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The "System of Systems" Receiver: an Australian Opportunity?

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ABSTRACT

In the near future, there could be as many as four global navigation satellite systems (GNSS) and three regional navigation satellite systems (RNSS). This paper examines the visibility of these systems, identifying Australia as a good location to view all of them. The impacts on receiver design are also examined at sub-system level, revealing that a "system of systems" receiver would be far more sophisticated than a basic GPS L1 receiver.

KEYWORDS: Satellite navigation, GPS, Galileo, Glonass, GNSS

1. INTRODUCTION

The first Global Navigation Satellite Systems (GNSS) grew out of the cold war: the US had GPS and the USSR (and later Russia) had Glonass. As it became clear that the utility offered by GPS in particular was far outgrowing its original military purpose, the Europeans decided to participate, and proposed Galileo. China launched Beidou, which was the first Regional Navigation Satellite System (RNSS), and then announced Compass, a GNSS. Japan tried to solve the urban canyon problem by planning their own regional augmentation to GPS: the Quasi-Zenith Satellite System (QZSS). Then India proposed the Indian RNSS (IRNSS). Who knows who next will propose a navigation satellite system (or NSS, which includes both GNSS and RNSS), but most of the big space players are all now represented. And what do all of these systems have in common? Some systems, or at least their signals, look very similar to each other: GPS and QZSS, for instance. Others, such as IRNSS, are very different from all the others. But one thing they all have in common: *they can be seen from mainland Australia*.

One of the advantages that new systems can always be argued to provide is simply "more satellites". GNSS users can argue that the more satellites they have the better. Indeed, the advantage that the "extra" Glonass satellites provided for RTK GPS saw Topcon gain market share. Now most manufacturers offer a GPS/Glonass product. So nominally, this rapid increase in satellites systems and constellations means that ever more satellites will be available and a receiver that can exploit all of the new signals may be the "ultimate" in satellite navigation. The concept of the "System of Systems" (SoS), using as many systems as possible, is a relatively new one (the first real discussions only emerged this year [1, 2]) and deserves some examination. This paper looks at the new systems and tries to gauge if there is a genuine advantage in a system-of-systems receiver, and whether Australia's unique location offers an opportunity for such a development.

2. THE NAVIGATION SATELLITE SYSTEMS (NSS)

2.1 GLOBAL NAVIGATION SATELLITE SYSTEMS (GNSS)

2.1.1 GPS

GPS (US) does not need to be introduced to this audience, but for the record, it is a system designed for 24 satellites in 6 orbit planes. At the time of writing (April 2007) [3], the constellation consisted of 30 satellites (with 32 being the maximum allowable). All transmit civilian signals on the L1 frequency (1.57542 GHz), three transmit on the new L2C frequency (1.2276 GHz) and “real soon”, we expect transmissions on the L5 frequency (1.17645 GHz).

2.1.2 Glonass

Glonass (Russia) is a system which was designed to have 24 satellites in 3 orbit planes. It was fully operational only for a short time in the mid-90s but recent commitments by the Russian government are to have it fully functional again “soon”. At the time of writing (April 2007) [4], there were 9 functioning satellites, 10 “temporarily switched off” and one in “commissioning phase”. All transmit on different frequencies in the “G1” (Glonass frequencies are sometimes called L1, L2 etc but here will be called “G1”, “G2” etc because the carriers are not the same as GPS L1, L2) range 1.602 – 1.6093125 GHz, some transmit in the “G2” range 1.246 – 1.2526875 GHz, and soon there will be transmissions at “G3”, starting at 1.201.5GHz. Unlike all of the other systems, which are CDMA, Glonass uses FDMA (hence the carrier ranges above), although the signals on those carriers are spread by a pseudorandom code – the same for each satellite.

2.1.3 Galileo

Galileo (Europe) is designed to have 27 active satellites and 3 in-orbit spares in 3 orbit planes. It launched its first prototype, GIOVE-A in 2005. This prototype can transmit on two of the Galileo carriers, E1 (1.57542 GHz), E5a (1.17645 GHz), E5b (1.20714 GHz) and E6 (1.27875 GHz), but not all at once. Tantalisingly, even the belated ICD [5] did not describe the actual signal transmitted by this satellite: that had to wait until 2007 [6]. The most significant innovation with these signals is their use of binary offset carrier (BOC) modulation, which splits the transmitted energy around the carrier. For the E1 signal, which nominally will look the same as the future GPS L1C signal, an advanced MBOC code has been proposed [7].

2.1.4 Compass/ Beidou-2

Compass (China) has only recently been announced [8] but the ambitious aim is for it to work by end 2008! The 35-satellite constellation will have 5 GEO satellites and 30 MEO, the first of which was launched in April, 2007. How Compass/Beidou-2 differs from the RNSS Compass/ Beidou-1 (see below) is not entirely clear but some authors [9] say the satellite launched in Feb 2007 was the last of the earlier series. Carrier frequencies are nominally 1.20714 GHz, 1.26852 GHz and 1.561098/1.589742 GHz [1] and signals at these frequencies have been recorded from the first MEO satellite [10].

2.2 REGIONAL NAVIGATION SATELLITE SYSTEMS (RNSS)

2.2.1 QZSS

The Quasi-Zenith Satellite System (QZSS) (Japan) has been proposed as an augmentation to GPS – to provide more “overhead” satellites in high-rise Japanese cities where “urban canyons" obscure enough satellites to disable GPS. The satellites will transmit signals identical in type to GPS [11], and are likely to be the first to transmit the GPS III signal L1C. Geosynchronous "figure-of-8" orbits keep at least one of the three satellites at high elevation over Japan [12].

2.2.2 IRNSS

The Indian Regional Navigation Satellite System (IRNSS) is a stand-alone positioning system [13], unlike QZSS which is a GPS augmentation. It consists of three geostationary satellites (which are also GAGAN satellites – see below) and four geosynchronous satellites in figure-of-eight orbits. A single carrier at 1.191795 GHz is proposed [1].

2.2.3 Compass/Beidou-1

China launched two satellites as its Beidou navigation system in 2000 and a third "backup" in 2003. These are geostationary satellites and provide navigation over China and the region using a duplex system (eliminating the "local clock" problem that requires a fourth satellite for position in GPS) and a height model (eliminating the need for the third satellite). It uses an uplink frequency 1.61568 GHz, and downlink frequencies of 2.49175 GHz [14]. For four reasons, we do not consider Beidou further in this combined scenario: the uplink frequency is in L band and therefore is likely to interfere with other L band signals, Beidou will be "replaced" by Compass/ Beidou-2, the duplex system makes interoperability difficult, and the signal is not openly available.

2.3 SPACE-BASED AUGMENTATION SYSTEMS (SBAS)

As an aid to aviation, primarily to provide integrity, various SBAS systems have been developed to augment GPS, with extension to other GNSS possible. Because these satellites also provide ranging signals, they can also be considered as contributing to the "system of systems" receiver. The satellites are all geostationary and transmit at the L1 frequency (and some at L5). Europe's EGNOS has three satellites, the US WAAS has four, Japan's MSAS has two and India's GAGAN will have three. Nigeria is also planning NIGCOMSAT.

3. SATELLITE VISIBILITY

This large number of potential pseudorange-providing satellites means that there will be places that are favoured by having greater visibility of these satellites. This is obvious in Figure 1 which shows best visibility in south-east Asia, as could be expected. For low mask angles, there is a "hot" area around Singapore, but for larger mask angles, the best region is larger, and incorporates most of Australia.

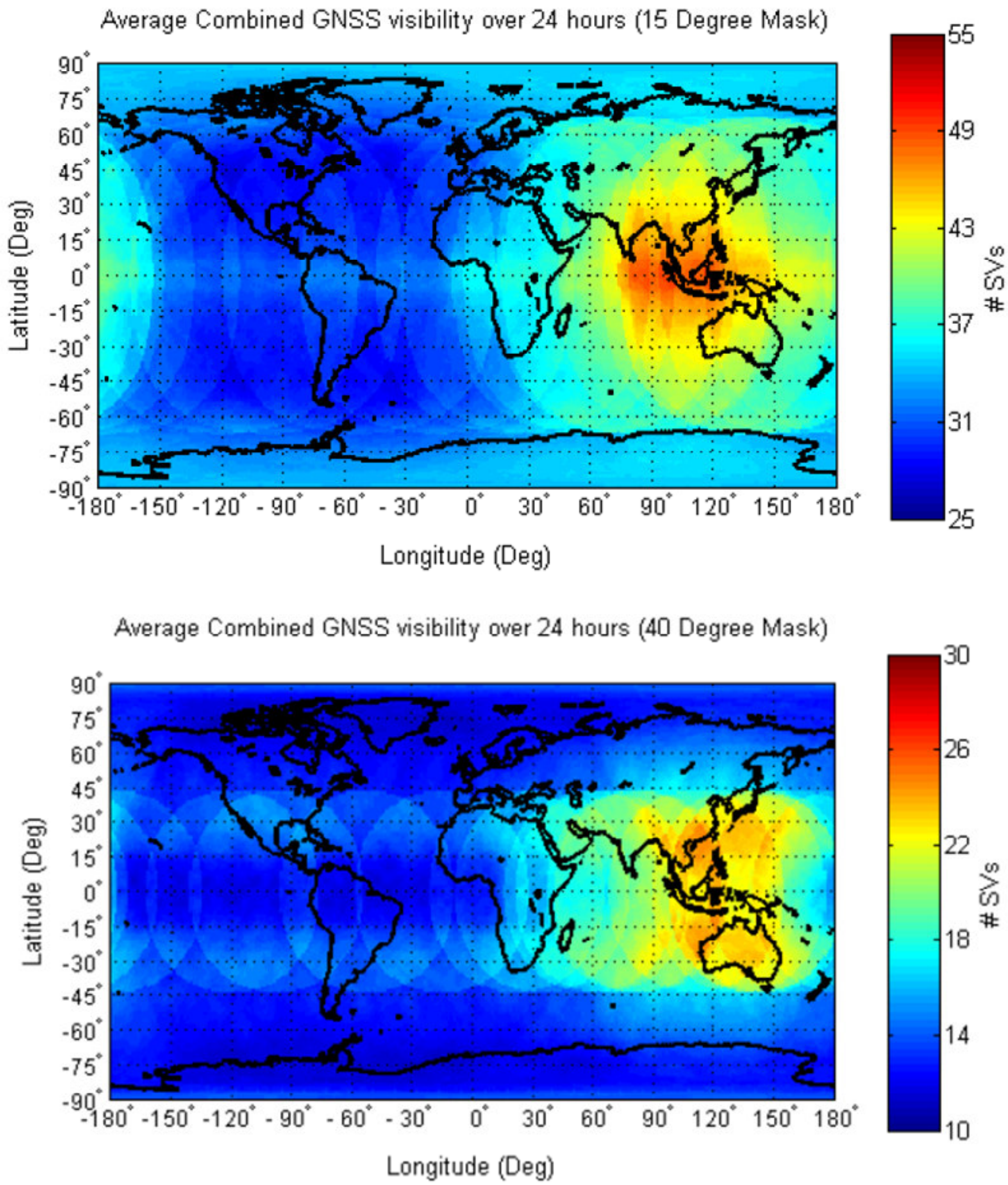

Figure 1 Global "system-of-systems" satellite visibility – with mask angles of 15° (above) and 40° (below)

These statements are borne out in Figure 2 which examines visibility in particular locations. It can be seen that for a 15° mask, Singapore can see as many as 52 satellites at a time and generally has greater visibility than the three Australian cities listed. For a 15° mask, this advantage disappears, with each of Perth, Darwin and Sydney having the most satellites visible at different times. For comparison, Colorado Springs in the centre of the US is shown – both cases examined, it has far fewer satellites visible than the Asian and Australian cities.

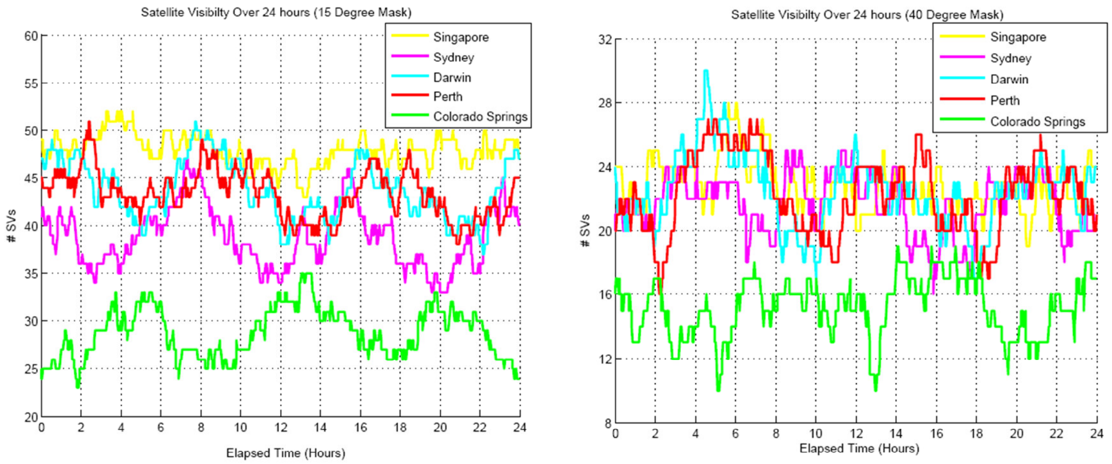

Figure 2 Satellite visibility in individual locations with mask angles of 15° (left) and 40° (right)

To generate the figures, the nominal constellation designs of each GNSS were implemented for the determination of satellite visibility from various locations using a heavily modified version of the GPSoft Satellite Navigation MATLAB toolbox. The nominal constellations for GPS and GLONASS were implemented as described in [31] and [30], respectively. The orbit parameters for the constellations of Compass and the augmentation systems WAAS, EGNOS, QZSS, MSAS, IRNSS and GAGAN were determined from information provided in [1]. Information on the nominal Galileo constellation design was obtained from [28] [29] and [1].

The average visibility global colormaps where generated for a period of 24 hours with temporal and spatial resolutions of 48min and 1 degree, respectively, while the 24 hour specific location plots were generated with a temporal resolution of 2 min.

4. A "SYSTEM OF SYSTEMS" RECEIVER

4.1 RF Design

In Figure 3, the range of NSS carrier frequencies is shown. There is a significant number of different carriers and bandwidths. However, from a receiver front end design point of view, where all signals must be received, they can be grouped into two bands, from the bottom of the E5 band to the top of the E6 band (1.166 – 1.294 GHz, a 128MHz band) and from the bottom of the Compass L1 band to the top of the Glonass G1 band (1.559 – 1.616 GHz, a 57MHz band).

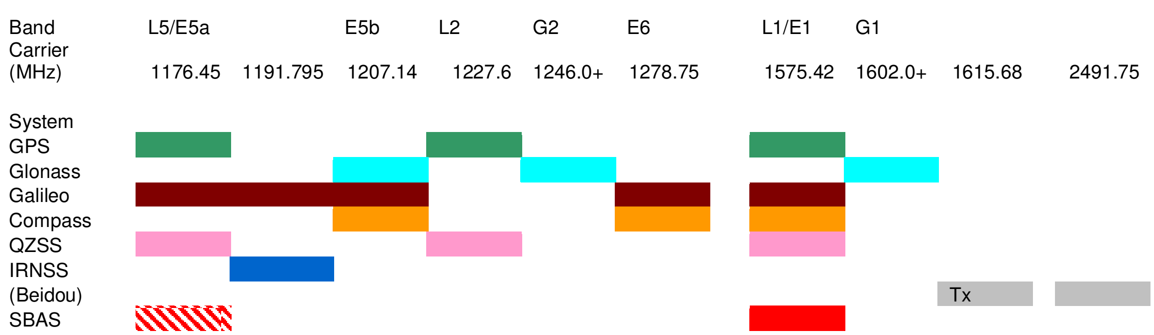

Figure 3 NSS Frequency bands

Designing antennas to cover this range with good "isotropic" gain and phase centre behaviour is a real challenge. Some initial research has shown antennas of this type are possible [15] but there is of course the extra challenge of making it commercial. Antenna designs for the combination of GPS L1, L2 and L5 have used stacked patches to achieve two relatively wide bands, with L2 and L5 in a single band [16] (More usually patch designs have quite narrow-band dual-frequency designs, see e.g. [17]). Commercial L1/L2/L5 antennas, presumably designed along these lines, have started to emerge [18, 19]. These designs could be the basis for a "system-of-systems" antenna.

Designing wide-band front ends for these two bands also presents significant challenge.

4.2 Analogue-to-Digital Conversion (ADC)

The analogue-to-digital conversion (ADC) usually occurs at the output of the RF chip. One problem is that any automatic gain control (AGC) applied to the whole band(s) will attenuate all the signals in the presence of interference anywhere in the band(s) of interest. To alleviate this, a larger than usual number of bits must be allowed, each giving 6dB more immunity to AGC problems. Obviously, the sampling rate is going to be high. To sample the total bandwidth discussed above (185MHz) requires a minimum sampling rate according to Nyquist of 370MHz, compared to the single-digit MHz sampling rates of L1 GPS receivers. However, when performing bandpass sampling of multiple bands, certain criteria need to be fulfilled [20] – the bands must not overlay 0Hz or the Nyquist frequency and must not overlay each other. Using the techniques in [20, 21, 22], the minimum sampling frequency for the bands identified above that meets the criteria can be calculated as 450MHz (and then any frequency up to 454.1MHz). Whereas a standard L1 GPS front end such as the Zarlink 2015 [23] might use 2-bit samples at 5.7Mhz, creating digital data at 11.4Mbits/sec, a System of Systems receiver would require a minimum 900Mbits/sec without any extra overhead for dealing with interference. For every extra bit (i.e. 6dB of interference margin), an extra load of 450Mbits/sec is added.

4.3 Digital Baseband

The design of the digital baseband circuitry (or firmware) depends on the specifications of the signals to be exploited. Table 1 indicates some estimates of the impacts that new signals make compared with GPS L1. The data can be found in the ICDs for GPS L1/L2C [24] and L5 [25], Glonass [26], Galileo [5, 6] and QZSS [27]. Some additional data is taken from [1]. It is assumed all publicly available signals (including those that attract a fee, as in the Galileo Commercial Service) are received.

So, instead of 12 pseudoranges to process from an "all-in-sight" GPS L1 receiver, there may be as many as 61 if the allocations of Table 1 are adopted. Instead of 12 correlators in tracking loops, there may be as many as 288. On average, these correlators will be clocked at 5.0 times the speed of an L1 correlator, meaning that power consumption of the digital baseband chip can be expected to be 5.0 x 288/12 = 120 times higher than an L1 receiver when tracking, i.e. a battery that lasted for two hours instead would last only a minute. BOC-type signals may require 5 "fingers" (Very Early/ Early/ Prompt/ Late / Very Late) to track signals, rather than three (Early/ Prompt/ Late) so if that was the case, the average power would be 6.0 x 288/12 = 144 times higher than an L1 receiver. It can be argued that this is still a conservative estimate because the code generators for all new register-generated codes are longer than for L1. A power estimate for the digital baseband chip at 150-200 times a GPS L1 receiver seems reasonable, especially if the bandpass sampling rates mentioned above are used. Even greater power would be consumed if extra ADC bits were allocated for interference mitigation.

If all the correlators were the same size, a digital baseband chip 24 (=288/12) times the size of an existing GPS L1 chip would be required. Given the use of BOC and long codes, in fact the chip would need to be larger, possibly more like 50 times the size.

Signal	Correlators allocated	Code register length	Chip rate (x 1.023M)	BOC?
GPS L1	12	10	1	N
GPS L2C	12	23	0.5 x 2	N
GPS L5	12	13	10 x 2	N
Glonass G1	12	9	0.5	N
Glonass G2	12	9	0.5	N
Glonass G3	12	?	4 x 2	N
Galileo E1	12	(memory)	1 x 2	Y
Galileo E5	12	14	10 x 2	Y
Galileo E6	12	?	5 x 2	Y
Compass L1	12	?	2 x 2	Y
Compass E5b	12	?	2, 10	N
Compass C3	12	?	10 x 2	N
QZSS L1	2	10	1	N
QZSS L2C	2	23	0.5 x 2	N
QZSS L5	2	13	10	N
QZSS L1C	2	?	1	Y
IRNSS	7	?	10 x 2	N
SBAS L1	4	10	1	N
SBAS L5	4	13	10 x 2	N

Table 1. Information used for estimating hardware impacts of signals in System of Systems receivers. Where two signals are modulated onto a single carrier (data-carrying and dataless), this is indicated as "x 2" in the chip rate.

4.4 Navigation Computer

When estimating the computational load, the following assumptions were made:

- Every correlator requires a code and carrier loop to be maintained
- Each satellite contributes only one pseudorange to the PNT solution

The low-level loop control software thus requires an effort proportional to the number of correlators, or 288/12 = 120 times the GPS L1 effort. The PNT solution relies heavily on matrix calculations, proportional to the square of the number or pseudoranges, or $(61/12)^2$ = 26 times the GPS L1 effort. Much of the housekeeping effort is proportional to the number of satellites tracked, or 61/12 = 5 5 times the effort. How these numbers combine depends somewhat on the rate at which position is calculated, loop update rates and other factors, but a value of 50 times seems reasonable. More effort will be applied to this problem in future.

5. CONCLUSIONS

A “System-of-systems” receiver makes some sense in the Australian context, where all the systems are visible. Such a receiver would requires significantly more resources than are required for a simple GPS L1 receiver – for the digital baseband processor, power (200x) and chip area (50x) much greater, and processing effort (50x) is also greater. In addition, antenna and RF front end design are far more sophisticated and likely to be more expensive. Such a receiver is unlikely to be useful for “portable” applications.

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