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Satellite Navigation: New Signals, New Challenges

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***Abstract*—This paper acts as the introduction to the Special Session "Circuits for Satellite Navigation Receivers" at ISCAS 2007. It summarises the challenges faced by circuit designers when trying to exploit the new signals available from GPS, Glonass and Galileo. These challenges occur from end to end of the receiver – from the antenna to the positioning software.**

I. New Signals

Signals used by satellite navigation systems such as GPS, Glonass and Galileo are all direct-sequence spread-spectrum signals. They are characterised by their carrier, spreading code and (in the case of Galileo) offset carrier (discussed in more detail below). GPS and Galileo use CDMA, i.e. a single carrier spread by different codes, and Glonass uses FDMA, several carriers spread by a single code.

Now is a very exciting time in satellite navigation. For many years, since the 70s in fact, civilians have effectively only had two signals available for satellite navigation: the GPS L1 (1.57542 MHz) [1] signal and the Glonass G1 (1602.0 + 0.5625n MHz, n = 1..12) [2] signal. Except for a short time in the mid-90s, the Glonass constellation has been only partially populated. However, in recent times, several more signals have appeared. A Glonass satellite carrying a second civilian signal was launched 9 Dec 2004; a GPS satellite carrying the new L2C (1.2276 GHz) signal was launched 26 Sep 2005; and the European Galileo system launched its first prototype GIOVE-A satellite 28 Dec 2005, transmitting on several frequencies for civilians (effectively 4 different carriers). Interestingly the interface control document released this year [3] does not describe this signal, which had to be "cracked" by Cornell University [4], nor does it describe the signal planned for the eventual constellation [5]. Still to come are third civilian signals on both GPS L5 (1.17645 GHz) [6] and Glonass. The signal spectral locations are shown in Figure 1.

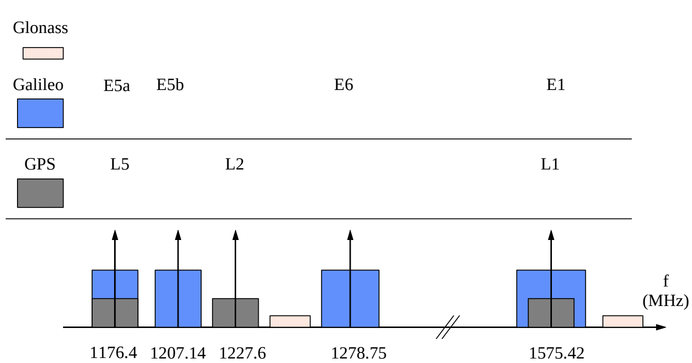

Figure 1 Spectral locations of GNSS signals

It is clearly therefore not accurate to describe satellite navigation receiver design simply as "GPS". The generic term now used for systems of this type is Global Navigation Satellite Systems (GNSS).

With such a wide variety of new signals, receiver designers find that there are many new design questions, not the least of which is the selection of the best signals to use for a given application. There are challenges from one end of the receiver (the antenna) to the other (the software providing the user with position). Many of these challenges are new and require a new approach in order to solve them.

II. Receiver Architectures

The basic functions of a GNSS receiver are shown in **Figure 2**. Allocating them to analogue and/or digital hardware and/or software leads four basic receiver architectures:

- Traditional architecture. The assignment of hardware and software shown in **Figure 2** is traditional. The signal is downconverted to an intermediate frequency by analogue circuitry, the "correlation" is performed by digital hardware, and the position solution is produced in software.
- "Software receiver". The software receiver replaces the digital hardware functionality of **Figure 2** with software, i.e. software is used immediately following the ADC at IF.
- "Software-defined" radio or receiver. In this case the digital hardware is programmable from the software, implying that it is reconfigurable, typically a field-programmable gate array (FPGA).
- "Software radio". In this case, the ADC is pushed as close to the antenna as possible, i.e. the "digital hardware" section disappears altogether and the correlator and part of the RF front end are absorbed into software.

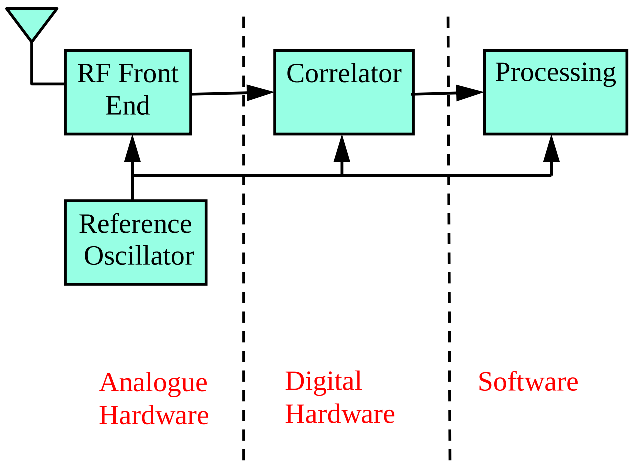

Figure 2 Typical Receiver Architecture

The challenges presented by the new signals differ between architectures. For instance a correlator implemented in digital hardware incurs different changes than a software correlator.

III. MULTI-FREQUENCY RECEIVERS

There is a wide variety of different combinations of GNSS signals that make sense. Combining GPS L1 and L2C is one simple option, giving a good separation between frequencies which allows good elimination of ionospheric error. However, the wider bandwidth L5 and E5 signals are also attractive as they are less vulnerable to noise and multipath. The more signals selected, the better the performance, but also the more difficult the RF design, the greater the computation load and power consumption. GNSS receiver design does not require the full complexity of a multiple-input-multiple-output (MIMO) system [7] firstly because there is no requirement for transmit but also because only a single antenna is required. In fact, the position produced by the receiver is that of the phase centre of the antenna so calibrating that phase centre for all the required frequencies is an important activity.

IV. ANTENNA DESIGN

Once the required frequencies are selected, the antenna must be designed that can receive across the whole bandwidth at each of these frequencies. This represents a relatively difficult task. Studies have shown [8] that for several frequency bands, patch antennas tend to be difficult to design, especially when, as for some GNSS signals, the bandwidth is relatively high. The problem is that for commercial receivers, the antenna needs to be cheap, and for a dual-frequency patch design, stacked patches have been proposed [9, 10], which are more expensive to produce, and some single-layer slotted patches [11, 12]. One triple-frequency GPS design is a quite large: 4.7 inch square [13]. So an inexpensive multi-frequency antenna design still seems some way off.

V. RF FRONT END

In a software radio architecture, downconversion of the RF signals can be achieved by using bandpass sampling [14] which can be used to sample several RF bands simultaneously [15]. This can lead to required sampling rates of only around 11MHz for a simple L1/L2C receiver and up to around 450MHz for a receiver designed for all civilian GPS/ Galileo/ Glonass signals [16]. Because bandpass sampling exploits aliasing, several aliased bands appear in the baseband after sampling and this means that the RF bandpass filters must be significantly better than usual in order to reject these bands, by up to 30dB in the worst case [17].

For the other architectures, the filter requirements are much the same as for L1 GPS, except that carriers and bandwidths vary. Careful attention must be paid to the frequency plan, with interactions between different local oscillators and intermediate frequencies likely to cause problems. All the GNSS signals are quite weak when received, so designers must be wary of this type of interference. Currently, there is also a problem sourcing components, e.g. ceramic filters, for the new signals.

VI. CORRELATION

Significant emphasis in GPS receivers is put on the design of the "correlator", as it is this device which tracks the received signal and affects the accuracy with which it measures its time of arrival, from which it derives the distance to the satellite and calculates position. Correlators are used for two increasingly separate activities: acquisition and tracking. Acquisition is a search process where two dimensions are searched: Doppler frequency and code delay. Tracking uses the outputs of several "correlators" to keep the code tracking loop locked, i.e. to keep the spreading code produced in the receiver aligned with the code received from the satellite.

The acquisition process is slow when the SNR is poor, so techniques to speed this process up have been developed, particularly to reduce the power consumption of mobile devices. To this end, chip designers have come up with massively parallel devices called "search engines". Apart from manufacturers' literature (such as that from Global Locate [18] or SiRF [19]) there is very little published about search engines that is useful to the research community, although we are attempting to address that [20].

One of the problems facing the acquisition process for L1 is that there is 50bps data that can reverse the phase of the signal. Given that part of the correlation process involves integration of the signal, a signal inversion could mean that pre-transition and post-transition integrations cancel each other out. It is for this reason that all of the new signals include a dataless channel. For L2C, there are two signals, time multiplexed with separate spreading codes, one carrying data and the other data-free. For L5 and the Galileo signals, QPSK or other phase modulation schemes are used to carry data-carrying and data-free versions of the signal – which always have different spreading codes.

The new L2C signal is received at a lower power level than L1. Also the data-carrying (using the moderate-length CM code) and data-free (using the long CL code) parts of the signal are each allowed only half of this power. Because SNR is thus weaker, longer integrations are required for L2C than for L1 in order to give the same probability of detection. Also, the codes are longer so more candidate code delays must also be examined during the search. Thus it takes longer to acquire the L2C signal so in a receiver that handles both L1 and L2C, L1 should be acquired first and once its phase is established, it is easy then to lock on to ("hand over to") L2C [21]. When using software correlation (i.e. in a software receiver or software radio architecture), the usual process is to use an FFT approach [22]. Unfortunately, because of the longer code length, this means that L2C takes even longer (several hundred times) than L1 to acquire so again, the better choice is to acquire L1 and hand over [21].

For L5 and Galileo, the statements above about longer codes also apply, but often the SNR is better so the L2C case is likely to be the worst in terms of extra acquisition effort.

Turning to tracking, different problems arise. A "normal" L1 tracking correlator will have one local code generator set, say, half a chip early and another half a chip late, so they sit on the shoulders of the triangular correlation function (see Figure 5). The difference between these levels is fed back into the code-locked loop in order to keep the local code aligned with the received code. Because of the time-multiplexed nature of the L2C signal, it is necessary to use a three-level RZ version of the local code [21] – see Figure 3. This is for two reasons – i) if the NRZ version was used, a flat-topped correlation function results, so the early and late tracking correlators end up being spaced a long way apart if they are to remain on the "shoulders", which gives poor performance in the presence of multipath (a standard solution to the multipath problem is to use the "narrow correlator" where early and late circuits have very little delay between them [23]), and ii) "zeroing" the unwanted CL code minimises the amount of integrated noise, increasing the post-integration SNR.

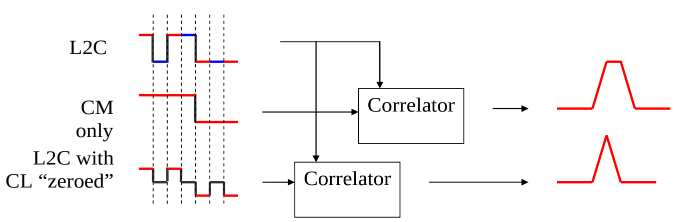

Figure 3 Correlation functions that result from using a non-return to zero (NRZ) version of the CM code (top) and a return to zero version (RZ) (bottom) in the L2C correlation process

The L5 signal can be tracked using circuitry quite similar to that for L1 because each its QPSK channels can be treated as a BPSK channel. The Galileo signals on the other hand are quite different. The signal that Galileo will transmit on E1 (same carrier as L1) has been the subject of debate between the US and Europe for some time, and it has still not been finalised. The best that can be said at the time of writing is that the spectrum of the signal has been agreed but not the time-domain version [5]. In order to understand the new signal specification, it is necessary first to understand the use of "binary offset carrier" or BOC. A familiar version of BOC is Manchester encoding, illustrated in Figure 4. The Manchester encoded signal can be considered to be a set of bipolar symbols, each with a transition in the middle, or it can be thought of as the original data multiplied by a binary (offset) "carrier" at the same frequency as the data rate. The "offset" describes the fact that the baseband spectrum has no dc component but instead has peaks near the "carrier" frequency. In Manchester encoding, the offset carrier has the same frequency as the data (or more correctly in the current context, the spreading code) and is designated BOC(n,n), In the language of satellite navigation, there is a base frequency unit of 1.023MHz so a BOC(1,1) signal has both offset carrier and spreading code operating at 1.023MHz. Thus the BOC signal has approximately twice the bandwidth of the equivalent BPSK signal. The GIOVE-A prototype Galileo satellite is transmitting a BOC(1,1) signal on L1. However, the agreed signal for future satellites is a combination of BOC(1,1) and BOC(6,1), i.e. a signal that has an offset carrier at 6 x 1.023MHz [5]. There is insufficient space here to go into the detail of this signal and its current time domain options – the reader is refered to the references. The reason that this complicated signal has been selected is that is that it delivers improved multipath performance in the "same" bandwidth.

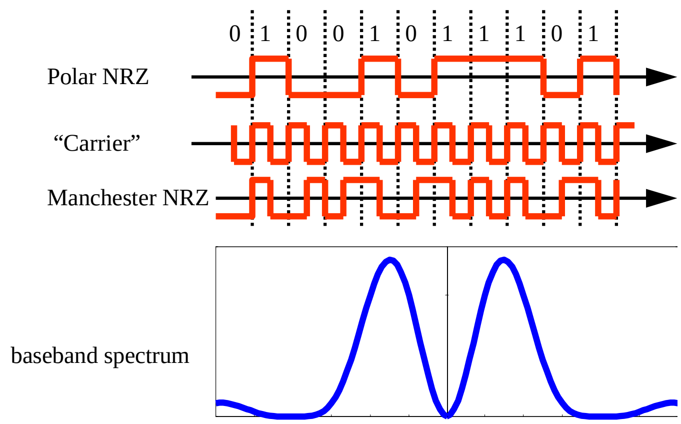

Figure 4 Manchester encoding, or BOC(n,n)

Correlators that deal with BOC signals are inherently more complex than those for BPSK because the autocorrelation shape has several peaks and the aim is to ensure the wrong peak is not tracked. In Figure 5, it can be seen that large negative peaks occur next to the central positive peak. To avoid tracking one of these side peaks, new correlation control strategies have merged. The "bump-jump" method [24] uses the extra correlators of Figure 5 to ensure that both early/late and very early/ late are balanced. If they are not, the circuit jumps half a chip to the higher peak. Another method is to treat one side of the spectrum in Figure 4 as a "BPSK-like" signal and then use a normal BPSK early/late correlator [24]. This has an unambiguous correlation function but wastes half of the signal power, and doesn't exploit the multipath benefits of BOC. A third method [25] uses a weighted sum of the squares of several correlator spacings. This also produces an unambiguous discriminator function in the code tracking loop. It would appear, however, that the "best" correlator design for BOC signals is yet to be designed.

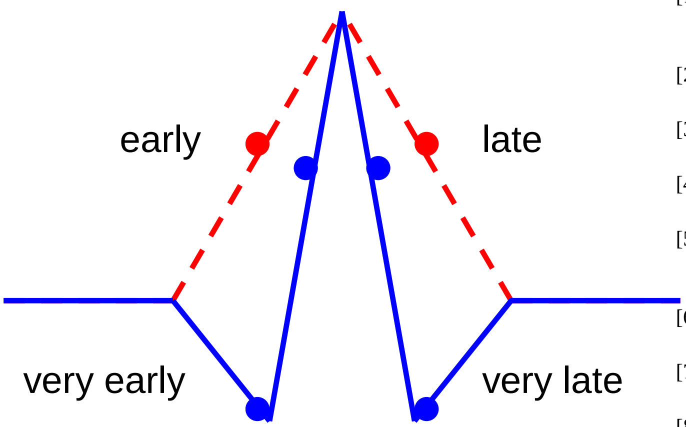

Figure 5 A BPSK(n) autocorrelation function (red dashed) with early and late tracking positions, and a BOC(n,n) autocorrelation function, with the extra very early/late correlator positions shown

The BOC(1,1) signal on E1 discussed at length above is only one of the Galileo signals. There is also an Alternative BOC or AltBOC(15,10) signal on E5, which places different signals in each spectral sidelobe of the BOC signal, and another BOC signal in the restricted service. Further comment on these will not be pursued further here.

VII. Positioning and Control Software

There are many benefits from the use of multiple signals. These include the ability to use one to help assist acquire another as discussed above, the ability for each tracking loop from a given satellite to be used to assist each other so tracking is as smooth as possible, using the phases of the various carriers to resolve speedily the phase ambiguity problem when performing carrier phase positioning. These could be considered "software considerations" and hence are left for another forum for discussion.

VIII. Conclusion

This tutorial paper summarises the challenges faced by the designer of a satellite navigation receiver exploiting the newly available signals, particularly those of Galileo and GPS. Significant challenges exist in the design of antennas, RF front ends, analogue-to-digital conversion, correlator hardware, acquisition algorithms and tracking functions. Here only an introduction to all of these issues has been presented but hopefully it is a useful overview.

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