International Global Navigation Satellite Systems Society
IGNSS Symposium 2015

Outrigger Gold Coast, Qld Australia
14-16 July, 2015

Predictability of GNSS signal observations in support of Space Situational Awareness using passive radar

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ABSTRACT

GNSS signals have been proposed as emitters of opportunity to enhance Space Situational Awareness (SSA) by tracking small items of space debris using bistatic radar. Although the scattered GNSS signal levels from small items of space debris are incredibly low, the dynamic disturbances of the observed object are very small, and the phase of the scattered signals is well behaved. It is therefore plausible that coherent integration periods on the order of many minutes could be achieved. However, even with long integration periods, very large receiver arrays with extensive, but probably viable, processing are required to recover the scattered signal. Such large arrays will be expensive, and smaller more affordable arrays will collect insufficient signal power to detect the small objects (relative to wavelength) that are necessary to maintain the necessary phase coherency. The investments necessary to build a large receiver array are unlikely without substantial risk reduction.

Pini and Akos have previously reported on use of very large radio telescopes to analyse the short-term modulation performance of GNSS satellite signals. In this work we report on tracking of GPS satellites with a radio-astronomy VLBI antenna system to assess the stability of the observed GPS signal over a time period indicative of that proposed for passive radar. We also confirm some of the processing techniques that may be used in both demonstrations and the final system. We conclude from the limited data set that the signal stability when observed by a high-gain tracking antenna and compared against a high quality, low phase-noise clock is excellent, as expected. We conclude by framing further works to reduce risk for a passive radar SSA capability using GNSS signals.

KEYWORDS: GPS, temporal coherency, passive radar

1. INTRODUCTION

Human civilisation is gaining increasing benefits from the use of space. Although popular culture is obsessed with manned spaceflight, it is unmanned space systems that are currently delivering the greatest benefits to mankind. The rate of unmanned space launches is increasing rapidly, and the number of objects in Earth orbit is growing at an exponential rate.

In the early days of space flight there were very few objects in orbit so collisions were extremely unlikely, and most sizeable orbiting objects could be manually tracked. However over the last 60 years the number of objects in orbit has increased to the point where the probability of collision is no longer remote. Space Situational Awareness (SSA) is an overarching term used to describe having knowledge present and future space weather, the nature of orbiting bodies and their present and future trajectories.

Some orbiting objects are operational satellites. Many of the objects orbiting the Earth are greater than 10 cm in at least one dimension. These relatively large objects can be tracked with some measure of ease by a combination of optical, radar, laser or radio-interferometry. Smaller objects are however more difficult to track. In addition, the number of objects of small dimension vastly outnumbers the number with large dimensions so the number of tracking operations required to obtain SSA grows dramatically as the lower bound on tracked object size reduces.

Although small objects in orbit have very low mass, their velocity is very high, representing considerable kinetic energy. Furthermore, because of weight sensitivity, most satellites have little or no shielding for impact with high velocity objects. Therefore collisions of functional satellites with even very small items of debris can result in a satellite being disabled.

The commercial cost of collision is today tolerated as one of the many risks that can cause a satellite to be lost at launch or in operation. However as the number of orbital objects grows this may not remain the case. Further, the consequence of any collision between satellites, or satellites and large debris is the creation of many thousands of new small items of debris. The well-reported Kessler Syndrome (Kessler 1978) is one hypothesis on the consequence of growing orbital debris density.

Existing SSA is relatively poor at predicting trajectories more than a few days into the future, and even then there can be substantial uncertainties. This is partly due to accuracy limits on measurement of existing trajectories and partly due to limits on our understanding of the microscopic forces acting on orbital bodies. Our lack of precision in understanding those microscopic forces lies in part in a lack of a large body of accurate trajectory observations. Therefore improved observation accuracy, at low cost per observation of a large and growing number of small orbital objects is needed. In this paper we focus on making measurements of the trajectory of orbiting objects.

The paper is structured as follows. In Section 2 we describe existing orbit tracking techniques and provide additional background on radar tracking of orbital objects and GNSS as an illumination source for bistatic radar. In Section 3 we present and analyse results from a relevant experiment to address the main contribution of the paper. The conclusion reiterates the key points and suggests future work.

2. BACKGROUND

2.1 Literature

Laas-Bourez et al. (2009) describe the observation of satellites in geostationary orbit with TAROT, a robotic ground based automated telescope. Based on mathematical morphology, the authors develop a new algorithm that uses only one image rather than several to reduce the computational complexity of that observation without substantially compromising efficiency. Different sizes of space debris are hard to track, as the length of the structural element used in the morphological operations directly governs the detection of objects. The structuring element has to be small enough to adapt itself to the variation of intensity of the expected objects to be detected. Although the false detection rate has decreased, challenges remain, such as bad responses in cloudy images or images with a brighter background.
Single-range Doppler interferometry (SRDI), proposed by Sato (1999), uses the magnitude distribution of a Doppler spectrogram to identify the shape of space debris. A two-dimensional (2D) image is reconstructed using an integral along the sine waves. However, the method is low in resolution and invalid in cases of low signal to noise ratio (SNR), as it is not a coherent integral. The system overcomes the major drawback of range-Doppler interferometry (RDI), being that it is applicable only if the radar wavelength is larger than the size of the object. However, the images of a conductive object are governed by strong scattering centres with major reflections.

The robotic optical telescope network (Laas-Bourez *et al*, 2011), which consists of three 1-metre telescopes, confirms the access to almost all geostationary belt objects. The geographical distribution of sensors ensures that, space objects in all orbits can be tracked. However, since these space targets are located at a long distance from the observation stations, the shape and texture attributes of these space targets are almost entirely lost as the objects are barely resolved. Moreover, the effects of atmospheric turbulence and the imaging device's imprecision lead to further difficulties for identification and tracking.

The use of ground-based lasers to move space debris (Mason *et al*, 2011) whether it is gentle push utilizing photon weight for crash evasion or evacuation utilizing beat laser removal has been researched as a promising remediation procedure (Phipps *et al*, 2012) to control the probability of collision. These strategies require the laser beam to lock onto the target object and to track the orbit very precisely. Maintaining a catalogue of tracking information is important for space situational awareness as well as the development of new strategies to improve orbit prediction accuracy.

Optical observation of space debris in low earth orbits requires sunlight with a dark-sky background. This time period is limited to one or two hours and is available only during the sunrise and sunset. However, for objects in geostationary orbits, observations can be continued through the entire night. Thus, the requirement for a dark and clear sky is a limitation on the achievable duty cycle of Earth based optical SSA sensors.

2.2 Radar Tracking of Small Orbital Objects

Orbital objects can be observed by monostatic reflector-based radar (Eastment *et al*, 2014), however the required radar size and therefore operating cost is high, while the rate at which it can provide observations (say, as observations per operating hour) is relatively low.

The United States have operated a radar based space fence, and are building a new space fence on Kwajalein Atoll (Lockheed-Martin, 2014). This appears to be an S-band phased array radar system costing of the order of $1b USD.

Space objects, namely the International Space Station (ISS) have been tracked using bistatic radar and emitters of opportunity. Tingay *et al* (2013) describe tracking of the ISS using a commercial FM broadcast station and the Murchisson wideband array. However the wavelengths of commercial FM broadcast are of order 3m, so the signature of small objects will be very small as they are deep in the Rayleigh scattering region.

Further, work has been undertaken to use GNSS signals for bistatic radar. Chow and Trinkle (2013) reported on tracking of aircraft at short ranges, and systems have been developed to monitor oceans (Gleason *et al*, 2005).

Previous work (Benson, 2014) has proposed a GNSS illuminated bi-static radar system for tracking objects in Low Earth Orbit (LEO). The rationale for this is that GNSS signals are readily available, their wavelength means that objects of a few centimeters dimension are at the very top of the Rayleigh scattering region, and the diversity of geometries provides knowledge of the object's track in all dimensions. Further, the collection system is best implemented as a massive array of elements, so the collection aperture can be shared over as many simultaneous observations as the processing can handle. This scaling is not available to telescopes, laser trackers or active radar tracking systems.

2.3 GNSS illuminated Bi-static Radar

GNSS emitters are at MEO, and the space debris of interest at LEO. The therefore most of the radio signals collected will be of forward scattered signals, where the angle of incidence and the angle of re-emission form an obtuse angle. Furthermore, most space debris is small, so at GNSS wavelengths is on the boundary between the Mie and Rayleigh scattering regions.

The Babinet principle applies to forward scatter when the object is smaller than the wavelength of illumination, including for radar (Glaser, 1985). In summary, this means that the forward scattered signal is equivalent to the diffraction pattern formed by a hole of the same silhouette as the object. The key property here is that the forward scattered signal has a known phase relationship with the incident signal, eliminating the scintillation that generally limits the coherent integration period of a radar. Obtaining long coherent integration periods is difficult, as many parameters must be controlled and there is a high processing cost, but it is possible, as evidenced by the widespread application of Synthetic Aperture Radar (SAR).

Given the predictable phase of the scattering from the small orbital object, and the very small dynamic disturbance forces on both the illuminator and the object to be tracked, there is an opportunity for very long periods of coherent integration. However integration over very long periods is subject to resolving a range of technical difficulties, which include: correction for ionospheric and tropospheric delays, correction for receiver clock instability, availability of sufficient computational capacity and algorithms to search an adequate uncertainty volume, and provision of a collection aperture of sufficient area.

The signal power density at the Earth due to scattering of GNSS signals from small objects is very low. This is because the already low energy density in the GNSS signal arriving at the debris is then made weaker by the small radar cross section (which will be less than unity), and finally experiences a very large spreading loss over the path from the debris to the ground based receiver, which is of the order of 1000km. The expected signal levels require a collection array with tens of thousands to millions of elements (Benson, 2014). In spite of the potentially low cost of each receiver element the cost of such an array is likely to exceed $10 m. Investments of this scale should not be made without demonstration of the key behaviors to mitigate risk. In particular these are: Demonstration that GNSS signals arriving through the ionosphere and troposphere are stable enough in phase to integrate blindly, scattering from space debris is approximated by the Babinet principle – having consistent phase and sufficient radar cross section, signals can be collected and processed in an efficient manner, and that the acquisition and operating costs of such a system are tolerable.

This paper addresses the phase stability of the illumination signal as received at the Earth. For the bi-static radar application the emitter phase stability is not critical, since we are interested only in the time delay and rate of time delay change (Doppler) of the scattered signal relative to the illuminator. However variations in the signal propagation time through the ionosphere and troposphere are important, because it will be necessary to calibrate for them in a practical system. The key behavior is therefore the stability of the perceived delay over an integration time of the order of tens of seconds to minutes.

Furthermore, for engineering a practical system it is also convenient if the illuminator and receiver have excellent timing stability, since this relieves the receiver processing system of an additional adjustment parameter.

The primary question addressed herein is “Does a GNSS signal collected by a large aperture receiver at the surface of the Earth display consistent and low-noise phase behavior?” An answer in the affirmative indicates that ionospheric and tropospheric delays are likely to be relatively stationary at both the micro and macro levels. Hence, with sufficient effort, they can be calibrated out under typical conditions, not only on average (on the macro), but also at the cycle-by-cycle (micro) level. A secondary question “Is the receiver clock stable at the micro level relative to the arriving signal?” addresses the issue of timing stability to ascertain whether the receiver cock jitter relative to the arrival signals is sufficiently small to be left un-calibrated in a physical implementation.

This primary question differs in detail from evidence derived from the operation of, say, RTK survey systems because we expect to operate in such a low-SNR regime for the reflected signals that no tracking loop feedback is possible during the whole observation, being a time period that totals many minutes.

The method used is to observe the GNSS signal directly form the satellite with a radio telescope. GNSS satellites have been observed this way before (Pini and Akos, 2008), but the intent and reporting of that test was of the signal fidelity rather than an analysis of medium-term stability as we report here.

3. EXPERIMENT CONDUCT

3.1 Data Collection

With assistance from CSIRO (Peters, 2014) direct arrival GPS L1 signals from a Block IIF GPS satellite were collected via the VLBI ASKAP radio telescope. Although ASAKP is an array, only a single dish is configured for direct recording of the down-converted signal to support VLBI. The radio telescope dish was commanded to track the expected trajectory of satellite based on a current Two Line Element (TLE) obtained from space-track.org. We assume that tracking error is negligible. The Gain on Temperature (G/T) of the system is high, but signal quality is quantisation limited to 2 bits because the hardware is designed to be used for radio astronomy interferometry.

Several recordings were made each of one minute duration. The recordings were stored as VDIF files at 2 bits per sample, 128Msps after downshifting and Nyquist filtering. From these recordings the correct receiver polarisation was selected based on viewing the SNR of each polarisation. An averaged spectral power density plot is shown in figure 1. From this image we confirm that the signal is indeed a block IIF satellite and that the Intermediate Frequency (IF) is approximately 32.42 MHz, before Doppler correction.

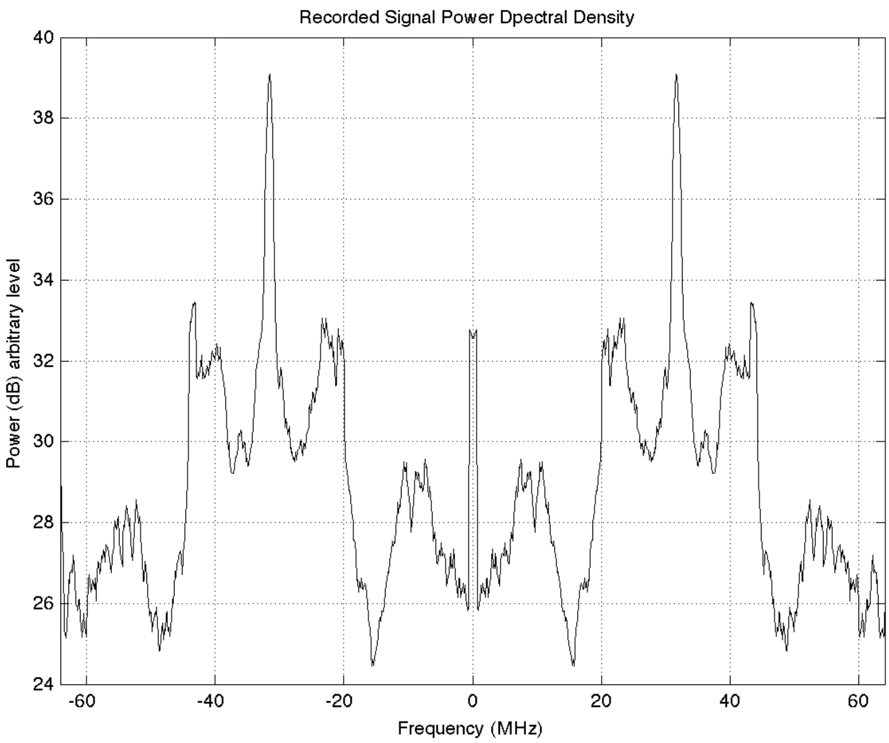

Figure 1. Spectral Power Density of recorded signal

3.2 Data Processing

The next stage of processing is a Costas loop with wide tracking loop bandwidth. The Costas loop can be implemented before spread spectrum processing because the GNSS spread spectrum signal appears as a BPSK communication signal since the signal is well above the noise floor. We track the C/A code by implementing a low pass filter of just over 1MHz on the I and Q signals, and force the orthogonal signal (Y-code) to average zero. This works because the Y-code rate is 10 times higher than C/A-code, and averages zero. Thus the average feedback into the Costa's loop approximates tracking the C/A spreading code in the presence of white noise on the orthogonal channel. Likewise, although the block IIF satellite has M-code on the same carrier as C/A, the BOC(10,5) spreading of M-code causes it to have minimal effect on C/A-code tracking. Which is to say the majority of the M-code signal power is rejected by the low pass filter. The result is plotted as figure 2.

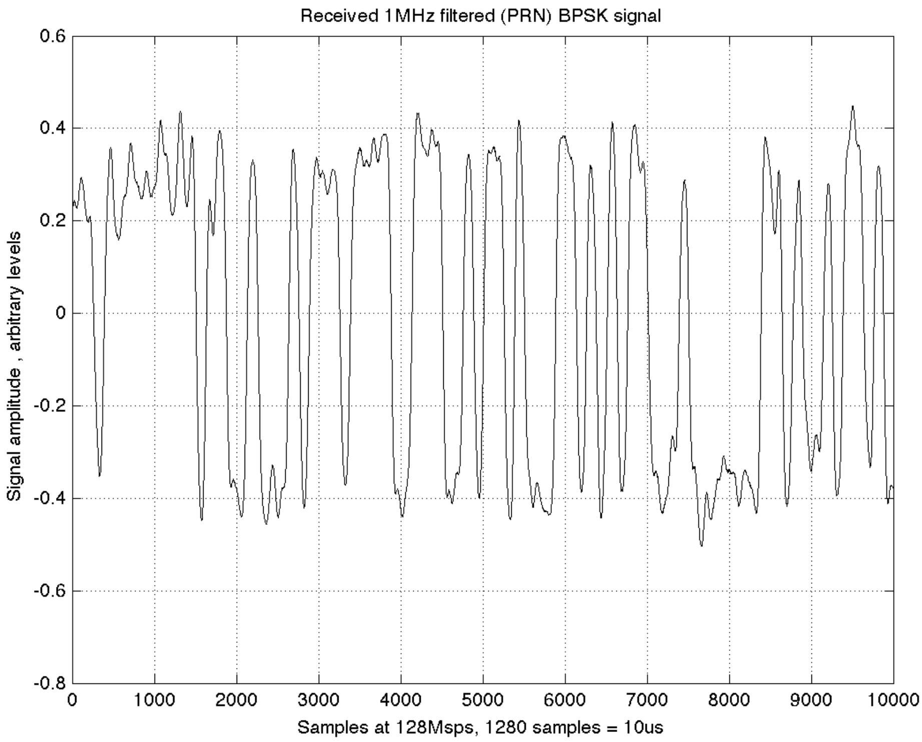

Figure 2. C/A spreading code appearing as BPSK

By visual reference to figure 2 we confirm that we are decoding C/A code into the Pseudo-Random Noise (PRN) sequence that was used to create the spread spectrum C/A-code signal. A cross-correlation of the received 1.023Mcps BPSK signal against the satellite PRN is shown in figure 3. Again confirming that the signal is being correctly detected and the Doppler shift tracked by the Costa's loop, as the correlations are of amplitude 1023 and occur at a rate of 1 every 1023 code samples.

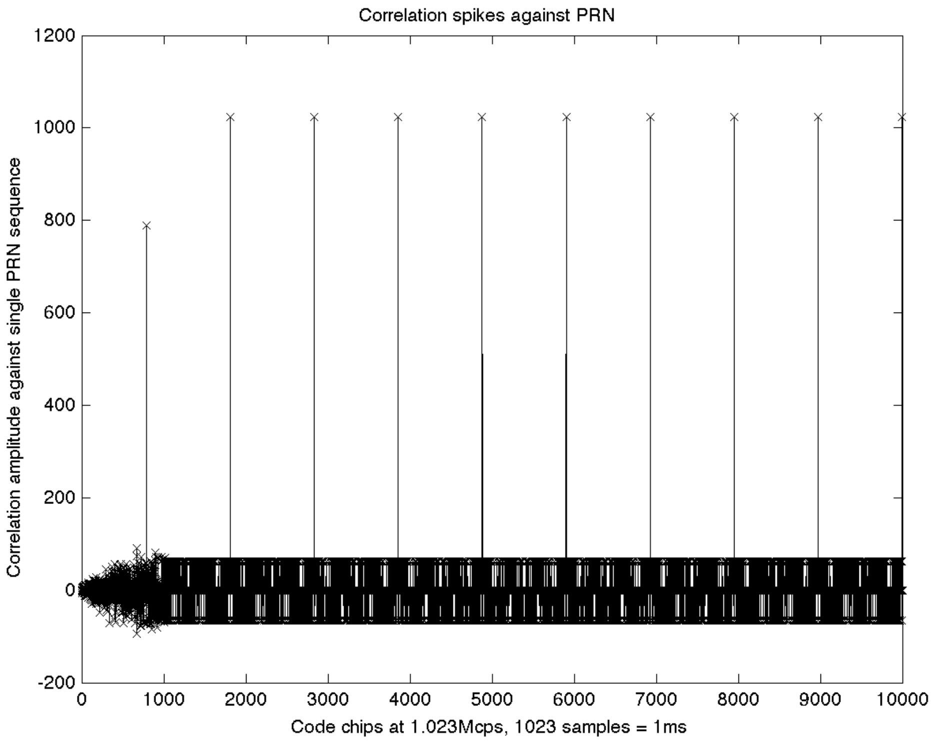

Figure 3. C/A code correlation spikes

Finally, the 50bps data on the GPS signal is observed as a potential reversal of phase every 20 PRN cycles. This data signal is shown in figure 4.

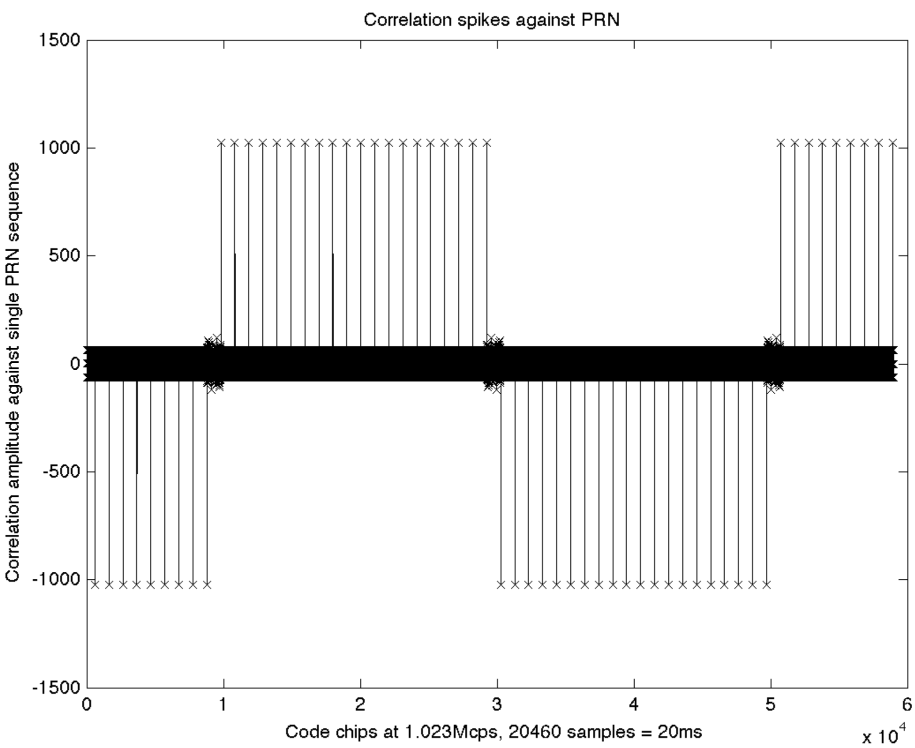

Figure 4. 50 bps data as an optional phase reversal each 20 C/A-code periods

These measurements provide confidence that the signal being tracked is correct, and that the tracking loop is operating reliably. We now address the primary question to be answered in this work, "Does a GNSS signal collected by a large aperture receiver at the surface of the Earth display consistent and low-noise phase behavior?"

3.3 Phase Stability Analysis

The accumulated phase in the Costa's loop was recorded every 10,000 samples resulting in 12,800 recordings of accumulated phase per second. These were stored as 64-bit integers with resolution of 1024th of a cycle, or approximately 0.35 degrees. Any effects from phase instability and tracking noise are very small relative to the accumulated phase. The rate of change in phase rate (rate of change in apparent signal frequency) can be seen clearly only after removing the average frequency and plotting the remaining phase against time.

The processing windows used are just over 10 seconds in duration to allow load sharing of the extremely computational intensive tracking – especially in Matlab. Figure 5 shows the result for a 10 second processing window, and figure 6 (a) and (b) show the same plot for two other 10 second processing windows. All other examined signal processing windows produced similar results.

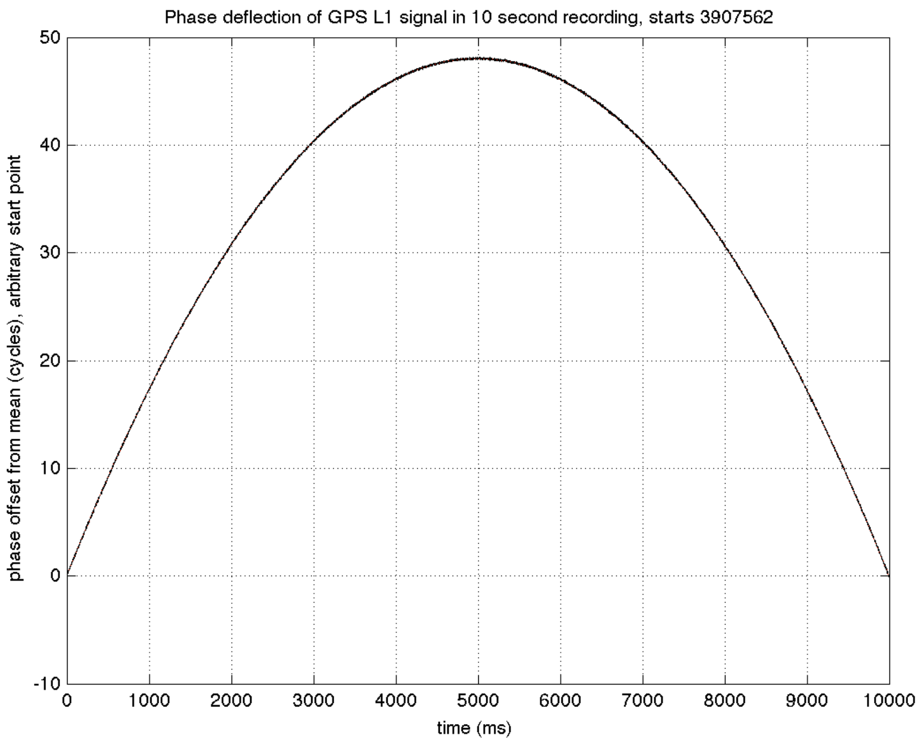

Figure 5. Phase variation in 10 second processing window

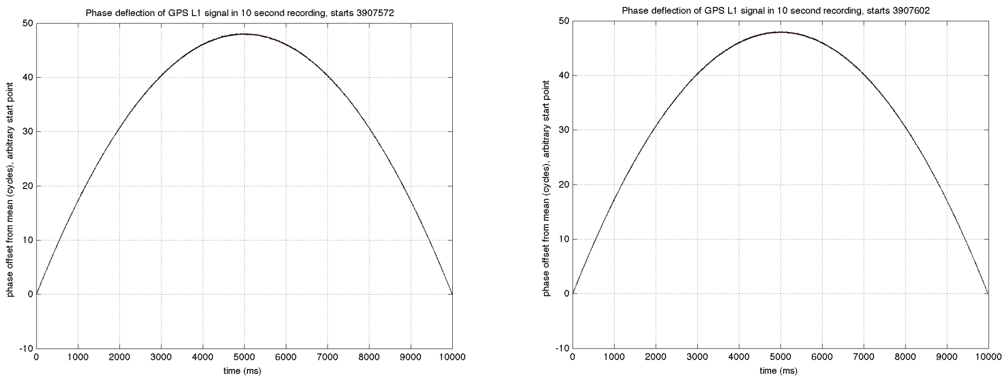

Figure 6(a) and (b). Phase variation in two other 10 second processing windows

Noting that the phase variation is approximately parabolic, a second order curve was fitted by minimizing mean squared error. This fitted curve is shown on each plot in as a dashed line but is impossible to see in figures 5 and 6 because it very closely matches the observed phase in the recordings. The RMS error of the phase of the Costas tracking loop to this fitted curve is between 17.18 and 17.69 degrees for all tested processing windows as shown in table 1. The actual rate of change in Doppler is not necessarily a second order function, but the phase error is dominated by the irregular variations in the phase of the Costas tracking loop as shown by the expanded view in figure 7. It is not yet clear whether these variations reflect phase variations in the arriving signal, or tracking noise in the Costas loop due to selection of a very broad loop bandwidth and an assumption that the orthogonal Y-code signal appears as white noise.

Sample Tag	Calculated RMS Phase Error (deg)	Observation Duration (sec)
3907552	17.53	7.5
3907562	17.69	10
3907572	17.50	10
3907582	17.18	5
3907602	17.46	10

Table 1. Phase Error Between Tracked Signal and Fitted Curve

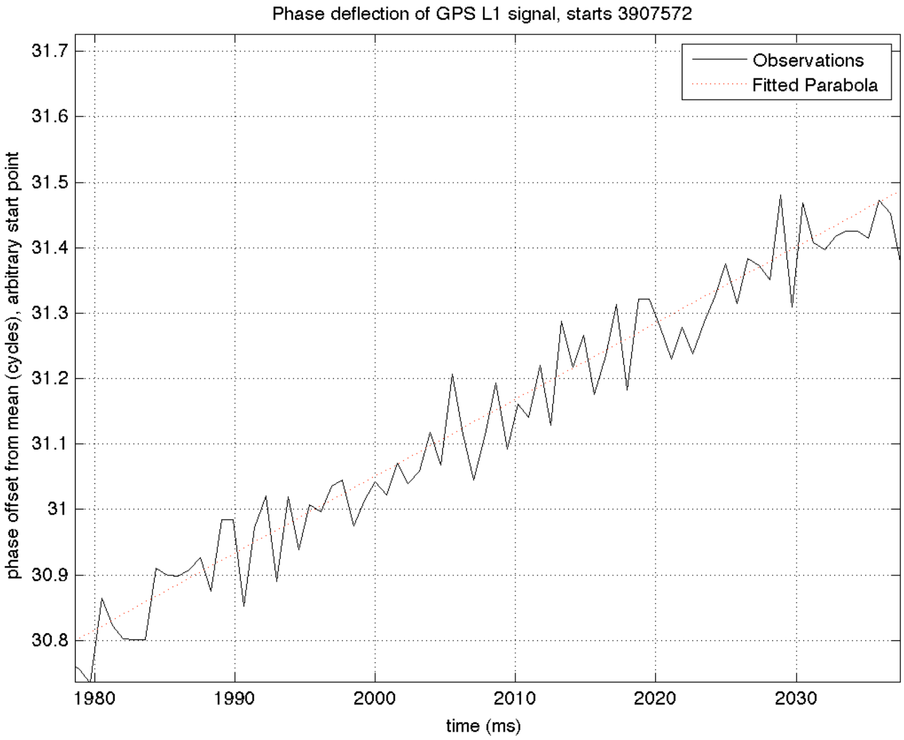

Figure 7. Typical detail of observed phase variation

A demonstrated RMS phase error of less than 18 degrees on an actual L1 GPS signal arriving through the atmosphere over a long duration to a large capture area collector provides a strong indication that arriving GNSS signals will be well behaved at the micro level, allowing long duration integration with a strong probability that the integration loss due to phase errors can be kept low. This work therefore indicates that a GNSS signal collected by a large aperture receiver at the surface of the Earth does display consistent and low-noise phase behavior. In addition, we have also seen that the clock at the receiver was sufficiently stable that the GNSS signal could be directly observed with a sampling clock derived at the receiver. There is no need to correct the sampling rate for jitter in the receiver clock in order to maintain a smooth phase response over a period of many seconds. We note for the benefit of the reader that the time and frequency standard used for this experiment was a Hydrogen Maser.

The three obvious concerns remaining about the phase stability of the scattered signal are: whether the forward scattering from objects smaller than the wavelength does display predictable phase; whether the higher angular velocity of the objects to be tracked changes the phase stability through cutting more rapidly through different ionospheric regions; and finally how typical are the conditions under which the measurements were taken.

4. CONCLUSIONS AND FUTURE WORK

In this work we have reported on a typical received GNSS signal that does have very low non-uniform phase variation over a period of many seconds. This indicates that the radio channel from the satellite to the Earth based receiver is sufficiently stationary that correction for channel delays due to signal refraction along it's path should be possible, even for an indirect path via an orbiting object. Further we found that there was no need to adjust for short-term variations in the receiver clock.

Future work toward fully understanding the requirements for passive radar based SSA should now turn to (i) demonstration of long-duration blind integration of GNSS signals, which include appropriate orbit and refraction predictions (ii) extended observations to confirm the likelihood of the benign propagation conditions observed herein, and (iii) development of GNSS receiver arrays to demonstrate fabrication and processing techniques.

ACKNOWLEDGEMENTS

The authors thank Dr Chris Phillips and CSIRO Australia for making the recordings used in this work.

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