)(30)(1+m)}{650 + 34(1+m)}$$

$$= \frac{0.049(1+m)}{650 + 34(1+m)}$$

Thus dW/dt varies from 0.00007 lb/hr at zero stage ($m = 0$)
to 0.00025 lb/hr at 100 ft stage ($m = 3$ approx.).

A further error is possible if the flow of gas is insufficient to cope with sudden decreases in temperature, as discussed in Section 4.3.2.4.6. It is of course not very probable that these sudden drops in temperature would occur at the same time as extremely fast stream rises, and a satisfactory design could be worked out using the more critical of the two criteria. However, if the flow rates defined by the criteria are added, a very safe design should result.

Eq. (4.22), here repeated as Eq. (5.10), specifies the minimum volume flow of gas which will maintain bubbling for a given rate of change of temperature.

$$\frac{dV}{dt} = -\frac{V_o}{T_1} \cdot \frac{dT}{dt} \qquad (5.10)$$

The corresponding weight flow is

$$\frac{dW}{dt} = -\lambda(1+m)\frac{V_o}{T_1} \cdot \frac{dT}{dt} \qquad (5.11)$$

In the example mentioned above, assuming $T_1 = 525^o$ A , adopting a design value of $dT/dt = -30^oF/hr$, and putting $m = 3$, Eq. (5.11) becomes

$$\frac{dW}{dt} = (0.12).(4)\frac{0.0136}{525} .(30)$$

$$= 0.00036 \text{ lb/hr.}$$

For a very safe design, the two values of dW/dt are added to give:

Minimum safe $\frac{dW}{dt} = 0.00036 + 0.00025 = 0.0006$ lb/hr approx.

$= 5.3$ lb/annum.

The corresponding volume flow (at atmospheric pressure) is

$$\frac{dV}{dt} = 50 \text{ ft}^3\text{/annum approximately.}$$

Some difficulty may be expected in regulating such a small flow if a high pressure source is used (bottled gas, for example), and in practice a higher consumption may be necessary to ensure reliability of operation.

5.3.2.4 Temperature Errors in Transducers

Temperature errors in elastic pressure transducers can be practically eliminated, as discussed in Section 4.3.2.4.10, by using a material with negligible temperature coefficient of elastic modulus and by ensuring that movements caused by differential expansions are eliminated by careful design. Alternatively, partial correction can be obtained by fitting a compensator. A well-designed instrument should have only second-order thermal errors remaining.

Mercury manometers present a more difficult problem. When used in systems where pressure is detected by measuring the length of the mercury column, there appears to be no easy way of eliminating the error resulting from volumetric changes of the mercury.

Eq. (4.27) shows that, when the difference in levels in the tubes is measured, the error depends on β and not on α, so that the tubing material is of no consequence.

Eq. (4.30) shows that for cistern manometers, in which only one leg is measured, the error can be eliminated if $b_o\beta = 2a_o\alpha$. Unfortunately this method is useless when b_o is continuously varying.

Compensation might be accomplished by reading on a scale which expanded with temperature at the appropriate rate, but there is no suitable material with a sufficiently high coefficient of expansion.

Examination of Eq. (4.26) and (4.27) shows that whilst the differential height of the column varies as j, the specific weight of the column varies inversely as j, and this leads to the conclusion that, provided the areas of the columns do not change, the weight of the super-elevated column will not change. This line of attack is further investigated below.

Fig. 5.10 shows a manometer, with each tube of the same material, in which the right-hand tube is weighed in order to sense the pressure changes. It will be assumed that the linking tube connecting the two legs has negligible volume and infinite compliance in the vertical direction, (i.e., no force is required to bend it). The notation uses subscript "o" to refer to the initial state and no subscript to refer to the final state which exists after a temperature change ΔT.

Let α = coefficient of linear expansion of tube

β = coefficient of volumetric expansion of mercury

γ = specific weight of mercury

A, B = areas of left and right legs respectively

a, b = lengths of left and right legs respectively

z = difference in leg lengths

v = volume of mercury

f = non-variable part of weight on balance

F = weight on balance

It has previously been shown (Section 4.3.2.4.10) that

$$\gamma = \gamma_o / j \qquad (5.13)$$

$$v = j\, v_o \qquad (5.14)$$

$$A = k\, A_o \qquad (5.15)$$

$$B = k\, B_o \qquad (5.16)$$

$$z = j\, z_o \qquad (5.17)$$

where $j = 1 + \beta . \Delta T$

and $k = 1 + 2\alpha . \Delta T$

From (5.14), $Aa + Bb = j(A_o a_o + B_o b_o)$

i.e., $kA_o a + kB_o b = j(A_o a_o + B_o b_o)$

$$k[A_o a + B_o(a+z)] = j[A_o a_o + B_o(a_o + z_o)]$$

$$k[(A_o + B_o)a + jB_o z_o] = j[(A_o + B_o)a_o + B_o z_o]$$

from which $$a = \frac{j}{k}\left[a_o + \frac{B_o z_o(1-k)}{A_o + B_o}\right]$$

and $$b = a + z = \frac{j}{k}\left[kz_o + a_o + (1-k)\frac{B_o z_o}{A_o + B_o}\right] \quad \text{— (5.18)}$$

The weight on the balance beam is equal to the constant weight f plus the weight of the right mercury column;

$$F = f + \gamma Bb$$

$$= f + \frac{\gamma_o}{j}\cdot kB_o \cdot \frac{j}{k}\left[kz_o + a_o + (1-k)\frac{B_o z_o}{A_o + B_o}\right]$$

$$= f + \gamma_o B_o\left[a_o + z_o\left\{k + (1-k)\frac{B_o}{A_o + B_o}\right\}\right] \quad \text{— (5.19)}$$

If the mercury tubes are of Invar, for which it may be assumed that $\alpha = 0$, then k is unity and (5.19) becomes

$$F = f + \gamma_o B_o[a_o + z_o]$$

$$= f + \gamma_o b_o B_o \quad \text{——— (5.20)}$$

This is the same weight as was initially on the beam so that a weighing manometer with Invar tubes possesses no thermal error.

As a complement to the above investigation, it is of interest to discuss some of the problems associated with weighing manometers.

An obvious disadvantage is that the flexible connecting tube does not in fact have infinite compliance and may also be subject to friction or hysteresis effects. Friction can be eliminated by suitable design and other forces can be made small by ensuring that deflections are small. A beam balance which is maintained close to the state of equilibrium by applying balancing moments (error actuated) would appear to be a fairly satisfactory practical proposition. Moreover, it would have the advantage that it should be easily adaptable to event-timing methods of measurement, by applying the balancing moment in uniform discrete steps.

It remains to check on differences in sensitivity between the U-tube and cistern systems when one of the legs is weighed.

Let the pressure in the left leg change from p_o (atmospheric) to p with corresponding changes of leg lengths from a_o to a and b_o to b. The manometric head z = b - a.

$$\therefore \quad z = (b - b_o) + (b_o - a)$$

Since at initial balance, $b_o = a_o$,

$$z = (b - b_o) + (a_o - a) \qquad (5.21)$$

Since the volume of mercury does not change,

$$A(a_o - a) = B(b - b_o)$$

giving

$$a_o - a = \frac{B}{A}(b - b_o) \qquad (5.22)$$

Substitute (5.22) in (5.21)

$$z = (b - b_o)\left[1 + \frac{B}{A}\right]$$

or

$$b - b_o = \frac{A}{A+B} \cdot z$$

The change in weight (ΔF) of the column is given by

$$\Delta F = \gamma B (b - b_o)$$

$$= \frac{\gamma A B}{A+B} \cdot z$$

or

$$\Delta F = \frac{AB}{A+B}(p - p_o) \qquad (5.23)$$

Eq. (5.23) shows that the thing detected, the change in weight of the column, is strictly proportional to the pressure change, indicating that any ratio of leg areas may be used without error, provided the appropriate calibration factor is used. If one fixes (from other considerations) the area B of the weighed leg, then Eq. (5.23) shows that large values of $\frac{A}{A+B}$ lead to larger weight changes, indicating that cistern manometers are more sensitive. (It seems paradoxical that, if one fixes A from other considerations, then greatest sensitivity is obtained by making B very large, but this conclusion is in fact quite true).

5.3.2.5 Meniscus Errors in Manometer Transducers

Section 4.3.2.4.11 presents a discussion on meniscus errors which is summarised below.

Assuming that pressure changes are sensed by measuring column lengths, there are two sources of error:

(a) a biasing error which can be allowed for as a zero error. This depends on differences in leg diameters and is zero when the legs are identical. For cistern manometers, the error is negative and equal approximately to the capillary depression in the small-diameter tube.

(b) variable errors depending on changes in surface tension and angle of contact. Even when the errors of (a) are compensated, these variable errors still occur. The magnitude of the errors increases as the leg diameter decreases and by opening one leg of the manometer into a wide cistern, the errors can be roughly halved.

The biasing errors, being easily correctable, are not so important, but the variable errors should be reduced if possible.

It has been seen (last paragraph of Section 4.3.2.4.11) that for a cistern manometer with a leg diameter of 0.4 inch, these variable errors might lead to errors in water level of $\pm$ 1/16 in (or $\pm$ 0.02 ft). For a tube with 0.2 inch diameter, the errors increase to $\pm$ 1/4 in (or $\pm$ 0.07 ft). The only way of reducing the errors is to increase the diameter of the leg.

It is of interest to investigate the problem from the point of view of a weighing manometer.

Fig. 5.11 (a) illustrates the hypothetical case with $\tau = 0$, and Fig. 5.11 (b) the real case with surface tension causing curved menisci. The notation of Section 4.3.2.4.11 will be used, and in addition, let

G = vertical force on the right hand manometer tube due to surface tension

f = constant part of weight on balance beam

F = force on balance beam in actual case

F_o = force on balance beam in hypothetical case

B_1 = area of walls of right hand tube.

Consider first the hypothetical case. The total downward force applied to the balance beam is found by considering all vertical forces which act on the right hand manometer tube.

$$F_o = p_o B_1 + (p_o + \gamma b_o) B - p_o (B + B_1) + f$$

or $$F_o = \gamma b_o B + f \qquad (5.24)$$

Repeating the calculation for the ideal case

$$F = p_o B_1 - G + (p_b + \gamma b) B - p_o (B + B_1) + f$$

or $$F = -G + B(p_b - p_o + \gamma b) + f \qquad (5.25)$$

The error in measurement is represented by the difference between forces

$$\Delta F = F - F_o$$

$$\Delta F = -G + B\left[(p_b - p_o) + \gamma(b - b_o)\right] \quad \text{—— (5.26)}$$

Now G is in fact the force due to the pressure difference $(p_b - p_o)$.

$$\text{i.e.,} \quad G = B(p_b - p_o) \quad \text{—— (5.27)}$$

Substitute (5.27) in (5.26)

$$\Delta F = B\gamma(b - b_o) \quad \text{—— (5.28)}$$

Eq. (4.43) states:

$$\Delta F = b - b_o = -\frac{2\tau q}{\gamma}\left[\frac{\cos\theta_b}{r_b} - \frac{\cos\theta_a}{r_a}\right] \quad \text{—— (5.29)}$$

Substitute (5.29) in (5.28)

$$\Delta F = -2\tau B q\left[\frac{\cos\theta_b}{r_b} - \frac{\cos\theta_a}{r_a}\right] \quad \text{—— (5.30)}$$

For cistern manometers, $q \doteqdot 1$, and $\frac{\cos\theta_a}{r_a}$ may be neglected, giving

$$\Delta F \doteqdot -\frac{2\pi\tau r_b^2 \cos\theta_b}{r_b}$$

or

$$\Delta F \doteqdot -2\pi r_b \tau \cos\theta_b \quad \text{—— (5.31)}$$

which represents the capillary force on the leg.

To a first approximation then it is the capillary force itself, acting upwards on the manometer leg, which causes the biasing, correctable error, and variations in τ and θ_b which cause the variable error.

It is noted that a rise of dh in the stream causes a rise $db = \frac{w}{\gamma} dh$ in the manometer leg and a force change

$$dF = \gamma B\, db = w B\, dh$$

so

$$dh = \frac{dF}{wB} \qquad (5.32)$$

Expressed in terms of error in water level Δh, Eq. (5.31) gives

$$\Delta h = \frac{-2\pi r_b \tau \cos\theta_b}{w \pi r_b^2}$$

or

$$\Delta h = -\frac{2\tau \cos\theta_b}{w r_b} \qquad (5.33)$$

which is exactly the same as (4.48). Thus, weighing manometers and linear-measuring manometers are subject to the same surface tension errors. Accordingly, these errors can be reduced in the same way, by increasing the diameter of the tube and making one leg a cistern. In order to reduce the variable error to 0.01 ft of water (half of the total error specified in Section 2.3.5.5) we require a tubing diameter greater than about 0.3 inch, using the argument presented in the final paragraph of Section 4.3.2.4.11.

5.3.2.6 Static Head of Gas in Piezometer Tube

As has been shown in Section 4.3.2.4.13, relatively simple adjustments for zero and scale factor of the instrument can give complete compensation for this effect. It is recommended that these adjustments be incorporated in the design of any instrument used as a pressure limnometer.

6. TELEMETRY OF RAINFALL AND STREAM LEVEL

6.1 PROBLEMS OF HYDROLOGICAL TELEMETRY

6.1.1 Preamble

Telemetry means measurement at a distance, a definition which in practice refers only to those distances which are so long that special problems are introduced in getting the information from the point of origin to the point of measurement. As a rough guide, these distances are upwards of 100 yards. Any system of measurement introduces errors, and telemetry systems usually introduce additional errors which are associated with the generation, transmission and detection of the signals carrying the information required.

The definition of telemetry does not imply that electrical signals be used, and in fact telemetry using mechanical movements or sound waves is used in certain situations; light (an electro-magnetic phenomenon) can be, and is used for telemetry. However, for hydrological telemetry, it is universal practice to use some form of electrical signal, and this implies in general the existence of five separate elements:

(a) a primary transducer to convert the original mechanical movement to an electrical signal;
(b) a transmitter to apply the signal to the link medium;
(c) a link medium to carry the signal over the required distance;
(d) a receiver which detects the transmitted signal and delivers a corresponding electrical signal;
(e) a secondary transducer which converts the electrical signal to an intelligible form, usually by the mechanical movement of an indicator.

In some systems the same device may perform the functions of two of the above elements.

Each of the five elements involves special problems of design which must be solved before a telemetry system can operate satisfactorily. As can be imagined, there are different solutions for each of the elements and a very large number of acceptable combinations can be made, each representing a possible solution to a telemetry problem.

Telemetry of hydrological data often imposes special conditions which make some of the possible solutions unacceptable. In particular, there are four conditions which in combination make hydrological telemetry differ from many other telemetry problems: difficulty of access to transmitters, rugged topography between transmitter and receiver, the activity of storms and floods, and low information rates. The first three conditions restrict freedom in design, but the fourth can be turned to advantage, freeing the design in certain ways.

It is not intended to discuss in this thesis the relative economics of installing either a recording instrument or a telemeter. It will simply be accepted that telemeters are necessary and the problems of designing telemeters (in particular universal telemeters) will be discussed.

6.1.2 Problems Caused by Difficult Access

There are several reasons why hydrological data are telemetered. Not the least of these is that the information is required more quickly than is possible by normal measuring methods. Problems which require that action be taken shortly after events have occurred (dam system operation, flood forecasting) cannot usually be solved by an instrumentation scheme in which observers take readings, or maintain recording gauges, and send periodical reports to a central office. This system can be made to work sporadically with very keen observers and a suitable warning procedure, but even then it becomes unreliable when storms and floods occur during sleeping hours. Telemetry is often the only practical solution.

Another reason for telemetry is that data must often be obtained from locations where no observer, or no suitable observer exists. The only possible solutions to this problem are installation of a recording instrument which must be visited at intervals to recover its stored data, or installation of a telemeter. The choice between the two usually is a matter of economics in which a number of factors must be considered:

(a) the urgency with which the information is required;

(b) the relative costs of recording instrument and telemeter;

(c) the difficulty of access.

This third of these is linked inextricably with the costs of installation and periodical servicing. In fact it is the cost of access, rather than actual physical difficulty, which in most cases will be the controlling factor; physical hardship in reaching a site might be lessened by using helicopters, but this solution will usually be ruled out by the available budget.

The difficulty of access is quite real in many installations, where long distances, rain, floods, dense undergrowth and similar difficulties may have to be overcome. Under such conditions, it is not unreasonable to suppose that a week might be spent in reaching an instrument and returning to base, much of this time being on horseback or on foot. It is evidently desirable that the equipment to be installed be light and convenient in size and shape to make it as easy as possible to transport. This is important in the intial installation, but in particular, subsequent servicing visits, of which there may be many during the period of record, should involve carrying no cumbersome equipment.

As a corollary, it is desirable that the transmitter be economical in its use of power, since the power supply will usually have to be transported on each servicing visit. Ideally, the instrument should be self-sufficient for its power requirements. A mains supply is the obvious answer, but in most cases quite impracticable; harnessing of solar or wind energy is a more likely solution.

The prospect of a self-sufficient telemetry transmitter makes it all the more important that the field equipment have high reliability, conferring the extra advantage that the period between service visits can be lengthened. However, it becomes particularly desirable in such equipment that a fault in a transmitter should be notified soon after it has occurred, in order that a servicing visit may be organized to reach the instrument quickly. This notification of a fault would usually take the form of failure to receive an expected signal.

6.1.3 Problems Caused by Topography

Many radio telemetry transmitters can be located on fairly high ground, at or near a good location for a transmitting aerial. However, this is not always the case. Rainfall must be recorded at high and low elevations in order to get satisfactory space sampling over the catchment, so that one would expect some rainfall transmitters in valleys. Stream level transmitters must be operated by some sensing device in or close to the stream, and therefore by the very nature of streams, in a valley. There is often a real problem in sending the radio signal out of the valley to the receiving station.

The signal must be sent by modulating a carrier wave of a certain frequency. Without considering for the moment the legal problems of frequency allocations, the carrier frequency used may be as low as 30 kilocycles/sec or as high as about

3000 megacycles/sec, corresponding to wave lengths of about 10,000 metres and 0.1 metre respectively. This represents a range of about 17 octaves, and it is not surprising that transmission characteristics should vary widely from one end of the scale to the other. These characteristics are briefly discussed as follows:

(a) <u>Frequencies above 30 megacycles/sec</u>

Visible light is transmitted at very much lower wave lengths and very much higher frequencies than the shortest radio waves, but both light and radio waves are part of the electro-magnetic wave spectrum. Thus the higher the frequency of a radio wave, the more it tends to behave like light; in practice, line-of-sight transmission paths are necessary for good reception at frequencies above 30 megacycles/sec although some diffraction around small-scale land-forms can be used. Transmission of signals by reflection or refraction from the ionosphere is usually not possible at these frequencies.

(b) <u>Frequencies between 3 and 30 megacycles/sec</u>

At frequencies between 3 and 30 megacycles/sec, transmission by ionospheric reflection becomes possible, but reception varies with time under the influence of a number of cycles ranging from the 24 hour rotation of the earth to the 11.1 year cycle of sunspot activity. Transmission on line-of-sight paths is of course still possible and is not affected by ionospheric activity.

(c) <u>Frequencies below 3 megacycles/sec</u>

Below 3 megacycles/sec, ionospheric reflection can be used, but more reliable transmission by the so-called "ground wave" becomes feasible. This wave is diffracted around landforms of fairly large dimensions and at the lower end of the frequency spectrum permits long distance transmission on paths following the earth's curvature. The ground wave is not affected by the cycles which cause ionospheric transmissions to vary.

When using frequencies above 30 megacycles/sec, line-of-sight transmission from the transmitting aerial to the receiving aerial can often be achieved by raising both aerials as high as possible. This might entail the use of land-lines from the primary sensing device to the top of a nearby mountain and also perhaps a similar line at the receiving end.

If such methods still give inadequate reception, one or more relay stations can be used to intercept and retransmit the signal. Relay stations are expensive and contribute nothing to the information being transmitted. They have a number of other disadvantages which will be discussed in Section 6.2.2.7.

When using the frequencies below 3 megacycles/sec, it becomes possible to be sure of getting the signal out of the valley by using the ground wave, but the problem of interference becomes important. Transmission of information by radio requires the use, not of a single carrier frequency, but of a small band of the spectrum (the channel) close to the carrier frequency. The band width necessary in the channel increases as the information rate increases. It has been found that there are not enough channels available at the lower radio frequencies to ensure that each user has a channel of his own; sharing of channels among stations, widely separated geographically, is the rule. It is therefore quite likely that at some time the signals from the telemeter will interfere with and will suffer interference from, other stations on the same channel. This problem is discussed in Sections 6.2.2.8, 6.4.2 and Appendix J.

A further disadvantage in the use of low frequencies is that aerial dimensions are much larger than for the high frequencies. An aerial which has a length of half a wave length is a fairly efficient one and as its length decreases so does its efficiency. Half-wave aerials become impracticable when wave lengths are of the order of 1000 metres. The directional characteristics of an aerial can be increased by using multiple aerials arranged in specially designed patterns. Whilst this is feasible with high frequency carriers it becomes prohibitively expensive at low frequencies, and as a result the transmitter must be made more powerful to provide equivalent reception.

The use of the frequencies between 3 and 30 megacycles/sec is also subject to common channel interference. The ground wave is relatively weak and suitable only for short distances. The sky wave (reflected from the ionosphere) is variable in cycles.

6.1.4 Problems Caused by Storms and Floods

During storm and flood events, it is often vital to be certain of receiving the data sent via the telemeter. Indeed short-term flood forecasting is one of the most important uses of hydrological telemetry, and involves analysis of the first-reported rainfall data, in some cases even before the storm has ceased and before the stream has begun to rise. The operation of a telemeter in such circumstances is made more difficult by

(a) atmospheric electrical disturbances which can cause noise interference in radio transmission;

(b) damage to or electrical shorting of land lines by falling branches, landslides and flooding.

6.1.5 Advantages of Low Information Rates

Since the early days of telecommunications, the trend of development has been toward a continual increase in rates of transmission of information until it is possible now to transmit many millions of bits of information per second. Current research in telemetry is largely geared to transmission at these high information rates. However, the disadvantage inherent in the use of high information rates is that the bandwidth required for transmission is very wide.

Telemetry of hydrological variates can, at least theoretically, be accomplished at extremely low information rates, considerably less than one bit per second. Accordingly the band width necessary is extremely small and a number of telemetry channels can be fitted into a single allocated channel.

6.2 REQUIREMENTS OF A UNIVERSAL HYDROLOGICAL TELEMETER

6.2.1 Preamble

One of the main reasons for telemetry is simply that the site for the field instrument is difficult to reach. This condition does not fundamentally influence the quality of data which the instrument should give, although it is often the practice to lower the standards of range, accuracy or sensitivity when a telemeter is installed. This lowering of standards simply reflects the reality that telemeters which deliver satisfactory information either do not exist or are very expensive.

Ideally, a telemeter suitable for universal use should be capable of handling data to the same standards as a universal pluviograph and limnograph. Accordingly the specifications given in Section 2.3.5 must apply to a universal telemeter.

In addition, other requirements must be satisfied, and the design must be based on an examination of the data needed by users of hydrological telemetry, and in particular on the requirements of the most demanding user.

Section 6.2.2 endeavours to specify the features which must be included in a telemeter to satisfy all who might need to measure stream level and rainfall by remote means. Associated design problems are also discussed.

6.2.2 Requirements of Telemeter

6.2.2.1 Compatibility with Universal Pluviographs and Limnograph.

Ideally, the primary transducer of the telemeter should be identical with the sensing elements of the other universal recording instruments, provided this is feasible. Likewise the secondary transducer, which indicates the measurement, should be usable either with the universal recorders or with the telemeter. There are evident economic advantages in such a scheme from the viewpoint of both manufacturerer and user; the manufacturer can confine his efforts to producing larger quantities of a smaller range of goods and the user can relatively easily convert telemeters to direct recorders and vice versa. Thus the special problems of telemeter design are confined to the transmitter, link and receiver.

6.2.2.2 Portability

As discussed in Section 6.1.2, field instruments and the equipment necessary for periodical maintenance should be portable to ensure rapid and easy transport to difficult sites.

6.2.2.3 Economy in Use of Power

The telemetry transmitter which draws its power from a mains supply has one great advantage over other types; it is not necessary for the designer to make the various elements sparing in their use of power. He can afford to be generous and give a big push where only a little push is needed, with the consequent benefit of increased reliability. However, many if not most telemetry transmitters must be installed where no power mains exist, and the instrument must supply its own power. It may generally be assumed that ample power is available (not necessarily a mains supply) at the base station. In some cases power for the field equipment can be supplied by a special land line, but this is by no means always possible. Therefore a universal telemeter must have its field equipment designed for low power drain, and should preferably draw on the elements (sun, wind, etc.) for its energy. Extensive, and preferably exclusive, use of semi-conductors in electronic equipment is highly desirable to eliminate the heavy power drain of cathode heaters in vacuum tubes.

6.2.2.4 Reliability of Field Equipment

For remote installations, the fewer servicing visits, the better. This calls for a high degree of reliability in the equipment. High reliability usually goes hand in hand with simplicity, so this too is very desirable. It is the writer's experience that clocks are one of the most troublesome items of field equipment and elimination of the clock would confer considerable advantages. The use of semiconductors should also contribute towards reliable operation.

6.2.2.5 Notification of Equipment Failures

Especially when very remote transmitters are being used, early notification of failures in field equipment is desirable. A long delay in notification decreases the chance of a service party's being able to reach the instrument in a race against bad weather. In fact, without special measures for notification it is quite probable that failure to transmit expected signals during a storm period may be the first inkling of an equipment failure.

Notification of failures is relatively easy when signals are sent on a regular time schedule or when means of interrogating the instrument are provided. In the latter case, there is the disadvantage that the field equipment must have a facility to receive as well as transmit (introducing complications and probable extra power drain). The former case of time-controlled signals normally requires a clock (extra complication). Event-controlled telemeters require no field clocks but are likely to be silent for long periods. However, since the event-controlled system offers many other advantages it is considered worth while to introduce some extra complication to provide a notification of failure. A solution is suggested in Section 6.4.3.2.

6.2.2.6 Adaptability to Radio and Land Line Links

Telemetry systems may use either land lines or radio as the link medium between transmitter and receiver. Where land lines already exist, or where the distance of transmission is relatively short, it is usually more economical to use land line transmission. Radio links become more economical as the distance of transmission increases. The economic advantages of one method over the other, depending on the circumstances of the individual case, are usually so pronounced that it appears undesirable to specify that a universal telemeter should use one and not the other medium. It is suggested therefore that the universal telemeter should be adaptable to both radio and line transmission.

6.2.2.7 Elimination of Relay Stations

It is considered extremely desirable that these middle men, the relay stations should not exist in a universal telemetry system. They contribute nothing to the information being transmitted, yet can be the most expensive parts of the radio telemeter. Their design is complicated because they cannot receive and transmit on the same frequency; they therefore require two frequency allocations instead of one. Considerable thought has been given to the problem of their elimination and a possible solution is described in Section 6.4.2.

6.2.2.8 Interference from Other Stations

No communications channel can be relied on to give error-free transmission all the time, and spurious signals entering the channel are one of the main causes of error. Since channel sharing is common practice, it is quite likely that stations on the same channel will interfere with one another at times. Also interference between stations on adjacent channels is possible for a number of reasons which will not be discussed here.

In many fields of communication this interference is of nuisance value only, especially where a high degree of redundancy is incorporated in the transmitted information. For example, speech can usually be understood even with a large amount of interference, because it is not necessary that every minor wave form in the speech be heard. However, when a measurement is being made, there may be not much redundancy and unless all, or a large part, of the transmission is received, the measurement will be in error. Systems of telemetry in which each message contains a measurement of the magnitude of the variate have a relatively large redundancy, since if messages are missed, the next to be received will tell the current value of the variate. It is rather unfortunate that impulse-counting methods incorporate little or no redundancy, so that if an impulse is missed, or a spurious impulse received, the telemeter is thereafter in error.

To ensure that an impulse has a high probability of being received, and that spurious impulses have a high probability of being rejected, it is essential to give considerable thought to elimination of common-channel and adjacent-channel interference. This is discussed, and a proposed solution offered, in Section 6.4.

6.2.2.9 Noise Problem

The problem of noise is closely linked with the problem of interference between channels. Noise is always present to some degree in any channel, arising from extra-terrestrial and terrestrial radiations, also from accidental and uncontrollable effects within the electrical circuits of the telemeter. Its presence increases the probability of error, and this probability may become quite large when the signal-to-noise ratio is small. The effect is more important in transmission with little or no redundancy. In particular, an impulse counting telemeter should be designed with an inherently low probability of noise errors.

6.2.2.10 Availability of Current Value

For many problems it is sufficient to know the value of the telemetered variate at certain fixed times only, but for certain other problems (for example, optimum operation of a system of reservoirs), it may be necessary to know the value of a variate at any time when it is desired to take action to vary the state of the system. This can be done by designing the telemeter so that the transmitter can be interrogated, a method which entails considerable complication and possibly increased power drain in the field equipment.

The current value of the variate is always known (within specified limits) when a properly functioning event-controlled impulse counting system is used, and this is achieved without the use of interrogation equipment. It must be emphasized, however, that the counting must be perfect: faulty counting leads to permanent errors. Whilst errors of a few counts may be permissible in a rainfall telemeter (they are probably masked by sampling and instrumental errors), a few such errors in a stream level telemeter may lead to gross errors in discharge. The problem of designing an error-checking facility into an impulse counting system has been carefully considered and a solution is suggested in Section 6.4.3.1.

6.3 REVIEW OF TELEMETRY SYSTEMS

6.3.1 Preamble

It is pertinent to examine the systems of telemetry of rainfall and streamlevel which are currently employed, and to see in what respects they fail to meet the specification for a universal telemeter. From the following discussion, it will be seen that at present there is no available system which can be installed in all situations, although it is usually possible to select one or more systems which will operate satisfactorily in any particular case.

6.3.2 Telemetry Systems

6.3.2.1 Current or Voltage Systems

These systems transmit an analogue signal over lines, the signal being represented by one or more currents or potential differences associated with the lines.

6.3.2.1.1 Amplitude Systems

The value of the current in, or voltage across, a two-conductor landline link is the analogue of the value of the variate. Fig. 6.1 shows a typical system. It has these important drawbacks as a universal telemeter:

(a) it is subject to large temperature errors, especially when the lines are long;

(b) it cannot be used with a radio link.

6.3.2.1.2 Ratio Systems

Many of these systems are available, using different types of primary transducers. They all use the ratio of two currents (or voltages) as the analogue of the measured value. Transmission is normally over a three-conductor line. Temperature errors are eliminated since each current will be equally affected, the current ratio being therefore unchanged. One disadvantage as a universal telemeter is that the systems are not designed to use radio links.

6.3.2.2 Frequency Systems

Fig. 6.2 shows the elements of this system. The measured value has as its analogue a frequency, and provided this frequency can be detected at the receiver it can be measured accurately without any possibility of errors such as temperature errors. The only errors which can be introduced in transmission are caused by noise and interference, and in such cases, the result is complete loss of information, since the frequency is either detected or it is not. There is no fundamental reason why a frequency system should not be designed to satisfy all other requirements of a telemeter, and in the writer's opinion this would entail susing an event-controlled transmitter sending frequency-analogue signals to the base station. However, it is felt that the problem can be solved more simply by impulse counting. At present, there is no event-controlled frequency system available.

6.3.2.3 Position Systems

Systems usually classified as position systems are those in which self-synchronizing (selsyn) motors are used. The shaft position of the primary motor is controlled by the variate being measured; the windings of the two motors are connected together by land lines in such a fashion that the shaft of the secondary motor follows the movements of the primary shaft. Since this is accomplished by varying the ratios of currents in the different windings, the system might also be classified as a current ratio system. Except for the fact that five lines are normally used, the comments of Section 6.3.2.1.2 apply.

6.3.2.4 Impulse Systems

6.3.2.4.1 Impulse Spacing Systems

Fig. 6.3 demonstrates how this system works. The period of time between a reference impulse A and the variable impulse B is the analogue of the measured value. The system has much in common with the impulse duration system, which is more frequently used for hydrological telemetry. The comments of Section 6.3.2.4.2 apply.

6.3.2.4.2 Impulse Duration Systems

Fig. 6.4 demonstrates the working of the system, in which the duration of the impulse is analogous to the measured value. Errors introduced during transmission can be caused only by the masking effect of noise or interference and can result in either complete loss of information or errors in measurement. As with frequency systems, there is no fundamental reason why the impulse duration system (and the impulse spacing system) could not be used satisfactorily in a universal telemeter, and this would, in the writer's opinion, involve event-control of the transmission. However, simpler equipment should result from the use of an impulse counting system. At present, event-control has not been applied to impulse spacing or impulse duration systems.

6.3.2.4.3 Impulse Counting Systems (including Deltamodulation)

It is possible to use impulse counting as a rough analogue system of telemetry, making the number of impulses in each message proportional to the current value of the variate. However, it is more usual for each message to consist of only one impulse which indicates that the variate has changed by one increment. A polarity indicator must also be used for variates which can increase and decrease. The main advantage of the system is that it is suited to event-control and can easily be made compatible with event-timing instruments. A number of event-controlled systems is available, but none intended to use radio links; however, this is relatively easy to arrange, if required. Existing event-controlled impulse counting systems have two disadvantages as universal telemeters:

(a) no provision is made for notification of failures in the transmitter;

(b) there is no check to detect errors in transmission.

These two disadvantages can be at least partly overcome by combining clock-control with impulse counting, and an ingenious system of telemetry known as deltamodulation has been devised (Bowers, 1959). The method uses polarised impulses, each representing one increment of the variate, and these impulses are sent at regular time intervals, being counted <u>at the transmitter</u> to build up a primary step-function. At each transmission, the step-function is compared with the analogue function being measured; if the step-function is the greater, a negative impulse is transmitted, and vice versa. Another counter <u>at the receiver</u> builds up from the transmitted impulses an exactly similar secondary step-function which allows the current value of the variate to be read. The step-functions will normally remain within one increment of the true value, provided the variate does not change too rapidly.

An advantage of the system is that, should the primary step-function ever get out of synchronization with the variate (as in very rapid surface movements of a stream), the error will eventually be corrected. However, errors in transmission can still cause permanent lack of synchronization at the receiver.

Deltamodulation is not considered suitable for a universal hydrological telemeter for the following reasons:

(a) since the system is clock-controlled, it suffers from all the disadvantages mentioned in Section 3.2 when used to record an essentially sporadic variate;

(b) it requires a clock in the transmitter;

(c) it is difficult to see how the system could be used when an analogue function is not available for comparison with the step-function (as, for example, when rainfall is measured by a tipping bucket gauge).

6.3.2.4.4 Impulse Coding Systems

Instead of making the content of each message an analogue of the measured value, it is sometimes advantageous to convert the information into a train of impulses arranged according to some particular code. The train of impulses is then decoded at the receiving station to recover the measured value. This system is relatively free from transmission errors and has the important advantage over analogue systems that sensitivity of measurement can be very high, if this is required. Many such digital systems are available, but none are event-controlled, which is a disadvantage to their use as universal telemeters. However, there is no reason why event-control could not be used. Nevertheless, it is thought that the same results can be obtained more simply from an impulse counting system.

6.3.2.5 Miscellaneous Systems

Many systems which do not fit into the above categories are available, most of them using pre-recorded spoken messages. The disadvantage common to all is their incompatibility with normal methods of measurement.

6.4 PROPOSED UNIVERSAL TELEMETER

6.4.1 Brief Description of the System

The primary transducer may be any of the following, all of which are standard items of the universal instruments proposed in Appendices E, G and H:

(a) a tipping bucket device, for rainfall;

(b) a float-operated, event-controlled impulse generator, for stream level;

(c) a pressure-operated, event controlled impulse generator, for stream level.

The last two generate different impulses with rising and falling stream level.

These electrical impulses can be applied directly to a land line, if it is desired to use this method of transmission. Alternatively, with radio, the impulse is used to switch on the radio transmitter for about 0.1 second. A third system of transmission is to apply to a land line an alternating carrier current, and when existing land-lines are used, this is sometimes the only permissible method. In this case, a carrier-current generator and modulator will be necessary, these being similar in function to the radio transmitter.

The character of the signal varies with the information being sent. It is in general necessary to send four different types of signal: signals for increment and decrement of the variate, a signal for checking the magnitude of the variate, and a signal for checking the functioning of the field equipment.

On land lines without carrier current, this can be accomplished by using D.C. of two polarities and A.C.; with carrier systems, either radio or land line, the frequency of modulation is varied. It is easy, by this method, to arrange for a number of instruments to share a transmitter.

Proposed radio systems use carrier frequencies low enough to ensure good reception by means of the relatively stable ground wave. The problem of interference in these channels, and also to some extent the noise problem is overcome by using narrow-band frequency modulation instead of the amplitude modulation which is more commonly used at these frequencies.

The base station for the carrier wave systems is equipped with a receiver which detects the information modulated on the carrier and passes the resulting impulse to a bank of (in general) four tuned reed-relays, one or more of which will respond, depending on the frequencies of modulation. It is thus possible to differentiate between the four types of signal. For land-line (no carrier) systems the detector is not needed.

The secondary transducer may be any or all of the following standard parts of the universal instruments described in Appendices E, G, H and L:

(a) an indicating counter;

(b) a printing chronograph;

(c) a TAPPET.

Field equipment is fully transistorized, giving the advantage of high reliability, low power drain, quick response (no warm-up time) and simple power supplies.

6.4.2 Carrier Frequency and Type of Modulation

The use of an impulse counting system of telemetry makes it imperative that there are few missed or spurious counts. Even when a means of periodical checking for errors is incorporated, the errors still are a nuisance when they do occur. It is therefore essential to use a transmission method which is not subject to fading. This is substantially true of the ground wave, which is not affected by the changes in the ionosphere, but ground wave transmission over reasonable distances becomes poor as the frequency is raised.

At those high frequencies where line-of-sight transmission must be used, it is also possible to obtain stable transmissions, and there is but little objection to these channels in situations where they are feasible. It must be appreciated, however, that the power available from transistors decreases as frequency increases, and it might become impracticable to use transistors in the output stage of a very high-frequency radio transmitter.

If vacuum tubes must be used to get adequate transmission power, they have two inherent disadvantages: their heaters waste a lot of energy and take time to warm up. The warm-up time is of the order of 15 seconds in most cases and this will rule out their use as truly universal rainfall and stream level telemeters, where the period between impulses might be as low as about 2 seconds (18 in/hr rainfall rate).

Two great advantages in the use of the higher frequencies are the small physical size of the aerials and the ease with which an aerial system can be made highly directional. However, for a truly universal telemeter, capable of sending messages by radio from a deep valley without relay stations, high frequencies must be ruled out.

The problem thus resolves into finding a way of using ground wave transmission in the low end of the radio frequency spectrum, without the usual worries from noise and interference between channels.

Nearly all transmissions in these bands use amplitude modulation (AM) of the carrier. The reason for this is that the band width necessary for AM transmissions is considerably smaller than for frequency modulation (FM) transmissions for the same degree of fidelity. Since the lower frequency bands are very crowded, it is not feasible to allow the wide-band FM stations to use them, and in fact such use is illegal. However, it is possible to transmit relatively low-fidelity FM messages by deliberately restricting the band-width of the transmission. The main result of this is that audio frequencies above a certain value cannot be transmitted. In different words, the use of narrow-band FM instead of wide-band FM means that the information rate is restricted. It is legal to use this narrow-band FM transmission in the lower frequency bands, provided the band-width does not exceed the limits set for the AM stations using the same channels.

The information rates which are needed in telemetry of hydrological data by impulse counting methods are very low, and it is not necessary to use high audio frequencies for modulation. This means that narrow-band FM is a feasible method for radio telemetry of hydrological data in the lower frequency bands.

The problem of interference between the FM telemeter and an AM station transmitting on the same channel has been studied fairly fully (see Appendix J). The results of this study can be summarized as follows:

(a) The FM telemeter can cause interference with an AM station on the same channel, but this interference is negligible. Firstly, the interference will usually be of small amplitude; secondly, the interference lasts only for the duration of the impulse (0.1 second); thirdly, listeners to AM transmissions normally hear, and expect to hear, all sorts of other noise and interference which are more objectionable than the FM interference.

(b) it is possible to design the telemetry receiver so that AM stations do not interfere appreciably with the counting of the impulses transmitted on the FM telemeter.

Another advantage which comes from the use of FM is that the masking effects of noise are smaller. The reason for this is that the main effect of noise is to amplitude-modulate the carrier wave. Most, but not all of this amplitude modulation is removed by the limiter in the FM receiver, providing a significant increase in signal-to-noise ratio and in reliability of transmission. However, it is true that narrow-band FM systems are not so effective at reducing noise as are wide-band FM systems.

The most important disadvantages of lower frequency transmission are the large size of the aerials (a half-wave aerial is about 50 metres long for a frequency of 3 megacycles/second) and the difficulty of making the radiation pattern highly directional.

6.4.3 Field Equipment

It is not intended here to describe the primary transducers which must exist at the transmitting end of the telemeter. These are fully described in Appendices E, G and H.

(a) The simplest field installation is one which uses a land line system without carrier wave. The equipment here consists of one of the primary transducers (an impulse generator operated by a tipping bucket, pressure capsule or float) together with the apparatus for checking counting errors. No check on the functioning of the transmitter is provided since there is no transmitter. (It is not considered worthwhile to check the functioning of a tipping bucket transducer, which is a comparatively simple mechanism. Periodical checks on stream level transducers can be obtained during quiescent periods by studying the reported readings, which should reproduce the typical hydrograph shape). Power supplies at the transmitter may or may not be necessary depending on the number of conductors available in the line and on the design of the equipment.

(b) Installations which use carrier wave transmission by land line must have, in addition to the equipment of (a) above a transmitter comprising a carrier wave generator and modulator, together with apparatus for checking the functioning of the transmitter. Power supply may or may not be provided via the line, and if not, a battery will be required in most cases.

(c) Radio installations must have in addition to the equipment of (a) above, a radio transmitter comprising a carrier wave generator, modulator and aerial, together with apparatus for checking the functioning of the transmitter. If a mains power supply is not provided, it will in general be necessary to supply a battery.

6.4.3.1 Apparatus for Checking Counting Errors

In a well-designed impulse counting system with low noise and very small probability of interference, there is little chance of errors during actual transmission. Errors will most likely be caused by faults in the primary and secondary transducers, usually from switching troubles. With well designed switch equipment these errors should be rare, and it is unlikely that the measurement will be out of step by more than one or two increments, except in the event of a major breakdown.

The mechanism proposed to detect these errors involves the transmission of a different signal at definite values of the variate.

In the rainfall telemeter, a special counter is fitted to the field instrument and contacts on this counter close at each tenth impulse. The closure of the contacts has the effect of switching in an extra resonant circuit which adds another frequency of modulation. Accordingly the telemeter will send nine impulses of one frequency whilst each tenth impulse (marking each 10 points of rain) will possess two modulation frequencies.

Stream level telemeters likewise will be fitted with a special gear which, at each tenth impulse (marking even feet) adds another modulation frequency.

With land line telemeters which do not use a carrier wave, the contact marking each tenth impulse is arranged to add an alternating component to the D.C. impulse already being sent on the land line.

6.4.3.2 Apparatus for Checking Field Equipment

The signal which checks that the telemeter is functioning properly is provided by a device which closes a mercury switch whenever the air temperature reverses. The checking signal will thus be sent at least twice a day. Fig. 6.5 shows the operation of the mechanism. The temperature is detected by a mercury-in-steel thermometer, which is in fact a type of Bourdon-tube instrument. Whenever the temperature reverses, the actuator A, moving under the influence of the thermometer, changes direction and moves away from the follower B, which it has been nudging. Any further change in temperature in the same direction results in the mercury switch C being tripped from one stable position to another, closing the circuit as it passes the mid-position.

Closure of the circuit causes the transmitter to emit an impulse, modulated by a special audio frequency identifiable as an equipment check.

6.4.3.3 Transmitter Electronics

Radio transmitters will employ quite simple circuits, completely transistorized, which will amplify a carrier wave whose frequency is very stable (piezo-electric crystal oscillators will be used). A carrier frequency of about 3 megacycles/sec is envisaged. An output power of about 50 watts, obtainable from transistors at this frequency, should provide reliable transmission over distances of about 50 miles. Increased distances might require increased power output. The carrier is modulated by one or more frequencies less than 500 cycles/sec, the particular frequency used depending on the function of the impulse being sent: increment or decrement, equipment check or counting check. Resonant elements decide the modulation frequencies, and these elements can be switched in or out, depending on the closure of various contacts in the primary transducer. An electrically short, vertical aerial will be used, earthed at one end.

6.4.3.4 Power Supplies

It is proposed to use dry cells to supply the power requirements of the transmitter, although chargeable cells, kept charged by solar cells, might be extremely satisfactory. A battery of dry cells, providing an e.m.f of 24 volts, containing about 50 watt-hours of energy, and weighing about 10 lb. should provide ample energy for a year's operation. This is made possible by the low power drain of the fully transistorized transmitter, and the short duration of each impulse.

6.4.4 Base Equipment

Two completely separate sets of base equipment are necessary to make it highly probable that a message will get through in the event of a failure in the receiving, detecting, or recording units; it is very unlikely that both sets will be out of action simultaneously. Two separate power supplies are provided, with automatic change-over if one of them fails. The paragraphs which follow describe the items which are necessary in one set of base equipment only; it must be understood that in practice these items will be duplicated.

(a) The simplest equipment is for a land line system not using carrier transmission. At least one secondary transducer is necessary. These transducers are standard components of the universal recorders described in Appendices E, G, H and L, and will not be described here. A filter must be incorporated to select the counting-check signal when it is present, and a further transducer is necessary to record this check.

(b) Radio base stations must incorporate a receiving aerial, coupled to a receiver which detects the modulation frequencies. These frequencies are then passed to filters which separate them according to their function and pass them on to the appropriate transducer. Standard secondary transducers from universal recorders are used for the signals indicating increment and decrement, and special transducers are used for checking the operation of the transmitter.

(c) Similar equipment, without the receiving aerial must be installed at base stations for land line carrier systems.

Whilst it is evident that this base equipment is complicated and probably expensive, it certainly uses no techniques which are not well established and its reliability should be extremely high. (It is worthwhile emphasizing that this complication occurs at the base station, where facilities for servicing and housing the equipment should be reasonably good.

The field instruments, on the other hand, are particularly simple, the absence of clocks being a major advantage).

It is possible to design a system so that a number of outlying transmitters should all be able to use at least some parts of the same base equipment, and a telemetry system of this sort is described in Appendix K.

6.4.5 Fulfilment of Specification

The requirements of Section 6.2.2 should be satisfied by the proposed telemeter. The telemeter is compatible with the other universal recording instruments, and in fact is simply inserted between the sensing and recording elements of these instruments. The field equipment is simple, reliable, easily portable and economical in its use of power. Failures in the field transmitters are discoverable by non-receipt of the checking signals sent at least twice a day. Radio or land line links can be used and relay stations should not be required. The modulation system and carrier frequency are such that noise and interference troubles should be small. At all times, the current value of the variate is available within the limits of the instrument's least count.

THE UNIVERSITY OF NEW SOUTH WALES

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The Collection and Analysis of Rainfall and Stream Level Data

Vol. 2

by

J. R. Learmonth

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THE COLLECTION AND ANALYSIS OF RAINFALL AND STREAM LEVEL DATA - VOL. II

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J. R. Learmonth

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FOREWORD

This report covers the first phase of a current programme of research in hydrologic instrumentation undertaken by the author as a partial requirement for the award of the Degree of Master of Engineering. The succeeding phases include the manufacture, testing and trial installations of the equipment described and the development of other instruments and improved methods of collection and analysis of hydrologic data.

The programme is under the direction of Professor C. H. Munro, Foundation Professor of Civil Engineering.

H. R. Vallentine,
Officer-in-Charge,
The Water Research Laboratory.

7. PROCESSING HYDROLOGICAL RECORDS

7.1 PREAMBLE

Classical methods of recording variates are by use of a constant speed chart and a stylus moving transversely across it. It is hardly surprising that the same system has found almost universal use in recording rainfall and stream level. This system has already been discussed under the heading "Continuous Sampling" in Section 3.4, and its disadvantages have been stressed.

When such analogue records are analyzed, the data contained in them are normally converted to digital form for use in the solution of the problem in hand. Since eventual conversion to digits is essential, it is pertinent to investigate the relative advantages of making the conversion at an early or late stage in the whole process of collection, analysis and use.

The electronic computers of today must be used to gain large savings in money, time and drudgery, but this is possible only by feeding data into them in digital form. (Analogue computers have their own particular uses, and input of data in analogue form is desirable for them. However, by far the greatest volume of data will in future be processed by digital computers.)

Data from an analogue chart can be analyzed by having an investigator (henceforth called the clerk) inspect, correct, and measure the chart and abstract from it the information which is relevant to the problem, presenting this information in digital form. In such manual processing, mistakes in calculation and misreading creep in to cause error, even when a first-class chart record is available. With records of poor quality, errors are worse.

The advantages of the digital computer are put to best use when the whole work of analysis of records is handed over to the computer, and this can be done only when the original records are presented digitally, and in a form which requires no mental processes to get the records into the computer, not even transcription by clerks. It appears then that the ideal solution is to have a universal recorder which outputs its record in a form which can either be fed directly to a digital computer, or undergo automatic transcription to reach this form.

The computer can be used to analyze the data into forms which are quite complex, and can if required be programmed to solve many problems which make use of these data. It should be borne in mind however, that the original data are valuable records, and should be available to any person who wishes to make use of them. One user may be interested in minute details in the record and other might require only insensitive data; both should be able to get the information they want easily and quickly.

It is therefore of interest to examine methods of obtaining from the computer all the original data in a form which makes reference easy by a variety of users. It would be an advantage if those corrections which are possible could be made by the computer before output.

It has been seen that event-timing methods offer marked advantages in recording hydrological variates, and an investigation has also been carried out on the use of these methods in presenting data to interested users. A time-table of events appears to be a convenient logical form of presentation for rainfall, although certain difficulties exist for time-tabling stream levels or discharges.

7..2 PROCESSING ANALOGUE RECORDS

7.2.1 Graphical Methods

Pluviograph and limnograph charts may be analyzed by a clerk, and in the simplest form, his task is to note the coordinates of certain points on the graph and transcribe these numbers into a table. The errors which can occur in this case are limited to transcription errors, misreadings, and uncertainty as to the true value of a co-ordinate. Misreadings and transcription errors, whilst always possible, can be made less probable by well-designed, clearly marked charts.

Uncertainties as to the true value are caused by faults in the chart, some of them resulting from instruments inadequately designed for the job in hand. In particular, the following flaws can lead to uncertainties:

(a) weak or obliterated trace, caused by ink failing to flow, flowing too slowly, fading or washing out, or insufficient pressure on stylus;

(b) thick trace, caused by overflow, unsuitable stylus, or inadequate instrument. (Pluviographs with cramped time scales often show this fault, which appears as a single thick trace instead of many separated ones, as shown in Fig. 7.1);

(c) backlash, bounce, or vibration in mechanism.

More advanced clerical work involves elementary arithmetical analysis to obtain, for example, hourly increments of rainfall, and here errors of calculation are possible. The analysis can become more and more complex, ranging from calculation of rates of change (here errors are quite likely on charts using curvilinear co-ordinates) to analysis of intensities for frequency studies. This latter is typified by filling in lower part of Form No.B.14 of the Commonwealth Bureau of Meteorology (attached as Fig. 7.2).

Completion of Form B.14 involves making complex decisions, as for example whether to include or exclude a particular storm burst depending on whether it is included in, or overlaps a certain time interval. Errors in this sort of work are extremely likely to occur because of logical difficulties in following a complex set of instructions.

All the above discussion has assumed that the original record is correct. In practice, clocks run fast or slow, instrument calibration factors may be necessary, and compensation may have to be made for missing parts of the record (e.g. off-duty errors in pluviographs). This correction process by manual methods is tedious and error-prone.

7.2.2 Digital Conversion

Instruments are available which can process an analogue record to produce a digital record. They all must involve some device for coding the analogue value into a series of digits, usually in binary form. Some of these are completely automatic, and some require that an observer follow the trace as it moves past an index mark. Whilst these instruments have definite uses in converting past records to digital form, they are outside the scope of this thesis, which is mainly concerned with digital methods of both recording and analysing data. In a completely digital system, such instruments would be redundant.

7.3 PROCESSING DIGITAL RECORDS

7.3.1 Manual Processing

Records in digital form may appear in a number of guises: the data may take the form of decimal digits on a chart, or of binary digits (usually as holes in paper tape or in cards, but occasionally as magnetized elements on tape or disc). The only form suitable for manual processing is the decimal record, all the others being intended for automatic processing. The following discussion is limited to the decimal form.

During manual processing, errors of transcription can occur but are very unlikely. Well-designed instruments very rarely produce blurred or missing digits, although the errors of uncertainty from this cause cannot completely be disregarded. As the processing becomes more complex, errors of computation increase just as with manual processing of analogue records. They may even become greater than their analogue counterparts when a very complex analysis is being done. This is because the graphical method of presentation makes comprehension of the overall behaviour of the variate relatively easy. In frequency analyses for example, it would be very difficult to spot quickly the highest intensity in a 5-minute period from a table of event times, whereas this is fairly easy with a good graphical record.

7.3.2 Automatic Processing by Computers

A digital record is fed into a computer programmed to process the data, but firstly the data must be in a form which the computer will accept. This may involve some manual transcription of data. For example, the original record might be a series of event times, printed on a chart. To convert these into a suitable form would require a clerk to read the original decimal digits and punch appropriate holes in tape or cards using a special keyboard-type punch. Since errors of transcription are quite likely, it is the usual practice to have two clerks do this job and then to compare the two sets of punched data, special comparators for this work being available. If the comparator indicates no discrepancy, it is assumed that the data have been correctly punched, although it is remotely probable that both clerks have made identical errors.

When the record is already in punched form, it still may require automatic translation. Whilst undesirable, this cannot always be avoided: for example, if the original data are on punched paper tape and the computer will not accept this, then translators must be used. Fortunately, computer manufacturers recognise this problem and tape-to-card translators are usually available.

The ideal situation is one in which the original record can be fed directly into the computer, and this is treated in Section 7.4.

7.4 DIGITAL RECORDING FOR COMPUTER INPUT

7.4.1 Preamble

At present, computers get information into their memories either through punched tape, punched cards or magnetic records, the latter being stored on drums, discs, or tapes. One of these must be used as the output medium of an instrument whose record is to be fed directly into a computer.

Magnetic records seem to be out of the question because the recording equipment associated with them is complex, unsuited to a field instrument, and difficult to adapt to the slow-speed operation which would be preferable for an event timing system. Further, magnetic tape especially should be stored in an atmosphere with controlled temperature and humidity. For a field instrument, it appears to be impracticable.

For recording data describing the action of serial variates such as rainfall and stream level, there are evident disadvantages in using punched cards. Even indoors, there are occasional feeding troubles with cards, whose dimensions change with humidity. In the field, equipment to feed cards from one magazine to another past the punching head, appears too complex to be practicable when compared with a continuous medium.

Paper tape, on the other hand, being in a continuous form itself, is suited to recording of serial events. It has few feeding problems and changes of dimensions with humidity are not critical. Since many computers are able to accept the various standard paper tapes which are available, it would be an advantage for one of these standard tapes to be used in the recording instrument so as to avoid the need for a translating device.

7.4.2 Existing Instruments

To the writer's knowledge, there is only one instrument at present available (Fischer and Porter, 1959) which is designed to record hydrological variates for computer input. This instrument is marketed by the firm of Fischer and Porter, (Hatboro, U.S.A.). Briefly, it is designed to be operated by a float, the movement of which controls the position of two coding wheels. The faces of the wheels are provided with ridges, in the form of circular arcs of different lengths and radii. The position of these ridges relative to a fixed index mark determines whether a hole will or will not be punched in a paper tape. The wheels are coupled together through a 100/1 reduction gear, the least significant digits (hundredths and tenths of a foot) being registered by the wheel coupled to the float. The other wheel registers feet and tens of feet, so that a range of levels from 00.00 ft to 99.99 ft can be recorded to the nearest 0.01 ft, without ambiguity. Each of the 10,000 possible readings of level corresponds to a unique pattern of holes, which are punched in a single line across the tape as shown in Fig. 7.3. A binary-coded decimal system of coding is used.

Punching of the reading of stream level occurs every 15 minutes, after which the tape is advanced by step.

From the viewpoint of a tape-punching device applicable to the proposed system of universal instruments, the disadvantages of the Fisher and Porter recorder are:

(a) it is not event-controlled;
(b) it is not easily adaptable to record rainfall;
(c) it is not suitable for pressure-operated limnometers;
(d) its time scale is not sufficiently sensitive;
(e) it is not easily adaptable to telemetry;

(f) it uses non-standard tape which is not directly acceptable by computers.

7.4.3 Requirements of a Universal Digital Recorder for Computer Input.

7.4.3.1 Preamble

The system of universal instruments being suggested has aimed at using relatively few standard components which may be combined to suit the needs of any particular user. Therefore, in designing a universal tape-punching recorder, it should be borne in mind that it has to record data provided by the other universal instruments, including the telemeter. It is considered that it must record on standard paper tape and that some method should be available for detecting, and preferably correcting, errors which might occur.

7.4.3.2 Compatibility with Universal Instruments.

A tape-punching recorder is in fact a form of secondary transducer, and it should be able to be used in addition to, or to replace any other secondary transducer in the universal system. This is evidently of economic importance when an existing network of data collecting instruments has to be converted to completely automatic operation.

Secondary transducers must often be used in the field, where power consumption must be small; therefore it follows that a universal tape-punching recorder should be designed for low power drain. Likewise it should be able to operate for periods of up to 1 year without attention. Since times as low as one half-minute are important, it must record times to this sensitivity.

7.4.3.3 Compatibility with Telemetry System

Just as secondary transducers are used at the receiving end of the impulse-counting telemetry system, so should the universal tape-punching recorder be usable in these locations. The telemetry system has extra complications at the base station, in that signals must be received for checking on counting errors, transmitter failures and receiver failures. It is not necessary that the latter two be part of the record, since firstly a transmitter failure will usually result, not in errors, but in complete loss of record, and secondly, faults in the receiver should not affect the record, as the stand-by equipment takes over.

However, the fact that a counting error has been made is a piece of information which is needed to correct the error and it is necessary to record the counting check signals.

7.4.3.4 Output Medium and Coding

As discussed in Section 7.4.1, paper tape appears to be the logical medium on which the digital record should be recorded, and since direct input to a computer is desired, it is necessary to select some standard form of paper tape.

Most modern computers which accept paper tape use standard 5-hole or standard 7-hole telegraphic tape; some computers are able to accept either. It is considered that tape-punching recorders should be available for use with either of these standard tapes, but not necessarily both. However, the suggested design for such an instrument (in Section 7.4.4) is confined to the use of 5-hole tape.

The information punched will firstly have to be the time of occurrence of the event; this must be punched for any use to which the recorder is put. Secondly, stream level recording will require in addition an indication of rise or fall. Thirdly, telemetered data will require a further indication of any miscount which may have occurred.

The requirement that power and tape be conserved suggests that the data be packed as closely as possible on the tape; this dictates the use of binary coding of the information (instead of, for example, the frequently used binary-coded-decimal, which requires more bits to register the same information).

7.4.3.5 Error Detection and Correction

Errors in the punched record can arise from a number of causes. Some of these are the result of imperfect sensing by the primary transducer and these have been treated in Sections 4 and 5.

Miscounts can be caused by faults in the primary and secondary transducers, or in the telemetry link. In stream level instruments, errors from any of these three causes can be detected (provided they are relatively infrequent) by providing a special checking signed at definite values of stream level. This method can be applied for rainfall measurement, but will detect errors only in the telemetry link and secondary transducer; the reason is that rainfall depth is a vague variate compared with stream level, for which a fixed datum level is available.

The only other errors which can occur are errors in the punched times. These may be caused by clock faults or by faults in the punching mechanism. Clock stoppages and erratic running of the clock can be overcome only by using good equipment and maintaining it in good order. Errors resulting from a fast or slow running clock are discoverable, and can be corrected (by the computer preferably).

The remaining punching errors arise from two causes: faulty operation of the punching mechanism or errors caused by ambiguities in reading. The first of these can be detected and corrected by incorporating one or more redundant bits in the original record, but this method has the disadvantage of mechanical complexity. For a field instrument, it is felt that a better method is to make the instrument as rugged and simple as possible, with only one punching actuator, so that if a failure does occur, no holes at all are punched. This can be sensed by the computer, which can be programmed to stop in these circumstances.

Errors from ambiguity in reading are well known in digital instrumentation and standard methods are available for preventing them. In this instrument, they can be easily prevented by using a cylcic permuting binary code (often called the Gray code) instead of the usual binary code (See Appendix A).

7.4.4 The TAPPET

In this section will be presented the main features of a proposed universal tape-punching event timer, called the TAPPET. The design is outlined in more detail in Appendix L.

The TAPPET is designed to be used as a secondary transducer which can be coupled to any of the following primary transducers either with or without a telemetry link:

(a) a universal pluviograph transducer (tipping bucket);
(b) a universal float-operated stream level transducer (bi-directional impulse generator coupled to a float);
(c) a universal pressure-operated stream level transducer (weighing manometer impulse generator coupled by piezometer tube to the stream).

In all cases, the full accuracy and sensitivity of these primary transducers is retained by the TAPPET.

The impulses sent by the primary transducer are received by the TAPPET, which punches a coded pattern of holes (20 binary digits) in standard 5-hole paper tape. The paper tape is then fed forward 4 positions (0.4 inch) where it remains until the next impulse.

The holes represent in a binary code the time in half-minutes, and it is possible to record times for a period of about 1 year, correct to the nearest half-minute, if all 20 bits are used for time registration.

Some of the bits may be reserved for indication of special information such as: rise or fall (1 bit required); count check (1 bit required).

With these two bits as spares, the instrument can record, half-minute by half-minute, unambiguous times for a period of about 3 months; the time patterns then start to repeat. (Alternatively, minute by minute times may be recorded for 6 months.)

For use in remote locations, the TAPPET can be battery-operated, including the clock which drives the timing mechanism. The dry cells used should weigh about 10 lb. and provide sufficient energy for registration of either 150 inches of rainfall (point-by-point), or 1500 ft of stream travel (by steps of 0.1 ft). Since the use of power and paper depends on the activity of the variate, it is not possible to state the maximum period of unattended operation, but 1 year seems a conservative estimate.

There are no redundant bits reserved for detection and correction of punching errors. The design uses only one punching actuator and if this fails to work, it will mean that a major fault has occurred and further records are unlikely. Provided the punching actuator works, the correct pattern of holes is practically sure to be produced.

7.5 FORMAT FOR HYDROLOGICAL RECORDS

7.5.1 Preamble

Hydrological records of stream level or rainfall can be presented graphically or digitally, and in the latter case, some form of tabular presentation is usual to facilitate reference.

It is true that records in graphical form are very useful for display, or where a large amount of information must be quickly comprehended. As previously discussed in Section 7.3.1, a particularly complex analysis, involving a simultaneous appraisal of broad trends and fine details, is made easier when graphical display is used.

However, when using digital computers to process the data provided by instruments, a graphical display is, whilst not quite impossible,[1] very inconvenient. Accordingly, the discussion in Section 7.5 will be limited to digital methods of presentation.

7.5.2 Unprocessed Print-out

The simplest way of obtaining in readable form the information (punched as times) on a TAPPET tape is to feed the tape into the computer, have it do some elementary arithmetic and output the identical times in printed form, converted for example to days, hours and minutes. This is very wasteful, since most of the computer's expensive operating time will be spent in input and output. With only a small increase in total expense, the computer can be made to do much more arithmetic; for example, elementary corrections can be applied.

7.5.2 Corrected Print-out

An obvious improvement on the unprocessed print-out is to correct for those errors of time which might be known to exist. These errors will not occur with synchronous clocks (barring power failures) but significant errors are likely when other clocks are used. However, by noting the correct times of start and finish of the record, it is possible to programme the computer to apply a pro-rata correction to all the punched times.

Further, if the primary transducer has errors which can

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(1) A computer can be programmed for example, to draw weather maps of a sort.

be estimated (zero errors, backlash errors, scale factor errors etc.), it is also possible to correct these by suitable programming. In the extreme case, a calibration table or calibration equation, stored in the computer's memory, could be referred to and used to compute the true values.

The writer feels that these corrections are well worthwhile.

7.5.4 Time-Tables

7.5.4.1 Preamble

It has been shown that clock-controlled time sampling systems are a wasteful way of recording hydrological variates because many readings convey little of importance during quiescent periods. The same is true of methods of presenting the data in tables divided into compartments, each of which corresponds to a certain time co-ordinate. This is the most common way of presenting a hydrological time series when digital methods are employed. For example, the forms which are supplied to rainfall observers are usually compartmented in the following way: one page corresponds to one calendar month, one line to one day. The Commonwealth Bureau of Meteorology's Form No. B.14 (Fig. 7.2) is similarly arranged: one compartment per hour. The wastefulness of this method is at once apparent when glancing through stacks of these forms. There are huge blank areas (corresponding the quiescent periods) with occasional spots of information scattered throughout.

The alternative presentation is the event-controlled method. Each compartment represents an event (i.e. a certain magnitude through which the variate passes), and the time of occurrence of the event is written down in the compartment. The saving in space is quite substantial in most cases, although some waste space is usually necessary in the interests of ease of reference.

These event-controlled methods are well known to everybody, and their peculiar space-saving advantages are used in the drawing up of time-tables for public transport. The compartments here represent events to wit, the arrival or departure of the next vehicle. In the compartments, the times of arrival or departure are written. It is worth pointing out that public transport usually behaves sporadically just as hydrological variates, there being peak hours, slack periods, and times when nothing happens (early morning).

When using computers, the adoption of the time-table system may also give some reduction in output time, since very little irrelevant information need be output. It should also be noted that all the information contained in the original record can be economically packed into the time-table, whereas time-controlled methods of presentation with a least count of 1 minute would be very difficult to handle. Witness the B.14 form where the least count is 1 hour and much detail still remains untranscribed on the pluviograph chart. An even larger form would be required for a 1-minute least count.

7.5.4.2 Rainfall Time-Tables

Fig. 7.4 shows a typical example of a rainfall time-table, proposed as a method for computer output of corrected rainfall data from universal pluviographs.

The table is practically self-explanatory provided one remembers to read it exactly as a train or bus time-table. It will be noted that there is still considerable waste space in the table if the rain falls as a large number of small showers. However, for rain which falls as a few heavy storms, the saving in space would be considerable. It is estimated that the yearly rainfall data, point by-point and half-minute by half-minute, could be fitted on ten foolscap pages for a station such as

Observatory Hill, Sydney. (Compare this with twelve B.14 forms, which accommodate only hour by hour data.)

For the user who does not want detail, hourly, daily, monthly and annual totals appear in the right hand columns of the time-table.

7.5.4.3 Stream Level Time-Tables

With rainfall, presentation of a time-table is relatively simple, and reading it is quite easy and rapid after a brief period of initiation. However, rainfall depth continuously increases, whilst stream level both rises and falls; this introduces a few complications in presentation of a time-table for stream level.

Fig. 7.5 shows a proposed form for output by a computer of stream level time-tables. Firstly, since hourly or daily analyses of stream level (not discharge) are meaningless in practice, advantage has been taken of this to pack the information more tightly than for the rainfall time-table. The times written in the compartments give both the day and the time-of-day at which the stream level passes through the value indicated by the figures at the top and to the left of the table. Figures written in heavy print correspond to a rising stream and in light print to a falling stream. (In an actual print-out from a computer these two states might be represented by different colours, say red and black; in this thesis, colour differences have been avoided because of reproduction problems). When reading the heavy print, the true time sequence of the events is obtained by reading left to right, but with the light print one must read from right to left to keep the event times increasing as they should.

7.5.5 Complex Processing

7.5.5.1 Preamble

The methods of processing suggested in Section 7.5.4. simply present the original data with its known errors corrected. It is emphasized that this record contains all the available information in the original record and is therefore a valuable document, containing enough detail to satisfy any likely investigator. It should therefore always be produced and carefully kept, together with the same information (on magnetic records, cards, or paper tape) which represents the actual output from the computer. The original tape from the TAPPET should also be kept.

However, many investigators will require more than a time-table of the basic data, and, by feeding back into a suitably-programmed computer the corrected record in time-table form, the data can be processed in a variety of ways, simple or complex. Two of these are briefly examined in the following sections.

7.5.5.2 Discharge Computations

The main reason for collecting data on stream level is to enable the stream discharge to be computed. This is usually done by using a relation between stream level and discharge, built up by taking simultaneous measurements of these two variates over a considerable range of levels. When this stage-discharge relation is established, past records of level can be converted to records of discharge.

The simplest case is when a definite stable single-valued relation exists. It is then a simple matter to set this relation into the computer (either as a table or as an equation), after which the stream level time-table can be fed in. Elementary arithmetic is done and the discharges are output.

Complications arise when the stage-discharge relation is not stable, but the problem can be handled by feeding in appropriate information about the way the relation varies.

For many streams, there exist what are known as complex stage-discharge relations, meaning that the relation is not single-valued: the discharge depends not only on stream level, but also on a number of other factors. The most important of these are the slope and rate-of-rise of the stream surface. However these two factors are so inter-related that in practice, satisfactory results can usually be achieved by considering either one or the other (not both).

Measurement of stream surface slope requires that two recorders be used, and both records must be fed into the computer. However, a simpler solution is to use rate-of-rise, which can be found from the data of only one recorder.

For complex relations, it is necessary to set into the computer the function expressing how discharge varies with stage and rate-of-rise, and afterwards to feed in the data in the stream level time-table. Elementary arithmetic gives the discharges, which can be output.

The form in which the discharges are output merits some discussion. The writer feels that output should be either in the form of a discharge time-table, or a cumulative runoff time-table for each year. The cumulative runoff time table would be similar in form to the rainfall time-table of Fig. 7.4, whilst the discharge time-table would be patterned on Fig. 7.5.

7.5.5.3 Frequency Analysis of Data

An extremely important use of rainfall and stream level data is in frequency analysis, aimed at providing answers to questions such as:

(a) "What is the depth of rainfall P, falling in a 10-minute period, such that falls greater than P will occur on the average once in 10 years?"

(b) "How often, on the average, would one expect a flood peak in excess of 500 cusecs?"

The corrected time-tables do not present information in convenient form for direct solution to such problems; the time-tables must first be analysed and the data re-arranged, not serially but in order of rank. There is no doubt that programmes could be written to allow a computer to do this ranking, but the best way of doing this would require much further study.

It is not intended in this thesis to undertake this problem, but it is suggested that for rainfall studies, it might prove more economical to reverse one's usual ideas in approaching the problem. The classical methods of approach have entailed selecting certain definite intervals of time (such as 10, 30, 60 minutes etc.) and examining the pluviograph record to determine the values of (say) the highest 10-minute fall, 2nd-highest 10-minute fall and so on down the line; this ranking of depths is repeated for other time intervals.

With event-timing methods, it might prove simpler to select definite depths (such as 0.5, 1, 2, inches) and by examining the time table, to select the shortest time for a 1-inch fall, the 2nd shortest time, and so on.

The ranking of the data abstracted could certainly be done by the computer, but it would be worthwhile investigating the relative economics of using a computer or punched-card sorters for this part of the analysis.

8. CONCLUSIONS

Some of the ideas proposed in this thesis, even if completely sound, may not in fact prove immediately feasible. As an example, whilst there is no doubt that thermal errors in a weighing manometer can be eliminated by using Invar construction, the weighing manometer may itself have unforeseen problems in its application to stream level measurement. Other proposals, such as the cellular rain gauge shield, may in fact be quite unsound. And it is the writer's intention, as a future research project, to construct a number of instruments as outlined in the appendices in order to test their feasibility.

However, there are other proposals which are, in the writer's opinion, well worth using in future systems of instrumentation. These are:

(a) the double tipping bucket pluviograph mechanism;
(b) water repellent materials or surface treatments in rain gauges and pluviographs;
(c) the event timing system of recording;
(d) the time-table system of presentation of data on rainfall, stream level, and stream discharge.

Of those ideas which have not yet been tested, the writer feels that several may be extremely important to the technology of hydrological instrumentation, provided the ideas can be successfully developed. The following especially are suggested, in approximate order of importance, as being worth immediate research or development:

(a) the TAPPET, for the reason that an event timer for direct input to a computer is not yet available (to the writer's knowledge), and is vital to any fully automatic event timing instrumentation system;
(b) the Invar weighing manometer device, because at present there is no pressure-operated impulse

generator suitable for use in an event timing system;

(c) an investigation into the use of fully-transistorized F.M. radio transmitters operating on the lower radio frequencies;

(d) an investigation into the worth of the cellular rain gauge shield, for until the problems of wind and splash have been overcome, the data from rain gauges will always be suspect.

It is the writer's opinion that the estimation of the rainfall on our catchments will not be really satisfactory until non-sampling methods (e.g., radar) have been developed to give reliable quantitative measurements, probably by correlating their data with measurements from a network of sampling gauges of high accuracy.

Also the writer feels that, as long as measurement of stream level remains the basis for estimating discharge, the main advantage of pressure-operated instruments (low cost of installation) should be vigorously exploited in an endeavour to increase the number of gauged catchments. Any development aimed at improving the quality of data provided by pressure-operated instruments (particularly if applicable to the cheaper closed system gauges), whilst at the same time keeping their purchase price below that of a float recorder, should be an appreciable step toward a general improvement in the assessment of runoff.

APPENDIX A

GLOSSARY AND LIST OF SYMBOLS

A.1 GLOSSARY

Technical terms used in this thesis are defined here. Whilst it is difficult to be completely consistent in indexing, the normal rule has been to index specifically rather than generally (e.g., the term "External instrumental errors" appears under that heading rather than as "Errors, instrumental, external" or "Instrumental errors, external". In cases where some doubt may exist regarding the heading for indexing, a cross reference has been used.

Accuracy: The extent to which an instrument or a measurement of a quantity is free from error.

Adjacent-channel interference: Interference between transmissions which make use of carrier waves of slightly different frequencies.

Aerodynamic errors: Errors in pluviometers caused by the fact that the wind field in the vicinity of the pluviometer is distorted by the instrument itself.

Aerodynamic neutrality: The condition of having no aerodynamic errors.

Amplitude modulation: A method of transmitting information by causing the strength of a carrier wave to vary in sympathy with the strength of the information signal.

Amplitude modulation ratio: See Modulation ratio (AM)

Analogue: A general term for that type of correspondence between variates in which a continuous variation in one of them results in a continuous variation in the other. The function relating the two variates is invariable but not necessarily linear.

Band-width: That portion of the frequency spectrum which is used for the transmission of information. It is a fundamental theorem that the band-width necessary is proportional to the information rate.

Bias errors: Errors which are always or predominantly of the same sign.

Binary code: A system of depicting a number, or other information, by the use of only two distinct digits. They are usually written as "0" and "1", but any other marks may be used if more convenient, as long as they are distinguishable from each other.

Binary-coded decimal code: A special form of binary code in which the digits of a decimal number are separately converted to a binary code, instead of converting the whole number to straight binary. As an example, the decimal number 27 is written in straight binary as 11011, and in binary-coded decimal as 10 111, in which 10 is the binary equivalent of 2 and 111 the binary equivalent of 7.

Bit: The smallest possible piece of information which can be indicated. It corresponds to a single binary digit (0 or 1) and its name is a contracted form of the words "binary digit".

Bore: A moving hydraulic jump.

Carrier wave: A wave whose frequency is much higher than the frequencies contained in the information being transmitted. Some characteristic of the carrier wave is varied in sympathy with the information signal. (See Modulation.)

Carry-over: Water which is caught in the up-and-coming section of a tipping bucket mechanism, after the lag time of the bucket.

Catch: The water which actually reaches the surfaces of a pluviometer below the collector orifice.

Channel: A part of the frequency spectrum, of definite bandwidth, allocated or used in transmitting information.

Chronograph: An instrument for recording times.

Cistern manometer: A manometer in which one leg is much wider than the other. The variations in level in the wide leg (the cistern) are usually very small and are often neglected.

Climatology: The science dealing broadly with the average weather and its variation at a certain place.

Clock-controlled system: A system of registration in which a clock-operated switch is used to trigger the mechanism of registration, or in which recording is done continuously.

Closed pressure system: A method of measuring liquid level by means of a gas-filled capsule immersed in the liquid, the variations of gas pressure being detected by a pressure-sensitive transducer. The capsule may be either open at the bottom or be fitted with a flexible diaphragm, but no gas should escape from the system.

Coder: A device for converting a variate from analogue to digital form.

Common-channel interference: Interference between transmissions which use identical carrier wave allocations.

Compliance: The deflexion of a mechanical system per unit applied force.

Contact interval: As used in this thesis, the increment of the variate separating two consecutive events in an event-controlled sampling system.

Control: A site on a watercourse which is selected to have (ideally) a single-valued, invariable relationship between stage and discharge.

Cyclic permuting binary code: A special form of binary code designed to minimize ambiguity in reading. For any two consecutive numbers, the coded patterns of 0's and 1's are the same, except for one bit which is changed from 0 to 1, or vice versa. See also Gray code.

Deltamodulation: A method of telemetry in which regular clock-control is combined with impulse counting. The impulse transmitted has a polarity which is determined by the sign of the error which exists, at the moment of transmission, in the step function built up by counting the polarised impulses. The system is, in certain circumstances, self-correcting if miscounts occur.

Depression errors: Errors caused by differential capillary depressions of the columns of a manometer.

Detector: The portion of a radio receiver in which the information in the message is recovered by separating the modulation from the carrier.

Digital: Relating to the system of expressing numbers (or other information) in discrete form, coded into patterns of digits. It is the opposite of "analogue".

Discriminator: The detector in an FM receiver. The discriminator senses the difference between the frequency of the modulated carrier wave and the frequency to which the discriminator is tuned (this being equal to the unmodulated carrier frequency). The output from the discriminator is proportional to the frequency difference sensed.

Discharge: The rate of flow in a watercourse, expressed as volume per unit time.

Event: Any happening in a time continuum.

Event-controlled system: A system of registration in which the occurrence of an event (such as a change in the variate being considered) is responsible for triggering the mechanism of registration.

Event-timing: A method of recording by event-control, in which the times of occurrence of the events are recorded, sometimes together with other data.

Exposure: The position of an instrument, particularly a pluviometer, in relation to surrounding objects and landforms.

External instrumental errors: Errors arising from distortion of the variate being measured by the very presence of the measuring instrument.

Filter: In communications engineering, a device which permits the transmission of a particular group of frequencies and which rejects other frequencies.

Flash flood: A flood with an extremely abrupt wave front.

Float lag: Error in registration of a float recorder, caused by variations in the depth of flotation of the float as the force required to operate the instrument changes.

Flood forecasting: Prediction of the occurrence of a flood, together with quantitative estimates of the flood hydrograph, usually involving the time of occurrence and magnitude of the peak stage.

Flood warning: Prediction of the occurrence of a flood.

Frequency modulation (FM): A method of transmitting information by causing the frequency of a carrier wave to vary in sympathy with the strength of the information signal.

Frequency modulation ratio: See Modulation ratio (FM)

Gas compression errors: Errors in closed pressure systems caused by rise of water inside the capsule as the gas in the system compresses.

Gray code: A form of cyclic permuting binary code. The first sixteen numbers (corresponding to the decimal numbers 0 to 15) are written:

0000, 0001, 0011, 0010, 0110, 0111, 0101, 0100, 1100, 1101, 1111, 1110, 1010, 1011, 1001, 1000.

It will be noted that any misalignment in the reading mechanism of the coder, resulting in reading some digits of one number and some digits of its neighbour, cannot cause an error greater than one unit. This is because the code patterns differ in only one bit.

Ground wave: A radio wave which is transmitted along the surface of the earth, as distinct from waves travelling along paths such that the signal is little affected by the electrical characteristics of the earth.

Half-wave aerial: An aerial whose length is equal to half the wave-length of the transmitted (or received) carrier.

Hydrograph: A graph showing the variation of stream discharge (or level) with time.

Hydrology: The science dealing with the occurrence of water over the earth, beginning with its precipitation on land surfaces and ending with its discharge into the oceans, and treating all phenomena which occur during the intervening period.

Hydrometeorology: A science treating the borderline problems of meteorology and hydrology.

Impulse counting: A method of measurement, often used in telemeters, in which an impulse occurs at each increment of the variate, the impulses being counted at the recorder to recover the value of the variate.

Information: When a person A has to convey some intelligence to a person B, then A must first put the intelligence in some form of code, secondly the code must be communicated to B over some channel, and thirdly B must be able to understand the code used in order to understand what A is saying. (This is true whether the code be speech, writing or some form of telegraphic code.) The first and third links in the chain require mutual knowledge of the code being used before comprehension can take place. The second link, the communications link, is concerned only with the transmission of a sequence of variations over a channel; whether these variations convey comprehensible intelligence or utter nonsense does not matter in describing the behaviour of such a channel. One may thus describe the channel as carrying a large or small amount of "information" depending on the rapidity with which the sequence of variations changes. In particular, it is the so-called unexpectedness of the variations which is important in transmitting information. If the transmission contains variations without any unexpectedness (for example, if a continuous unmodulated carrier wave is being transmitted), then no information can be conveyed from A to B; as far as B is concerned, A could be a lunatic screaming a note of constant pitch. The unit of information is the bit (q.v.).

<u>Information rate</u>: The speed with which information is transmitted over a channel, expressed in bauds. (1 baud = 1 bit/sec).

<u>Information theory</u>: The theory of the behaviour of communications systems, describing amongst other things the relationships among information rate, band-width and frequency of modulation.

<u>Instrumental errors</u>: Errors caused by the presence of, or arising within the instrument itself.

<u>Interference</u>: The disturbance to the receipt of information transmitted over a channel, caused by the presence of unwanted signals.

<u>Interference factor</u>: In this thesis, the term is defined as the ratio of the amplitude of the interfering carrier wave to that of the desired carrier wave.

Internal instrumental errors: Errors arising within the instrument, leading to false registration of the data sensed by the instrument, regardless of whether these data are true or false in themselves.

Ionosphere: The series of ionised layers in the upper atmosphere, by reflection from which it is possible, under certain conditions, to send radio signals over long distances.

Lag time: The time taken for a tipping bucket to reach its mid-position.

Least count: The smallest increment which an instrument is capable of registering. It is usually somewhat greater than the limit of reading, since one can often estimate to a fraction of the least count.

Limiter: Part of an FM receiver. It changes the wave-form of the modulated carrier by clipping off the peaks and troughs, leaving a wave of very small amplitude. Its function is to make the receiver insensitive to any AM which might be present on the carrier.

Limnograph: A recording limnometer.

Limnometer: An instrument for measuring water level in streams or lakes.

Line shift: Errors caused by the change in weight as float line moves from one side of the pulley to the other.

Link medium: In a telemeter, the medium over which information is sent from the field station to the base.

Masking: The loss of information caused by the presence of interference or noise.

Message: In this thesis, the word "message" means the information contained in a single period of transmission.

Meteorology: The science dealing broadly with the temporal variation of the weather elements.

Modulation The process by which the information to be conveyed is impressed on the carrier wave, by arranging for some characteristic of the carrier to change in sympathy with the information signal.

Modulation ratio (AM) The ratio of the amplitude of the modulating wave to that of the carrier wave.

Modulation ratio (FM): The ratio of the frequency deviation (from the carrier frequency) to the frequency of modulation.

Modulator: That portion of a transmitter which performs the work of modulation.

Narrow-band FM: A system of frequency modulation in which the band-width is limited to that which would exist if the same information were to be transmitted on an AM system. In practice, this means that only the fundamental of the modulating frequency (no higher harmonics) is contained in the side-bands. The modulation ratio (FM) is about 0.2 or less.

Natural siphon: A siphon with no moving parts, depending for its action on the complete filling of a small-diameter siphon tube.

Noise: Unwanted, and usually random, variations which exist on a channel used for transmitting information. They arise from a variety of causes.

Off-duty errors: Errors occurring during the off-duty period and arising from the action of the intermittent mechanism.

Off-duty period: The period during which an instrument does not measure the variate. It usually occurs in those instruments which make use of an intermittent mechanism operating in cycles, and represents the time taken from the end of one cycle to the beginning of the next.

Open pressure system: A method of measuring liquid level in which gas is bubbled from a tube immersed in the liquid, the back pressure in the tube being detected by a pressure-sensitive transducer.

Pluviograph: A recording pluviometer.

Pluviometer: An instrument for measuring precipitation (in this thesis, restricted to rainfall depth).

Point: A measure of rainfall depth (1 point = 0.01 inch).

Primary transducer: A transducer which converts the variate to be measured into an electrical signal to be passed on to a secondary transducer, perhaps via a telemetry link.

Receiver: An electronic device for receiving and detecting signals on a carrier wave system. It comprises essentially a detector and a series of amplifiers, and (for radio signals) an aerial.

Recession curve. The last portion of a flood hydrograph, characterized by a continuously falling stream level as water drains from storage in the catchment.

Redundancy: Information contained in a message in excess of the minimum amount required for comprehension. It is only by incorporating some redundancy that errors in transmission can be detected and perhaps even corrected.

Regulator: A valve which delivers gas at reasonably constant output pressure even though the input pressure varies (also known as a pressure-reducing valve).

Resonant element: A device used either to generate a wave of a certain frequency or to respond to that frequency for the purpose of selective filtering. It is commonly either an electrical tuned circuit, a tuned reed, or piezo-electric crystal.

Runoff: That part of streamflow which has its origin as precipitation on the catchment.

Sampling rate (or Sampling frequency): The number of measurements taken per unit time.

Sampling theorem: A theorem of information theory which states that the whole of the information in a message can be transmitted by time-sampling the information wave at a rate just higher than twice the highest frequency contained in the wave.

Secondary transducer: A transducer which converts the electrical impulse from a primary transducer (received perhaps via a telemetry link) to a form suitable for recording and/or display.

Sensitivity: The degree of response of an instrument to unit change in the measured variate. The word is often used (wrongly) as a synonym for least count (q.v.). This misuse has occasionally been retained in this thesis for the sake of convenience.

Shield: A device placed around a pluviometer with the object of reducing or eliminating external instrumental errors.

Short aerial: An aerial which is short compared with half a wave-length.

Sidebands: That part of the spectrum, on one or both sides of the carrier, which is used when information is being transmitted over a channel. The sidebands widen as the information rate (i.e., frequency of modulation) increases.

Side frequencies: The frequencies contained in the sidebands. These are normally the sum and difference frequencies obtained by combining the carrier frequency with the modulation frequency (AM and narrow-band FM), but wide-band FM has additional side frequencies associated with the harmonics of the modulation frequency.

Sky wave: Radio waves transmitted upwards and received after reflection or refraction from the ionosphere.

Solar cells: Solid-state devices for the direct conversion of radiant energy to electrical energy.

Stage: The level of water in a stream.

Step-by-step system: A system of measurement in which the variate is measured by increments.

Straight binary code: The most commonly used form of binary code in which each number is formed by adding 1 to the number next below it, the 1 being added in the least significant position. The first sixteen numbers in this code (corresponding to the decimal numbers 0 to 15) are:
0000, 0001, 0010, 0011, 0100, 0101, 0110, 0111, 1000,
1001, 1010, 1011, 1100, 1101, 1110, 1111.

Stream gauging station: A site on a stream where measurements of stage and discharge are made for the purpose of estimating runoff.

Strength: In this thesis the term "strength" refers to the instantaneous value of a cyclically varying quantity.

Systematic errors: See Bias errors.

Telemeter: An instrument or chain of instruments for the purpose of measuring a variate at some point remote from the source of the variations.

Telemetry: Measurement using a telemeter.

Threshold intensity: The rainfall intensity at which the period between successive drops emerging from the funnel equals the lag time of the tipping bucket.

Tilting siphon: A siphon which is designed to start positively by making the siphon tube tilt suddenly.

Time-sampling: A method of measurement of a temporally changing quantity by taking sample measurements at certain times, including as a special case, continuous measurement.

Tipping bucket: A bi-stable balance mechanism for measuring flow of liquids, comprising a beam with two containers, one of which is in a position to receive the liquid being measured while the other is draining. Measurement is by counting the number of tips as the beam overbalances from one stable position to the other after receiving a known quantity of liquid.

Trace (1): An amount of precipitation less than half a point.

Trace (2): The marks made by a recording instrument, in particular the continuous line drawn by an analogue recorder.

Transducer: A device for converting the variations in one energy system to corresponding variations in another system.

Transmitter: An electronic device for impressing a signal on a carrier wave, comprising essentially a carrier wave generator and a modulator, and (for radio systems) an aerial.

Tuned reed: A mechanical resonant element for use in filter systems, having the characteristic of responding to a very narrow band of frequencies.

Universal: As used in this thesis, pertaining to equipment which can be incorporated in a system of instruments to provide data suitable for all likely users.

Variate: Any quantity which varies.

A.2 LIST OF SYMBOLS

Where possible, symbols have been used which have achieved some degree of standardization (as, for example, the symbol w for specific weight of water). Care has been taken to avoid duplication of symbols, but so many symbols were required that some duplication has been necessary throughout the thesis. However, the mathematical discussions of Sections 4 and 5 of the thesis form a self-sufficient system in which there is no symbol duplication; likewise, the mathematical discussion in Appendix J has a self-sufficient set of symbols. Some duplication of symbols occurs, however, between these two units.

The following list defines only those symbols used in the main body of the thesis (in fact, in Sections 4 and 5 only). Symbols used in Appendix J are listed at the beginning of that appendix.

A Cross-sectional area of the liquid in the manometer column which is connected to the piezometer tube.

B Cross-sectional area of the liquid in the manometer column which is open to atmosphere.

B' Cross-sectional area of the walls of the manometer tube which is open to atmosphere.

D Length of piezometer tube.

F Force applied to the arm of the balance beam by the manometer tubing and liquid column.

G Vertical force of surface tension on the manometer tubing which is open to atmosphere.

H Vertical distance between the lowest point of the pressure system and the transducer.

L Physical length of the bell.

L_o Effective length of the pressure system at the bell $= \frac{V_o}{S}$

S Cross-sectional area of bell.

T Temperature

U Volume of gas in pressure transducer when h = 0.

V Volume of gas in pressure system.

V_o Value of V when h = 0.

V_o' Volume of gas above the bell when h = 0.

W Weight of gas released so that bubbling is just maintained.

a Height of liquid in manometer column connected by piezometer tube.

b	Height of liquid in manometer column open to atmosphere.
c	Length of gas feed line between its lower end and the tapping for the piezometer tube.
d	Internal diameter of manometer tubing open to atmosphere.
f	The non-variable part of F.
h	Height of stream surface above the open end of bell.
j	Cubical expansion factor for manometer liquid = $1 + \beta \Delta T$.
k	Superficial expansion factor for manometer tube $= 1 + 2\alpha \Delta T$.
m	Stream height (h) expressed in atmospheres = $\frac{h}{p_o/w}$
n	Physical length of bell as a fraction of the effective length of the pressure system = L/L_o.
p	Pressure of gas in the bell, piezometer tube, and transducer.
p_o	Atmospheric pressure.
p_a	Pressure just below the meniscus in the manometer column which is connected to the piezometer tube.
p_b	Pressure just below the meniscus in the manometer tube which is open to atmosphere.
q	Ratio of cross-sectional area of liquid in the manometer tube connected to the piezometer tube to the total area of both manometer tubes = $A/(A + B)$.
r_a	Internal radius of manometer tube which is connected to the piezometer tube.
r_b	Internal radius of manometer tube which is open to atmosphere.
t	Time.
v	Volume of manometer liquid.
w	Specific weight of water.
x	Height of rise of water in the pressure system, either in the bell or the gas feed line.
y	Displacement of transducer element relative to its position when $h = 0$.
z	Manometric head = $(b - a)$.

α Coefficient of linear expansion of the material comprising the walls of the manometer tubes.

β Coefficient of cubical expansion of the manometer liquid.

γ Specific weight of manometer liquid.

Δ Symbol for an increment.

δ Internal diameter of piezometer tube

θ_a Contact angle between meniscus and wall in manometer tube which is connected to piezometer tube.

θ_b Contact angle between meniscus and wall in manometer tube which is open to atmosphere.

λ Specific weight of gas in the system at atmospheric pressure.

μ Velocity ratio between transducer and stream surface $= \frac{dy}{dh}$.

ρ Specific weight of air near the stream surface

σ Internal diameter of bell.

τ Surface tension of manometer liquid.

APPENDIX B

EXISTING PLUVIOMETERS

B.1 PREAMBLE

This appendix gives descriptions of the various types of pluviometers which are, or have been, commonly used by climatologists and engineers. No attempt is made to describe a number of instruments which for various reasons have not received, nor are likely to receive professional acceptance (for example, miniature gauges of various designs). Descriptions will be limited to the basic principle of the design with no attempt at discussing design details. Where the instruments fail to provide data suitable for all users, the main reasons will be stated.

B.2 DAILY-READ RAIN GAUGES

A wide variety of daily-read gauges is available and a full discussion on each type is not warranted, since some of the variations between gauges are only of a minor nature. A few gauges differing substantially from one another will be described, the gauges being selected to embrace a large number of design features. The selected gauges are the British 5-inch "Snowdon" pattern, and the Canadian, United States and Australian standard gauges. The first three are described and illustrated in "Meteorological Instruments" (Middleton and Spilhaus, 1953) and the latter in the Australian Meteorological Observer's Handbook (Commonwealth of Australia, Bureau of Meteorology, 1954).

All instruments are circular cylinders provided with a funnel leading the water to a storage vessel for subsequent measurement. The important design differences are in the rainfall capacity, collector diameter, position of the funnel relative to the collector orifice, height of collector above ground, type of mounting and method of measurement. These are summarized in Table B.1:

TABLE B.1

	British	Canadian	U.S.A.	Australian
Rainfall capacity	5.5 in	about 6 in	about 18in	10 in
Collector diameter	5 in	3.57 in	8 in	8 in
Distance from orifice to top of funnel	4.25 in	2.5 in	2 in	0.75 in
Height of orifice	12 in	12 in	about 30in	12 in
Type of mounting	sunk 7 in into ground	on wooden pile	on steel tripod	in wooden box
Method of measurement	decanting into glass	decanting into glass	dipstick	decanting into glass

None of the above gauges (unshielded) will be error-free, and even when fitted with shields, it is unlikely that aerodynamic neutrality will be achieved. The same will be true for other types of gauge meant to be mounted above the ground.

If any of the standard types of gauge have to be used (above ground) then it is the writer's opinion that best results would be achieved by selecting a gauge with a low-set funnel to lessen outsplash and then to use with it either a shield or a pit or both.

The alternative is to use a sunken gauge with the orifice at ground level. Such installations should be free from aerodynamic errors, and the problem remaining will be to eliminate splash errors. It appears that this could be done by surrounding the orifice with material which will either turn the drops away from the orifice (e.g., deflector plates sloping outwards) to absorb the energy of the raindrops progressively (e.g., brush or wood shavings). However, it is very difficult, perhaps impossible, to test the effectiveness of these measures since there is no rain gauge, universally accepted as error-free, which can be used for comparison.

Serious disadvantages are apparent however in the use of sunken gauges as universal instruments. They are more likely to catch wind-blown debris than are elevated gauges, and drainage of the hole in which they are sunk can be difficult in some installations.

B.3 STORAGE RAIN GAUGES

A storage rain gauge to collect more than about 150 inches of rain between visits is rarely required and if needed would probably be of a special design. It is not intended here to discuss these, but mention will be made of two standard containers which are often adopted for storage rain gauges in Australia: these are the 10-gallon milk can and the 5 -gallon ice-cream container.

Both of these are normally placed above ground, sunken installations being apparently too impractical.

The milk can is cylindrical with a diameter of $13\frac{1}{2}$ inches, this portion extending for a height of 15 inches. Above this is a conical shoulder leading to a neck whose diameter is $8\frac{3}{4}$ inches. Without any specially made orifice, 36 inches of rain can be stored in the cylindrical portion, and this could be increased to 110 inches by fitting an orifice of 5-inch diameter.

The ice-cream container is cylindrical with a diameter of 9 inches. Without a special orifice it can hold 22 inches of rain, and this can be increased to 70 inches by fitting an orifice of 5 -inch diameter.

Both types of storage gauge appear to be reasonably satisfactory except for the ubiquitous aerodynamic errors. Since the gauges are relatively tall ($23\frac{1}{2}$ inches for the milk can and 24 inches for the icecream container), it is desirable that a shield be fitted.

There are also available commercially several types of specially designed storage gauges, a typical one being the

the British "Octapent" design, manufactured by several firms. This gauge is available in capacities of 27 and 50 inches and, whilst a quite good design, is too small for universal use in Australia.

B.4 PLUVIOGRAPHS

B.4.1 Tipping Bucket Pluviographs

A number of gauges is available using the tipping bucket device. It will be convenient here to divide this discussion into two parts: one dealing with the tipping bucket mechanism itself and the other with the associated recording equipment.

B.4.1.1 Tipping Bucket Mechanisms

All known tipping bucket mechanisms have fundamentally similar behaviour with the exception of one marketed by Survey Equipment Pty. Ltd. of Melbourne. This mechanism is installed in a gauge known as the "Barker" Tilting Bucket Rain Gauge, an instrument which is, in the writer's opinion, a significant advance in pluviograph design. Its operation has been described in Section 5.2.2.5 and a calibration curve is presented in Fig. 5.7, illustrating how off-duty errors have been substantially reduced. All other tipping bucket mechanisms use only one bucket element and must have practically linear calibration curves, their errors over the useful range of intensities being greater than those of the "Barker" gauge.

The "Barker" gauge is provided with an electrically operated direct read-out counter mounted in the gauge itself, and there is provision for an external line to be connected, allowing the electrical impulses to be received up to several hundred feet away, if desired. The gauge itself does not record, although it may be used in conjunction with any suitable recording device, the combination becoming a pluviograph.

B.4.1.2 Recording Apparatus for Tipping Bucket Mechanisms

B.4.1.2.1 Constant-Speed Continuous Recorders

Nearly all recording mechanisms supplied in tipping bucket pluviographs use constant speed charts and pens. In most cases the charts are of the drum type (e.g., Negretti and Zambra) or else are strip charts rolling off a magazine on to a take-up spool (e.g., Akashi, Leupold and Stevens). Such gauges are subject to the disadvantages inherent in continuous time-sampling (see Section 3.4).

One recording mechanism is a variation on the simple drum. The "Casella" 95-day recorder uses a drum which rotates once a day about a horizontal axis. A stylus is slowly moved by a screw from the left side of the drum to the right, this motion taking 95 days. Thus, if the stylus were to draw a line on the drum, this line would be a helix of 95 turns. However, the stylus in fact makes a small hole in the chart for each 10 points of rain, this operation being initiated by a 10-point tipping bucket. The main disadvantage of this gauge is its large least count of 10 points.

It is the writer's strong opinion that when traditional constant-speed recording systems are used with an event-controlled device such as a tipping bucket, then the potential advantages of the event-controlled device are not nearly being realized.

B.4.1.2.2 The Pyrox "Sumner" Recorder

One instrument, the "Sumner" Recorder manufactured by Pyrox Ltd. of Melbourne, is sufficiently different from the usual run to warrant special discussion. The instrument has been described (Sumner, 1961) as a multi-purpose long-period recorder, and in fact can be purchased to record rainfall, water level, temperature, humidity, wind run, wind direction, barometric pressure, or evaporation. In addition, double-pen instruments are available for recording two variates on the same chart. A strip chart is used capable of lasting for 12 months at a standard rate of 4 in/day, and a reading is taken every 6 minutes.

The instrument is free from pen-to-paper friction, as it uses a chopper-bar system. The chart is marked with a small hole in the earlier instruments and current models give a clearly readable mark on a special plastic chart. The record is thus a discontinuous series of marks, and as such is free from some of the disadvantages of continuous records. For example, since the time interval between two adjacent marks is known quite accurately, and the increment of the measured variate can also be read with good precision, there is little error-of-reading introduced when computing rates-of-change of the variate. In contrast, a continuous record may have large errors-of-reading, associated with the very thickness of the trace (see Section 3.4).

When used as a pluviograph, the Pyrox recorder is connected to a tipping bucket gauge, signals from which cause a solenoid to step the stylus across the chart, each step representing 1 point of rain and each traverse 200 points; a cam returns the stylus to zero after each traverse. With a reading taken every 6 minutes, ambiguities associated with the number of traverses are possible if the rainfall intensity exceeds 20 in/hr (i.e., 200 points in 6 minutes) for a period of 6 minutes. In practice, there is very little chance of this occurrence.

It will be noted that the least count of the time scale (6 minutes) is considerably greater than the 0.5 minute specified in Section 2.3.5.3. However, the latter was specified in order that the intensity of a 5-minute burst of rain could be computed with 10% error, assuming that the timing errors were critical (see Section 2.3.3.3.3). In the Pyrox recorder, the 6-minute time interval is quite accurately known; therefore the mean intensity <u>for the 6-minute period between two chart</u>

marks should be computable as precisely as one can compute the rainfall increment. It appears at first sight then that the 6-minute least count of this instrument is quite reasonable. However, an important disadvantage still exists in the record, brought about by the use of clock control instead of event control. Fig. B.1 represents a mass curve of a hypothetical storm, and the dashed lines show the information available from a clock-controlled Pyrox recorder, being mean intensities over three 6-minute periods. These intensities (7.0, 10.0, and 6.0 in/hr) are, one may assume, readable to 1% or better. But it is apparent from the mass curve of this storm that the maximum 6-minute intensity was 14 in/hr, a fact not revealed by the clock-controlled recorder. In contrast, an event-controlled instrument reading to the nearest half-minute would have shown this maximum intensity, albeit with about 10% error associated with the least count of the time scale. Of the two alternatives, the writer prefers to have the fuller data provided by the event-controlled instrument, even if it is recorded less accurately.

The Pyrox recorder is available with faster chart speeds and correspondingly greater marking rates. For D.C. instruments, the fastest chart speed is 12 in/day and the marking rate 30 per hour; A.C. instruments, according to the makers, can have "almost any chart speed and marking rate". These alternative specifications may be invoked to overcome in part the disadvantage described in the previous paragraph, but there will normally be a corresponding decrease in chart life.

Summing up, the writer regards the Pyrox "Sumner" recorder as a very satisfactory instrument for most users of pluviograph data but feels that it does not measure up to the exacting requirements of a truly universal pluviograph, being rather unsatisfactory in recording information for short bursts of rain.

B.4.1.2.3 The "Barker" Rainfall Recorder

A completely different recording device (Barker, 1962) is available from the makers of the "Barker" rain gauge described in Section 5.2.2.5 and is intended for use with a tipping bucket rain gauge. The instrument uses a paper strip, marked by a stylus. Whenever an impulse is received from the tipping bucket, the paper strip is stepped forward a short distance; further, every t minutes, the strip is advanced and the stylus simultaneously moved sideways. The resulting trace is a series of triangular check marks, each indicating the passage of t minutes of time. If two check marks are adjacent, then no rain will have fallen in the t-minute period, but if the check marks are separated, then the length of the line between them is a measure of the rain which fell during the period to the nearest point. The value of t can be 60, 30, 15, or 5 minutes, to the specification of the user. With t = 15 minutes, the recorder has sufficient chart to record 150 inches of rain in a period of 1 month or 16 inches over 6 months. A sketch showing part of a typical record is given in Fig. B.2.

This ingenious recorder might be described as a mixture of an event timer and a regular clock-controlled time-sampling recorder. Its least count of 5 minutes is greater than the 0.5 minute specified in Section 2.3.5.3. However, as for the Pyrox recorder described in the previous section, the time period t is known quite accurately, and this makes the 5-minute least count more reasonable. But the argument of the previous section (illustrated in Fig. B.1) relating to the inability of clock-controlled recorders to reveal maximum intensities also applies to the "Barker" recorder.

B.4.2 Spring Balance (Weighing-Bucket) Pluviographs

Spring balance mechanisms are used widely (especially in U.S.A.) in pluviographs. They cannot be considered seriously for universal instruments for several reasons:

(a) They retain all the precipitation which falls between service visits. Therefore, if they are to be used as long-term pluviographs, they must be designed to retain large amounts of rain (100 inches or more). In fact none of them are so designed.

(b) They have inherently poor sensitivity of rainfall depth when used to store large amounts of rainfall. Any elastic element used in a field instrument, especially when coupled to a recording pen via a mechanical linkage with the associated friction and backlash, is doing well to show a least count of 0.5% of the full-scale deflexion. For a typical gauge designed to hold 12 inches of rain, this least count is 6 points, and if an instrument were designed for 100 inches, its least count could easily be as high as 0.5 inch.

(c) All known spring balance pluviographs use drum charts, and as a consequence either have insensitive time scales or do not run for long periods.

B.4.3 Natural Siphon Pluviographs

The "natural siphon" gauge is one which is emptied periodically by means of a siphon without moving parts. A typical design (the Dines pattern) is illustrated diagrammatically in Fig. B.3.

Rain enters the float chamber and also rises in the annulus surrounding the siphon tube. After the water rises to the top of the annulus, a convex meniscus forms and this eventually touches the glass plate. The water is drawn over the lip of the siphon tube and the siphoning continues until the float chamber has been emptied.

A serious drawback to the universal use of this gauge is its poor reliability. Whilst the operation of the siphon is quite regular when the instrument is well serviced, it becomes uncertain if maintenance is poor (and in remote locations it is impossible to give regular maintenance). Further, the off-duty error is relatively large and its correction cumbersome. Nor is the system easily adaptable as a telemeter. Finally, with the exception of the D.S.I.R. Combined Total Rainfall and Rate of Rainfall Recorder, all known siphon gauges have charts requiring either daily or weekly changing, definitely excluding these instruments as universal gauges.

B.4.4 Tilting Siphon Pluviographs

The tilting siphon was introduced in order to ensure that the siphon action always worked. The gauge is basically similar to the natural siphon gauge, but the siphon tube extends at an angle from the float chamber, and water rising in it provides a tilting moment. When the float reaches the top of the float chamber, it releases a catch, allowing the float chamber and siphon tube to tilt, starting the siphon positively. When the float chamber is empty, forces act so as to return it to its original position.

Even though the mechanism of the tilting siphon is quite reliable, these gauges are still unsatisfactory as universal instruments for the other reasons given in the final paragraph of Section B.4.3 above.

B.4.5 Cam-Type Float-Operated Pluviographs

Cams of various designs are often employed with float-operated pluviographs with the object of making the stylus traverse the chart a number of times; the advantage of this is that greater sensitivity can be obtained compared with an instrument in which the stylus makes only one traverse. The cam is usually designed to return the stylus to the chart's zero line (e.g., the "Hyetograph" of Negretti and Zambra and the "Mort" pluviograph) but at least one instrument uses a cam which causes the stylus to reverse its direction when it reaches the extremity of its travel (the Casella "Survey" pluviograph).

However, regardless of the differences in cam design, these gauges have this in common: operation of the cam mechanism is by a continuously rising float, and the instrument will cease funtioning when the float reaches the top of the float chamber. These gauges are therefore limited in capacity, the limit varying from 4 inches of rain for the "Hyetograph" to 20 inches for the larger of the two "Mort" instruments. For universal gauges, the capacities would have to be considerably increased. In this regard, suggestions have been made on methods for siphoning the water out of the float chamber when it becomes full, but to date no such gauge is available.

The charts used with cam pluviographs all require either daily or weekly changing, and this is another obstacle to the use of cam-type gauges universally.

APPENDIX C

PROPOSED DAILY-READ RAIN GAUGE

The design of the daily-read rain gauge suggested in this appendix and illustrated in Fig. C.1 has in the main been dictated by the form of its shield, which was introduced in Section 5.2.1 and Fig. 5.5.

The shield proposed is a square platform of water-repellent plastic in a cellular form, covering the gauge orifice and extending for some distance on all four sides. Its purpose is to prevent any convergent airflow over the gauge orifice and to produce a uniform splash field at the gauge.

Since the cells are in the form of a square mesh, a square orifice has been used, and also a square shape for the plan view of the body of the gauge.

The funnel meets the wall of the gauge just below the collector orifice, since it is considered that the shield, rather than the funnel position, will control splash. Hence there should be no need for a deeply-set funnel. The funnel is also of water-repellent plastic and is fairly tightly pressed into a channel in the shield.

The funnel-shield assembly is easily removed from the body of the gauge by releasing two plastic catches moulded with the gauge body, which is also of water-repellent plastic with all internal corners rounded to facilitate drainage and cleaning.

The mounting is a suitable base (timber or concrete) set into the ground, from which four holding-down cleats project. The body of the gauge is removed by twisting it until the heads of the four cleats are over the notches in the base of the gauge body, and then lifting. Whilst this is a simple procedure, it is extremely unlikely to occur by accident.

Water from the gauge funnel is discharged into a glass measure as supplied for standard 8-inch diameter rain gauges;

the measure is normally kept in the gauge. When the glass overflows, the excess is retained in the gauge body, and a total of about 10 inches of rain can safely be held without overflow.

For sites where a 10-inch capacity is deemed insufficient, extra capacity can be obtained by cementing one or more standard extension pieces to the top of the gauge body.

APPENDIX D

PROPOSED STORAGE RAIN GAUGE

The proposed storage rain gauge described in this appendix is illustrated in Fig. D.1.

The shield-funnel assembly is the same as that described in Appendix C for the daily-read gauge, except for the insertion of a screen (to pass material 3/32 inch in diameter) which is placed just above the outlet tube. The funnel is held to the gauge body by two clips, and a locking band can be readily fitted if considered necessary.

The gauge body is fabricated from steel, the whole assembly being hot-dip galvanized. The upper part is a square spigot, 12 inches high, to which the shield-funnel assembly is fixed. The main storage vessel is an inverted cone at the apex of which is a lockable drain cock. The gauge is raised above ground level on steel legs welded to the gauge body; the legs are set into a concrete mounting block or bolted to some other suitable base.

As standard, the gauge has a capacity of 150 inches of rain, but cylindrical extension pieces can be welded to the top of the conical vessel to increase the capacity as required.

Measurement is by dipstick, decanting being considered too tedious for such large volumes of water. The choice of this method of measurement was, in fact, the reason for adopting a conical storage vessel, permitting either small or large falls to be measured with approximately the same percentage error. It is estimated that observation errors in measuring depths of 5 and 150 inches would be about 1.5% and 0.5% respectively. Of course, a specially graduated non-linear dipstick will be necessary.

It will be standard practice to use a small quantity of oil or kerosene as an evaporation preventative.

APPENDIX E

PROPOSED PLUVIOGRAPH

The pluviograph proposed in this appendix, illustrated in Figs. 5.6 and E.1, is in two separate units, one being the collecting and measuring device and the other the recorder. If necessary, these units can be mounted together, but it is preferable for the recorder to be indoors if this is at all feasible.

The shield-funnel assembly is as described in Appendix C for the daily-read rain gauge, with a 3/32-inch mesh screen as described in Appendix D.

Below the funnel is a transparent filter bowl of the type commonly used in petrol lines, and this is used to trap dust and grit. The filter bowl is kept full of water and the upper surface of the water is in the lower part of the funnel. Evaporation from this surface is prevented by a layer of kerosene which also acts as a barrier to vermin.

The filter discharges into a "Barker" double tipping bucket measuring device housed in a square body of heavy galvanized steel which should afford some protection from the bullets of vandals. The shield-funnel-assembly is clipped and locked to the gauge body which is itself fixed to its mounting by three bolts accessible only after the funnel has been removed.

Water drains to waste through a porous plug in the base of the gauge body. There is normally a layer of water on the floor of the gauge and the function of this is to maintain the space within the gauge near saturation point with the object of lessening evaporation from the residual water left in the tipping buckets. The porous plug should offer some resistance to flow of water vapour, and this, coupled with the relatively still air conditions under the plug, should ensure that near-saturation conditions are maintained within the gauge for long periods. The plug also presents a very effective barrier to vermin.

As in the standard "Barker" gauge, a direct readout counter is provided, reading in points from 0 to 99999, and this is observable through a small window of heavy glass in the body of the gauge. In addition, an electrical outlet in the base of the gauge allows impulses to be transmitted to the recorder.

The recorder provided with the pluviograph is a printing chronograph driven by a clock, normally a synchronous clock except where A.C. mains are not available; in the latter cases a spring-driven clock electrically rewound by a battery-actuated solenoid is substituted. The clock drives a type wheel which rotates once per hour and on which the numbers 00 to 59 (representing minutes) are embossed. Each revolution of this minute wheel closes a contact which advances an hour wheel (with embossed figures 00 to 23) by one step. Each revolution of the hour wheel closes a contact which actuates a 3-digit decimal counter, registering the number of elapsed days. Energy for the solenoids is supplied either from a mains supply or from dry cells.

Each impulse from the tipping bucket, representing an increment of 1 point of rain, actuates an electrical 5-digit decimal counter which registers total rainfall from 0 to 99999 points. The impulse is also fed to a solenoid which actuates a paper feed mechanism and a printing head. Energy for rainfall count, paper feed and print comes either from the mains or from dry cells. An example of the print-out is shown as Fig. E.2.

The record is made on a paper strip which is supplied from a magazine, and for indoor installations is simply fed through a slot in the case of the recorder. For outdoor recorders, a take-up spool is provided. It is possible also to hand feed the paper without printing, and this is an advantage when loading and removing the chart. Sufficient paper is normally supplied to record 150 inches of rainfall.

If an impulse were to be applied to the solenoids which index the hour and day registers while a print-out was taking place, then some mechanical damage might occur. To prevent this, an interlock is provided which delays the operation of the time-indexing circuits until print-out and paper feed are completed.

The case of the recorder measures about 13 in x 9 in x 5 in, and stands on edge in indoor installations. However, for outdoor recording, it may be mounted flat, the obvious position being underneath the housing of the tipping bucket mechanism.

In battery-operated pluviographs, it is estimated that a battery weighing about 15 pounds should be able to operate the instrument for a period of one year.

The tipping bucket unit can also be coupled to a remote counter (indicating total rainfall only), a TAPPET (see Appendix L), or a telemetry transmitter. Provided adequate power is available, any or all of the methods of registration may be used.

The printing chronograph unit described is suitable without alteration for use as the secondary transducer in a rainfall telemetry system.

A pluviograph similar in concept to the one described in this appendix has been partially constructed but not tested. A brief description of this is given in Appendix N.

To the writer's knowledge, at least two firms, H. Wetzer of Germany and Sodeco of Switzerland offer printing chronographs which should suit many users, if not being universally suitable. Chronographs can be purchased to record, if necessary, times to a least count of less than 1 second, whilst others can continue recording for 1 year or more. A.C. and D.C. models are available. A counter can also be incorporated so that a running number (representing, for example, rainfall in points) can be printed alongside each record of time. Although the counter is not strictly necessary for recording rainfall, it is convenient and saves the trouble of tallying the number of printing operations when processing the record. In Appendix G is suggested a method whereby a readily available printing chronograph, fitted with one adding counter, may be used to record both rainfall and stream level on the same chart. The writer suggests that these avenues be explored by those interested in the immediate application of the methods advocated in this thesis.

APPENDIX F

EXISTING LIMNOGRAPHS

F.1 FLOAT-OPERATED LIMNOGRAPHS

F.1.1 "Traditional" Limnographs

Many excellent instruments are available, the best of which are capable of measuring water level very sensitively and accurately. The most common form uses a float and counterweight joined by a metallic wire or tape which passes over a sheave; the sheave is mechanically coupled to a stylus which marks a constant-speed chart. Most instruments have provision for changing the velocity ratio between float and stylus, either by change gears (as in the Leupold and Stevens A.35 recorder) or by pulley systems (Ott instruments).

The chart is driven by a clock which is usually either synchronous or weight-operated; spring drive is rare in float limnographs, but may become more common with the recent introduction of the long-life, constant-torque "negator" spring.

In some instruments it is possible to vary the chart speed by changing the gear train between the clock and the chart (in particular, the Leupold and Stevens A.35 recorder offers a very wide choice of chart speeds from 1.2 to 864 inches per day). The chart can be wrapped around a drum (for example, the Ott Type X or the Leupold and Stevens Type E), but the strip chart is more common since float recorders are often expected to run unattended for a month or more. The Leupold and Stevens A.35 recorder, for example, uses a strip chart and quite safely runs for a period of three months without attention.

In order to record a large range of levels and still give adequate sensitivity, it is usual for the pen to be able to make a number of traverses of the chart. In the Leupold and

Stevens A.35 recorder this is accomplished by an ingenious cam device which reverses the direction of stylus travel with practically no backlash. At the same time, an auxiliary stylus (optional) gives an indication that a reversal has occurred.

Another optional attachment on the A.35 recorder is a stylus which marks the chart at definite times to give a method for correcting for timing errors caused by expansion of the paper with increases in humidity.

Further features available with the A.35 recorder are provision of an extra float, sheave, and recording stylus if two different water levels are to be recorded on the same chart, and a solenoid-operated stylus designed to record rainfall, the signals coming from an external tipping bucket device.

Some gauges (the Esdaile tide recorder and the Leupold and Stevens Type F) use a method of recording in which a drum is geared to the float sheave. The rotation of the drum thus corresponds to stream level, and a large range of level can be easily recorded with high sensitivity by allowing the drum to rotate a number of times. A stylus marks the chart wrapped around the drum, moving across the chart under the control of a clock-driven screw. In the Esdaile instrument an open time scale is achieved by multiple traverses of the pen across the chart.

F.1.2 Event-Controlled Limnographs

A class of level-sensing devices exists which use event control. These are usually called impulse transmitters, and are all float-operated. A typical one is the Ott impulse transmitter in which the float sheave is coupled to a cam wheel fitted with a number of equally spaced lobes. As the stream rises, these lobes cause an electrical circuit to close for a short period at regular increments of stream level. With a falling stream, the lobes arrange for a different circuit to be closed in the same way. By feeding the impulses to a bi-directional counter, the level of the stream may be registered at either the same site or at a distance. This system is a standard method of telemetry and is discussed under the heading "Impulse Counting Systems" in Section 6.3.2.4.3 and also in Section 6.4. Special recorders are available for use with these impulse transmitters, and the Ott instruments are typical of all the others: recording is invariably done on a constant-speed chart, either wrapped around a drum or as a strip, thereby in the writer's opinion rejecting the possibilities of the event-controlled system.

F.1.3 Sloping Limnographs

One of the major problems in using float recorders is that some sites require excavation in the stream bank for a float well and trench for the inlet pipe. This can be very expensive, especially if rock is struck, and much research has gone into overcoming this problem by using a sloping well running down the stream bank. Sloping float wells are difficult to standardize and will probably continue to be designed to suit the particular bank conditions of individual sites. However, any standard recorder may be used in a sloping installation provided a correction is made for the angle (or angles) of the well.

F.1.4 Servo-Operated Limnographs

A level sensing device is available in the form of a servo system which maintains a bob at the water surface. This is not truly a float-operated instrument, since the bob would sink if not supported by its cable, but for convenience it will be dealt with in this section. Several such devices are available, a typical one being the Leupold and Stevens "Surface Detector". This consists of a bob on the end of a line which is coiled around a drum. Changes in water level cause variations in the depth of submergence of the bob and therefore in the tension in the supporting line. The balance of a beam is disturbed by the change in tension and the beam moves either up or down, closing one of two electrical circuits. The electrical signal is passed to a bi-directional motor, coupled to the drum previously mentioned. The motor rotates the drum, and line is paid out or reeled in to restore the bob to its original position relative to the water surface. Since equilibrium is restored, the circuit is broken and the motor stops. This mechanism is not in itself a recording device; however, the drum rotation is analogous to stream level and a record can be made by coupling the drum to the float sheave of a suitable recorder. The big advantage of the "Surface Detector" and similar instruments is that a large diameter well is not necessary; a small pipe is adequate. Further, the "Surface Detector" is also available for use in sloping wells, the bob being replaced by a small carriage on rollers. It is therefore possible to save on excavation costs by using these devices.

F.1.5 Printing Limnograph

A recorder made by Gurley in which a printed record is obtained has been used in the past, but is now rare. It is mentioned here because this thesis advocates the use of printing recorders. It is the opinion of the writer that the Gurley recorder did not take full advantage of the possibilities of printing methods of recording: it used a system of regular clock-control, recording both time and stream level at intervals of 30 minutes, whereas better records could have been obtained by using an event-controlled system.

F.1.6 Tape-Punching Limnograph

There is one float-operated limnograph at present available which gives a digital record, punched as holes in paper tape. This gauge is made by Fischer and Porter, U.S.A., and has been described in Section 7.4.2. This gauge, in the writer's opinion, has not fully taken advantage of the possibilities: true, it does not use a constant-speed chart but it still uses the traditional clock-controlled system of regular time-sampling. Further, the punched tape is non-standard and requires translation before being fed into a computer.

F.1.7 Pyrox "Sumner" Recorder

The Pyrox "Sumner" recorder described in Section B.4.1.2.2 is available as a float limnograph, either using one pen or two. In the single-pen instrument, the whole range of measured heights is represented by one traverse of the pen across the chart. Since the chart is only 3.5 inches wide, the scale is rather cramped. The two-pen recorder opens out this scale by having a coarse pen stepping across the chart and indicating (in a typical example)from 0 to 20 ft by 1 ft increments; a fine pen, moving continuously in sympathy with the float, passes to and fro across the chart, making one traverse for each 1 ft of water surface movement. Other ranges are available. The record produced by the pens is not continuous, a chopper bar being used to mark the chart at regular time intervals (normally once every 6 minutes). At a chart speed of 4 in/day, a roll of chart will last for 12 months.

As explained in Section B.4.1.2.2, the recorder has inherently quite high accuracy of reading, since it does not use a continuous trace. Whilst the instrument is excellent for many purposes, its main disadvantage as a universal limnograph, in the writer's opinion, is that its adaptation to a universal telemetry system would prove difficult.

F.2 PRESSURE-OPERATED LIMNOGRAPHS

F.2.1 Closed Systems

Closed pressure systems (i.e., those from which gas is not meant to escape) comprise a bell inverted in the stream, sometimes fitted with a flexible diaphragm, and coupled by a fine piezometer tube to a recording mechanism. Usually this is a Bourdon tube or a bellows whose movement is magnified by levers, causing a pen to travel over a constant-speed chart. The chart is usually circular (i.e., polar coordinates are used) and makes one revolution in a week, although daily rotation is usually available as an alternative. Typical of the instruments are those marketed by the Bristol Co. and Negretti and Zambra.

As universal limnographs, the above types of instrument are generally unsuitable, the main reasons being poor sensitivity, both in depth and time, and the use of a clock-controlled recording system. For certain sites, where long lines are necessary, the instruments may not be sufficiently accurate.

The Pyrox "Sumner" instrument is also available as a pressure-operated stream level recorder, but not in the double-pen form which gives an open scale of heights. The available single-pen recorder is quoted as having errors less than 1% of the range of heights, but this range is compressed into 3.5 inches of chart width. For recording ranges of levels of about 100 ft, the available sensitivity and accuracy are not nearly good enough for a universal limnograph. Difficulties would also exist in using this recorder in a universal telemeter.

F.2.2 Open Systems

The open pressure system comprises a gas supply, from which gas is bubbled out of a small-diameter tube immersed in the stream. The back pressure in the tube (a function of stream level) is measured by a transducer, connected by a piezometer tube to a point near the outlet of the gas feed line. Commercial instruments usually employ the same methods of measuring and recording as were described in Section F.2.1, i.e., Bourdon tube or bellows transducers, pens, and circular constant-speed charts.

One type, specially made by the Irrigation and Water Supply Commission of Queensland (Mortley, 1960), uses a mercury manometer as a transducer. Movement of the mercury surface is followed by a steel float, and any small movement of this float is detected by the closing of one of two electrical circuits, operated by contacts straddling a projection on the float. Closing of the circuit operates a bi-directional motor so as to move the contacts and open the circuit. Thus the contacts themselves, and the carriage on which they are mounted, follow the movement of the float. The rotation of the motor shaft is also proportional to float movement and hence to the vertical movement of the stream surface. Recording is accomplished by coupling the motor shaft to a Leupold and Stevens A.35 recorder. It is of interest to note that a similar servo system has recently been put on the market by Leupold and Stevens.

Once again, all the above instruments use the traditional clock-controlled recording system with its attendant disadvantages. The commercial instruments using Bourdon tubes or bellows suffer from inadequate sensitivity in depth and time, and the manometric gauges have thermal errors associated with the mercury manometer. These thermal errors can be serious when large depths are to be measured (see Sections 4.3.2.4.10 and 5.3.2.4) but can usually be reduced to negligible proportions by insulating the manometer. However, as this usually involves sinking the manometer into the ground, the solution to the problem may be expensive (relatively) in rocky sites.

APPENDIX G

PROPOSED FLOAT LIMNOGRAPH

A design is here suggested for a float limnograph to provide data suitable for all likely users. The instrument is illustrated in Fig. G.1.

The sensing device is an impulse transmitter which gives a brief electrical signal at each 0.1 ft increment of stream level, and a different signal for a corresponding decrement. Several devices which do this are available commercially, and it is suggested that one of these be used. A typical transmitter is the one made by Ott which operates from a D.C. supply of from 6 to 24 volts. If desired, its contact interval can be altered to 0.02, 0.05, or 0.2 ft, but it is suggested that 0.1 ft should be satisfactory for most purposes. With a contact interval of 0.1 ft, the Ott instrument is capable of measuring rises and falls as fast as 4 ft/min, and there is no limit (instrumentally) to the range of level which may be measured. If the stream surface rises or falls faster than 4 ft/min, as it may when the installation is in a sewer, a possible remedy is to increase the contact interval to 0.2 ft, doubling the maximum measurable rate of change of level. This will make the instrument less sensitive however, and in the rare cases where these fast rises are likely, a specially designed escapement is recommended to prevent the float sheave turning faster than the rate acceptable by the transmitter; this at least will ensure that the transmitter will eventually get back in step with the stream even though part of the hydrograph will be distorted during recording.

The recording mechanism normally used with the limnograph is the printing chronograph as described in Appendix E, except that instead of the 5-digit adding counter, a 4-digit add-subtract counter is used, registering the stream level from 0 to 999.9 ft. For contact intervals differing from 0.1 ft, a special counter may be used (counting by 2's or 5's as the case may be), or else each reading of the standard counter will have to be multiplied by an appropriate conversion factor.

It is estimated that battery operated instruments should be able to run for a year and to register stream movements of 1500 ft, with a power supply weighing about 15 pounds.

The impulse transmitter can also be used to operate a remote counter (add-subtract) for direct readout of stream level, a TAPPET (see Appendix L), or a telemetry transmitter. Provided adequate power is available, any or all the methods of registration may be used.

The printing chronograph described is suitable without alteration for use as the secondary transducer in a stream level telemetry system.

To the writer's knowledge, a printing chronograph possessing all the features of the one suggested in this appendix is not currently available, but one can purchase a chronograph which will print the time (days, hours, and minutes) together with a running number provided by an adding counter. This apparatus can be used to record stream level by using the counter simply as a polarity indicator; for example, one way of doing this would be to up-date the counter for each increment of level and to leave it unaffected for each decrement. It is also possible to go a step further and use this instrument to record both rainfall and stream level on the same chart. Various methods suggest themselves for recording these two variates unambiguously, and the writer suggests the following as being a reasonable compromise between instrumental complexity and difficulties in deciphering the record.

(a) A rainfall increment is registered by re-setting the counter to zero (a special circuit is available for this operation) before energizing the printing circuit.

(b) An increment of stream level is registered by re-setting to zero, adding 1, then printing.

(c) A decrement of stream level is registered by re-setting to zero, adding 2, then printing.

It will be necessary, in order to prevent damage to the instrument, to incorporate short time delays between the operations described above. Fig. G.2 illustrates a typical record from the instrument. Although the system described in this paragraph entails some trouble in processing, it does have the important advantage of immediate availability.

APPENDIX H

PROPOSED PRESSURE LIMNOGRAPH

The pressure-operated limnograph described in this appendix can be used either with a closed or open pressure system. When the site conditions are such that a closed system is practicable, it is suggested that this be used because of its low cost and simplicity. However, in some locations it may not be possible to install a satisfactory closed system, because it has been shown in Section 5.3.2.1 that design compromises are necessary among the controlling variables (bell and tube dimensions) in order to obtain low gas compression errors. In such cases, an open pressure system (which is not subject to gas compression errors) is recommended. The limnograph is illustrated in Fig. H.1.

The sensing element, either an open or closed pressure system, transmits pressure to a mercury manometer of the cistern type with a vertical leg about 0.25 inch in internal diameter. The length of the leg depends on the expected range of stage and is 90 inches for a range of 100 feet. The lower end of the leg is connected to the cistern by a long capillary tube with high compliance in the vertical direction. The cistern, tube, and leg are made of Invar, a nickel-steel alloy with negligible coefficient of thermal expansion and which does not amalgamate with mercury.

The leg of the manometer is suspended from one arm of a balance beam, damped by a dashpot, and provided with a contact arm. When the stream level varies, mercury rises or falls in the leg, and 0.1 ft change in level causes the weight of the leg to change by about 1 gm. The beam will be displaced sufficiently for the contact arm to touch one of two contacts. By means of a relay, a stepping motor is energized and the motor either pays out or reels in a fixed weight of chain, half of which affects the balance beam. The beam then returns to its equilibrium position under the influence of the weight of the newly-adjusted chain. Since the inertia of the system and the resistance of the dash-pot are considerable, a time delay of a few seconds exists; any trembling of the contacts during this period is not registered by the relay which is of a type incorporating a delayed release.

Preliminary calculations show that it will be feasible to make the capillary tube at the base of the manometer sufficiently compliant to have only a small effect on accuracy (it is estimated that errors of about 0.01 ft. of stream level might be introduced). Further, the capillary is not so fine as to restrict the response of the instrument to rapid rises and falls, and rates of 30 ft/hr have been estimated to be within the instrument's capabilities. If the stream surface moves faster than this, the mercury will lag behind the stream but the level of the mercury will still be correctly recorded. Since the mercury must eventually get back in step with the stream, the instrument itself cannot get permanently out of step.

Each time a contact is closed, resulting in an adjustment of the chain, the impulse is fed to an add-subtract counter via one or other of the two contacts; this counter (optional) therefore shows the stream level in units of 0.1 ft. Recording is accomplished by using the same printing chronograph as has been described in Appendix G.

Power supply is either battery or A.C. mains, a battery of about 15 lb being adequate for one year's operation, during which a stream surface movement of 1500 ft may be recorded.

As with the float limnograph described in Appendix G, any or all of the following methods of registration can be used:

(a) direct readout counter,

(b) printing chronograph,

(c) a TAPPET,

(d) a telemetry transmitter.

The printing chronograph is suitable without alteration for use as the secondary transducer in a stream level telemetry system.

The final paragraph of Appendix G deals with the use a currently available printing chronograph to record stream level, or both rainfall and stream level. This method is also available for use with the proposed weighing manometer.

Additional Note:

A more economical gauge with approximately the same performance might be possible by substituting for the manometer a piston transducer of a fairly new design, marketed under the name "Bellofram" by the Bellofram Corporation, U.S.A. This very neat device is stated to be almost frictionless, and consists of a rigid piston moving in a cylinder considerably larger than the piston. An airtight seal is maintained by a flexible element attached to both piston and cylinder, and working with a rolling action (see Fig. H.2). However, in order to use a reasonably convenient size of Bellofram (it is suggested that about 2 inches diameter would be feasible), the forces involved in measuring large stages become quite large. For example, a stream level of 100 ft will imply forces on the balance beam of about 150 lb. Compared with the manometer system, the whole balance device would be larger and heavier, and would require considerably more energy to operate.

The writer has had no experience with Belloframs, but it is suspected that the very small sizes might have enough friction in the rolling action to make them too coarse a device. After all, the least count being aimed at is about 0.1% of full scale (0.1 ft in 100 ft) and it is desirable that the instrument be accurate to 0.01%.

APPENDIX J

INTERFERENCE ANALYSIS

J.1 LIST OF SYMBOLS USED IN THIS APPENDIX

A = amplitude (1) of the FM carrier

c = $\cos\delta$

D = denominator of interference wave - See Expression (J.4)

k = amplitude modulation factor

N = numerator of interference wave - See Expression (J.4)

s = $\sin\delta$

t = time

u = $\tan\alpha = \frac{xys}{1 + xyc}$

x = $\left|\frac{\text{amplitude of unmodulated AM carrier}}{\text{amplitude of FM carrier}}\right|$ (known as the interference factor)

y = $1 + k \cos\gamma$

α = angle of resultant vector relative to FM vector

β = modulation ratio of FM

γ = $\nu_2 t + \phi$

δ = angle of AM vector relative to FM vector

$= (\omega_2 - \omega_1)t + \psi - \beta \sin \nu_1 t$

$\Delta\theta$ = instantaneous angle of FM vector rel. to its carrier $= \beta \sin \nu_1 t$

$\Delta\omega = \omega_2 - \omega_1$

θ = angle of vector

ν_1 = angular velocity of modulating signal vector (FM)

ν_2 = angular velocity of modulating signal vector (AM)

ϕ = phase angle of modulating signal vector (AM) relative to modulating signal vector (FM) at $t = 0$

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(1) "Amplitude" here means the peak deviation from the average value; the instantaneous deviation is referred to as "strength".

ψ = phase angle of AM carrier vector relative to FM carrier vector at $t = 0$.

ω_1 = angular velocity of FM carrier vector

ω_2 = angular velocity of AM carrier vector

Note: The use of the prime (') denotes differentiation with respect to time. e.g., $y' = \frac{dy}{dt}$

J.2 PREAMBLE

The problem of interference in the proposed radio telemetry system is two-fold; firstly the FM telemetry signals must cause negligible interference to any AM transmission on the same or adjacent channels, and secondly the probability of AM interference with the FM signals should be very small.

The first effect, as explained in Section 6.4.2, is negligible because of the short duration of the telemetry signals and the relatively high noise level expected on AM channels. The second problem is of importance, since any substantial interference may cause a signal to be missed or a spurious signal to be recorded; in either case a miscount occurs. Although this miscount will almost certainly be detected by the checking signal (see Section 6.4.1), it is nevertheless a nuisance and should occur only rarely. The writer has been unable to find any suitable analysis of the interference between AM and FM signals, even though an extensive bibliography on interference has been published (Institute of Radio Engineers, 1962). Accordingly this appendix aims at showing the effect, on the output from an FM receiver, of an AM wave which interferes with the desired FM wave.

In the following discussion it is assumed that the modulation ratio of FM (β) is small (narrow-band FM systems have $\beta < 0.2$). Also the FM receiver is assumed to have a perfect limiter and a perfect discriminator, so that the output from this combination is proportional only to the frequency deviation from the tuned frequency of the discriminator. This tuned frequency is assumed to be equal to the frequency of the desired carrier.

J.3 THE FREQUENCY-MODULATED WAVE AND ITS VECTOR

In this case, the modulating signal causes the frequency to deviate from the carrier frequency in proportion to the strength of the modulating signal.

If we adopt the usual convenient vectorial representation, (Fig. J.1) then the angular velocity of the rotating vector (which is proportional to frequency) also varies. An unmodulated carrier can be considered as being generated by a vector of constant length A rotating in a positive (anti-clockwise) sense at ω_1 rad/sec. When modulated, this vector will rotate at a varying angular velocity whose difference from ω_1 is proportional to the strength of the modulating signal.

In what follows, we shall confine discussion to modulating signals of sinoidal form.

Let us assume that the strength of the unmodulated carrier wave is given by

$$A \sin \omega_1 t$$

Then the strength of the frequency-modulated wave is given by

$$A \sin (\omega_1 t + \Delta\theta)$$

where $\Delta\theta$ is the instantaneous angle between the FM vector and the unmodulated carrier vector.

Now, if β is the modulation ratio and $\nu_1/2\pi$ the modulation frequency,

then $$\beta = \frac{\text{maximum frequency deviation}}{\nu_1/2\pi}$$

$$= \frac{\text{maximum deviation in angular velocity from } \omega_1}{\nu_1}$$

Therefore, max. deviation from $\omega_1 = \beta \nu_1$

If we assume the modulating signal to be of the form cos $\nu_1 t$,

then $$\frac{\text{instantaneous deviation from } \omega_1}{\text{maximum deviation from } \omega_1} = \cos \nu_1 t$$

i.e., instantaneous deviation from $\omega_1 = \beta \nu_1 \cos \nu_1 t$

i.e., $$d/dt\,(\Delta\theta) = \beta \nu_1 \cos \nu_1 t$$

Integrating,
$$\Delta\theta = \beta \sin \nu_1 t + [\Delta\theta]_{t=0}$$

We may, quite generally, select the origin for t so that the last term is zero, giving

$$\Delta\theta = \beta \sin \nu_1 t$$

and the strength of the FM wave therefore becomes

$$A \sin(\omega_1 t + \beta \sin \nu_1 t) \qquad \text{(J.1)}$$

J.4 THE AMPLITUDE-MODULATED WAVE AND ITS VECTOR

If x be the interference factor, then the amplitude of the unmodulated AM carrier is xA, where A is the amplitude of the FM carrier (Fig. J.2). The AM wave may be considered as generated by a vector, rotating uniformly in the positive sense at ω_2 rad/sec, but varying in length between the limits $xA(1 + k)$ and $xA(1 - k)$, where k is the amplitude modulation factor.

If we assume that the modulating signal has the form $\cos \nu_2 t$, then the length of the vector becomes

$$xA(1 + k \cos \nu_2 t)$$

and the strength of the modulated wave becomes

$$xA(1 + k \cos \nu_2 t) \sin \omega_2 t$$

In general, it will not be possible to select zero time so that the phase difference between AM and FM vectors is zero, since we have already arbitrarily assumed zero phase angle at t = 0 for the FM wave. Thus the above expression should be written

$$\text{Strength of AM wave} = x A\left[1 + k\cos(\nu_2 t + \phi)\right]\sin(\omega_2 t + \psi) \quad \text{———— (J.2)}$$

where ϕ = phase angle of AM signal relative to FM signal at t = 0,

and ψ = phase angle of AM carrier relative to FM carrier at t = 0.

J.5 THE RESULTANT WAVE AND ITS VECTOR

The desired FM wave and the interfering AM wave are superposed in the early stages of reception, and the strength of the resultant wave can be deduced by adding (vectorially) the rotating vectors associated with the two waves.

In general, the resultant is a vector of varying length rotating with a varying angular velocity. However, since the receiver is assumed to have a perfect limiter, it will be quite insensitive to the changes in length of the rotating vector. On the other hand, the variations in angular velocity are significant, and it will be our aim to find an expression for these variations.

Referring to Fig. J.3, the angle of the resultant vector is given by

$$(\omega_1 t + \Delta\theta + \alpha)$$

$$= (\omega_1 t + \beta \sin \nu_1 t + \alpha)$$

and its angular velocity by the time-derivative

$$\omega_1 + \beta\nu_1 \cos \nu_1 t + \alpha'$$

The output from the discriminator is proportional to the deviation from ω_1, and therefore

$$\text{Output} \propto \beta\nu_1 \cos \nu_1 t + \alpha' \quad \text{———— (J.3)}$$

Now $\alpha = \tan^{-1} \dfrac{xA[1+k\cos(\nu_2 t+\phi)]\sin\delta}{A + xA[1+k\cos(\nu_2 t+\phi)]\cos\delta}$

$$= \tan^{-1} \frac{x[1+k\cos\gamma]\sin\delta}{1+x[1+k\cos\gamma]\cos\delta}$$

$$= \tan^{-1} \frac{xys}{1+xyc} = \tan^{-1} u$$

where u, y, s, c and γ are as defined in Section J.1.

Differentiating, we have

$$\alpha' = \frac{1}{1+u^2} \cdot u'$$

$$= \left[\frac{1}{1+\left\{\frac{xys}{1+xyc}\right\}^2}\right]\left[\frac{(1+xyc)(xys)'-(xys)(1+xyc)'}{(1+xyc)^2}\right]$$

$$= \frac{x(1+xyc)(ys'+sy')-x(xys)(yc'+cy')}{1+2xyc+(xyc)^2+(xys)^2}$$

$$= \frac{x(ys'+sy'+xy^2cs'+xycsy'-xy^2sc'-xycsy'}{1+2xyc+x^2y^2}$$

$(\text{since } c^2+s^2=1)$

Now, $s' = d/dt(\sin\delta) = \cos\delta.\delta' = c\delta'$

and $c' = d/dt(\cos\delta) = -\sin\delta.\delta' = -s\delta'$

Therefore $\alpha' = \dfrac{x[yc\delta'+sy'+xy^2\delta'(c^2+s^2)]}{1+2xyc+x^2y^2}$

$$= \frac{x[y\delta'(c+xy)+sy']}{1+2xyc+x^2y^2}$$

Now $\delta' = \omega_2 - \omega_1 - \beta\nu_1\cos\nu_1 t = \Delta\omega - \beta\nu_1\cos\nu_1 t$

and $y' = -k\sin\gamma.\gamma' = -\nu_2 k\sin\gamma$

Thus $\alpha' = \dfrac{x\left[\begin{matrix}(1+k\cos\gamma)(\Delta\omega-\beta\nu_1\cos\nu_1 t)\{\cos\delta+x(1+k\cos\gamma)\}\\ -k\nu_2\sin\gamma\sin\delta\end{matrix}\right]}{1+2x(1+k\cos\gamma)\cos\delta+x^2(1+k\cos\gamma)^2}$

Therefore, from (J.3),

Output $\propto \beta\nu_1 \cos\nu_1 t$

$$+ \frac{x\left[(1+k\cos\gamma)(\Delta\omega-\beta\nu_1\cos\nu_1 t)\left\{\begin{array}{l}\cos(\Delta\omega t+\psi-\beta\sin\nu_1 t)\\ +x(1+k\cos\gamma)\end{array}\right\} - k\nu_2\sin\gamma\sin(\Delta\omega t+\psi-\beta\sin\nu_1 t)\right]}{1+2x(1+k\cos\gamma)\cos(\Delta\omega t+\psi-\beta\sin\nu_1 t) + x^2(1+k\cos\gamma)^2} \quad \text{(J.4)}$$

Therefore the output from the discriminator in general contains a component $\beta\nu_1\cos\nu_1 t$ at the desired frequency $\nu_1/2\pi$. In addition, a highly complex interference wave exists which can affect the telemetry system in two different ways. Firstly, the interference wave can in certain cases diminish or actually annul the desired component. Secondly, it is possible for certain frequencies to exist in the interference wave which cause spurious responses in one or more of the transducers not tuned to the frequency $\nu_1/2\pi$. These frequencies which cause spurious response could be expected to include $\Delta\omega/2\pi$ and $\nu_2/2\pi$; in addition, these frequencies could be combined with each other and with $\nu_1/2\pi$, their harmonics and various sum-and-difference frequencies also being possible causes of spurious response.

J.6 POSSIBILITY OF ANNULMENT

We consider firstly the case where annulment of $\beta\nu_1\cos\nu_1 t$ occurs. There are several ways in which this can happen, only one of which will be treated here. For example, if the following conditions were to exist concurrently, then the discriminator would give no output:

$$x = 1\ ;\ \Delta\omega = 0\ ;\ \nu_1 = \nu_2 = \nu\ ;\ \psi = \pi\ ;\ \phi = \frac{\pi}{2} \quad \text{(J.5)}$$

To demonstrate this, we first note that

$$\sin\gamma = \sin(\nu t + \pi/2) = \cos\nu t$$

and

$$\cos\gamma = \cos(\nu t + \pi/2) = -\sin\nu t$$

From (J.4), we have

Output $\propto \beta\nu \cos\nu t$

$$+ \frac{\left[(1-k\sin\nu t)(-\beta\nu\cos\nu t)\left\{\cos(\pi-\beta\sin\nu t)+(1-k\sin\nu t)\right\} - k\nu\cos\nu t \ \sin(\pi-\beta\sin\nu t)\right]}{1+2(1-k\sin\nu t)\cos(\pi-\beta\sin\nu t)+(1-k\sin\nu t)^2}$$

Since β is small, we may put

$$\cos(\pi - \beta\sin\nu t) \doteqdot 1$$

and

$$\sin(\pi - \beta\sin\nu t) \doteqdot \beta\sin\nu t$$

Therefore

Output $\propto \beta\nu\cos\nu t$

$$+ \frac{-\beta\nu\cos\nu t(1-k\sin\nu t)(-k\sin\nu t) - \beta\nu k\cos\nu t\sin\nu t}{1-2+2k\sin\nu t+1-2k\sin\nu t+k^2\sin^2\nu t}$$

$$\propto \beta\nu\cos\nu t\left[1+\frac{(k\sin\nu t)(1-k\sin\nu t)-k\sin\nu t)}{k^2\sin^2\nu t}\right]$$

$$\propto \beta\nu\cos\nu t\,(1-1)$$

$$\propto \beta\nu\cos\nu t\,(0) \qquad \text{(J.6)}$$

The same conclusion may be demonstrated graphically by adopting a system in which a modulated wave is considered to be generated by three rotating vectors of constant length (see Fig. J.4). The vectors generating the narrow-band FM wave are OA, OB, and OC. Vector OA is associated with the unmodulated carrier and in fact is rotating anti-clockwise at velocity ω. The small vectors OB and OC are associated with the upper and lower side frequencies and are in fact rotating anti-clockwise at $(\omega+\nu)$ and $(\omega-\nu)$ respectively. However, in the diagram, we have for convenience subtracted a velocity ω from each of the three vectors; this has the effect of bringing the carrier to rest and making the side vectors contra-rotating at velocities $+\nu$ and $-\nu$. The phase relationships have been so chosen that when the three vectors are added, their resultant is a vector which oscillates about the carrier vector at frequency $\nu/2\pi$ with negligible change in length. The semi-angle of oscillation is in fact equal to the modulation ratio β and must be small for narrow-band FM.

In a similar fashion, Oa, Ob, Oc are the generators of the AM wave. The vector Oa will be stationary in the diagram since we have as before subtracted a velocity ω from each of the vectors. The side vectors as before contra-rotate at velocities $+\nu$ and $-\nu$, but in this case, the phase relationships are such that (Oa + Ob + Oc) gives a vector whose angle does not change but whose length varies cyclically at frequency

When x = 1, OA and Oa will be equal in length, and if in addition $\psi = \pi$, the carrier vectors will have opposite sense and will annul each other. Thus only the four side vectors will be left to produce a signal. Two of these (OB and Ob) rotate at $+\nu$ and can be combined to give a vector (O1) rotating at $+\nu$. Similarly, vectors OC and Oc combine to form a vector (O2) rotating at $-\nu$. The vectors O1 and O2 (each of constant length) can be added to produce a vector (O3) which will fully represent the combined effect of the original FM and AM waves. It will be seen that the vector O3 varies in length but not in angle, meaning that it is in fact rotating at constant velocity ω. Since the discriminator is sensitive only to variations in angular velocity, there will be no output, confirming Expression (J.6).

The representation of modulated waves as vectors is of considerable help in understanding the interference phenomena, once it is realized that the discriminator senses only changes in angular velocity (wobble) of the resultant of all six vectors. When a telemetry transmitter is operating, vectors OA, OB, and

OC will always combine into a wobbling vector, and in general this wobble frequency will appear in the resultant except in extremely rare circumstances when several peculiar relations occur concurrently (as in (J.5) above).

It may be therefore stated that when a transmitter sends a signal, there is only a minute probability that the signal will be annulled by AM interference. It must be noted however that if x is large, there will be a tendency for the amplitude of wobble in the resultant to be small; if x is large enough, then the wobble may not be strong enough to cause the transducer to respond. It is considered unlikely that this will happen, since the interfering AM signals would normally come from a station well separated geographically from the telemetry transmitter and receiver.

J.7 POSSIBILITY OF SPURIOUS SIGNALS

The second case will now be discussed, in which AM interference causes spurious responses from transducers tuned to frequencies other than , the modulation signal frequency which is being received.

Expression (J.4) represents the output from the discriminator, the first term $\beta \nu_1 \cos \nu_1 t$ being the desired component at frequency $\nu_1 / 2\pi$ and the second term the interference, expressed as a fraction.

Since the denominator (D) of this fraction in general represents a wave whose value can pass through zero, then the fraction can at times be infinite. This means that the interference wave N/D is not in general expressible as a Fourier series, a form which demands that the wave be at all times finite. (In practice, of course, the wave which exists in the electronic circuits of the receiver cannot have infinities, and would be expressible as a Fourier series, but this is no help in simplifying the mathematical expression.)

The expression can be simplified by making the assumption (which in fact will correspond to most practical situations, where the AM and FM stations are far apart) that x is small. The denominator D then becomes (very roughly) unity, and the interference wave can be expressed, by expanding N, in terms of its component cosine waves.

Assuming β to be small (so that $\cos\{\beta \sin \nu_1 t\} = 1$ and $\sin\{\beta \sin \nu_1 t\} = \beta \sin \nu_1 t$ and using the trigonometrical formulae for sin (A $\pm$ B), cos (A $\pm$ B), cosAcosB, sinAsinB, the expression for output from the discriminator can be expressed [1] as:

$$
\begin{aligned}
\text{Output} &\propto \beta \nu_1 \cos \nu_1 t + N \\
&\propto \beta \nu_1 \cos \nu_1 t \\
&\quad + x^2 (1 + \tfrac{1}{2} k^2) \Delta\omega \\
&\quad + x \,\Delta\omega \cos(\Delta\omega t + \psi) \\
&\quad - x^2 \beta (1 + \tfrac{1}{2} k^2) \nu_1 \cos \nu_1 t \\
&\quad + 2 x^2 k \,\Delta\omega \cos(\nu_2 t + \phi) \\
&\quad + \tfrac{1}{2} x^2 k^2 \Delta\omega \cos(2\nu_2 t + 2\phi) \\
&\quad - \tfrac{1}{2} x \beta (\Delta\omega + \nu_1) \cos[(\Delta\omega + \nu_1)t + \psi] \\
&\quad + \tfrac{1}{2} x \beta (\Delta\omega - \nu_1) \cos[(\Delta\omega - \nu_1)t + \psi] \\
&\quad + \tfrac{1}{2} x k (\Delta\omega + \nu_2) \cos[(\Delta\omega + \nu_2)t + \psi + \phi] \\
&\quad + \tfrac{1}{2} x k (\Delta\omega - \nu_2) \cos[(\Delta\omega - \nu_2)t + \psi - \phi] \\
&\quad + \tfrac{1}{4} x \beta^2 \nu_1 \cos[(\Delta\omega + 2\nu_1)t + \psi] \\
&\quad - \tfrac{1}{4} x \beta^2 \nu_1 \cos[(\Delta\omega - 2\nu_1)t + \psi] \\
&\quad - \tfrac{1}{4} x k \beta (\Delta\omega + \nu_1 + \nu_2) \cos[(\Delta\omega + \nu_1 + \nu_2)t + \psi + \phi] \\
&\quad - \tfrac{1}{4} x k \beta (\Delta\omega + \nu_1 - \nu_2) \cos[(\Delta\omega + \nu_1 - \nu_2)t + \psi - \phi] \\
&\quad + \tfrac{1}{4} x k \beta (\Delta\omega - \nu_1 + \nu_2) \cos[(\Delta\omega - \nu_1 + \nu_2)t + \psi + \phi] \\
&\quad + \tfrac{1}{4} x k \beta (\Delta\omega - \nu_1 - \nu_2) \cos[(\Delta\omega - \nu_1 - \nu_2)t + \psi - \phi] \\
&\quad + \tfrac{1}{8} x k \beta^2 \nu_1 \cos[(\Delta\omega + 2\nu_1 + \nu_2)t + \psi + \phi]
\end{aligned}
$$

(continued)

---

(1) The intermediate steps in deriving this expression, whilst not in any way difficult, are tedious and too lengthy to set out here.

$$+\frac{1}{8}xk\beta^2\nu_1\cos[(\Delta\omega+2\nu_1-\nu_2)t+\psi-\phi]$$
$$-\frac{1}{8}xk\beta^2\nu_1\cos[(\Delta\omega-2\nu_1+\nu_2)t+\psi+\phi]$$
$$-\frac{1}{8}xk\beta^2\nu_1\cos[(\Delta\omega-2\nu_1-\nu_2)t+\psi-\phi]$$
$$-x^2k\beta\nu_1\cos[(\nu_1+\nu_2)t+\phi]$$
$$-x^2k\beta\nu_1\cos[(\nu_1-\nu_2)t-\phi]$$
$$-\frac{1}{4}x^2k^2\beta\nu_1\cos[(\nu_1+2\nu_2)t+2\phi]$$
$$-\frac{1}{4}x^2k^2\beta\nu_1\cos[(\nu_1-2\nu_2)t-2\phi]$$

The desired term is $\beta\nu_1\cos\nu_1 t$ so that the terms containing factors much smaller than β can probably be neglected (i.e., terms containing $x^2\beta$, $x\beta^2$). Further, the term $x^2(1 + 1/2\ k^2)\Delta\omega$ is not a wave and cannot cause response in a transducer. Thus the only terms likely to cause spurious response are those corresponding to the eleven frequencies:

$$\nu_2\ ;\quad 2\nu_2\ ;\quad \Delta\omega/2\pi\ ;\quad (\Delta\omega+\nu_1)/2\pi\ ;$$

$$(\Delta\omega-\nu_1)/2\pi\ ;\ (\Delta\omega+\nu_2)/2\pi\ ;\ (\Delta\omega-\nu_2)/2\pi\ ;\ (\Delta\omega+\nu_1+\nu_2)/2\pi\ ;$$

$$(\Delta\omega+\nu_1-\nu_2)/2\pi\ ;\ (\Delta\omega-\nu_1+\nu_2)/2\pi\ ;\ (\Delta\omega-\nu_1-\nu_2)/2\pi .$$

If any of the above eleven frequencies happen to correspond to a tuned frequency of one of the secondary transducers of the telemetry system, then there is a high probability of spurious response. However, spurious response from some transducers cannot affect the measurement (for example, response of the equipment-checking transducers).

Spurious response of the increment and decrement transducers can be detected and corrected when the next counting-check signal is sent.

Doubt as to the true measurement seems probable only when a spurious counting-check signal is registered. Let us examine the consequencies of this.

A counting-check signal is normally received together with a signal denoting an increment (or decrement), both signals being associated with the same variate (See Section 6.4.3.1). Accordingly, if the record indicates the receipt of a counting-check signal for a variate X without a corresponding increment signal for X, then we know that the counting-check must be spurious. The only case of practical importance thus is when the AM interference causes response in the counting-check transducer which corresponds to the variate being measured at the moment (a very rare occurrence). Even in this case, it may be possible to decide on the validity of the check signal by examining the previous and subsequent behaviour of the system. If behaviour seems otherwise quite normal, it is perhaps safest to assume that the check signal is erroneous. For stream level telemetry, the shape of the recorded hydrograph (which should be a well-behaved function) may be of assistance in making a decision to accept or reject the check signal.

J.8 SUMMARY

Summing up, it is felt that AM interference should have negligible effect in preventing receipt of desired signals and, whilst spurious signals may occasionally be received, there is enough redundancy in the system to allow almost all of these spurious signals to be detected and corrected.

APPENDIX K

DESCRIPTION OF A SMALL TELEMETRY PROJECT

K.1 PREAMBLE

In this appendix is described a hypothetical telemetry system to transmit signals by radio from a small catchment to a base station about 50 miles away. On the catchment are three telemetry field stations T_1, T_2, and T_3. Station T_1 is situated at the lowest point of the catchment at a stream gauging station, and transmits measurements of stream level and rainfall depth. Stations T_2 and T_3 transmit measurements of rainfall depth only.

The system is illustrated in the form of block diagrams, to which the supplementary discussion in the following sections refers.

K.2 FIELD EQUIPMENT

K.2.1 Equipment at Station T_1

Referring to Fig. K.1, a dry battery supplies energy to the transmitting equipment whenever one of the event-controlled impulse generators operates. The radio-frequency stages of the transmitter are energized at each impulse, but in most cases only one audio generator operates, depending on which impulse generator has functioned. The result is that a fixed-frequency carrier wave is transmitted, modulated by one of several possible audio frequencies, although it is possible at times for several modulating frequencies to co-exist. For example, if the stream level is falling through a reading of an even foot (e.g., 7.0 ft), the transmission will be a carrier wave of 2.996 megacycles/sec, and modulation frequencies of 255 and 240 cycles/sec will be present. Since the narrow-band FM system is being used, the transmitted spectrum will comprise the frequencies 2.996, 2.996 ± 0.000255 and 2.996 ± 0.000240 megacycles/sec. Since the electronic equipment uses transistors instead of vacuum tubes, response to the impulse is instantaneous. The transmitted signal lasts for about 0.1 second, and the radiated power is about 50 watts.

K.2.2 Equipment at Stations T_2 and T_3

Referring to Fig. K.1, the equipment at Stations T_2 and T_3 is similar to that at Station T_1 except that

(a) the devices associated with telemetry of stream level are not included,

(b) different modulation frequencies are used, as indicated,

(c) the carrier frequencies are different (2.998 and 3.002 megacycles/sec for T_2 and T_3 respectively.

K.3 BASE EQUIPMENT

K.3.1 General

Refer to Fig. K.2. The base, or receiving station is normally operated from an A.C. mains supply, transformed and rectified. An emergency battery supply is kept charged from the mains. The electronic equipment is duplicated to make it highly probable that one set is always available to receive signals from the transmitters, signals which may of course come at any time.

K.3.2 Normal Operation on Signals from Field Transmitters

Waves received by the aerial are fed to the early stages of the receiver, in which are incorporated three piezo-electric crystal band-pass filters. These are tuned respectively to the three transmitter frequencies (i.e., 2.996, 2.998, and 3.002 megacycles/sec). Each filter has a pass-band of 1000 cycles/sec, centred around the frequency to which the filter is tuned, and this narrow band ensures that very little other than the desired carrier and its sidebands is passed to the limiter-discriminator stage which follows. Three such stages are used to obviate the possibility of interference between FM signals arriving simultaneously from different field transmitters.

To make the explanation more easily understandable, it will be assumed that station T_1 is sending a signal for a falling stream level at 7.0 ft, i.e., a carrier of 2.996 megacycles/sec modulated by audio frequencies of 240 and 255 cycles/sec. This signal is selected by the crystal filter tuned to that carrier frequency, and passed to the limiter-discriminator stage where the modulating frequencies are recovered. The signal, by now reduced to the two audio frequencies, is passed to a bank of tuned reeds, two of which respond. The one tuned to 240 cycles/sec operates a relay which registers the receipt of a counting check signal for stream level and also sets the type ready for recording this. The reed tuned to 255 cycles/sec operates another relay which subtracts one from the counter registering stream level and sets the type of that counter.

The presence of the audio signal in the final stages of the receiver is used to operate the printing and paper-feed mechanism, making a record of the date, time-of-day, value of the stream level, and the occurrence of the counting check signal for stream level.

If the signal had originated at another transmitter (T_3 for example), then the crystal filter for 3.002 megacycles/sec would have selected the signal and passed it on to a different limiter-discriminator stage for detection.

Should two signals be received simultaneously, interlocking devices are incorporated to delay one of them until after the other has been recorded. Unless this is done, some mechanical damage may occur to the counters or printing apparatus.

An example of a typical record is given as Fig. K.3.

K.3.3 Failures in Base Station Equipment

The complete set of equipment at the base station, from aerial to recording instrument, is duplicated. The purpose of this is to ensure that a message has a good chance of being recorded even if a part of the equipment fails. It is extremely unlikely that the other concurrently operating set of equipment will have also failed to register the information.

Comparison of the two records produced will enable the fault in the receiver or recorder to be discovered and eliminated.

One further advantage suggests itself, arising from the use of two receiving aerials. By placing the aerials well apart it is possible to increase the reliability of reception in those cases where fading is a nuisance. Fading is usually caused by interference between waves which have taken different paths in travelling from the transmitter to the base station; if the waves arrive out of phase, it is possible for them to cancel each other. This phenomenon is greatly dependent on atmospheric conditions and varies at one position with time, and at the one time with position. It is possible for complete annulment to occur at one aerial, yet for good reception to be feasible at another site only a few wave lengths away.

<u>K.3.4 Failure of Power Supply</u>

In normal operation from the rectified mains supply, a relay R is continuously energized directly from the power source. Should the power fail, the relay drops out and causes automatic change-over to the reserve battery power supply. Restoration of the mains supply causes R to operate again, with automatic change-over back to the mains supply. (See Fig. K.2).

A source of trouble is the clock associated with the printing chronograph, which logically should be a mains-operated synchronous clock. When the supply fails, only a D.C. reserve is available and this is not suitable for the clock. It seems to the writer that the simplest solution is to arrange for the clock to be driven, during power failures, by a transistorised oscillator generating a signal at 50 cycles/sec. Whilst the frequency stability of this may not be very high (and hence timing errors may be introduced), lengthy power failures should be rare and thus there should not often be gross errors in timing.

K.4 USE OF CHANNEL SPECTRUM

Assuming that the channel allocated for use is from 2.995 to 3.005 megacycles/sec, this telemetry system uses only 30% of the available spectrum. There is then room on this channel for another six transmitters (allowing a 5% safety margin at each end of the channel). If all these are used, it may not be possible to allocate one reed frequency to each variate in the system, since only a limited number of standard frequencies may be available. However, duplication of reed frequencies among the variates is possible provided no two reed frequencies modulate the same carrier; in this way the variates can be separated at the base station.

APPENDIX L

THE TAPPET

L.1 PREAMBLE

The instrument described in this appendix is proposed as a solution of the problem of recording event times in a form which is suitable for direct input into an electronic digital computer. The data which it is primarily designed to record are rainfall depths and stream levels, although it is by no means restricted to these, and in fact could be adapted to record any events which occur at intervals of about 1 second or more.

The instrument is a tape-punching event timer, known as the TAPPET for short, and consists basically of a timing register in the form of a clock-driven set of coding drums, and a paper-feed and punching mechanism which is operated by an external electrical impulse. When this impulse occurs, the time of its occurrence is punched in standard 5-hole telegraphic tape, as a binary-coded pattern of holes. In addition, it is possible for a few of the bits normally used for coding time to be used (if necessary) for certain other uses which will be explained in Section L.7.

The instrument is capable of recording times unambiguously to the nearest half-minute over a period of 1 year (less a few hours), and is designed to run unattended for this period in field locations.

L.2 THE CLOCK

The clock's only duty is to drive at uniform speed one small coding drum which is loaded only by its own friction and at intervals by a light electrical contact. Thus a heavy-duty clock is not required. The clock must be fitted with a spindle rotating once every 16 minutes, but may have, as an aid to setting, a conventional dial and days counter. For use in field stations without an A.C. mains supply, a spring- or weight-driven clock, electrically rewound at intervals is suggested as a suitable type; another system which should prove quite satisfactory uses small driving impulses applied directly to the balance wheel. The obvious choice where A.C. mains are available is the synchronous clock. It is important that the backlash at the spindle be less than about 5 degrees to ensure that the least count of the coding drums is in fact available.

L.3 THE CODING DRUMS

Refer to Fig. L.1. There are four drums, each composed of six discs mounted side by side, five being coding discs and one a spacer. The circumference of each coding disc is provided with teeth and gaps, so arranged that a drum can be divided into 32 sectors, each of which, when scanned along the axis of the drum, has a unique pattern of teeth and gaps.

The least significant drum A (coupled to the clock spindle) has its teeth and gaps arranged according to the Gray code (see Appendix A) to overcome gross errors in readout. Drums B, C and D are coded using straight binary, there being no readout problem with these drums which move in discrete steps. The developed patterns of the Gray and straight binary drums are shown in Fig. L.1. Each coding disc corresponds to one hole-position across the standard 5-hole tape, the spacer disc corresponding to the position of the feed-sprocket holes.

Since Drum A rotates once every 16 minutes, the 32 sectors can be used to record times from 0 to 15.5 minutes by half-minute increments. Just when Drum A is about to reach its zero position, a contact is made which operates the indexing rod and causes Drum B to be indexed by its ratchet through 1/32 revolution. At the same time, Drum A is also indexed with Drum B to ensure that its zero is in fact registered. (However, in another few seconds the clock catches up with Drum A and continues to drive it for another revolution.) At the end of one revolution of B, a deep tooth in its ratchet wheel allows the indexing rod to drop, engaging the ratchet wheel of Drum C and indexing it. Likewise C has one deep tooth which causes D to be indexed at every revolution of C. Thus:

Drum	A	indexes	every	0.5	min.	&	does	1	revolution	in	16	min.
"	B	"	"	16	"	"	"	"	"	"	512	"
"	C	"	"	512	"	"	"	"	"	"	16,384	"
"	D	"	"	16,384	"	"	"	"	"	"	524,288	"

i.e., Drum D makes a revolution in 364 days 2 hours 4 minutes, meaning that times to the nearest half-minute can be registered unambiguously over a period of almost 1 year. A faster clock will allow more sensitive registration of time over a shorter period, and vice versa; it is suggested that these variations be incorporated as alternative specifications.

L.4 THE TRANSFER MECHANISM

The coded pattern of teeth and gaps in the drums is transferred on to the paper tape as a pattern of holes and blanks. This transfer is accomplished by twenty small rockers and twenty tappets as shown in Fig. L.1. The upper end of each rocker is fitted with a pecker, almost touching the coding drums. If the pecker is adjacent to a gap, then upward movement of the associated tappet will cause the pecker to enter the gap, and the force required to cause this action will be quite small, certainly too small to punch a hole in the paper tape. On the other hand, if the pecker strikes a tooth, the tappet can have considerable force exerted on it as the reaction between tooth and rocker is transferred; it is this force which is used to perforate the paper.

The tappets move in vertical bores in a platen, the paper being fed through a slot in the platen just below the tappets.

L.5 THE PAPER-FEED AND PUNCHING MECHANISM

Referring to Fig. L.2, a rotary solenoid is used to drive a mechanism which firstly (via the ratchetting intermittent) feeds the tape exactly 4 holes (0.4 inch), and then (by a toggle action) presses the platen upwards. The pattern of holes is thereby punched in the tape and a spring withdraws the platen. The rotary solenoid responds to the external impulse fed to the TAPPET.

L.6 INTERLOCKING MECHANISM

If an indexing impulse were to be applied to the coding drums with the punching cycle in operation, mechanical damage to the drums and rockers would be probable. Accordingly, an electrical interlocking mechanism ensures that the indexing circuit for the drums is broken whenever the feed-punch cycle operates, but as soon as the feeding and punching has been carried out, the indexing circuit is connected once more. If the indexing contacts on Drum A have touched in the intervening period (about 1 sec), they will still be touching when the feed-punch cycle ceases, and indexing will occur immediately.

L.7 SPARE BITS

It is possible to arrange for some of the coding discs to be moved independently of the timing indexing impulse. This is done by providing special solenoids for these discs. Such spare bits can be used for a variety of purposes, but for hydrological work they would normally be used as polarity indicators (i.e., rising or falling stream) or to register counting check signals (see Sections 6.4.3.1 and 6.4.4). It is suggested that equipment checking signals, if used in a telemetry system, be not registered on the TAPPET but on some other recording device; there seems to be no point in taking up tape and computer time in recording such purely auxiliary data.

The discs available as spare bits would normally be the ones which, if indicating times, would be the most significant (highest in value). As discussed in Section L.6, inter-locking mechanism may be required to prevent movement of the spare discs during the feed-punch cycle, if such movement is likely.

L.8 POWER SUPPLY

For locations where A.C. mains are available, it is suggested that this supply be transformed to a low voltage and rectified. For most field installations it will not be possible to use A.C. mains, and dry cells are suggested. It is estimated that a battery weighing about 10 lb should have sufficient energy for 15,000 separate punchings, and this would normally correspond to recording 150 inches of rain (point by point) or 1500 ft of stream movement (with a record made every 0.1 ft). In either case, about 500 ft of paper tape would be used. The energy requirements of the clock are expected to be quite negligible compared with the punching requirements.

L.9 INPUT TO THE COMPUTER

Provided the computer is able to read standard 5-hole tape, there should be no problem at all in programming the computer to decipher the code used on the tape, even though this is a mixed code, partly straight binary and partly Gray. Any reasonable computer would have a sufficiently flexible order code to make this translation, and to make it extremely quickly since little arithmetic is involved. The SILLIAC computer at Sydney University can certainly deal with a record from the TAPPET.

Computers which accept only tapes with levels other than 5 will not be able to use the TAPPET record directly, and special translation will be necessary. However if one wishes to avoid this, conversion of the TAPPET itself to punch, for example, five levels of a 7-hole tape should be relatively easy.

Whether such a record could be used effectively by a computer which accepts 7-hole tape will depend on the order code of the particular computer.

A short study of the problem of using the TAPPET with an IBM 1620 computer (which uses 8-level tape) has convinced the writer that the following changes in construction would give a workable instrument, recording about 500 days by half-minute intervals:

(a) clock to make 1 revolution in 18 minutes;

(b) each of the four drums to have 6 operating discs, with 36 available code patterns per drum;

(c) number of rocker-tappet units to be increased to 24 (four groups of six).

The IBM 1620 does not have as efficient a character code as does SILLIAC, in that some hole combinations are not used. This might cause an increase in computing time, but the computer should certainly be able to accept the data tape directly and process it without difficulty. A form of cyclic permuting code is also feasible for the least significant drum.

L.10 TYPICAL USES

The TAPPET is intended mainly to replace the recording units used in pluviographs and limnographs which use event-controlled primary transducers. Thus it can be used with any of the instruments in the universal system described in Appendices E, G, and H, requiring only an electrical impulse from either a tipping bucket, float-operated impulse generator or pressure-operated impulse generator. If required, it can be used in addition to the standard printing chronographs which are mentioned in the appendices. There is furthermore no difficulty in using it as a secondary transducer in a telemetry system, without requiring any changes in the system; all that is required is that a tuned reed (or several if the spare bits are being used) be allocated to provide the required recording impulse.

It is not proposed here to study non-hydrological uses for the TAPPET. However, it has occurred to the writer that that many variates show similar sporadic behaviour to rainfall and stream level, and any of these should be suited to recording by event timing methods using a TAPPET (perhaps with some modifications).

A very few will be indicated here. Wind run (and hence by differentiating, wind velocity) should be recordable without any modification by using an anemometer generating an impulse at each increment of wind run. Traffic counting may also be a fruitful field for these methods of recording, but here, since axle counts can occur too frequently for them to be recorded individually by a TAPPET, it is suggested that a buffer counter be used to count axles, passing an impulse to the TAPPET for every (say) tenth axle.

APPENDIX M

CALIBRATION TEST ON "BARKER" RAIN GAUGE

M.1 TEST PROCEDURE

The gauge was tested as received without any adjustments being made to the bucket mechanism. After first being levelled, the gauge was set up on a bench above a 2-litre measuring cylinder in which the discharge from the gauge was caught. Water was fed into the gauge funnel at a constant rate (controlled by a metering valve) from a constant-head supply tank.

At a moment when the counter on the gauge operated, indicating a tip of the measuring bucket, the measuring cylinder was moved under the gauge to catch the slug of water discharged, the reading on the counter was noted, and a stop-watch was started. After a satisfactory volume of water had been collected, and at a moment when the counter operated, the cylinder was removed (before the discharge just released had had time to enter it), the watch was stopped, and the counter read. The temperature of the collected water was also noted.

The mass of water collected was measured, and hence its volume was calculated and converted to points of rainfall. This figure was then compared with the difference between the readings of the counter.

The test was repeated for a number of rainfall intensities up to about 30 inches per hour.

M.2 TEST RESULTS

True Intensity (in/hr)	0.165	0.804	1.184	1.610	2.03	2.14	4.45
Indicated Intensity (in/hr)	0.163	0.791	1.171	1.555	1.963	2.075	4.44
Percent Error	-0.2	-1.6	-1.2	-3.1	-3.4	-3.0	-0.2

True Intensity (in/hr)	6.73	7.96	8.11	9.06	16.7	24.4	29.0
Indicated Intensity (in/hr)	6.78	8.03	8.15	9.02	16.4	22.2	24.8
Percent Error	+0.8	+0.9	+0.7	-0.5	-1.4	-8.9	-15

M.3 SAMPLE CALCULATION

Final Reading on Counter = 07660

Initial Reading on Counter = 07460

Difference in Readings = Indicated Rainfall = 200 points

Time of Test = 5 m. 24 s.

Indicated Intensity = 22.2 in/hr

Mass of Cylinder + Water = 6 lb 6.5 oz

Mass of Cylinder = 2 lb 15.9oz

Mass of Water = 3 lb 6.6 oz

Density of Water at 78°F = 0.0360 lb/in^3

Volume of Water = 94.9 in^3

Depth of Rain Collected(1 point = 0.503in^3) = 189 points

True Intensity = 24.4 in/hr

M.4 REMARKS

At intensities above about 12 inches per hour, it was noted that water built up as temporary storage in the funnel. The volume in storage increased with intensity, until at intensities approaching 30 inches per hour, the funnel was almost full of water, representing considerably more than 1 inch of rainfall. The time taken to build up this funnel storage to its equilibrium value was quite appreciable, being more than 15 minutes at the highest rates of flow. When funnel storage occurred, the test was not started until the equilibrium state had been reached.

An important practical consequence of this storage effect is evident: if during a storm there suddenly occurred a burst of rain at an intensity above about 12 inches per hour, the gauge would not show the true storm behaviour but would under-estimate the intensity and over-estimate the duration of the burst. The remedy appears simple: the diameter of the outlet tube from the funnel should be increased.

Errors in the test procedure are almost entirely associated with the measurement of the mass of water collected and are estimated to result in random errors of about 0.5% in measuring the true intensity. Errors in the indicated intensity are negligible.

The results of this test are plotted as Curve No. 1 in Fig. 5.7, and the reasons for the rather peculiar shape of this curve are given in Section 5.2.2.5.

APPENDIX N

PROGRESS STATEMENT OF WORK ON PRINTING PLUVIOGRAPH

This appendix describes very briefly the construction of a printing pluviograph, very similar in concept to that described in Appendix E. A fuller description of the instrument is available (Learmonth, 1959).

The writer began this work with the intention of producing an instrument which would satisfy the design specifications of Section 2.3.5.3 and in addition have the same external dimensions as a standard Australian rain gauge. The latter requirement forced a rather cramped design, and the writer no longer regards this requirement as essential, or even desirable, in a pluviograph. As things turned out, it proved extremely difficult to fit all the necessary components into the space available, and the gauge remains uncompleted. The most intractable component was the clock movement, it being found impossible to obtain a standard movement with all the necessary qualities (small size; battery-operated with low power drain; sufficient torque; two drive shafts with speeds of 1 rev. per hour and 1 rev. per day).

There is now available a movement with these characteristics with the exception of the provision of a daily drive shaft, and if construction of the pluviograph is resumed, the instrument and this clock movement will both require modification before they can be satisfactorily mated.

Fig. N shows the internal recording mechanism of the pluviograph mounted on its base plate. Clearly visible are:

(a) the chart (1), passing from the magazine spool (2) past the printing head (3) to the take-up spool (4);

(b) the printing hammers (5) driven by the small motor (6) via the gear box (7) and linkage (8);

(c) the two concentric time wheels (9), intended to be driven by a clock movement (not shown).

The view of the printing head shows the rainfall counter (10) and the days counter (11). An inked ribbon (not shown) normally circulates horizontally round the printing head.

The parts shown are intended to be mounted in the lower part of the case of a standard rain gauge, the operating impulses coming from a single tipping bucket (0.01 inch capacity) situated just below the gauge funnel.

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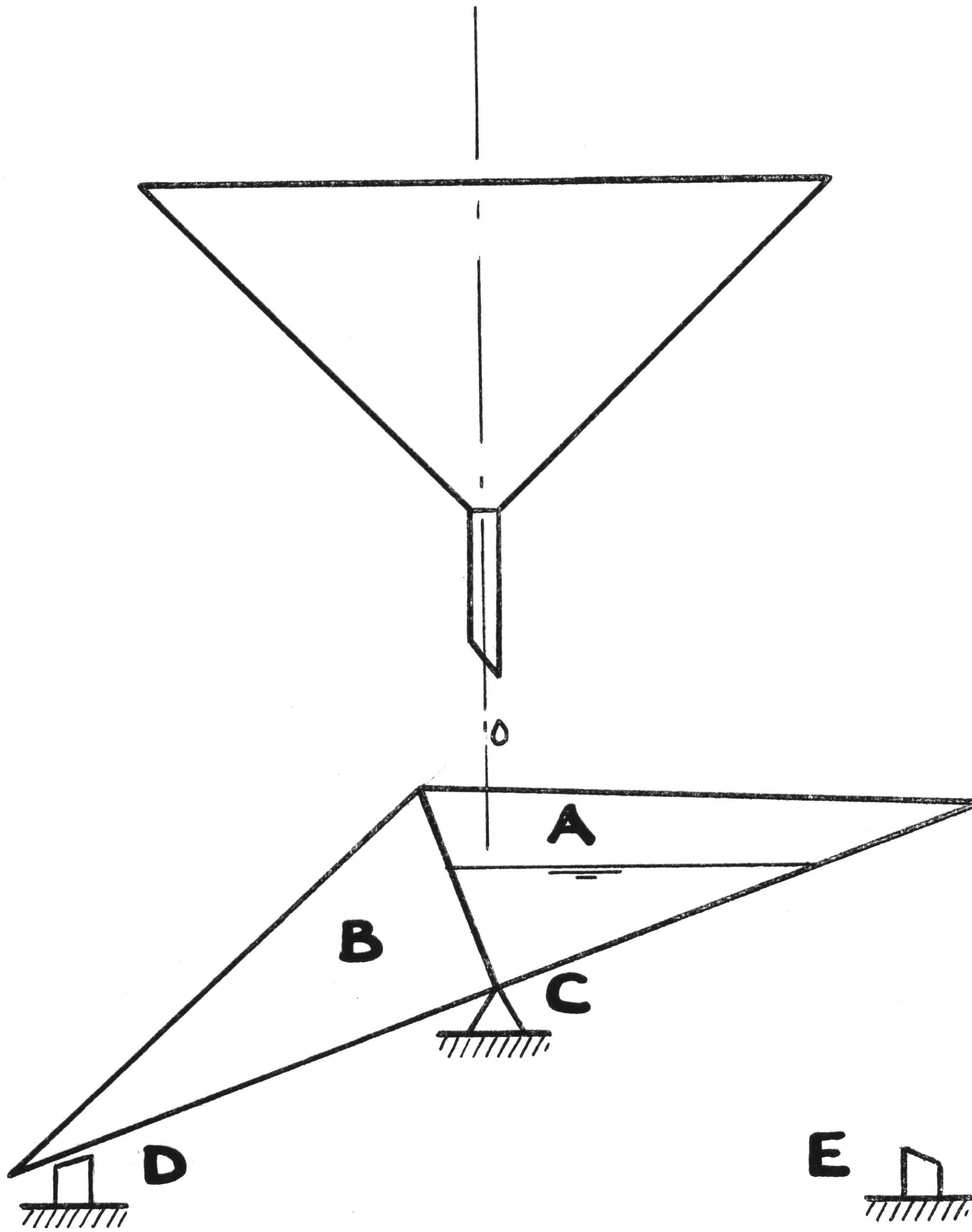


THE TIPPING BUCKET MECHANISM

FIG. 4.1

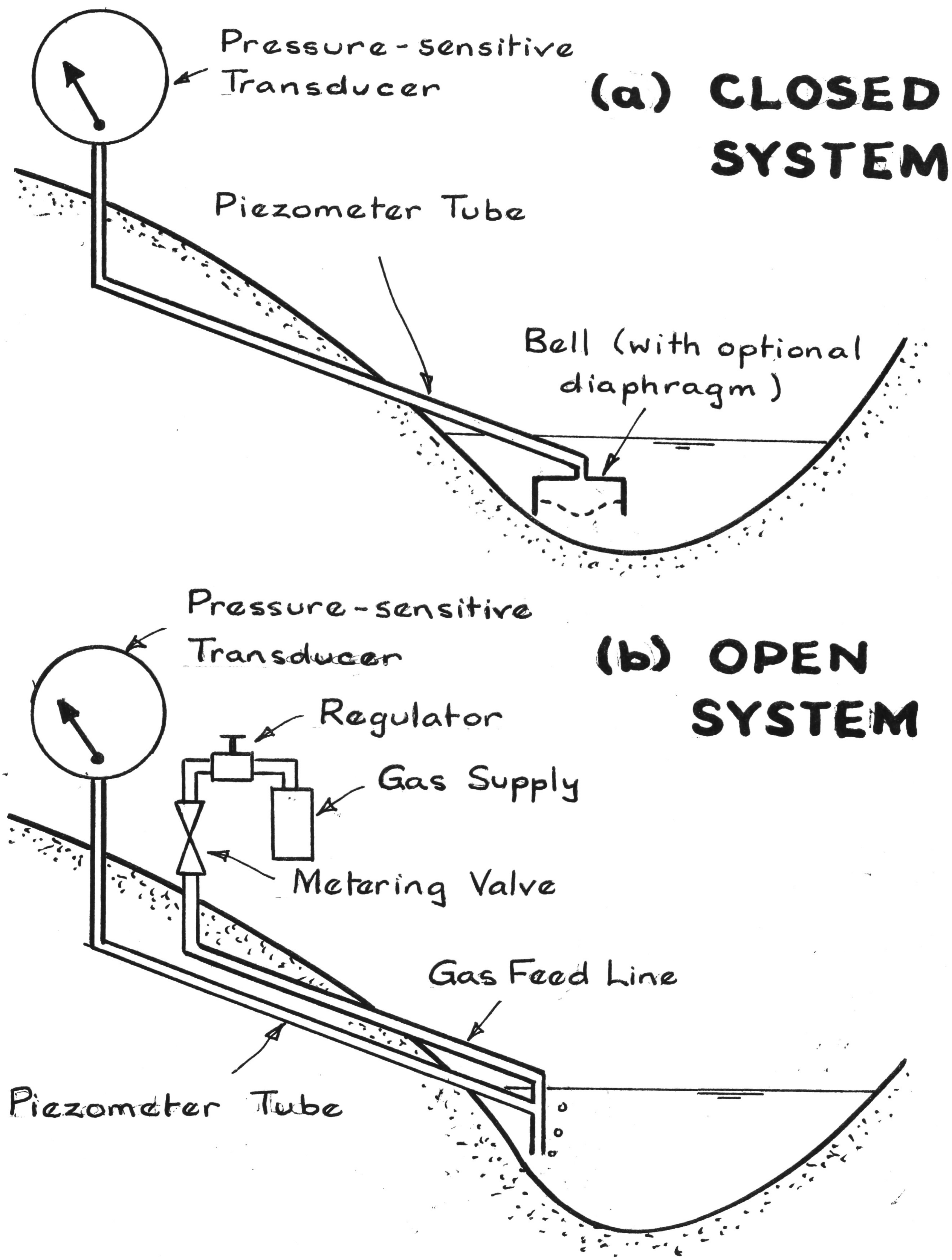
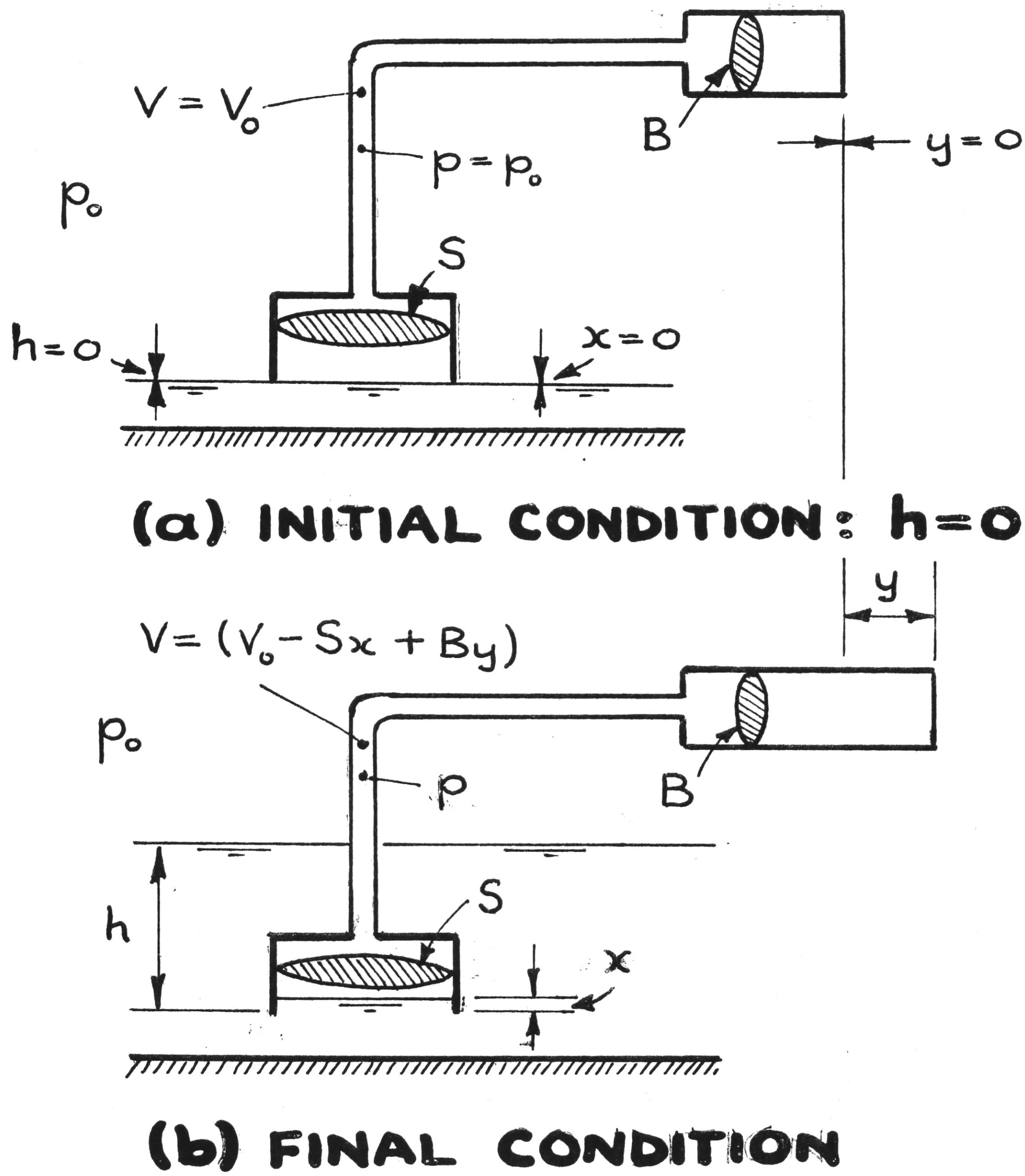
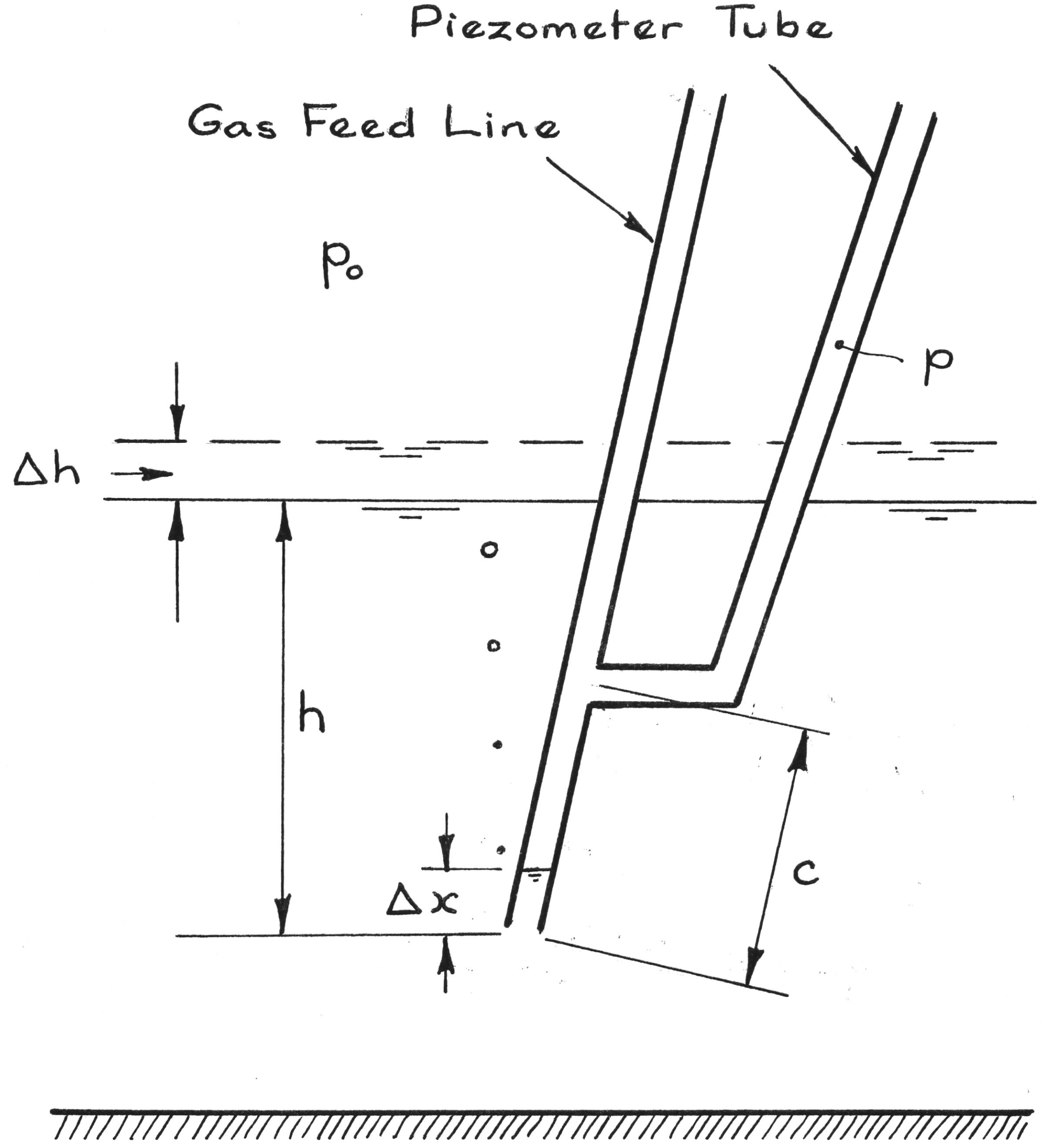


FIG.4.2 PRESSURE LIMNOMETERS



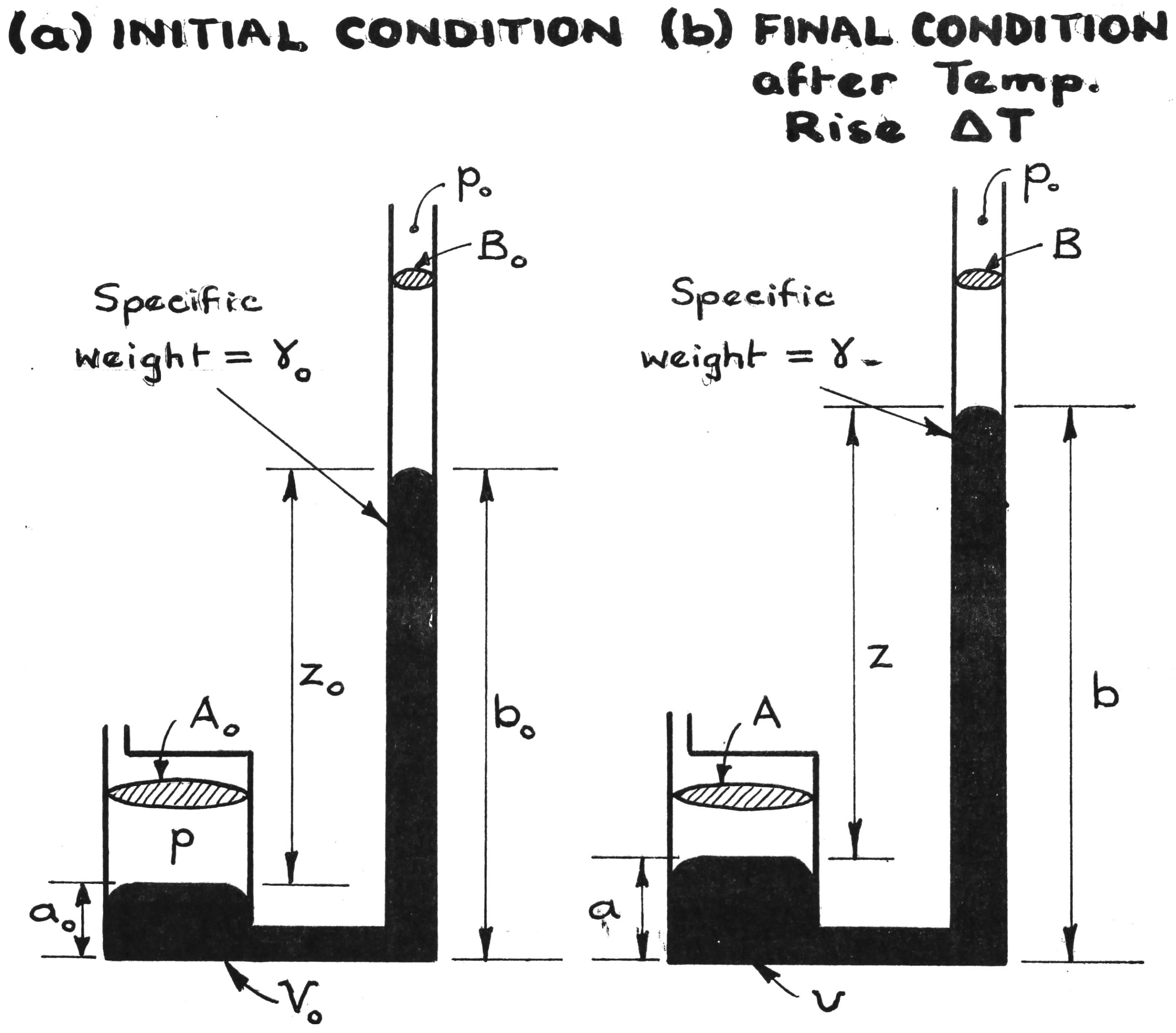
DEFINITION SKETCH FOR CLOSED PRESSURE SYSTEMS

FIG. 4.3



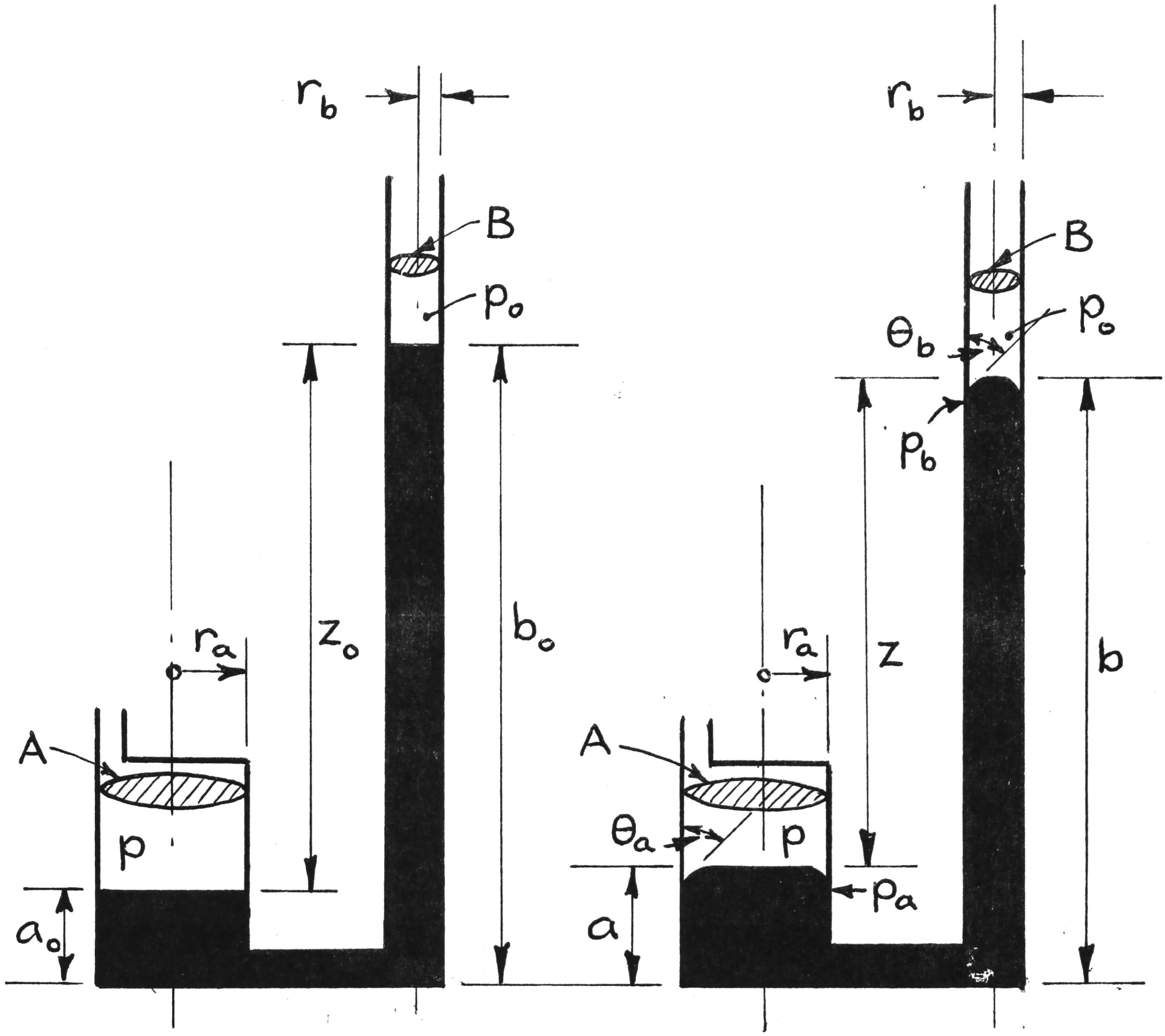
DEFINITION SKETCH FOR OPEN PRESSURE SYSTEMS

FIG. 4.4



DEFINITION SKETCH FOR THERMAL EFFECTS ON MANOMETERS

FIG. 4.5

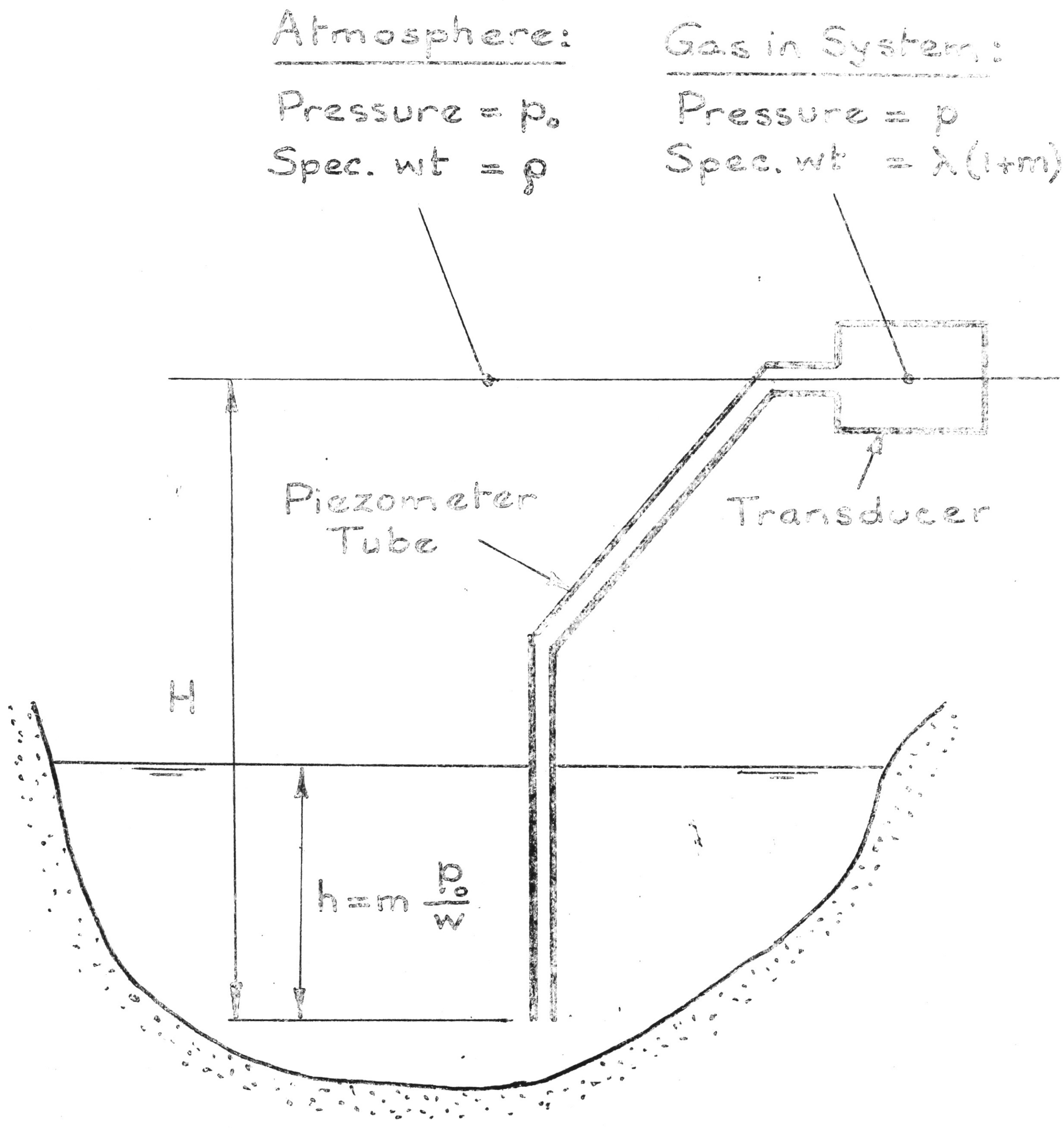


(a) IDEAL CASE
$\tau = 0$

(b) ACTUAL CASE

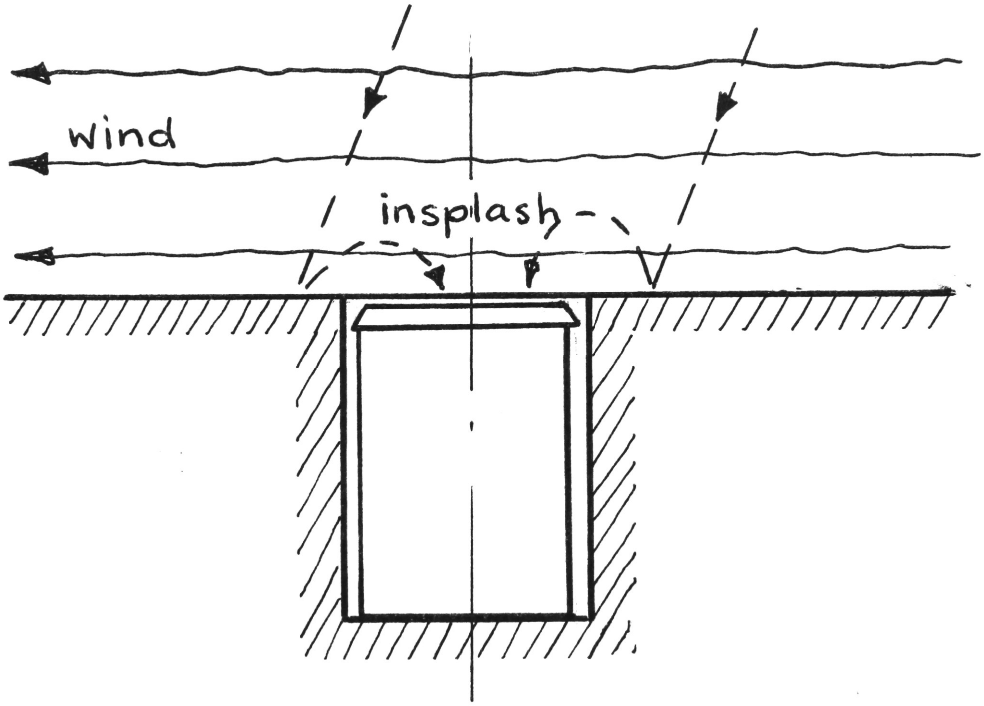
DEFINITION SKETCH FOR MENISCUS EFFECTS ON MANOMETERS

FIG. 4.6



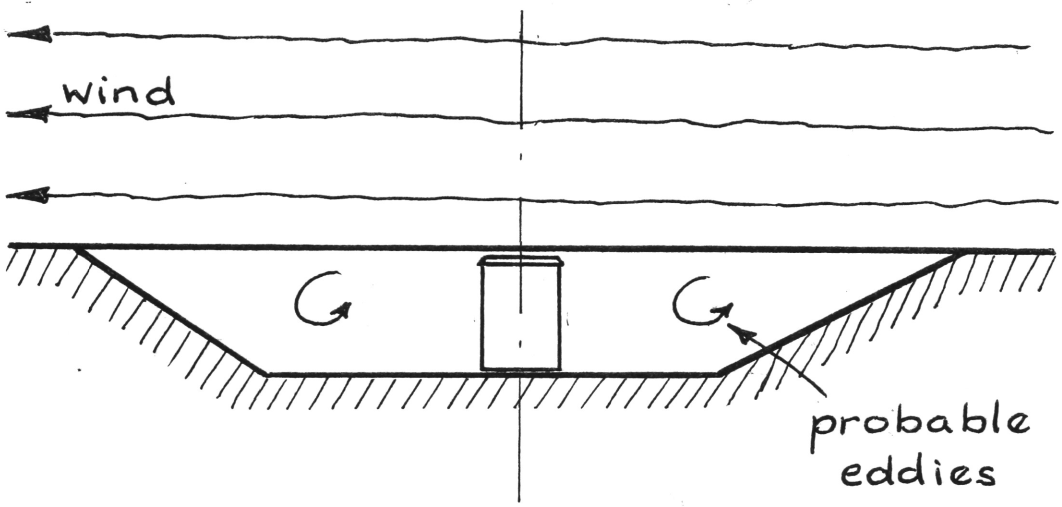
DEFINITION SKETCH FOR EFFECT OF STATIC HEAD OF GAS IN SYSTEM

FIG. 4.7



SUNKEN RAIN GAUGE

FIG. 5.1



PIT INSTALLATION
OF RAIN GAUGE

FIG. 5.2

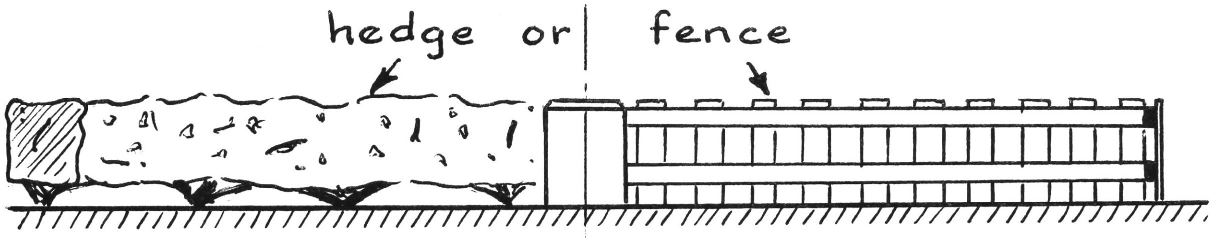


FIG. 5.3 FENCED RAIN GAUGE

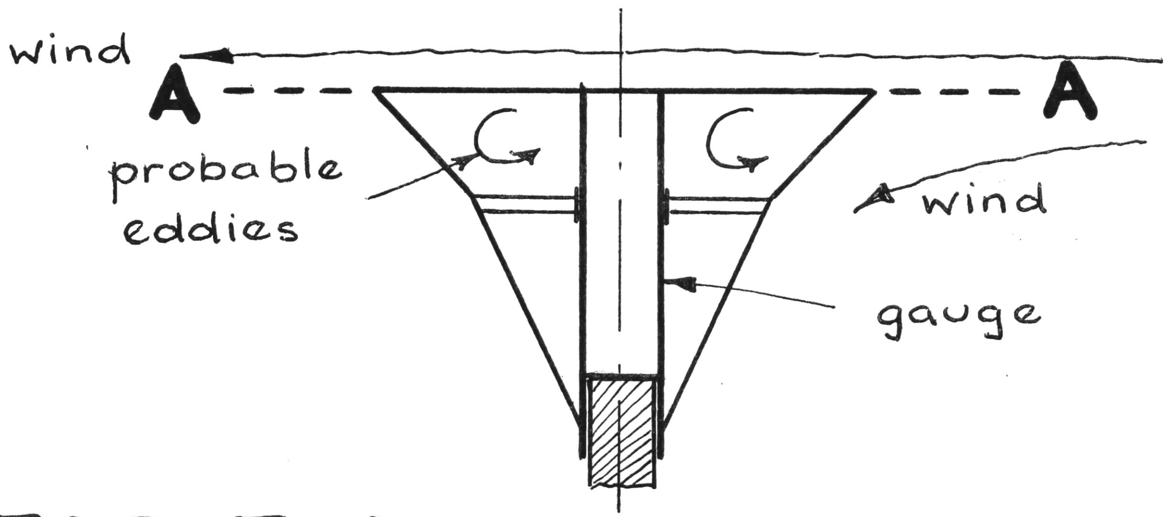


FIG. 5.4 NIPHER SHIELD

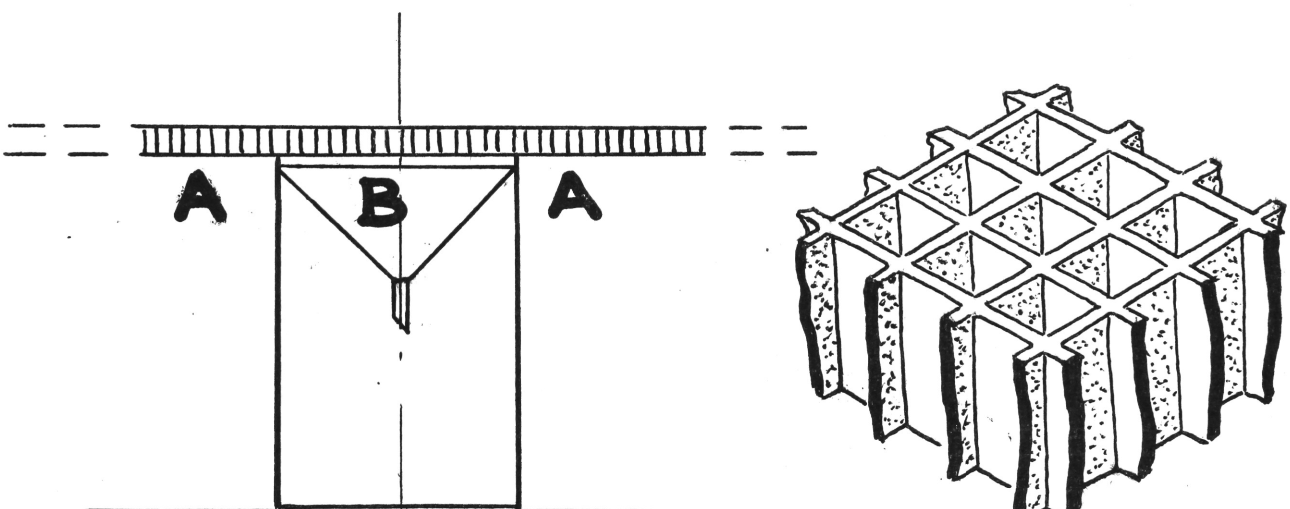
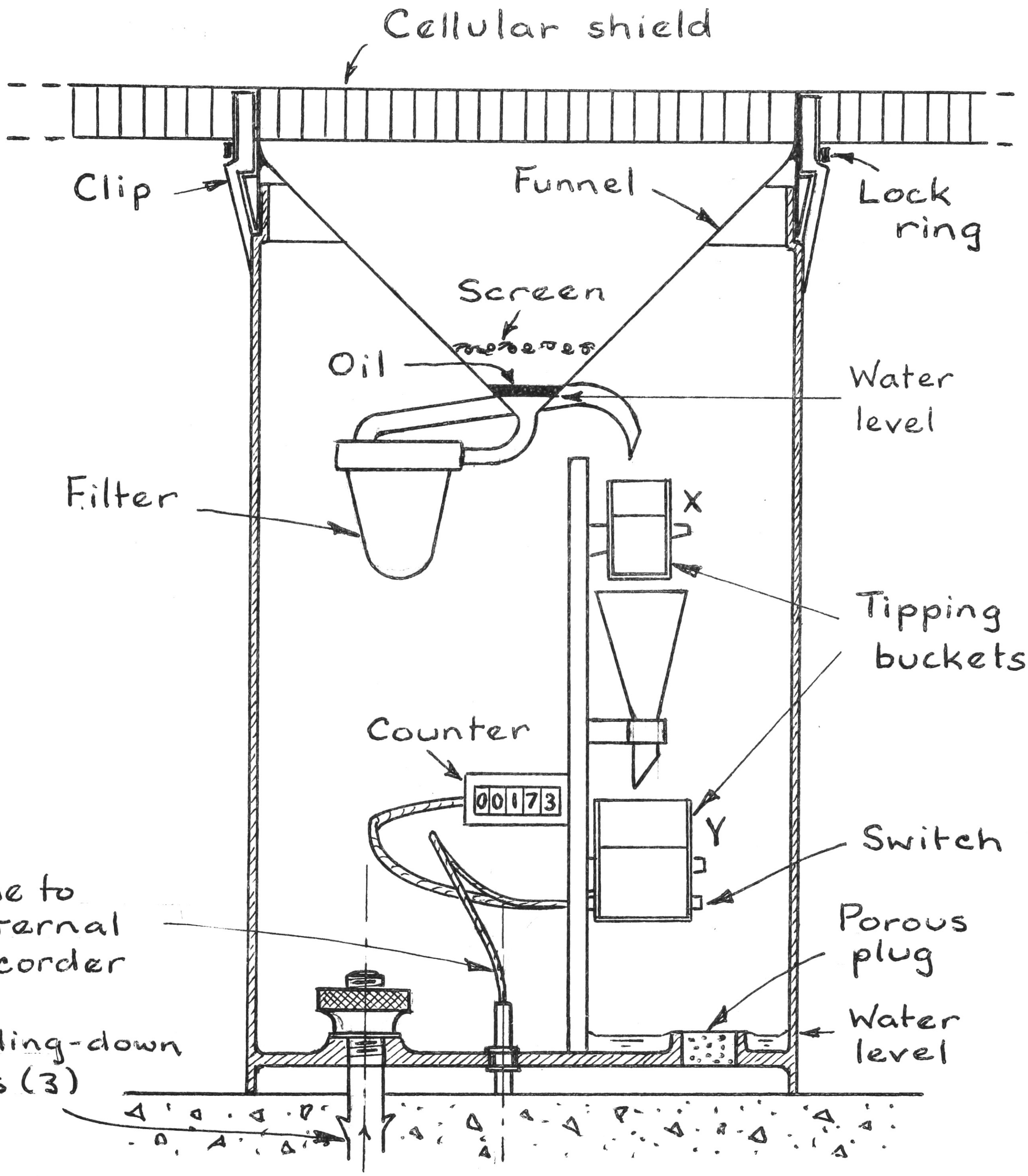


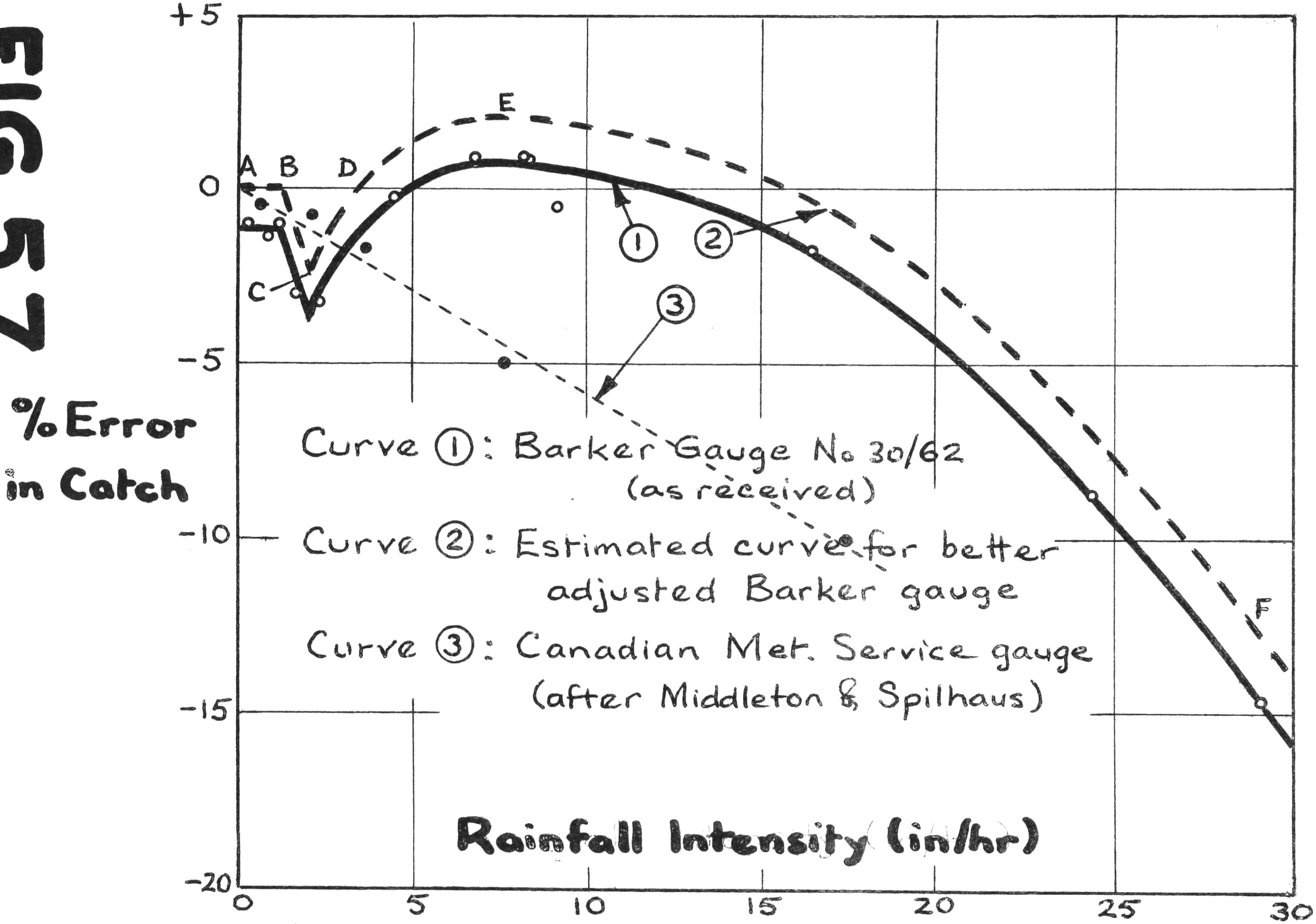
FIG. 5.5 PROPOSED SHIELD



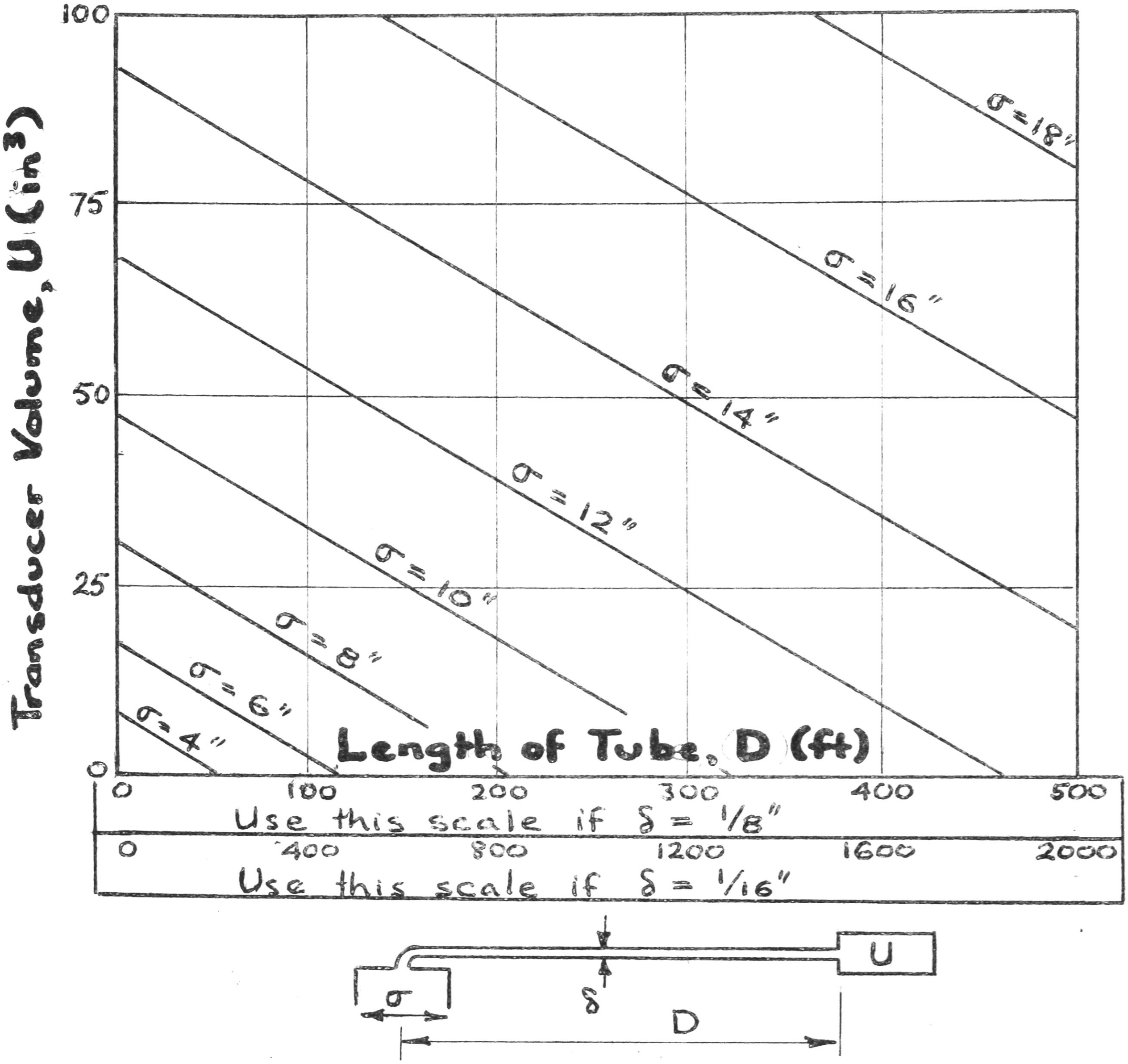
PLUVIOGRAPH SHOWING PROPOSALS FOR REDUCING INSTRUMENTAL ERRORS

FIG. 5.6

FIG. 5.7



CALIBRATION CURVES FOR TIPPING BUCKET PLUVIOGRAPHS

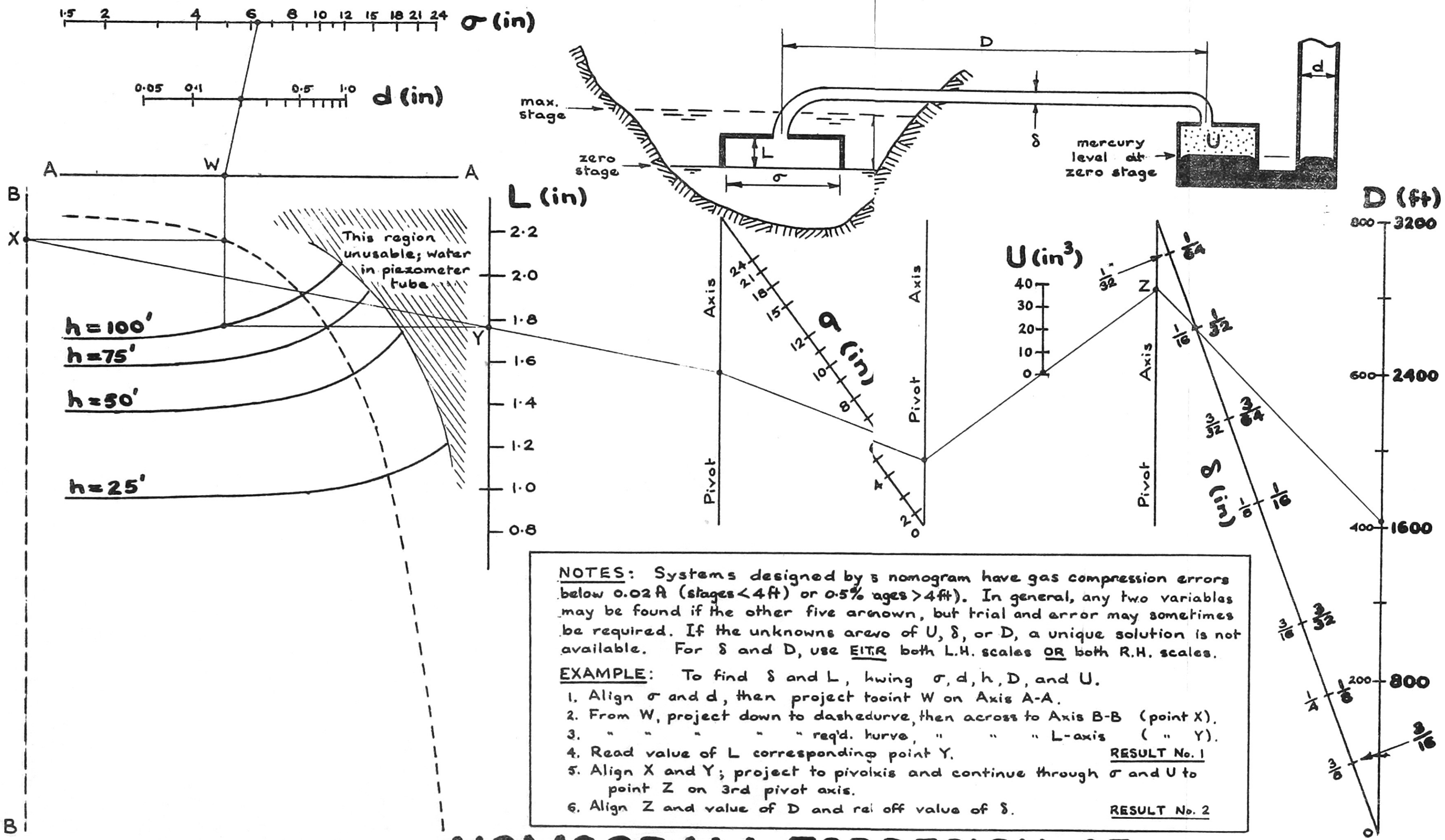


Notes:

1. The ratio $\frac{\text{transducer movement}}{\text{stream movement}}$ must be small.
2. Systems designed by this chart have gas compression errors below 0.02 ft (stages <4 ft) or below 0.5% for stages > 4ft to a max. stage of 100 ft

DESIGN CHART FOR CLOSED PRESSURE SYSTEMS

FIG. 5.8 (Stiff Transducers)

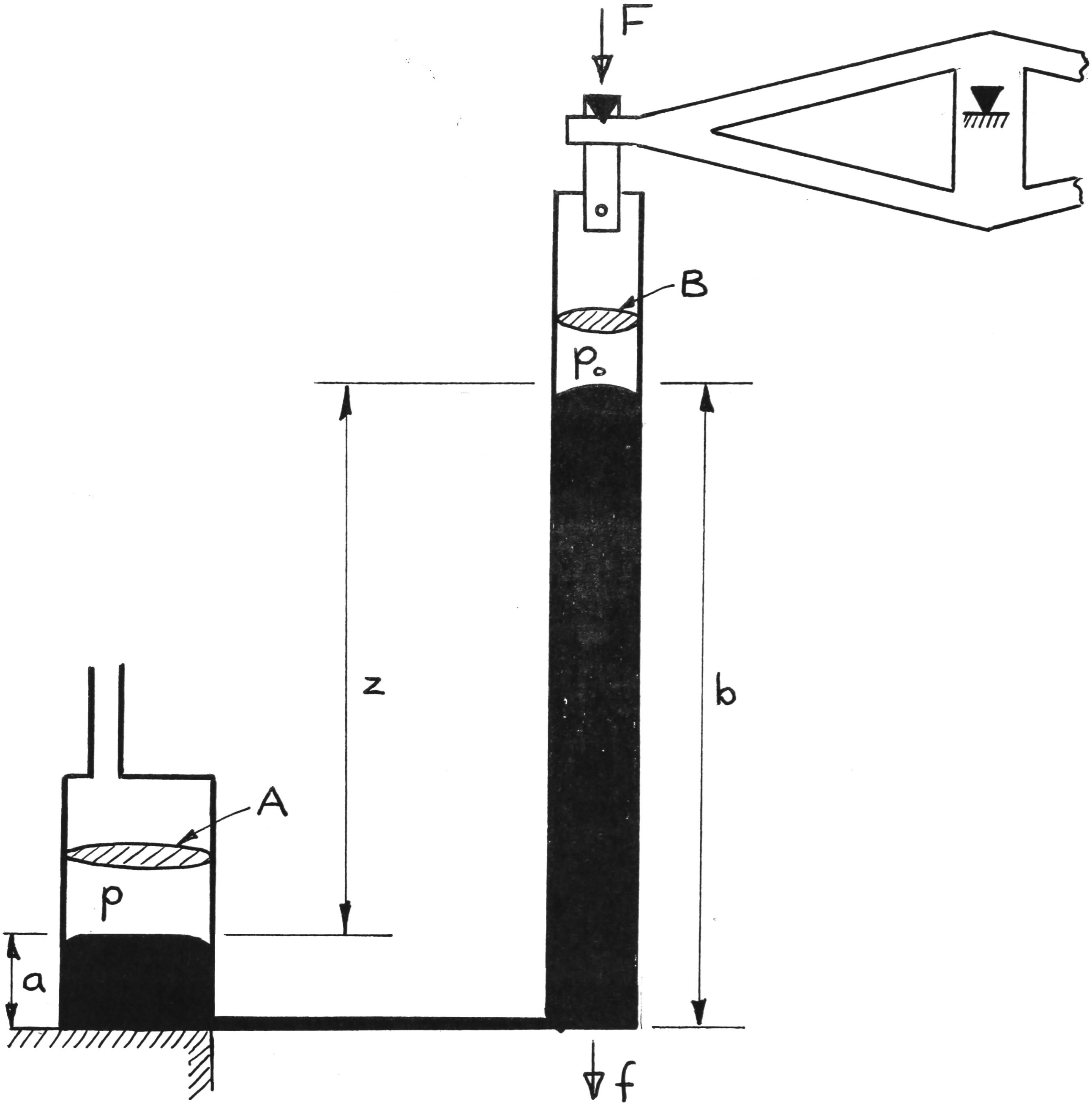


NOTES: Systems designed by s nomogram have gas compression errors below 0.02 ft (stages < 4 ft) or 0.5% ages > 4 ft). In general, any two variables may be found if the other five arenown, but trial and error may sometimes be required. If the unknowns arewo of U, δ, or D, a unique solution is not available. For δ and D, use EIT.R both L.H. scales OR both R.H. scales.

EXAMPLE: To find δ and L, hwing σ, d, h, D, and U.

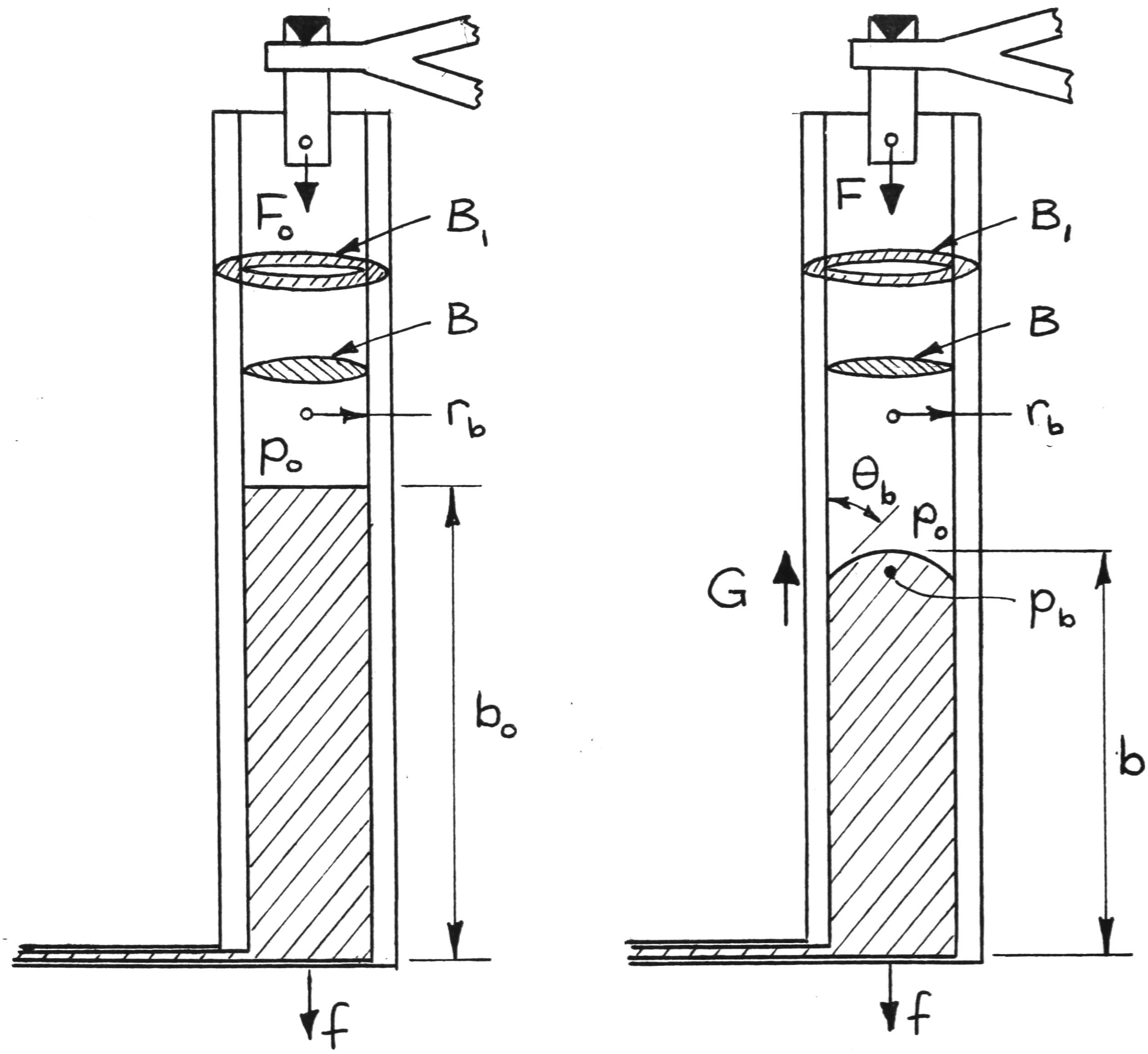
1. Align σ and d, then project tooint W on Axis A-A.
2. From W, project down to dashedurve, then across to Axis B-B (point X).
3. " " " " " req'd. hurve, " " " L-axis (" Y).
4. Read value of L corresponding point Y. RESULT No. 1
5. Align X and Y; project to pivolxis and continue through σ and U to point Z on 3rd pivot axis.
6. Align Z and value of D and rei off value of δ. RESULT No. 2

FIG. 5.9 NOMOGRAM FOR DESIGN OF CLOSED PRESSURE SYSTEMS — WITH CISTERN-TYPE MERCURY MANOMETERS



DEFINITION SKETCH FOR THERMAL EFFECTS ON WEIGHING MANOMETERS

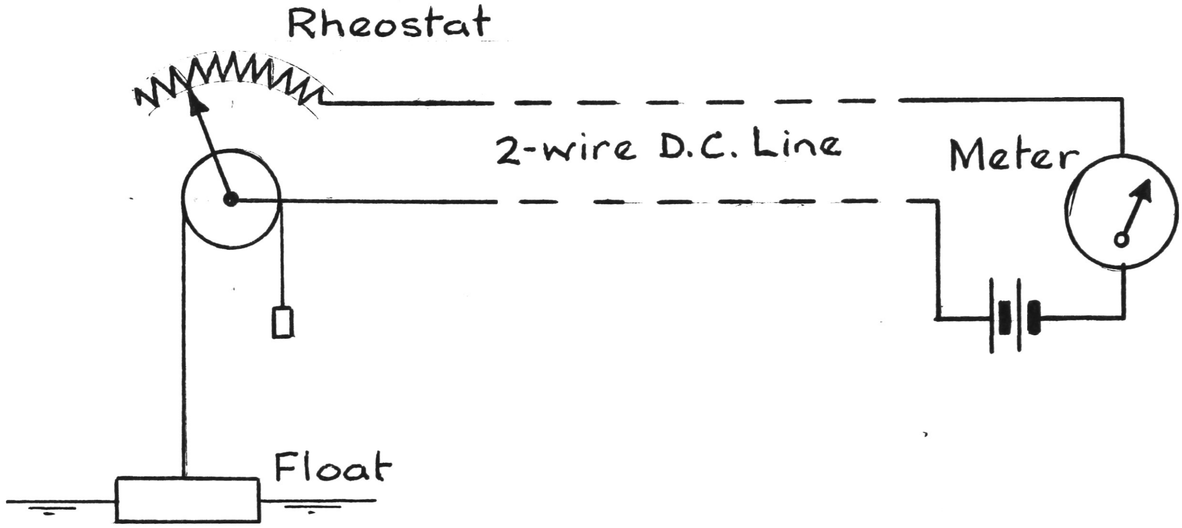
FIG. 5.10



(a) Ideal Case: $\tau = 0$ (b) Actual Case

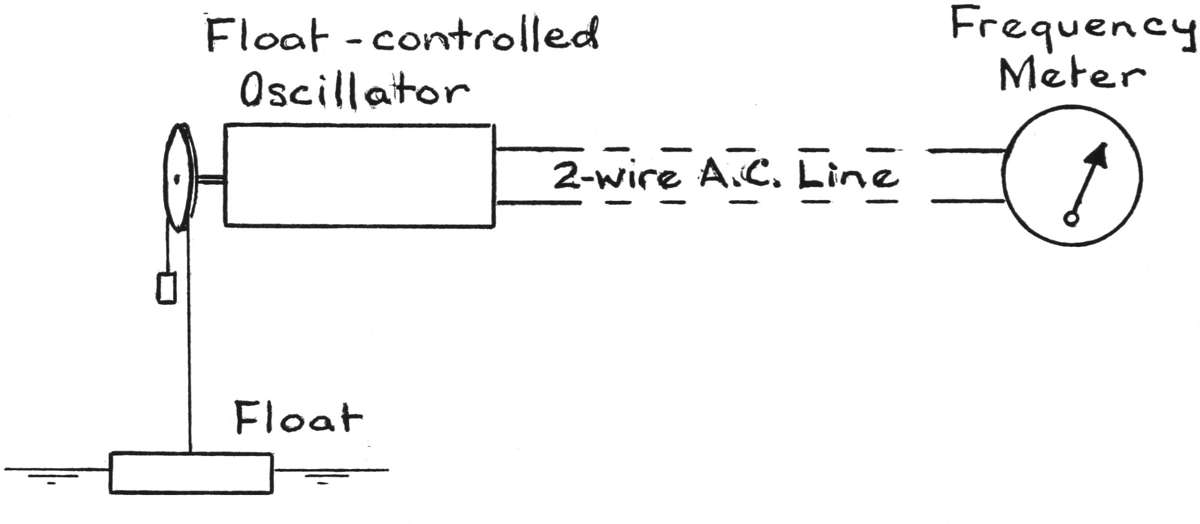
DEFINITION SKETCH FOR MENISCUS EFFECTS ON WEIGHING MANOMETERS

FIG. 5.11



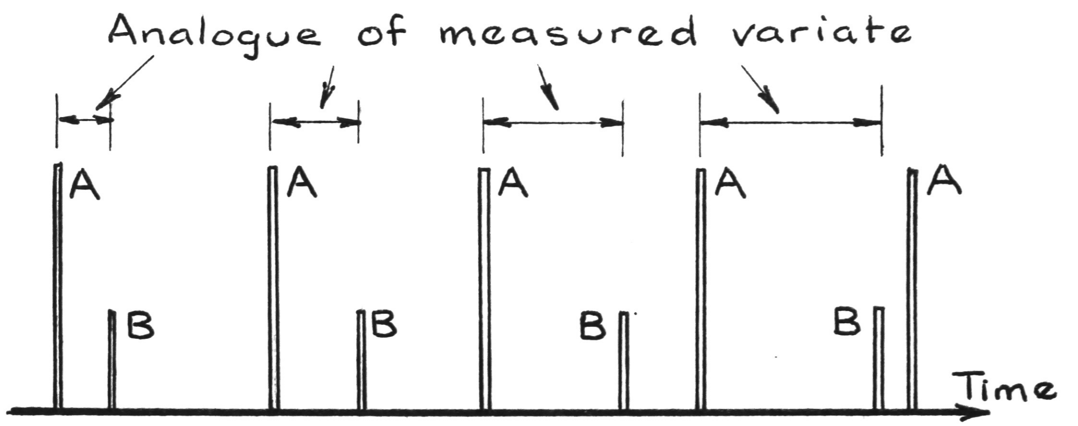
AMPLITUDE TELEMETRY SYSTEM

FIG.6.1



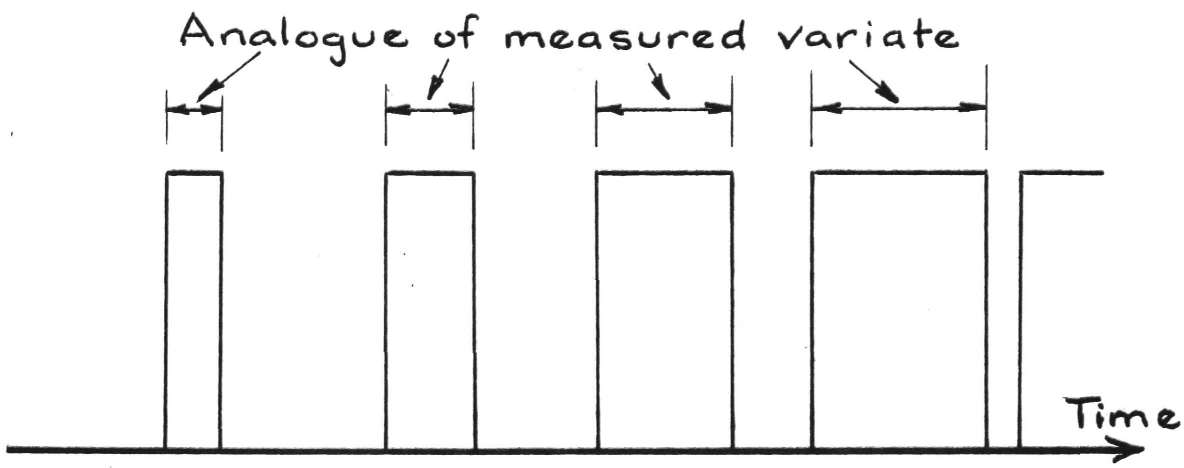
FREQUENCY TELEMETRY SYSTEM

FIG.6.2



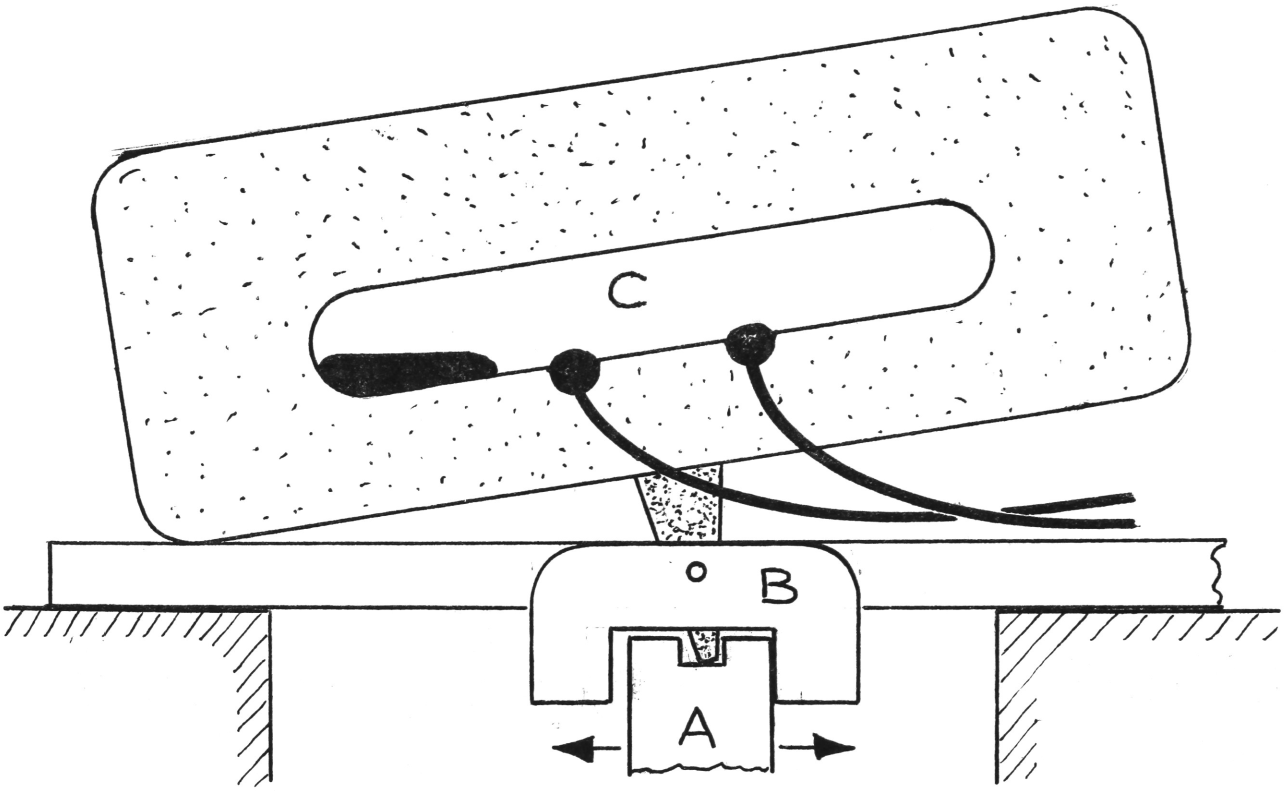
IMPULSE SPACING TELEMETRY SYSTEM

FIG.6.3



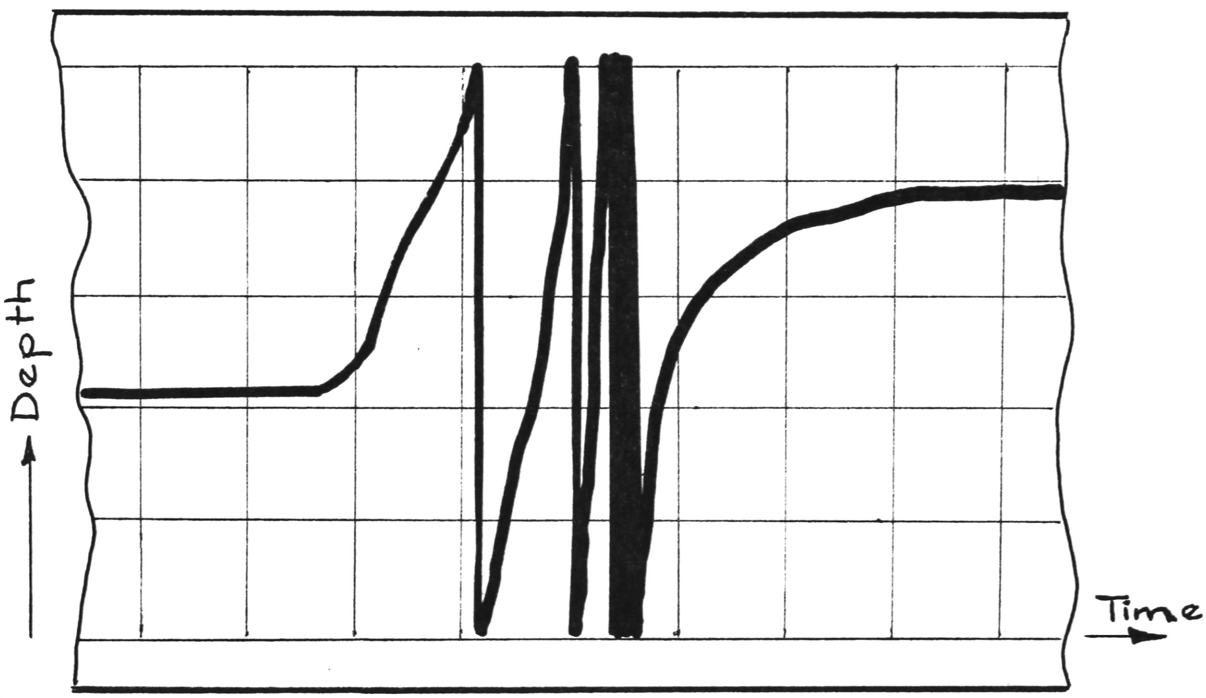
IMPULSE DURATION TELEMETRY SYSTEM

FIG.6.4



THERMAL SWITCH FOR CHECKING FIELD EQUIPMENT

FIG.6.5



EXAMPLE OF POOR RAINFALL RECORD CAUSED BY CRAMPED TIME SCALE AND THICK TRACE

FIG. 7.1

FIG. 7.2 FORM No B.14 (RAINFALL ANALYSIS)

B.14

COMMONWEALTH METEOROLOGICAL BUREAU

HOURLY RAINFALL ANALYSIS

STATION.................................... MONTH OF.............................. 19.........

DATE	00 TO 01	01 TO 02	02 TO 03	03 TO 04	04 TO 05	05 TO 06	06 TO 07	07 TO 08	08 TO 09	09 TO 10	10 TO 11	11 TO 12	12 TO 13	13 TO 14	14 TO 15	15 TO 16	16 TO 17	17 TO 18	18 TO 19	19 TO 20	20 TO 21	21 TO 22	22 TO 23	23 TO 24	TOTAL FOR 24 HRS.	DURATION IN HOURS	DATE
1																											1
2																											2
3																											3
4																											4
5																											5
6																											6
7																											7
8																											8
9																											9
10																											10
11																											11
12																											12
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25																											25
26																											26
27																											27
28																											28
29																											29
30																											30
31																											31
TOTAL																											TOTAL
NUMBER OF DAYS																											NUMBER OF DAYS

RAINFALL INTENSITY ANALYSIS

PRIMARY FALLS / SECONDARY FALLS

PERIOD	PRIMARY FALLS: IN MINUTES					PRIMARY FALLS: IN HOURS									SECONDARY FALLS: IN MINUTES					SECONDARY FALLS: IN HOURS							PERIOD
	5	10	15	20	30	1	2	4	6	8	12	24	48	72	5	10	15	20	30	1	2	4	6	8	12	24	
DATE / BASIC STAGE	10	15	20	25	30	40	50	60	65	70	80	100	125	150	10	15	20	25	30	40	50	60	65	70	80	100	BASIC STAGE / DATE

ALL RAINFALL DATA EXPRESSED IN POINTS

C.D.O.-2246.

MONTH OF.............................. 19.........

Expected page number is not in the original print copy.

DAY	HOUR	MINUTE for consecutive points of rain																				CUMULATIVE POINTS FOR HOUR	DAY	MONTH	YEAR
JANUARY		1965																							
3	09	11	11	11½	12	12½	13	13½	13½	14	15	16½	20½	28	34½	38	45	51½	54½	56½	58				
		58	59	59	59½																	24			
	10	00	00½	04	07	10½																5	29		
28	16	40	58																			2			
	17	12½	28	47	49½	52	53½	59														7			
	18	02½	08	18	22½																	4	13	42	
FEBRUARY		1965																						0	
MARCH		1965																							
12	08	03	07½	10	10	10½	10½	11	11½	11½	11½	12	14	18½	27							14	14	14	
APRIL		1965																							
	22	05	08	10	14	17	22½	30	30	31½	31½	32	32	35	35	35½	35½	36	37½	38	38				
		38½	41	42½	50	55																25	282	1071	
DECEMBER		1965																							
21	19	40½	49	53																		3	3	3	2348

PROPOSED RAINFALL TIME-TABLE

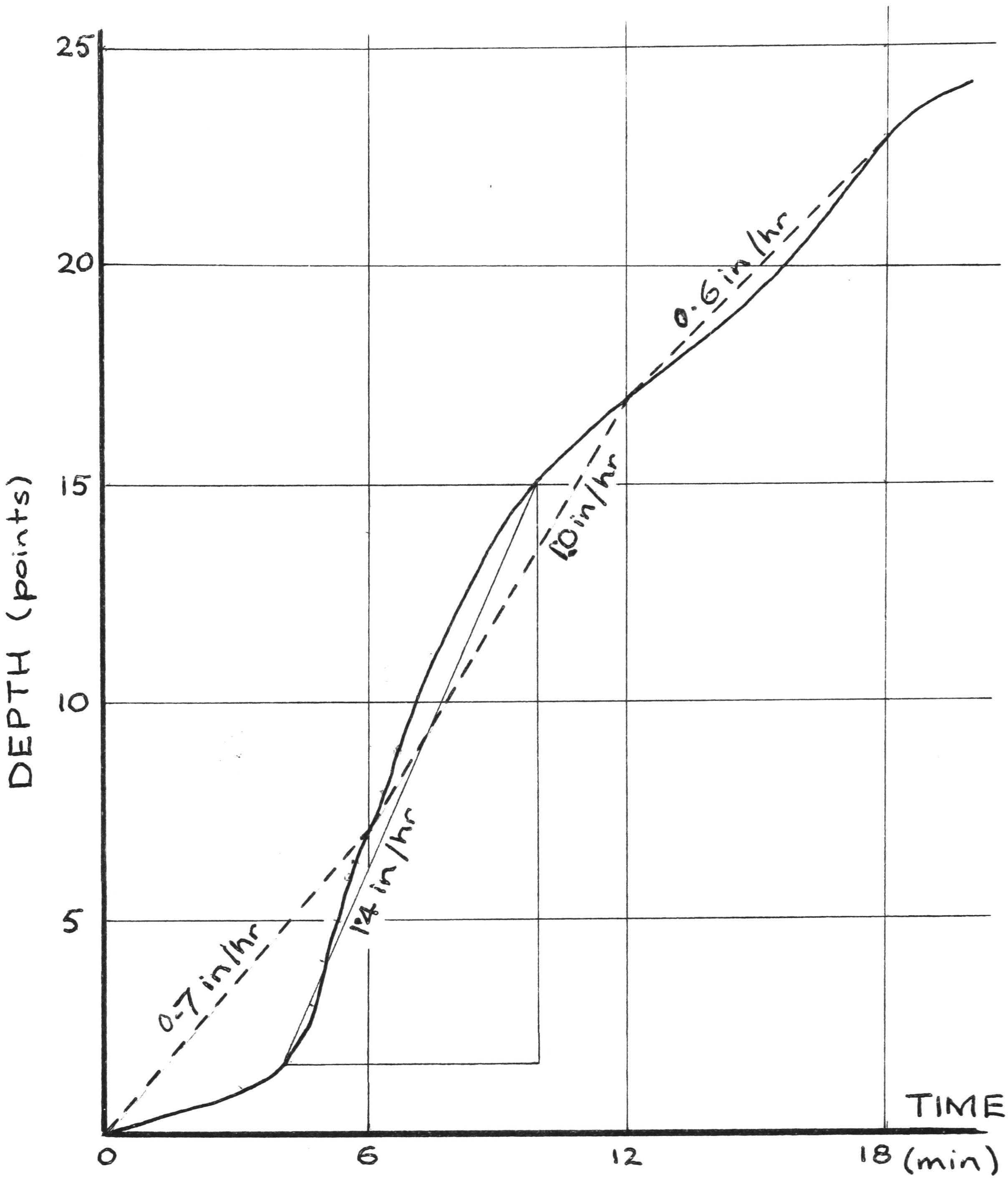
FIG. 7.4

FEET ↓	DAY/TIME-OF-DAY for stream level of — AND TENTHS OF A FOOT → ·0	·1	·2	·3	·4	·5	·6	·7	·8	·9	MONTH AND YEAR
2		**1/1043**	**2/1257**	**2/1403**	**2/1820**	**2/2057**	**2/2208**	**2/2340**	**3/0014**	**3/0108**	SEPTEMBER 1965
3	**3/0252**	**3/0400**	**3/0521**								
3	3/0917	3/0658	3/0640								
2	3/1816	3/1730	3/1652	3/1611	3/1533	3/1507	3/1429	3/1342	3/1221	3/1140	
1						4/0110	3/2350	3/2202	3/2050	3/1932	
1						**4/0131**	**4/0227**	**4/0313**	**4/0357**	**4/0428**	
2	**4/0512**	**4/0609**	**4/0721**	**4/0829**	**4/0940**	**4/1047**	**4/1155**	**4/1201**	**4/1310**	**4/1422**	
				etc.			etc.				
				etc.			etc.				
				etc.			etc.				

PROPOSED STREAM LEVEL TIME-TABLE

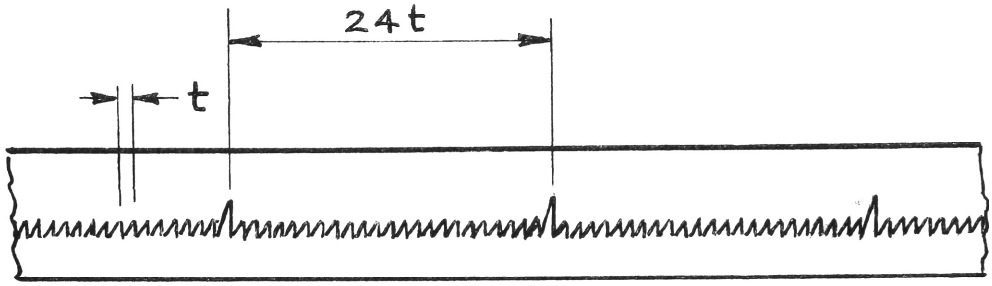
Note:
Heavy print indicates rising stream and is read L. to R.
Light " " falling " " " " R. to L.

FIG. 7.5

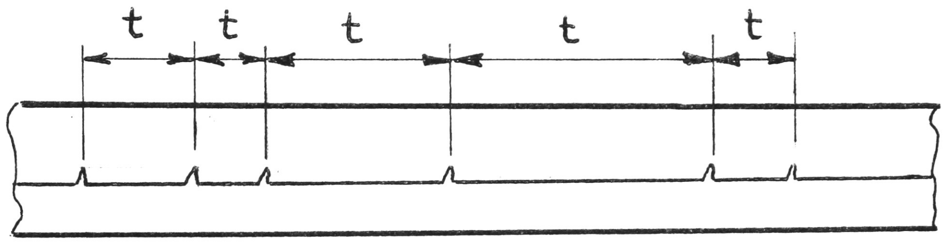


EXAMPLE SHOWING INADEQUACY OF REGULAR CLOCK-CONTROL IN MEASURING RAINFALL INTENSITY

FIG. B.1



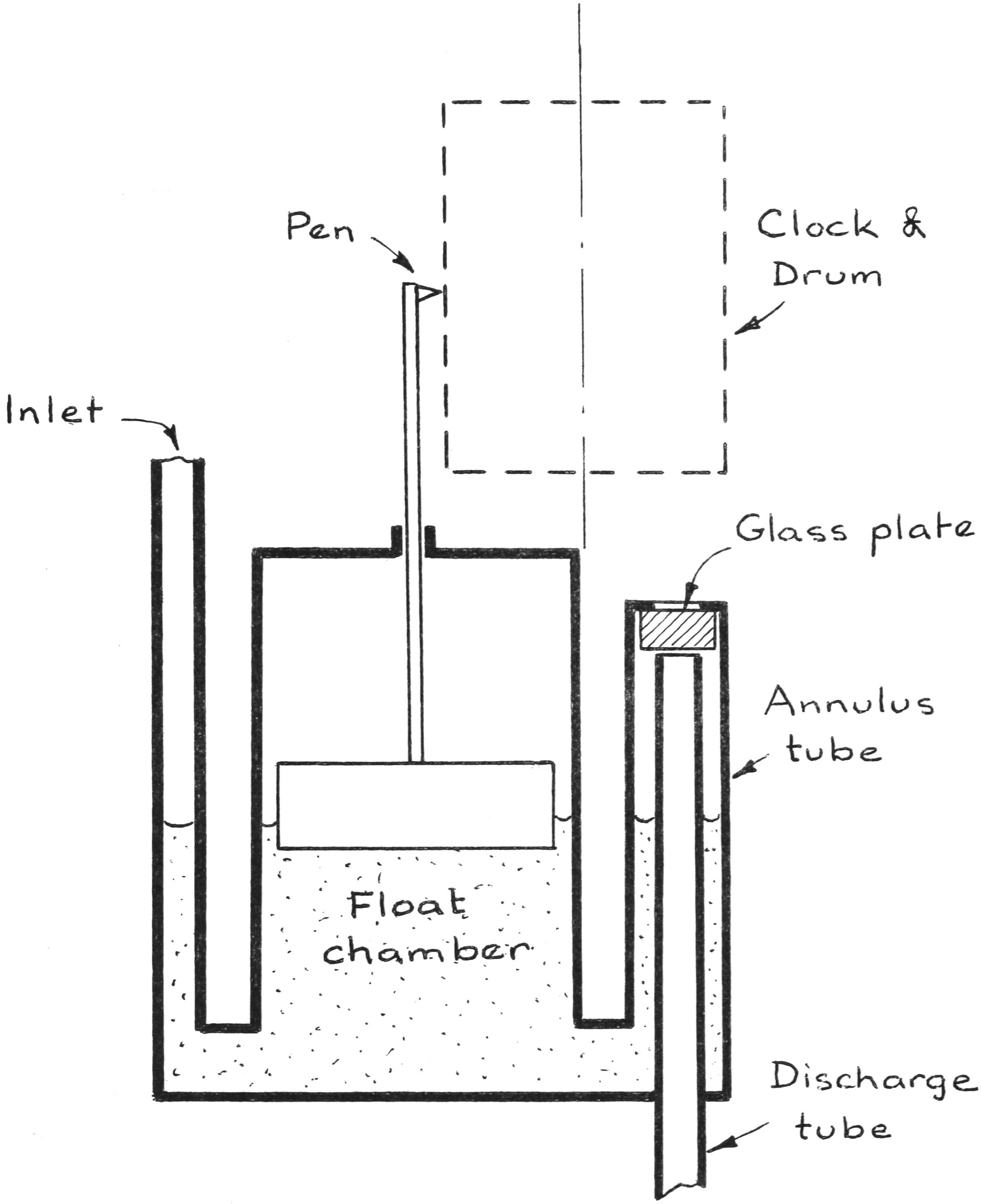
(a) Rain-free Period



(b) Rainy Period

TYPICAL RECORD FROM BARKER RAIN RECORDER

FIG. B.2



MECHANISM OF NATURAL
SIPHON PLUVIOGRAPH

FIG. B.3

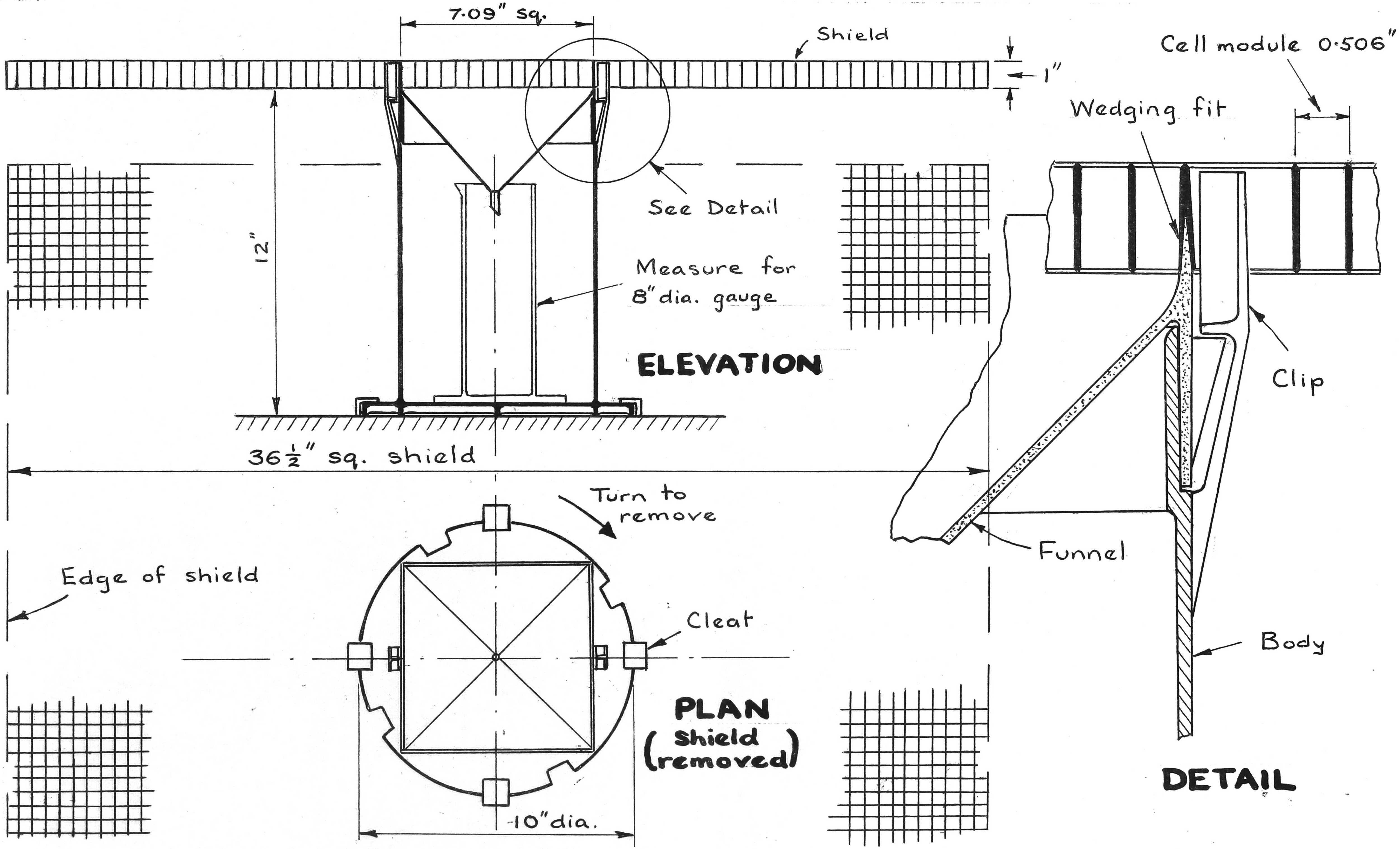
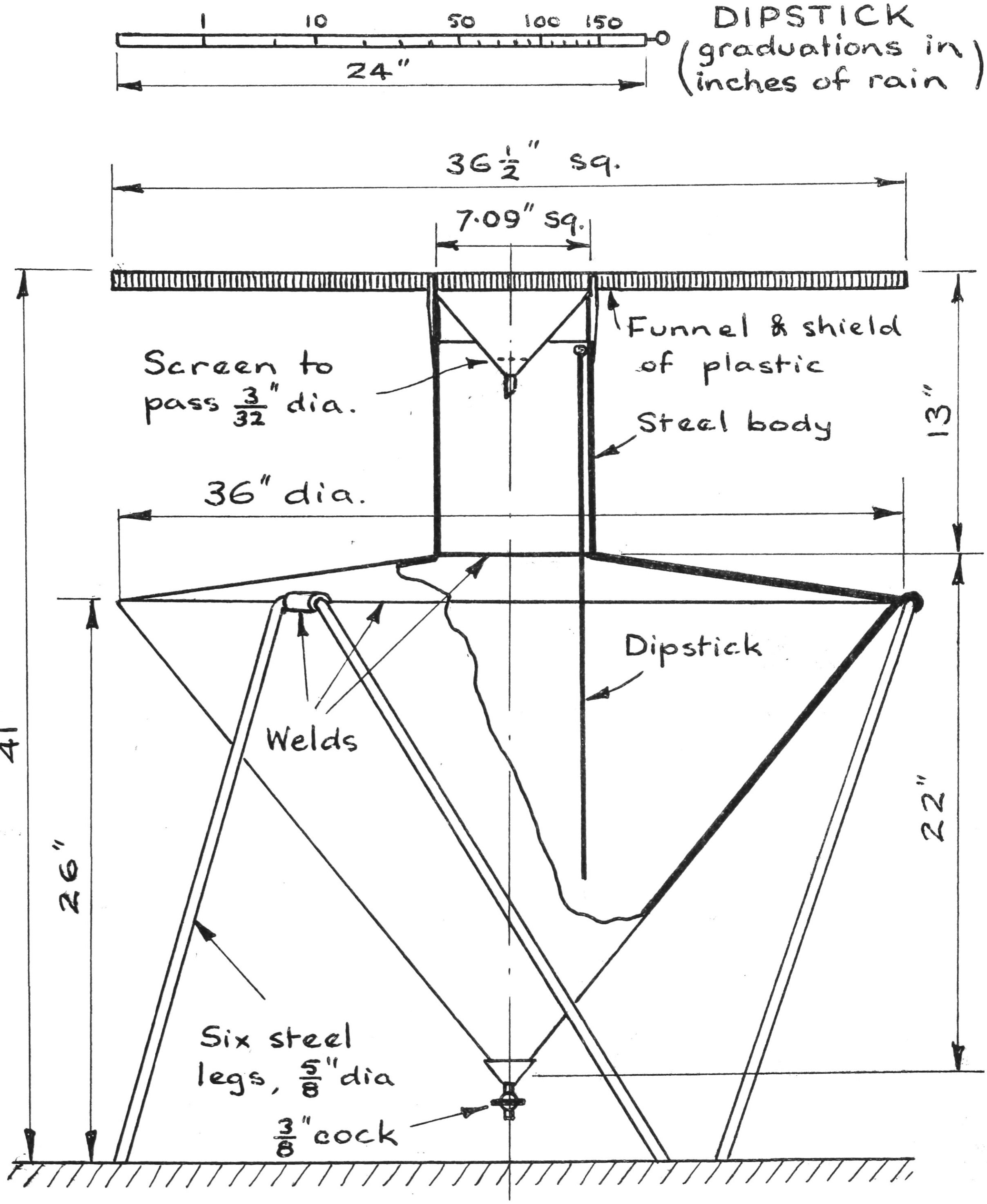
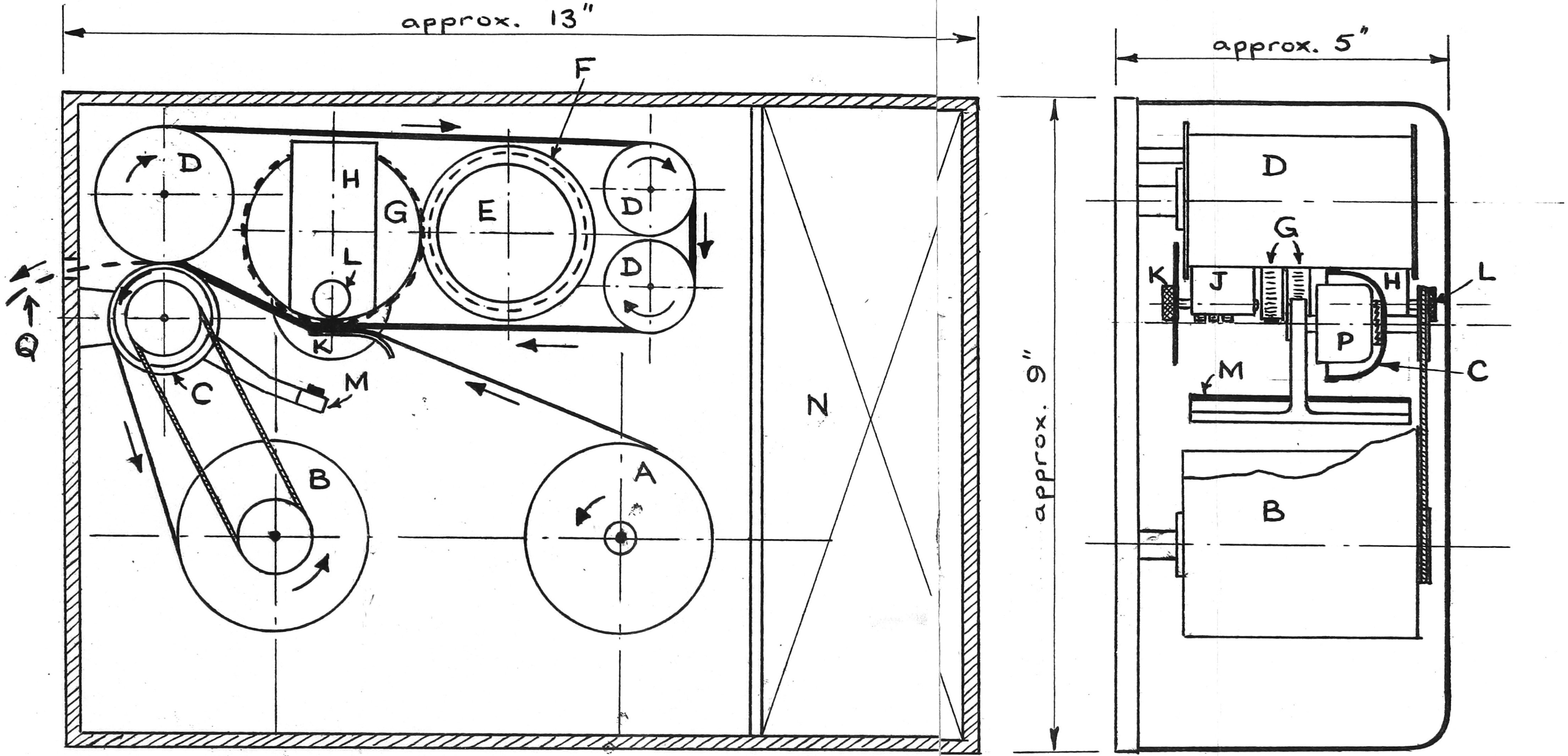


FIG. C.1 PROPOSED DAILY-READ RAIN GAUGE



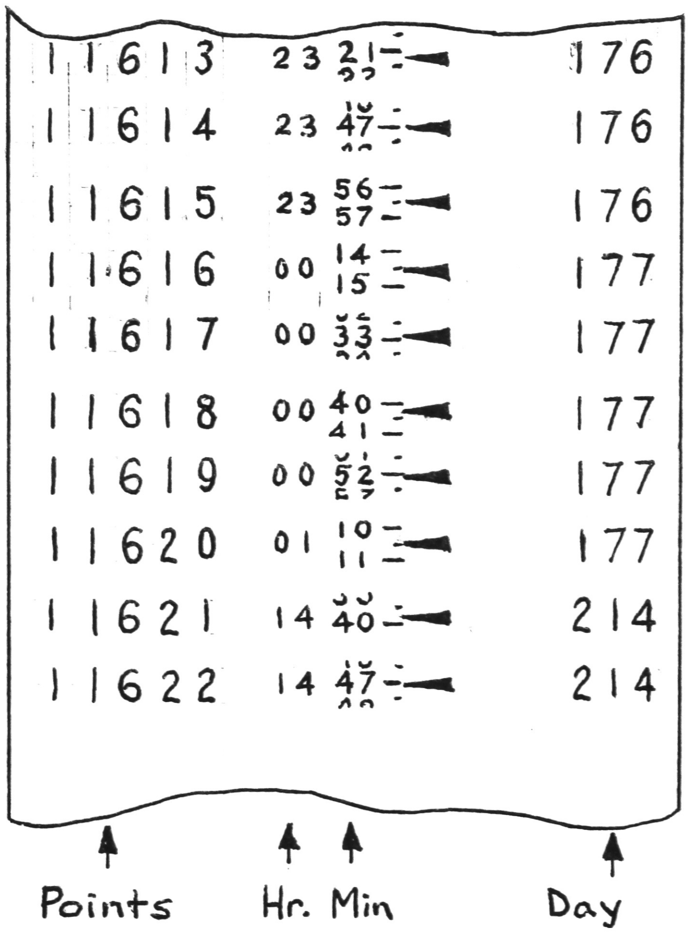
PROPOSED STORAGE RAIN GAUGE

FIG. D.1



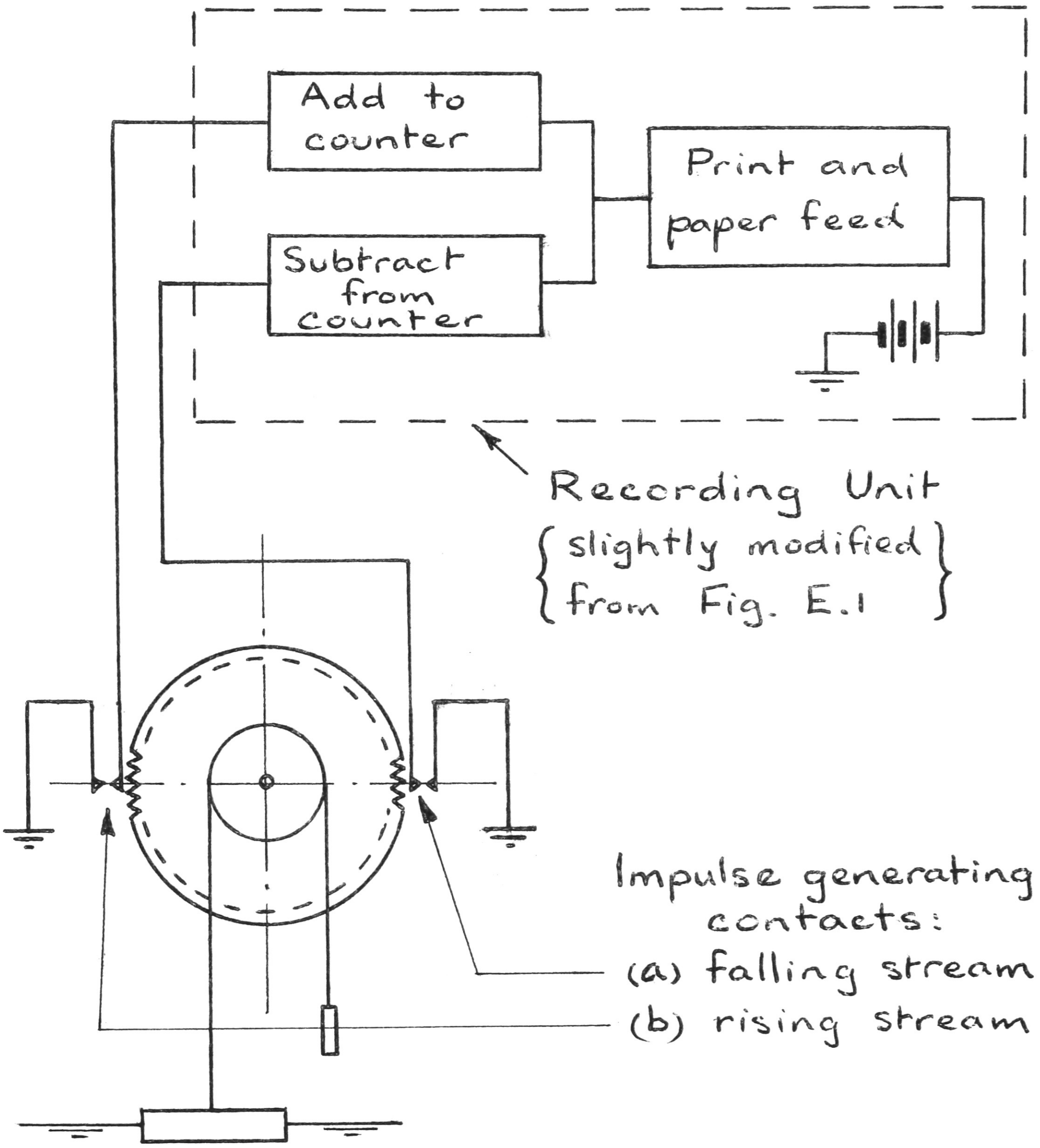
A	Magazine spool		H	ainfall counter
B	Take-up spool		J	ays counter
C	Ratchet feed wheel (friction drive)		K	e-set for days counter
D	Idlers for inked ribbon		L	e-set for rainfall counter
E	Clock		M	rinting hammer
F	Drive gear for time wheels		N	atteries
G	Time wheels (hours & minutes)		P	otary solenoid for print & feed
			Q	lternative paper outlet

FIG. E.1 RECORDER FOR PROPOSED PLUVIOGRAPH



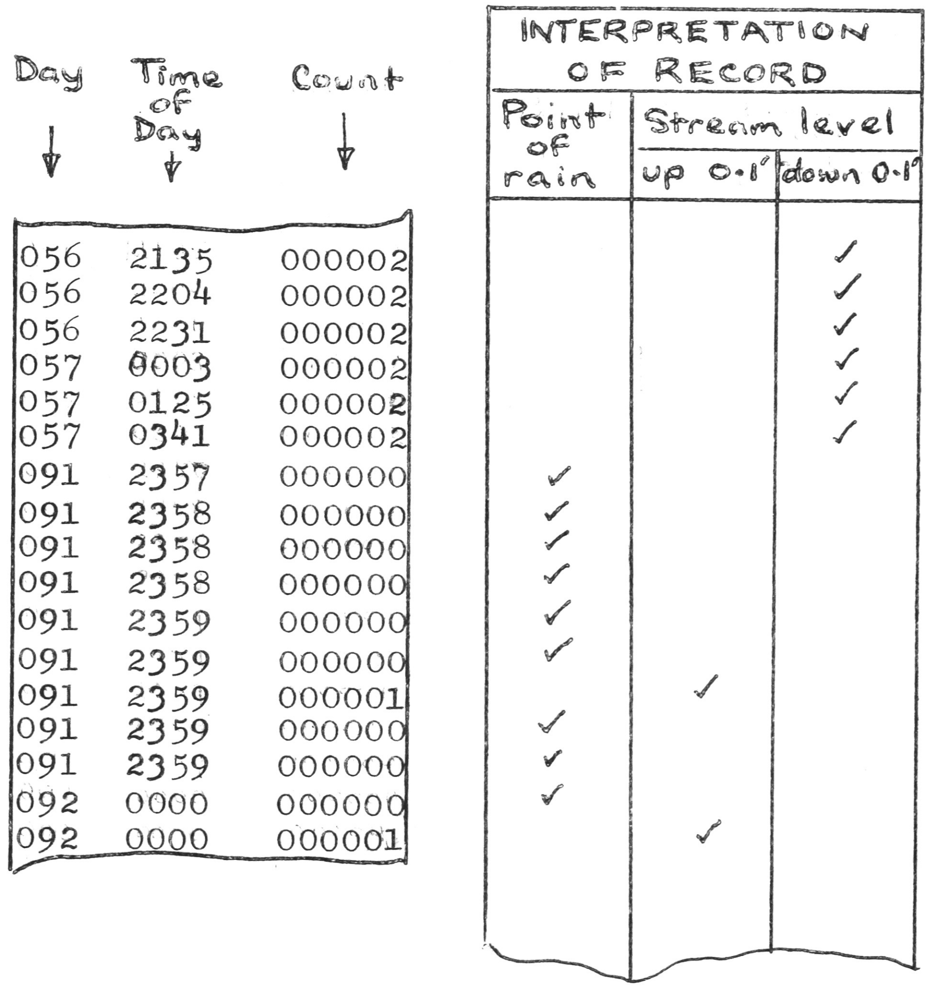
TYPICAL RECORD FROM PLUVIOGRAPH

FIG. E.2



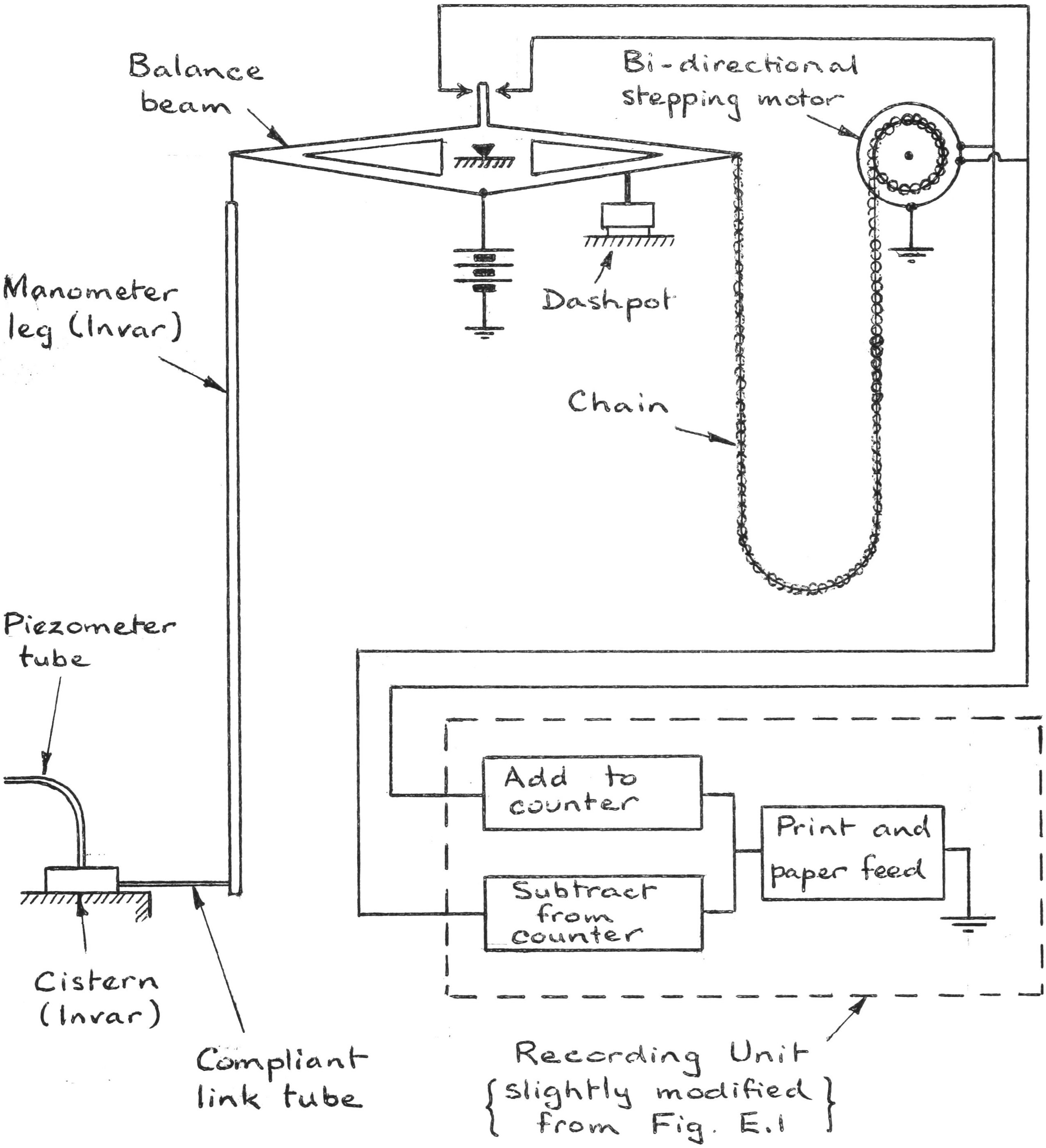
PROPOSED FLOAT-OPERATED LIMNOGRAPH (Schematic)

FIG. G.1



A METHOD OF USING A PRINTING CHRONOGRAPH WITH ADDING COUNTER TO RECORD RAINFALL AND STREAM LEVEL ON THE SAME CHART

FIG. G.2



PROPOSED PRESSURE-OPERATED LIMNOGRAPH (Schematic)

FIG. H.1

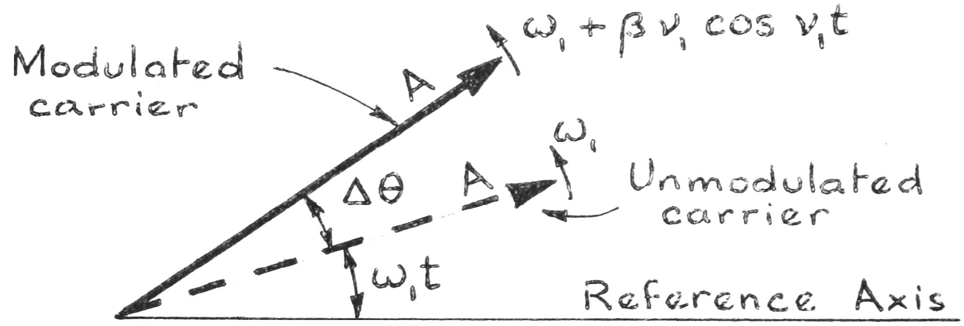


FIG. J.1 VECTORS FOR FM WAVE

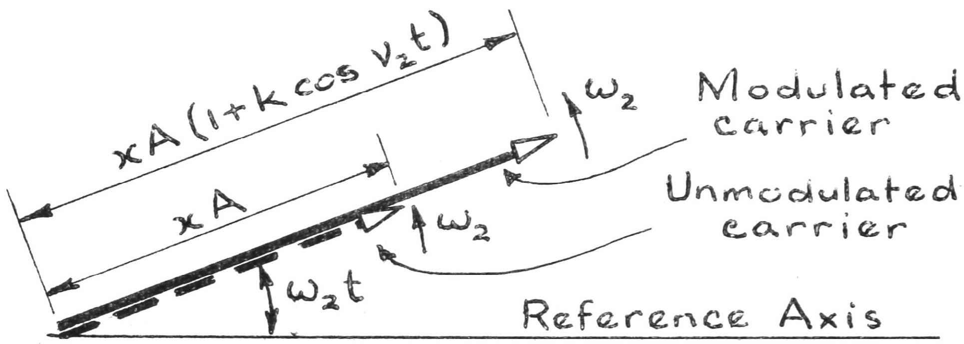


FIG. J.2 VECTORS FOR AM WAVE

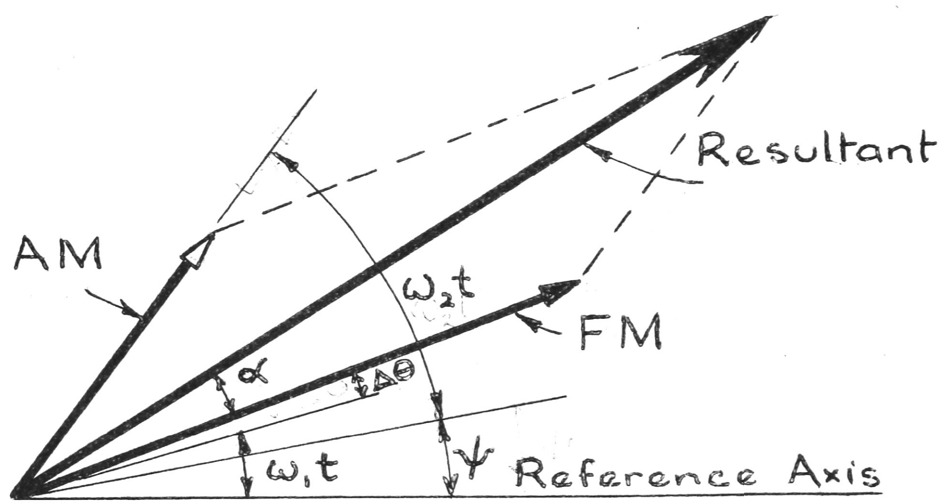
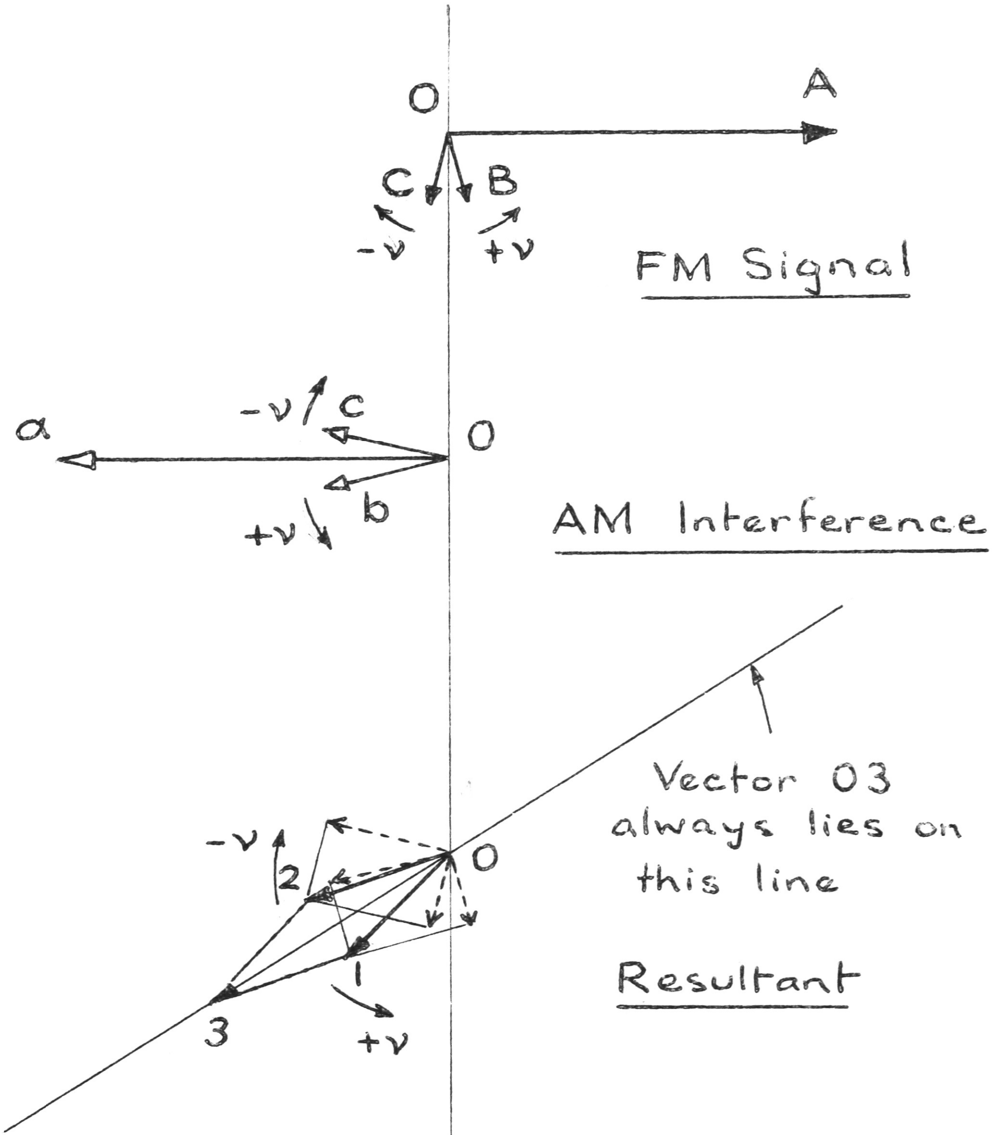


FIG. J.3 VECTORS FOR RESULTANT WAVE



CONDITIONS: $x = 1$ (carriers of equal amplitude)
$\Delta\omega = 0$ (" " " frequency)
$\nu_1 = \nu_2$ (modulation frequencies equal)
$\psi = \pi$ (carriers 180° out of phase)
$\phi = \pi/2$ (modulations 90° out of phase)

EXAMPLE OF ANNULMENT OF FM SIGNAL BY AM INTERFERENCE

FIG. J.4

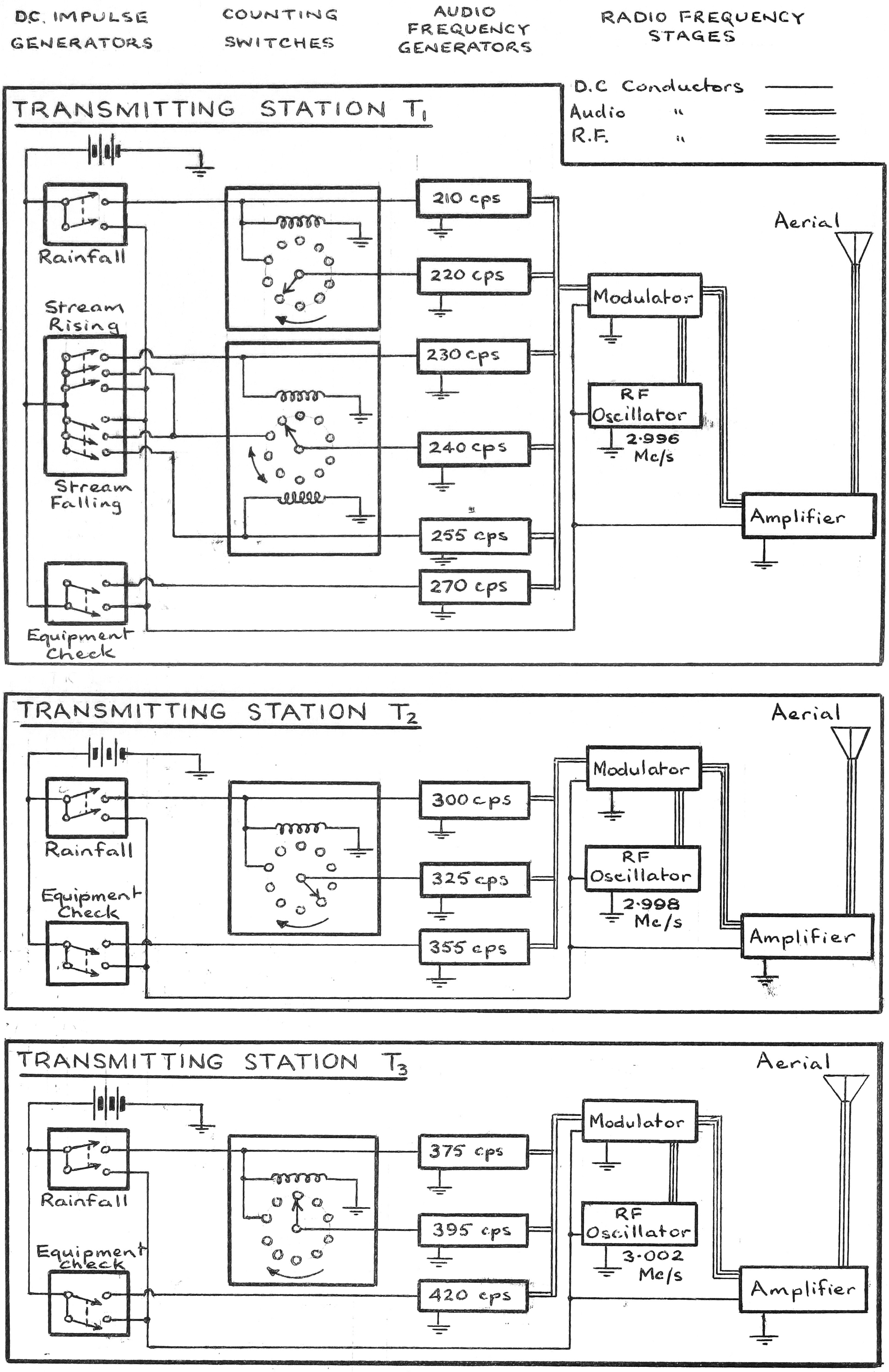


FIG. K.1 BLOCK DIAGRAMS FOR TELEMETRY FIELD STATIONS

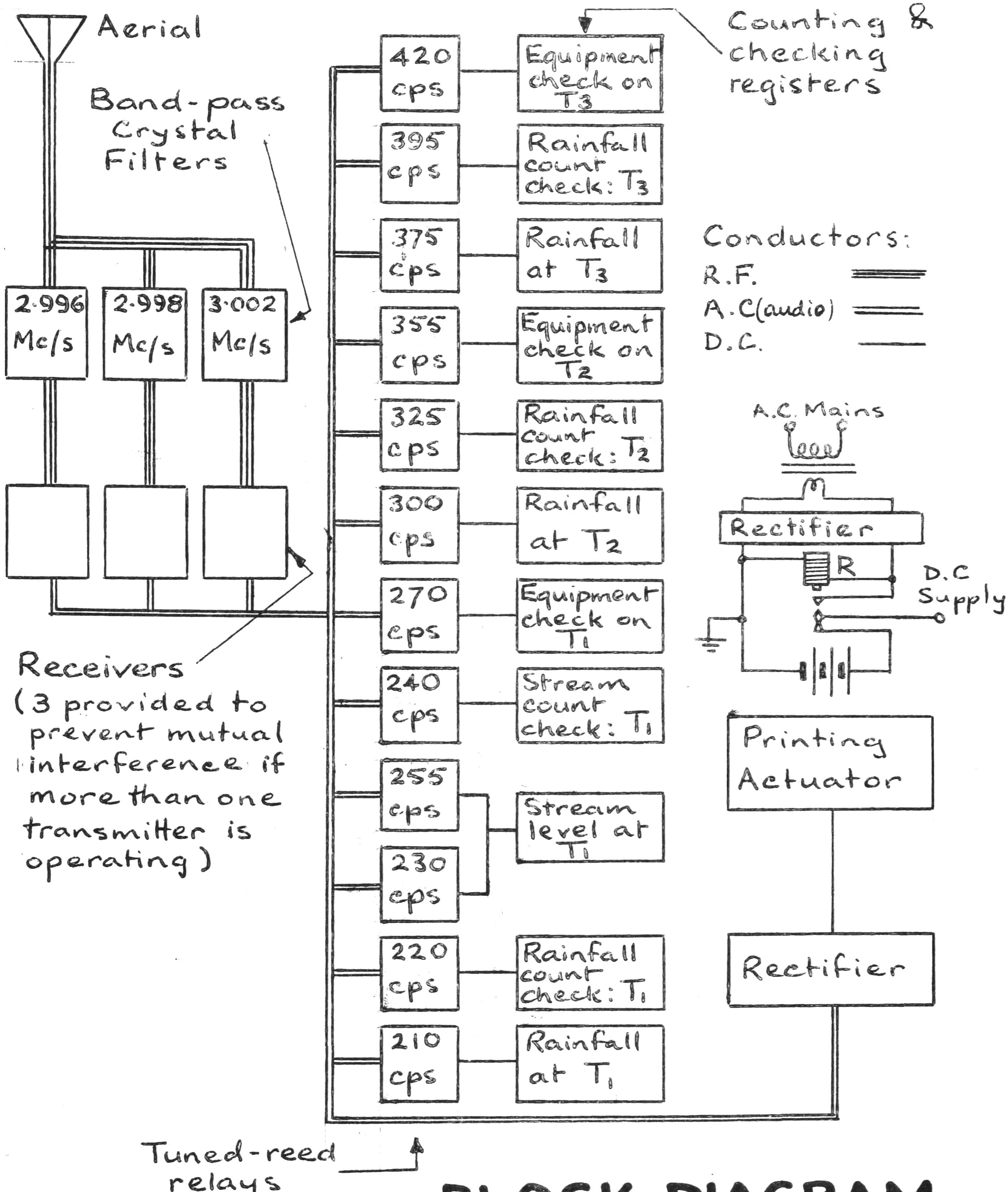


FIG. K.2 BLOCK DIAGRAM FOR TELEMETRY BASE STATION

NOTE: A stream level count has evidently been missed since check mark is on "29" instead of "30"

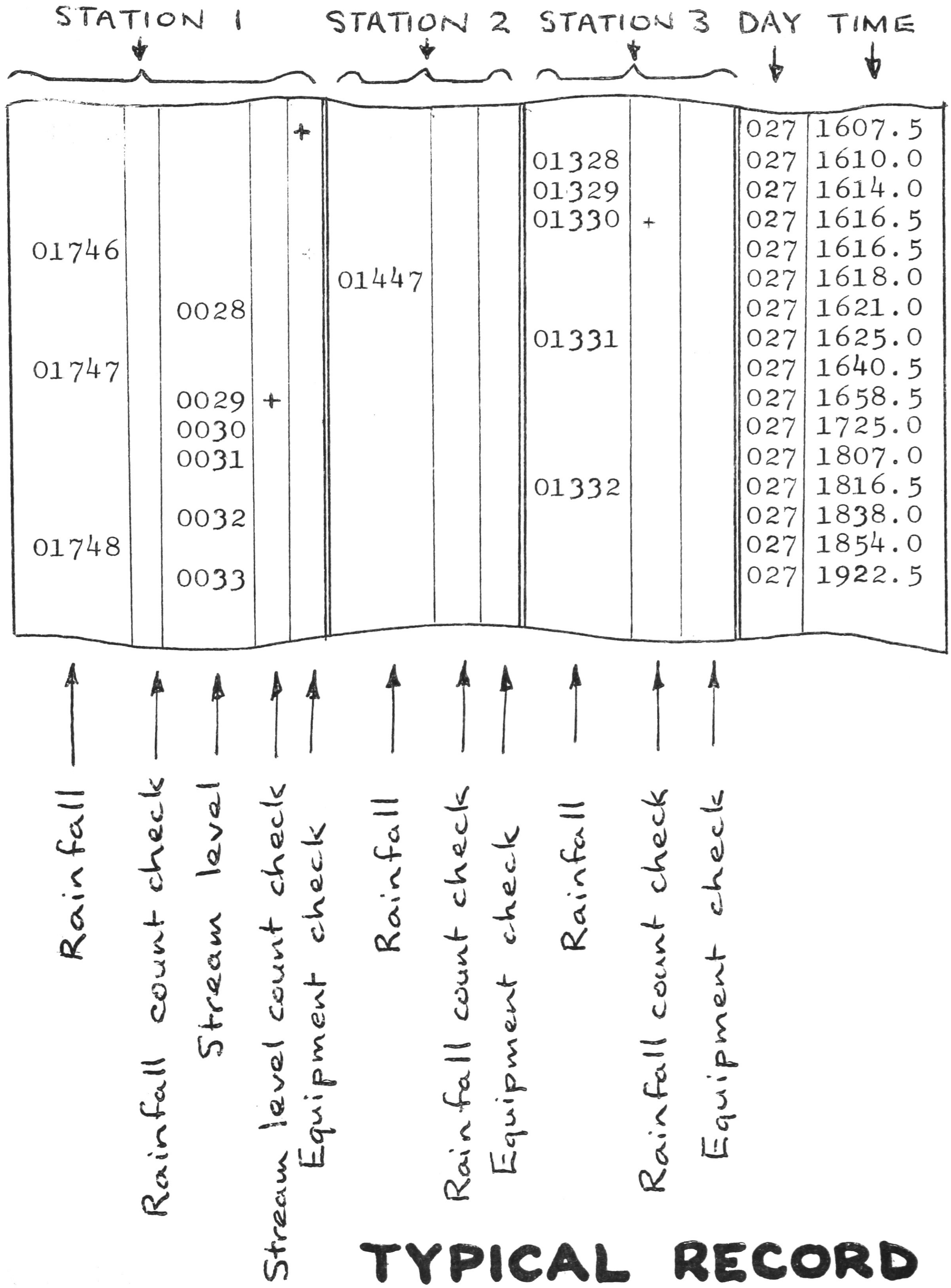
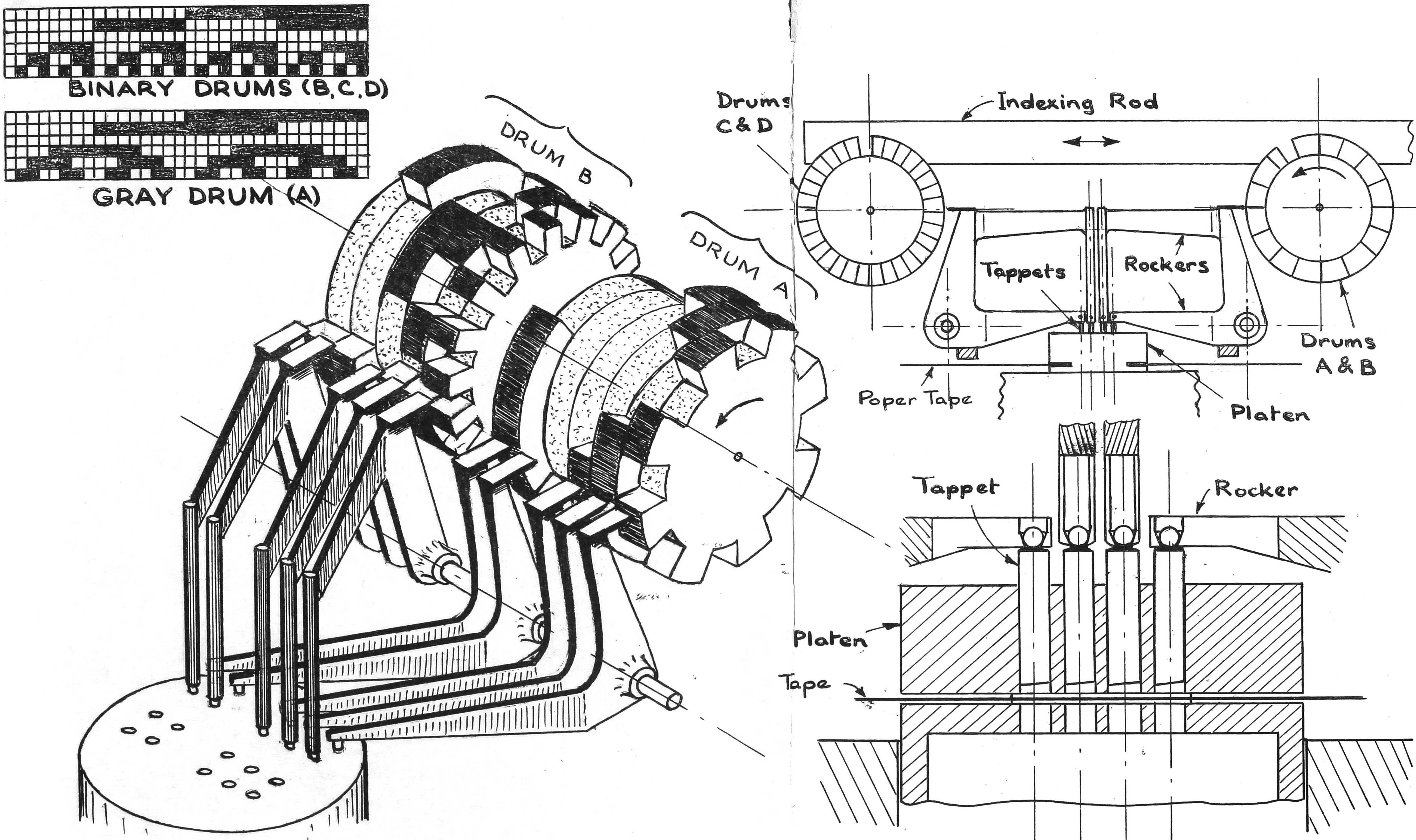
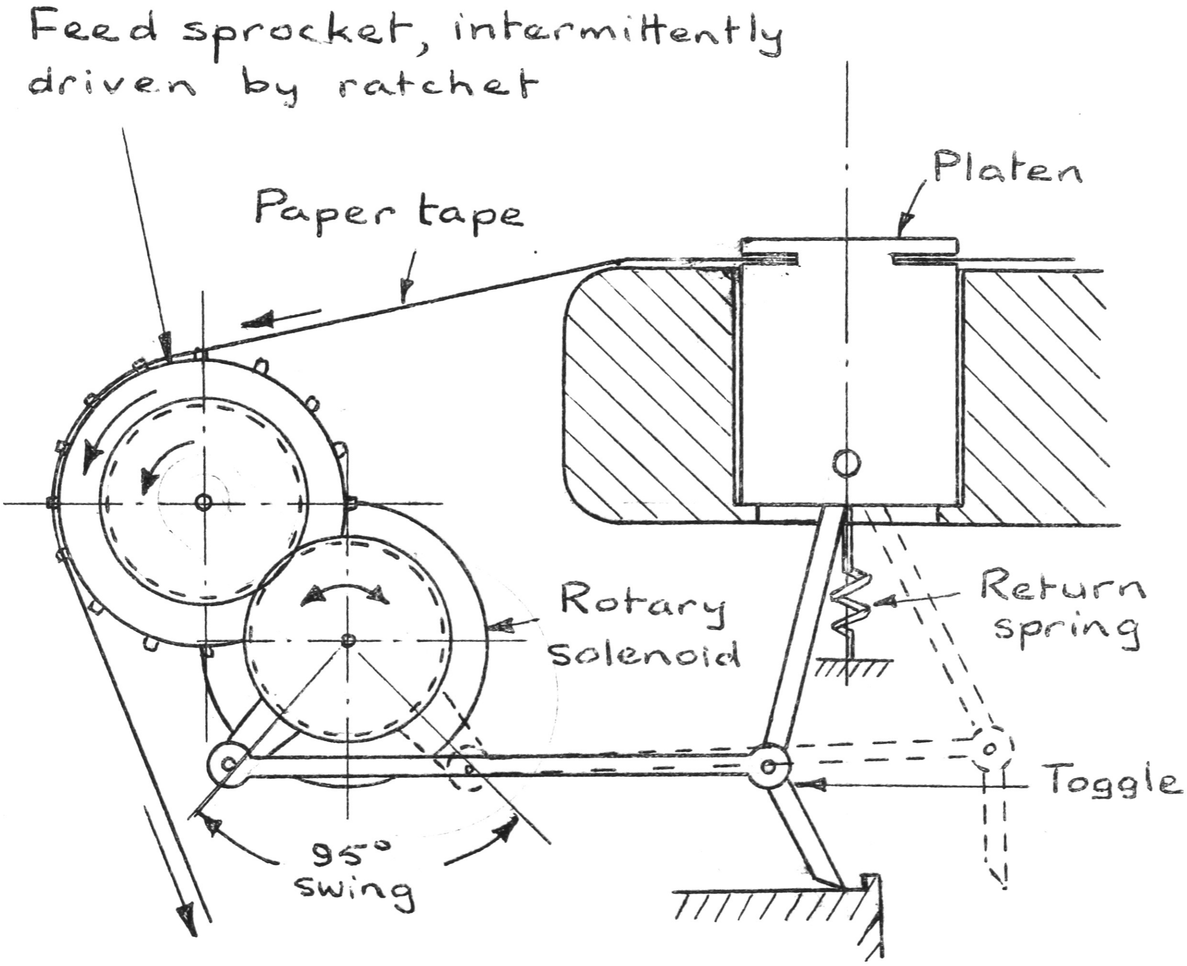


FIG. K.3 TYPICAL RECORD FROM TELEMETER



THE TAPPET —
CODING DRUMS & TRANSFER MECHANISM

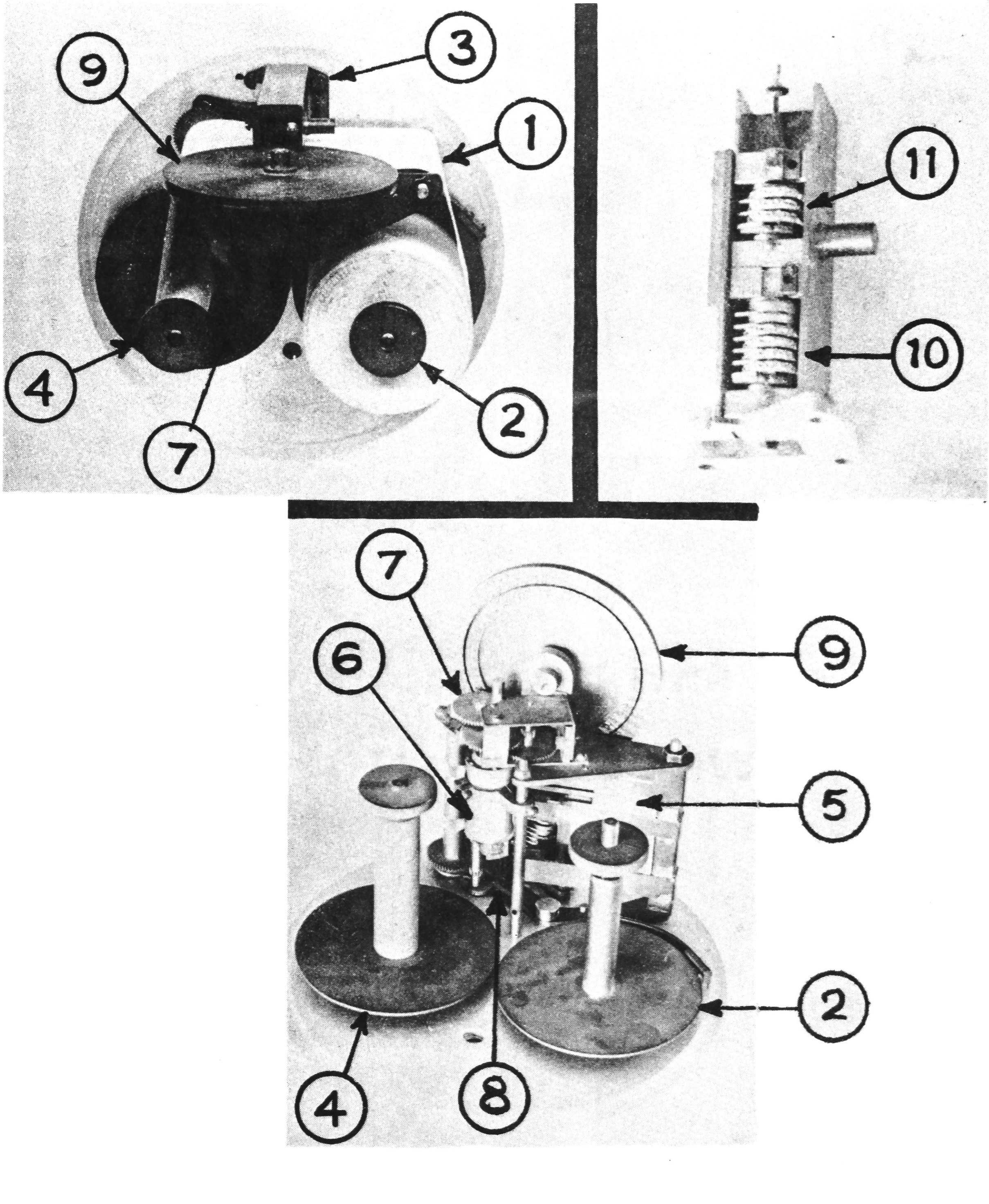
FIG. L.1



NOTE.
Mechanism shown half-way through cycle, after paper feed and before punching.

THE TAPPET — FEEDING & PUNCHING MECHANISM

FIG. L.2



PHOTOGRAPHS OF PRINTING PLUVIOGRAPH (EARLY DESIGN)

FIG. N