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Efficient Processing of Long Duration GNSS Signal Observations for Space Debris Tracking

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ABSTRACT

Space debris poses an increasing threat to space assets, and accurate, affordable tracking of all space objects is necessary to maintain efficient and safe space operations. Tracking space objects of very small sizes using GNSS bistatic radar has been proposed as a potential solution. Previous research efforts have discussed various aspects of the signal processing required for debris tracking including signal phase stability, viability of the signal power budget and the ability to isolate the weak reflected signal in the presence of the much stronger direct signal. A key difficulty of the tracking operation is that the object track is accurate to the order of a wavelength over the entire observation period (ten minutes). The computational cost of performing a large number of very long correlations has been partially addressed by previous works that show how the signal sampling rate can be reduced subject to the Nyquist limit of the largest possible Doppler uncertainty. This work confirms that the computational cost can be reduced further by exploiting the non-uniform distribution of the Doppler residual over time. Over most of the observation time, the phase rate of the residual frequency is very low whereas the region where it is high is known in advance. The confirmation first considers the basis for reduction of the signal sampling rates to near the Nyquist limit set by the maximum possible Doppler but then exploits the knowledge of the non-constant distribution of Doppler over the observation time to reduce the number of calculations per integration by more than an order of magnitude. Results are confirmed by simulation of a realistic scenario. Finally, the trade between losses and reduction in sampling rate is examined, including plots of integration loss versus sample rate reduction, and applications of the same principle to other GNSS processing challenges are discussed.

KEYWORDS: Space Debris, GNSS, Weak Signal, Long Integration, Audio Processing.

1. INTRODUCTION

Low Earth Orbit (LEO) space debris is an increasing threat to active satellites and spacecraft. An accurate and affordable tracking method for identifying the location and possible collisions of LEO debris with active space assets is required to prevent satellite loss as well as the growth of space debris. A population of more than 400,000 items space debris in the size range from 1 to 10 cm has been estimated in LEO (Orbital Debris Program, 2014). These large numbers of objects are a hazard to operational satellites and other space assets. Moreover, with the current rate of space operations the population will only increase in the future. Research shows that if no mitigation plan is taken in near future the current number will be doubled in 100 years and even with a mitigation plan, the same number can be reached in next 200 years (Wormnes et. al., 2013). Most of this debris is untracked by existing tracking facilities. A database of space debris larger than 10 cm is maintained by the United States Space Surveillance Network (SSN). The capability is limited to detection and tracking at debris larger than five cm in LEO (Sridharan and Pensa, 1998). Objects smaller than five cm can be detected by the ground-based radar systems but such systems are not necessarily scalable to the larger populations of small objects. Further smaller objects can be observed only by examining the impact of returned objects from orbits. LEO objects such as International Space Station (ISS) has been tracked using a FM broadcast station along with Murchison wideband array; however, Radar Cross Section (RCS) for small objects, say 10cm, will be very low as the wavelengths of such broadcast station is of order 3m (Tingay et al, 2013).

With the existing space surveillance techniques the prediction of the trajectories is relatively poor. As a result, there is demand for a more accurate and cost effective solution to avoid unnecessary cost associated with manoeuvre or other protecting measures. Global Navigation Satellite System (GNSS) has been proposed as an alternative solution in detecting LEO debris with precision (Benson, 2014). However, one of the major challenges identified is to accumulate sufficient energy to detect the signal in presence of other strong interferences. For an extended period of integration up to 10ms, the wavelet de-noising method together with differential coherent integration (DFC) has achieved an extra 2dB gain in compare to traditional DFC method. Clearly, handling the processing to gather such level of energy is another challenge. In this paper, we discuss and present simulated results of the possible ways of detecting debris-scattered weak signal at an affordable processing cost.

2. DETECTION OF SPACE DEBRIS WITH GNSS BISTATIC RADAR

2.1 What is GNSS Bistatic Radar?

Apart from navigation and standard positioning, GNSS has a wide range of applications and radar is considered as one of the potential applications in detecting space debris in LEO. GNSS satellites are flying in Medium Earth Orbit (MEO) at an altitude of about 20,200 km. Signals transmitted from MEO are refracted by the objects in LEO. Thus 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. Fig. 1 illustrates the concept of bistatic capabilities of GNSS satellites to detect LEO debris. It shows the two version of the GNSS signal. First, the direct GNSS signal arrives at the receiver without any major reflection. Second, the debris-scattered version of the same signal arrives with a delay and different features such as Doppler frequency. Most of the space debris is smaller than GNSS wavelengths (20cm) and thus falls into Rayleigh scattering region. The Babinet principle applies to forward scatter when the object is smaller than the wavelength of illumination, including for radar (Glaser, 1985). In later sections, we discuss the differences of these two signals and available technology as well as improvement needed to accumulate the signals.

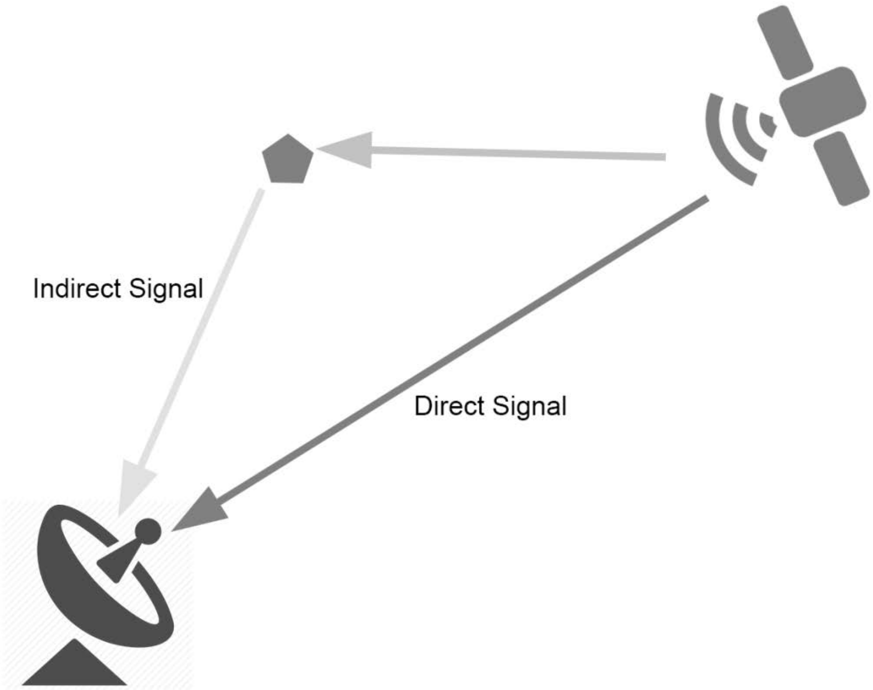

Figure 1: Illustration of direct and debris-scattered signal concept

2.2 Extremely Low Power of Desired Signals

Due to the large distance between the transmitter and receiver, there are substantial path losses in GNSS signals. The loss incurred by the direct arrival GNSS signal would be as much as 160dB (Benson, 2014). The signal power at the Earth from the scattered GNSS signals from small debris is perhaps 170dB lower. Detection of GNSS signals involves a correlation operation over a block of the incoming GNSS signal after down-converting it to an intermediate level. In general, 1ms is sufficient to detect the correlation peak in strong arrivals. However, for weak signals the integration period must be extended to improve the signal energy at the correlator. Two major problems arise in integrating signals for extended periods. Firstly, due to the long integration the processing burden per observation grows proportionally to its length. Furthermore, the resolution of the observation also grows proportionally to its duration. Therefore, for a given level of uncertainty in the track the processing cost grows exponentially with integration period. Secondly, long integration of GNSS signals is limited by data bit transitions. Each GNSS data bit contains twenty 1ms code epochs and if an integration period includes one of these edges, the integration gain can be lost. One way to overcome this problem is to strip the data bits from the incoming signal and integrate the carrier-only signal. In the case of LEO debris, the scattered signal will be delayed due to the indirect path. Meanwhile, the direct arrival signal provides prior knowledge of the data bits as well as clock offsets and the like. This information can be used to strip the data bits from the desired signal, thus bit transition effect can be neutralized.

2.3 Strong Direct GNSS Counter Signals

Weak spread spectrum signals at a receiver often face the near-far problem where cross-correlation artefacts from the strong (near) signals are more powerful than the correlation of the weak (far) signals. In the case of space debris in Low Earth Orbit, the desired signal has a very large and variable Doppler shift associated with it which makes it distinguishable among the interfering signals. As GNSS satellites are orbiting at an average altitude of 20,200 km from the Earth's surface while LEO debris is at a height of range from 400km to 2000km, their Doppler frequencies are different. As an example we found, the maximum Doppler for a GNSS direct signal is around ±5 kHz, whereas for the debris-scattered GNSS signal it is ±37 kHz (Mahmud, Qaisar and Benson, 2016). Fig.2 shows an illustration of the case where the difference in frequency range and rate of change for two signals are clear. In normal GNSS and CDMA communication, longer correlation doesn't recover the weak signal since the code periods and almost constant Doppler shift cause the same cross-correlation artefacts to repeat throughout the integration period.

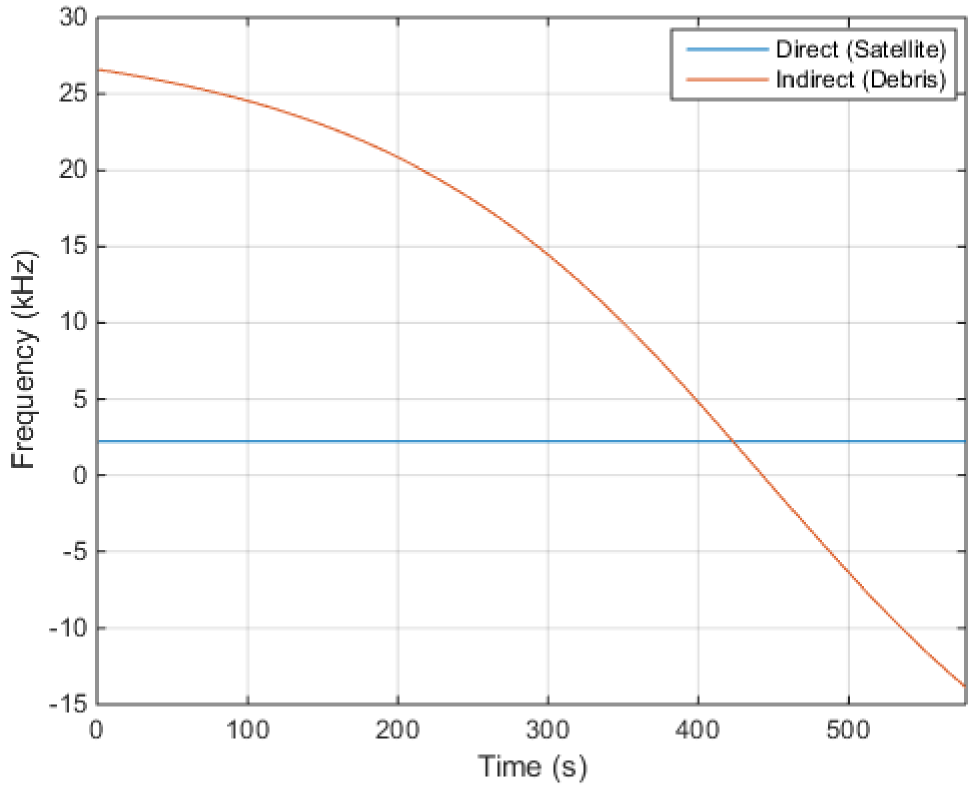

Figure 2: Doppler Frequency for Direct and Debris-Scattered GNSS Signals (Mahmud, Qaisar and Benson, 2016)

Over the observation period of nearly 10 minutes, the Doppler shift for the direct satellite signal remains almost constant, however, for the debris scattered signal, it changes from 27kHz to -14kHz. This relatively large range of Doppler shift occurs with a very short period, hence, the rate of change in Doppler over time is also high and non-constant. That means, if the desired Doppler frequency is followed during the correlation at receiver, it will cause a continuously varying phase offset with other interfering signals. Extension of a theoretical analysis of a standard GNSS correlator (Mahmud, Qaisar and Benson, 2016) has been shown in figure 3 illustrating that the cross correlation over the integration period is a function of relative Doppler offsets assuming that the received signal contains only the carrier and Doppler.

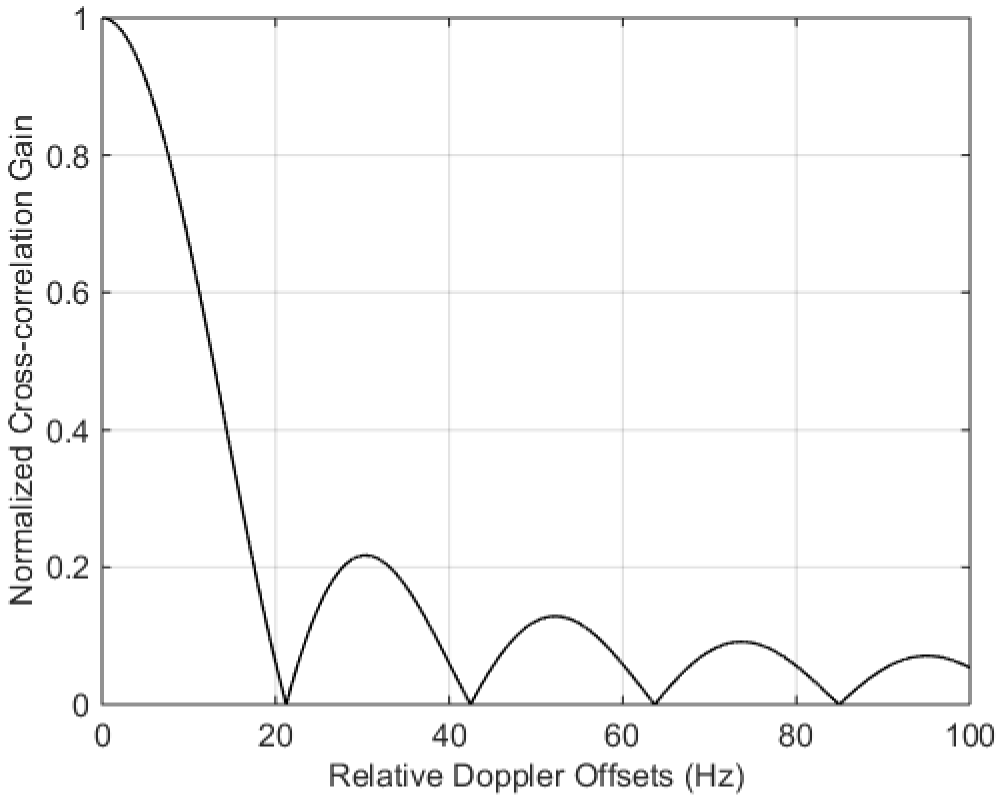

Figure 3: Cross-correlation response with Constant Frequency Offset (Mahmud, Qaisar and Benson, 2016)

2.4 Signal Observation over Extended Duration

Successful detection of the weak signal requires sufficient energy accumulation, which can be obtained by correlating over a time *T*. The minimum data length suggested for GNSS signal acquisition is 1 ms. The longer the correlation duration the greater is the processing cost. Longer duration correlation improves the signal to noise ratio, which is necessary in weak signal environments. The duration of *T* must be extended to the order of minutes to accumulate sufficient energy to detect the desired debris-scattered weak signal. In order to achieve a coherent integration gain, it is necessary to generate a phase stable local replica or in other words, a local replica that constantly matches the phase of the received signal.

As discussed earlier, correlating over T (more than 10 ms) is strictly limited by the navigation data bit. However, in this case we use a recorded data to detect the debris-scattered signal. We use this data to extract the navigation message and then take this information to next phase in detecting the weak signal. Thus, we can extend the integration period on order of minutes without losing correlation gain due to navigation data transitions. Moreover, from figure 4 and 5 it is readily apparent that over this long integration period the debris signal has a large range of Doppler frequency with relatively fast change rate. On the other hand, the direct signal has a Doppler which is almost constant. During the correlation, the local replica matches the debris signal and will continue to achieve gain whereas the direct signal will have only a random match over the whole integration. So the processing gain of the direct signal in the replica debris filter should approach that of a random signal.

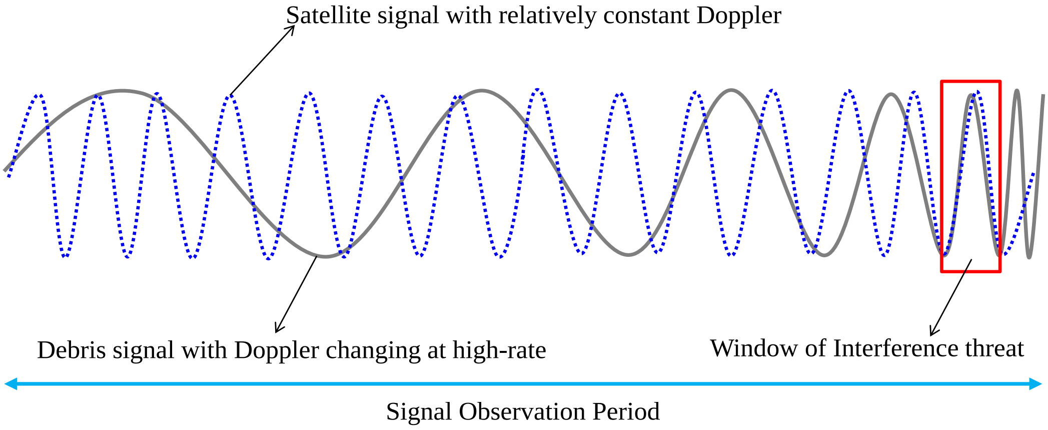

Figure 4: Direct Signal has a Constant Doppler; Indirect (Debris) Signal has a Fast Changing Doppler

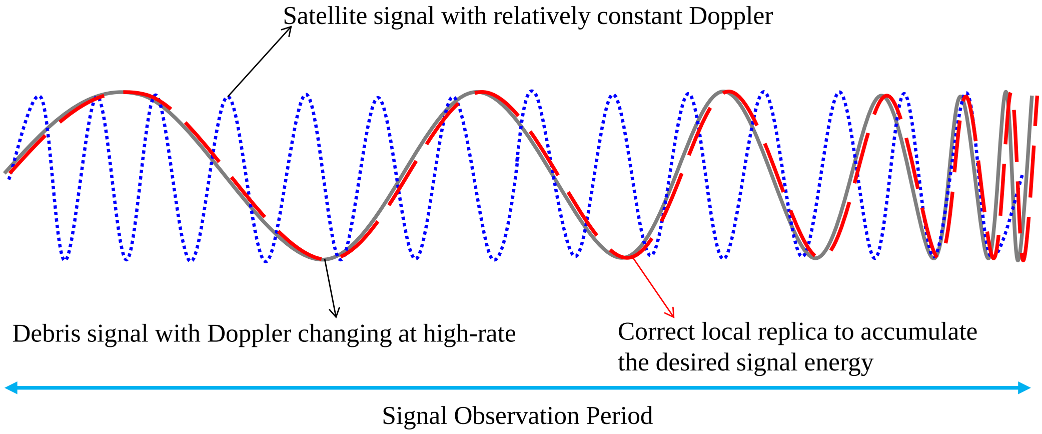

Figure 5: Local Replica Correlates with Debris Signal, Creates Random offset with Direct Signal

3. AFFORDABLE PROCESSING AT AUDIO FREQUENCY

Regardless of the fact that the weak signal can be detected in the presence of strong direct arrival GNSS signals, receiving and integrating such a weak signal is still a challenge. Considering the minimal Nyquist sampling rate for the spread spectrum signal, the calculation for each hypothesis trajectory may take as much as 1.2×10^9 Multiply and Accumulate (MAC) operations for an object visible for approximately 10 minutes in LEO (Mahmud, Qaisar and Benson, 2016). To handle this huge computational cost without compromising the integration gain a two stage processing can be used. The idea is to process the direct signal first to get the information required to generate the complex local replicas as hypothesis trials. Such a hypothesis is a replica of the anticipated scattered signal with carrier, Doppler, spreading code and data bits. This replica may also include estimates of ionospheric and tropospheric effects or clock offsets but these are optional. The complex replica is correlated with the incoming signal for small steps of, say 0.1 ms. The outcome of this complex Integration and Dump (I&D) is the difference in phase between the two signals. Over time the phase of the I&D result will change, representing the beat (difference) frequency between the replica and the actual scattered signal. Under reasonable assumptions this will be no more than an audio frequency (some kHz) and the correction or post-correlation operation can be performed in such a low sample rate. This integration is not sufficient to detect the desired weak signal. The next step is to add all those small integration results to accumulate sufficient gain after phase error resolved. Implementing this method the required MAC's per trajectory drops to 6×10^6, which is 200 times lower computational cost. In the next section, we describe the nonlinear shape of the frequency difference and hence possible improvements in the integration method that further reduce the computational cost.

4. NON-LINEAR ERROR SOLVING APPROACH

With knowledge of ephemeris and almanac data sources, it is possible to predict the trajectory path of the LEO debris with reasonable accuracy. However, with the prediction very small errors result in small along track errors that grow with each orbit period. Hence we use an along track error of 1 ms, or approximately 7 m as a case study. Figure 6 represents this case and is magnified to clearly show the difference in delay and frequency. The debris is only 7 m from the anticipated location, so the effect on GPS C/A chip period (293 m) is ignored; however, the effect at the order of wavelengths (20 cm) is not small and will be considered here.

As discussed in section 3.1, correlating the local replica with the incoming signal generates the frequency difference between the two signals. Using the almanac data sources we conduct a simulation with the predicted debris trajectory. We simulate a trajectory path of an object in the LEO at an altitude of 1000 km. we consider it as the debris and generate a signal that is equivalent to the scattered GNSS signal. Then we generate another signal following the same trajectory path but with 1ms (7m) lag. Figure 6 shows a magnified version of the residual frequency of the two signals. We limit it within the residual frequency because that is the only unknown parameter in this regard. The difference between the two signals is shown in Figure 7.

It is clear from the figure 7 that the difference is non-linear over the observation time. The I&D duration, which directly drives the cost of processing each trajectory hypotheses, is limited by the accumulated phase error between the replica and the actual signal during the I&D operation. A low Doppler allows for a long I&D duration, whereas a high Doppler necessitates a shorter I&D period since a phase offset will accumulate more quickly. Therefore, instead of using a constant integration period for the I&D operation, we now use the advantage of the non-uniform pattern in frequency difference.

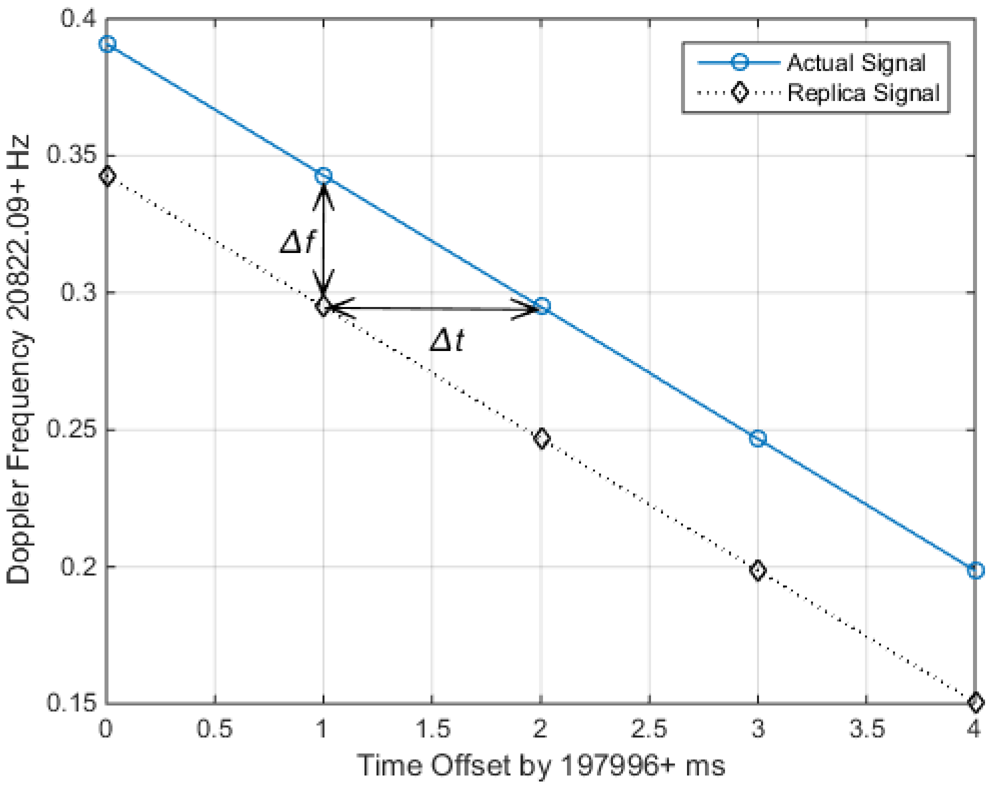

Figure 6: Doppler Frequency of the Actual and Replica Signal

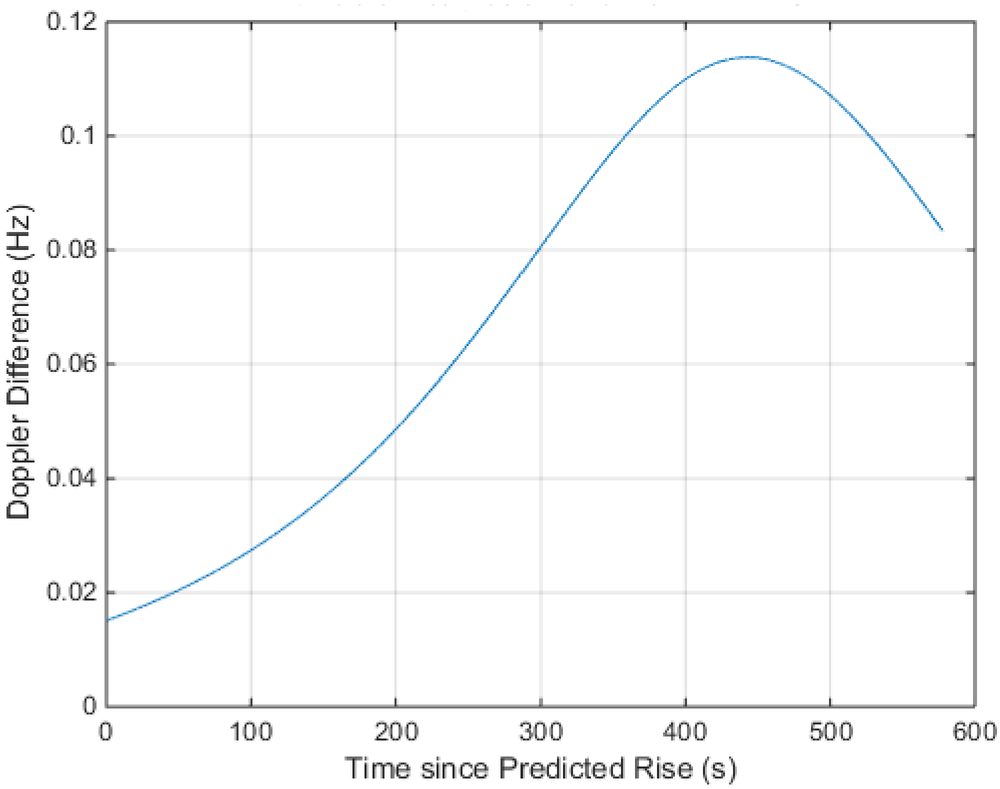

Figure 7: Doppler Frequency Difference between the Actual and Replica Signal

Previously, we selected an integration period (0.1ms) as short as necessary to keep integration losses acceptably small. With the new concept, the idea is to keep each integration as long as possible subject to a tolerable phase drift within the integration period. The selection of the integration period is therefore based on the area under the frequency difference curve shown in figure 7. For any two points in this curve, the area under that part is the Accumulated Phase Shift (APS) φ where,

$$\varphi = \int_0^{\Delta t} f(t).dt \tag{1}$$

Δt is the time interval after which, two signals initially synchronized in phase but differ in frequency Δf, create a total phase difference $\Delta\varphi$. Figure 8 shows the concept of variable integration period based on APS. Selection of threshold here is crucial as integration loss during this I&D step is irrecoverable in next. An APS of 0.5 cycles is used to generate the following figure 8.

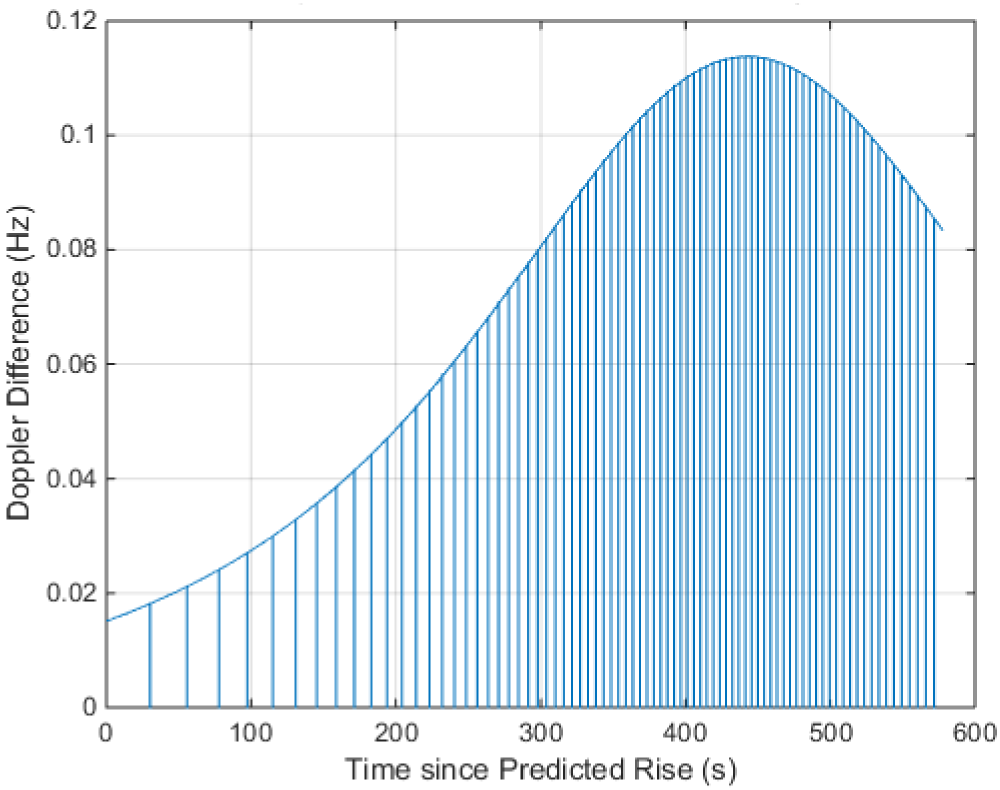

Figure 8: Variable Integration Length over the Nonlinear Differences, Each Area Represents 0.5 Cycles Accumulated

Allowing a larger shift in accumulated phase may bring integration loss which can ruin the ultimate gain to detect the desired signal. In this simulation, accumulated phase shifts equivalent up to 0.5 cycles are conducted to investigate the integration loss. Figure 9 shows that for a cycle offset of 0.5 the loss incurred is around 4 dB which is at or below the acceptable limit assuming an ideal condition includes absence of atmospheric effect and perfect stripping of spreading code and data bits. Much lower losses are possible by selecting a lower value for φ.

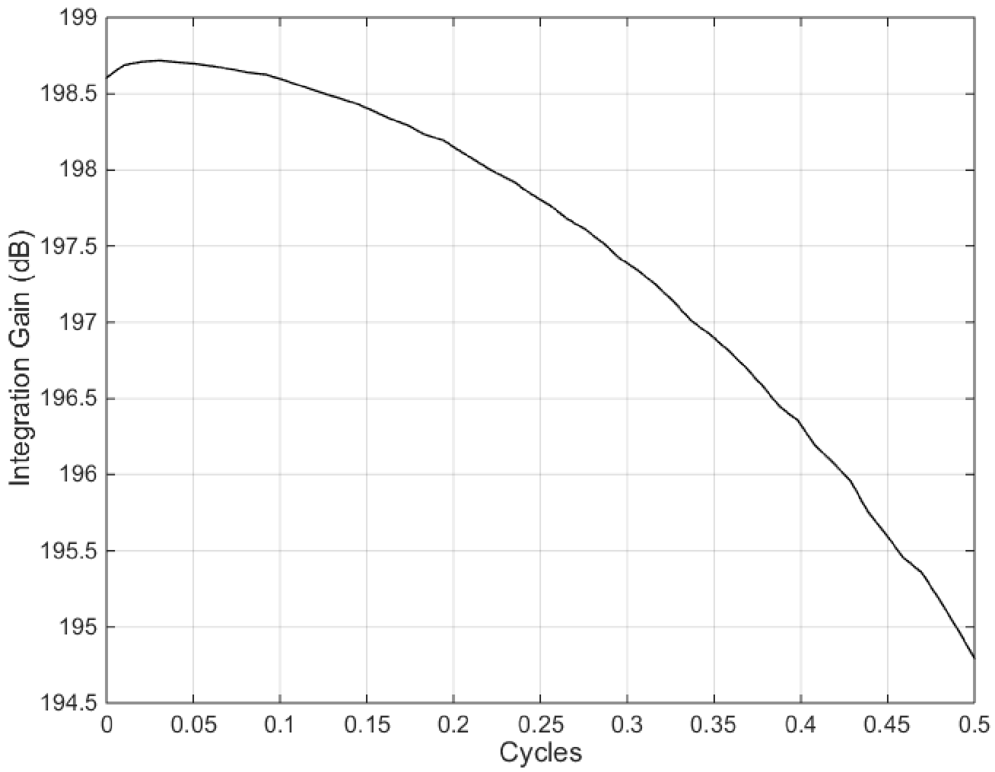

Figure 9: Integration Gain in dB Corresponding to Cycle Offsets

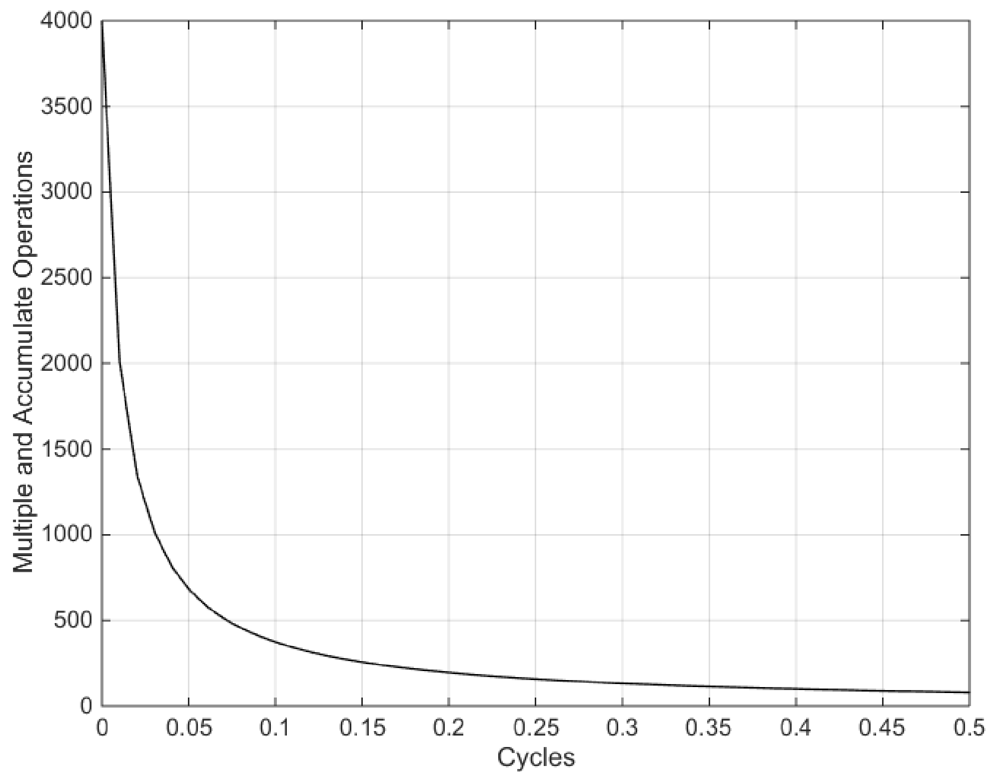

Figure 10: Computational Cost involved vs Allowed Phase Offset

The advantage of varying the effective audio sampling period is to lower the processing burden in further steps. Figure 10 shows the relation between the cycle offsets and corresponding calculations involved. Combining figure 9 and 10 it is apparent that with integration loss of 4 dB computational costs can be reduced to 80 MAC operations only. This illustrates the effectiveness of the approach proposed following the nonlinear frequency difference between the local replica and the incoming signal for phase error correction. The next step would be correcting the error by rotating the phase of the difference using some higher order equations but at a sampling rate at the kilohertz level.

The example using a 1ms along track (7 m) offset between the local replica and the anticipated signal is based on the fact that estimating a replica of that order is possible. However, the number of phase adjustments required increases approximately linearly with the offset between the replica and actual signal, as shown in figure 11. Therefore the computational cost of each tested hyopthesis grows approximately linearly with offset from the replica, with an overall cost that grows exponentially with offset. Efficient techniques to reduce the computational cost order *NlogN* suggest themselves.

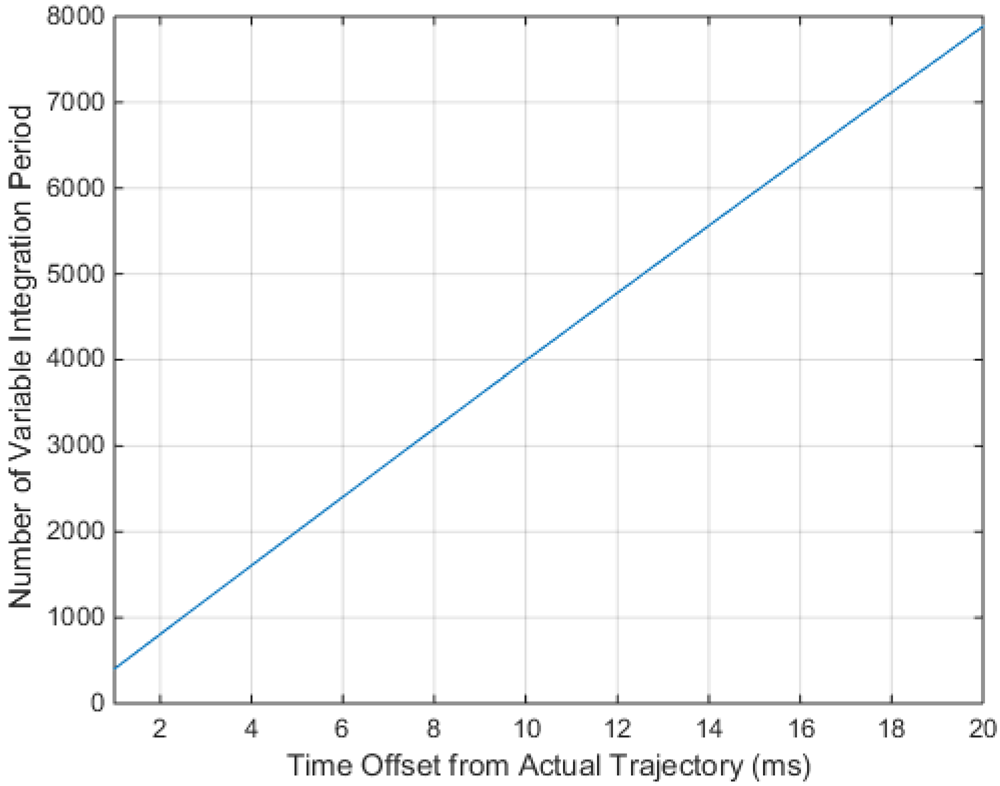

Figure 11: Linear Growth of Integration points with Time Offset as Predicted

3. CONCLUSIONS

The growing population of space debris is a major concern and increasingly accurate and affordable tracking is an ongoing demand. To enhance the existing tracking facilities, bistatic radar using GNSS satellites has been proposed to detect Low Earth Orbit debris. In this work the challenges involved in performing signal correlation over extended durations on the order of minutes have been discussed. It has been shown that via the proposed variable integration period technique the computational cost can be reduced to an affordable level without sacrificing any significant integration gain. Moreover, the nonlinear difference between phases during correlation provides scope for even better results in terms of the trade between computational complexity and integration loss.

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