Tracking Low Earth Orbit Small Debris with GPS Satellites as Bistatic Radar

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ABSTRACT

Space debris is a growing problem and collisions are potentially lethal to satellites. Trajectories for small objects are predicted based on infrequent measurements, and the scale and therefore cost of maneuver required to avoid collisions is a function of trajectory accuracy. Frequent and precise observations will improve trajectory accuracy. In this paper, we extend on aspects of the feasibility of tracking space debris in Low Earth Orbit using emissions from GNSS satellites as bistatic radar illuminators. The wavelengths of GNSS signals are of order 20 cm and our primary focus is to track debris smaller than this, thereby maintaining phase stability of the scattered signals, enabling very long coherent processing intervals. However, the signals scattered by debris will be very weak at a terrestrial receiver, requiring the computationally expensive integration of a large number of signals, over an extended duration and with a large phased array. Detection of such weak signals in the presence of relatively strong direct-arrival signals requires extremely high cross-correlation protection. We show that sufficient cross-correlation protection can be obtained due to the large and varying Doppler shift, and also illustrate a novel processing approach utilizing downshifting of the collected signal to audio frequency. This technique dramatically reduces the cost and complexity of updating debris trajectories. The processing cost of preserving an uncertainty volume of many hundreds of meters around the predicted debris track is very modest, and searching within that uncertainty volume is undertaken at audio sampling rates. Moreover, we explore techniques that further lower the already modest cost of the non-linear search within the preserved uncertainty volume. We conclude with an outline of a system using these techniques that could provide centimetre level tracking of large quantities of small orbital objects at a modest cost.

1. INTRODUCTION

Space debris is an existing and growing problem for active satellites and future space missions. Research shows that out of nearly 5000 satellites sent into Earth orbits only about 1000 are active today [1]. This large quantity of inactive satellites and numerous related objects increases the probability of collision, and any collisioncreates more debris in Earth orbit. Moreover, the current rate of space operations means that the number of orbital objects will increase dramatically in future. If no mitigation plan is taken in near future the current number of orbital objects will double in 100 years. Even with a mitigation plan, the same number can be reached in next 200 years [1]. Debris as small as 10 cm is tracked and catalogued in Low Earth Orbit (LEO) whereas in geostationary orbit (GEO) the size of tracked objects is of 30 cm to 1 meter. It has been reported that there are nearly 700,000 items of LEO debris with a size larger than 1 cm [1]. It is a matter of great concern that collisions may be the main source for new debris, accelerating the rate of debris production and driving the space environment into a state with unacceptable risk for future operations.

Several methods have been proposed to track and study space debris during last two decades. Single-range Doppler interferometry (SRDI), proposed by Sato, extends the concept of range-Doppler interferometry (RDI) of using the Doppler spreading to obtain the two-dimensional (2D) shape of space debris [2]. However, due to its non-coherent processing technique the resolution of SRDI is low. 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.

In [3], Laas-Bourez et al. 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.

To control the collision probability ground-based lasers [4] might be used to move space debris through a gentle push. Laser orbital debris removal has also been considered as a potential strategy to remove both large and small debris [5]. These strategies require a catalogue of accurate tracking information to track the orbit precisely.

The United States have operated a radar based space surveillance system, and are building a new space fence on Kwajalein Atoll. This is a radar system operating in the S-band frequency range costing of the order of $1b USD. It is planned to be operational in late 2018 [6].

In this paper, we present key aspects of a system that would track space debris in LEO via scattered Global Navigation Satellite Systems (GNSS) signals. In earlier works, we showed that despite facing the near-far problem, the very weak signal scattered by LEO debris can be detected using long coherent integration[10]. Furthermore, a method to reduce the processing cost needed for the long coherent integration period has been proposed as well[11]. Finally, this paper provides a method to obtain the required processing gain at a much lower computational cost than previously shown.

2. GPS AS A RADAR ILLUMINATOR

Beyond standard positioning, GPS has a wide range of applications and radar is considered as one of them. In [7], it has been shown that GPS satellites at MEO can possibly be used as emitters to track space debris at LEO. Most of the LEO debris is smaller than GPS wavelengths (20cm) and thus falls into Rayleigh scattering region. For objects smaller than the wavelength of illumination falls under Babinet's principle of forward scattering [8] applies. The basic application of Babinet's principle here is to show that the radiation pattern formed by a hole is identical to the object. Therefore the phase of the forward scattered signal is predictable. So long coherent integration periods are possible. However, the power reradiated by the object is extremely low so the power level at the receiver it is even lower. 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. Thus, a long coherent integration is required to raise the power level at an acceptable range. The expected signal levels require a collection array with tens of thousands to millions of elements [9]. To obtain a long coherent integration is difficult, as many factors must be controlled, including: 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.

3. GPS SIGNAL DETECTION AND LIMITATIONS ON EXTENDED INTEGRATION

The GPS signal is generated as a composition of carrier wave, spreading code and navigation data. In order to track and get the information passed by the GPS signal, an acquisition is the first step to detect the presence of the signal. Successful detection of the signal requires sufficient energy accumulation which can be obtained by correlating over T. The minimum data length suggested for the detection of a GPS signal is 1ms though it is not standard and can vary depending on the situation. The longer the data length the longer is the processing cost. Longer data improves signal to noise ratio which is mandatory in weak signal environment. However, the selection of longer data period is limited by few factors. Navigation data bit and Doppler frequency are two major factors. The length of T must need to be extended on order of minutes to accumulate required energy to detect the desired debris-scattered weak signal. In later section, we show the technique to handle the transition effect due to navigation data during detection.

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. Possible issues in such a system are instability in the physical LO at the receiver unit, non-predictable variation in the phase of the Radar Cross Section (RCS), non-predicted (and non-linear) wander in the geometry, untracked instability in the emitter, and the time that the object is usefully above the horizon. However, the LO stability problem doesn't appear to be challenging because of the opportunity to use the direct signal arrivals as a time synchronizer for the processing of the indirect signal. It is confirmed that there is a short delay, normally less than 5 ms, between the direct and indirect signal [9].

Following Babinet's principle [8], with an 180° phase change, a forward scattered signal of an object smaller than the GPS signal wavelength should carry a well-behaved signature on it. This solves the non-predictable variation of RCS phase, as our target objects are of a size smaller than 10 cm. The expected RCS of the target of projected area A is given by Babinet's Principle as:

$$\sigma = \frac{4\pi A^2}{\lambda^2} \tag{1}$$

High processing cost is another obvious problem to consider in case of long integration. In early works [10], it is shown that extensive processing gain is required to detect the extremely low power GNSS signals scattered by space debris. To achieve the required level of processing gain over an appropriately large tracking volume could present an unreasonable processing load at receiver, and appropriate means of achieving this are described in section 5.

4. WEAK SIGNAL DETECTION

In using GPS as a radar illuminator to track LEO debris, a terrestrial receiver receives a direct signal from a satellite without any obstruction, as well as a delayed, weaker, indirect version of the same signal scattered by space debris in Low Earth Orbit. To acquire the signal the receiver needs to search the code delay and carrier Doppler frequency of the desired signal. Both arrivals are weak enough of needing additional processing gain at receiver end. However, the debris-scattered signal is far weaker than the direct signal on the order of 150 dB [9]. This weak signal at receiver must be detected in the present of the strong and relatively similar, direct signal – the so called "Near-Far Problem". We note that in the case of space debris in Low Earth Orbit, the desired signal has a very large and different rate of Doppler shifts associated with it which makes it distinguishable among the interfering signals. As GPS satellites are orbiting at an average altitude of 20000 km from the Earth's surface and LEO debris are at a height of range from 800km to 2000km, their Doppler frequencies are different. Following the calculation of Doppler frequency shift, we found, the maximum value for GPS direct signal is around ±5kHz, whereas for debris-scattered GPS signal it is ±37kHz [10]. Fig.1 shows an illustration of the case where the difference in frequency range for the direct and indirect signals is clear.

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 also high. That means, if the desired Doppler frequency is followed during the correlation at receiver, it will continuously create an offset with other interfering signals. Extension of a theoretical analysis of standard GPS correlator [10] shows 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. It is possible as in case of LEO debris, the desired signal is a delayed version of the direct arrival. Fig. 2 illustrates that larger Doppler offsets drive the cross-correlation between the direct and indirect signal near to zero. In other words, the correlation of the interfering signal with the matched filter based on the indirect debris signal in the receiver approaches that of a random signal, so the available processing gain to select the indirect signal in presence of the strong direct signal is similar to the processing gain over white noise.

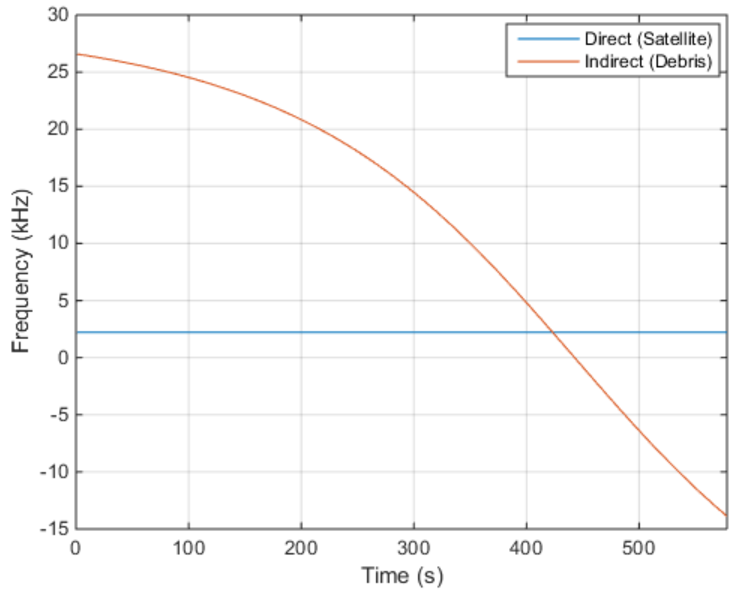

Fig. 1. Doppler frequencies observed over a period of 578 sec [11]

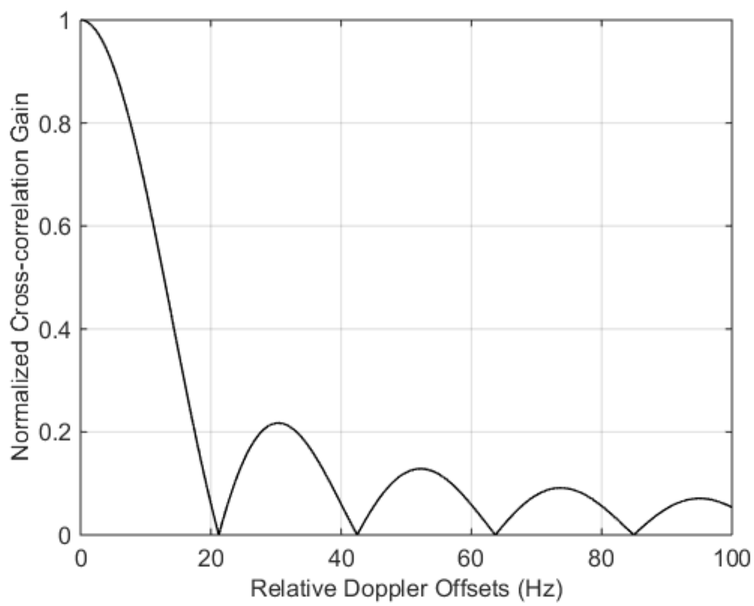

Fig. 2. Cross-correlation with Constant Frequency Offset

To confirm that the Doppler offset over the long integration period has sufficient cross-correlation rejection of strong (direct) interferer's signals, a simulation was conducted with the parameters in table 1 [10].

TABLE 1: Simulation Parameters [10]

	Strong	**Weak**
Test Case	1	1
Doppler Frequency Range	2.2kHz	+26.5 kHz to -13.8kHz
Amplitude	1	0.01
Initial Carrier Phase	Random	0
PRN	13	
Carrier Frequency	1.25 MHz	
Sampling Frequency	5.00 Msps	
Integration Time	T = 2ms, 20ms, 200ms	

Since the Doppler of the indirect signal from debris changes at a very high rate compared to the source GPS satellite signal, the critical relative Doppler offsets that have been shown to limit processing gain, are experienced for only very short durations over the long coherent integration period necessarily deployed to detect the desired weak signal. Additionally, the phase relationship between the received debris signal and the local replica is constant during the integration period whereas it appears random for the direct satellite signal. Furthermore, we check the cross correlation performance for the indirect or interfering signal for different dwell time periods. The results are shown in Fig. 3 where we plot the cross correlation power gain for the direct signal with respect to the indirect signal. As the integration period increases the auto-correlation constantly accumulates power in compare to the cross-correlation between the local and incoming signal. For each ten-fold increment in dwell time an extra 10 dB of cross-correlation rejection is achieved. For demonstration purposes the time is kept short; however, this is indicative that strong interfering signals can be handled in a weak signal environment provided the relative frequencies vary. The result shown in Fig. 3 validates that the cross correlation interference remains well below the desired signal level and this margin increases further by extending the dwell time.

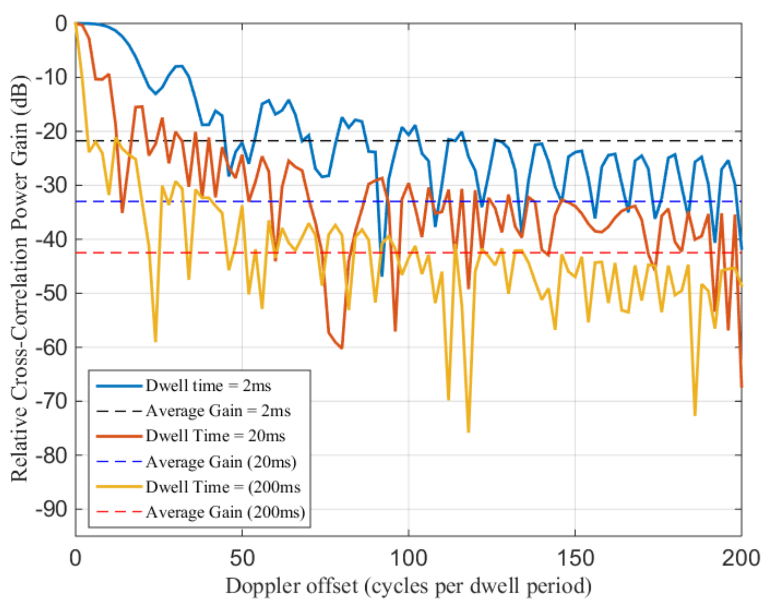

Fig. 3. Cross-correlation Rejection for Different Integration Times [11]

5. SIGNAL PROCESSING AT AFFORDABLE COST

Having confirmed that an indirect, weak signal can be detected in the presence of the much stronger, direct GNSS signal, the next step is to estimate the computational cost of detection, especially in the presence of uncertainty. In this section, we present an efficient processing strategy for the long coherent integration required for acquisition of extremely weak GNSS signals scattered by space debris.

Integrating the indirect signal for an extended period is a processing burden. At the receiver, a long coherent integration can be performed using the predicted and actual signal. In this case, the received signal provided to the correlator is stripped of both PRN and data bit. The process is error sensitive as a phase error of a period over full integration will demolish the coherency. As shown in [11], for a LEO object that was visible for around 10 minutes (T=600s), assuming minimal Nyquist sampling of the GPS C/A-code signal of 2 million samples per second, the calculation cost N as Multiply and Accumulate operations (MACs) to integrate each alternate apparent trajectory would be:

$$N = f_s \times T = 1.2\times 10^9 \quad (MAC) \tag{2}$$

Rather than performing all computations at Intermediate Frequency (IF), we propose to do it in stages. After passing a signal down to an IF, the incoming signal is processed or conventional cross-correlation means to detect the direct signal to facilitate the upcoming generation of replica signal. A complex replica of the debris signal is generated, including carrier, Doppler, spreading code and modulated data based on the estimated reference from the direct arrivals. The assumption made earlier that the PRN and navigation bit free signal is used for integration is thus valid since we use the direct arrival to get that information for later processing.

This replica is then correlated with the received signal over very short periods of time, for example, keeping the duration to 0.1 ms initially. The integration period of this operation is kept short enough that the phase error between the received signal and the replica is approximately constant over the integration period. To confirm that this technique works we process a GPS L1 C/A signal as observed by a radio telescope pointing towards a GPS Block IIF satellite for ten seconds duration. The actual signal was recorded at 128Msps at a 32.42 MHz IF. We strip the C/A code, data and most of the carrier and Doppler. However, we deliberately insert a frequency offset of around 40 Hz to check the performance of the proposed method [11]. After conversion to Audio Frequency (AF) we highlight a data bit error in the replica signal that causes a phase reversal in the complex AF signal for 100ms in Fig. 4.

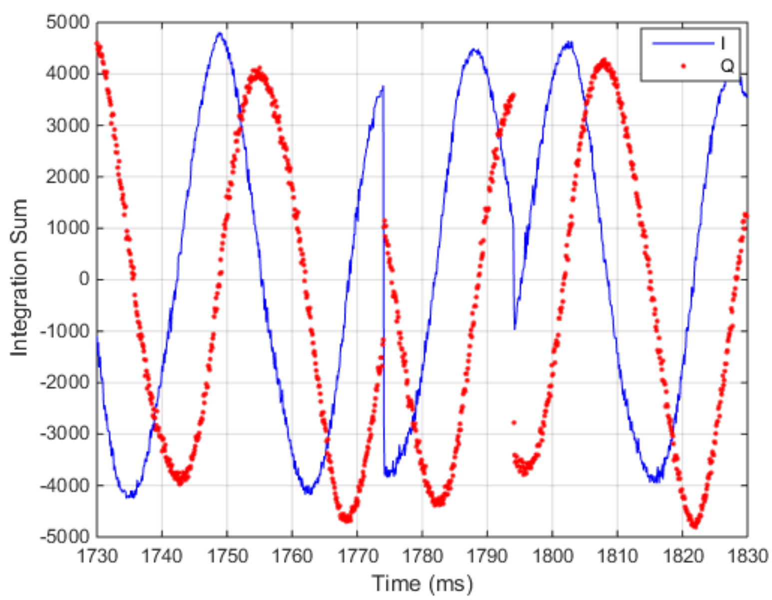

Fig. 4. Audio Signal with Data Incorrectly Stripped [11]

Now, correcting this resultant signal at audio frequency doesn't prove to be a burden provided that the data rate is substantially lower than the AF sampling rate, or that the data bit boundaries are appropriately synchronized with the AF sampling. Neutralising the effect of the data bit can be simply done by multiplying the signal with a binary matrix generated from the information of the direct arrival. Some portion of the audio signal following such correction is shown in Fig. 5.

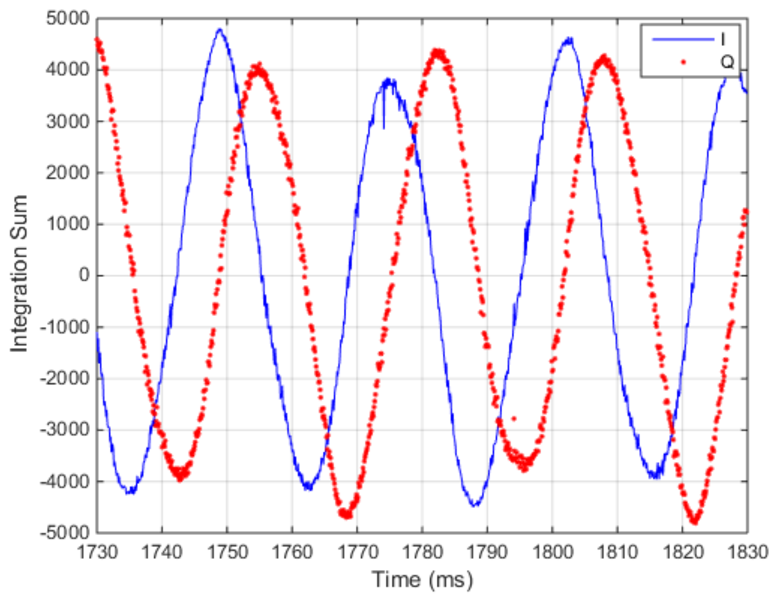

Fig. 5. Audio Signal with Data Correctly Stripped at Audio[11]

After successfully stripping out the PRN and data bits, the next task is to remove the phase difference between the two signals. The frequency difference of 40 Hz between the replica and received signal causes the phase difference over the entire correlation. In this case, we keep the replica signal with constant Doppler; however, the actual recorded signal contains a varying Doppler. Thus, for first few seconds the phase difference remains constant. The phase changes rapidly in the later part of the interval, indicating the effect of replica phase lag as shown in Fig. 6.

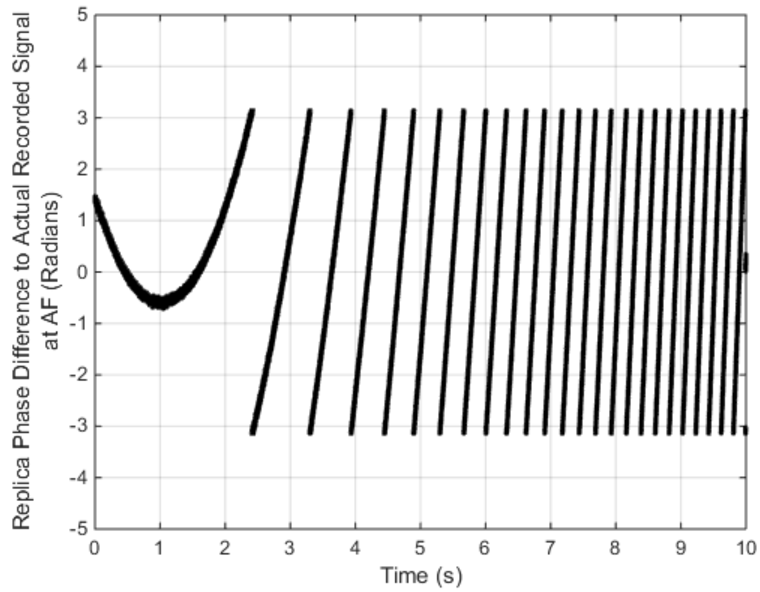

Fig. 6. Non-linear Phase Difference of Audio Signal [11]

In Fig. 7 we plot the angle of the audio-sampled signal from Fig. 6 after a phase rotation correction is applied to the signal at audio frequency. The correction equation in this particular simulation is applied as

$$LO_{AF} = 2\pi(0.23 + 36.6535t + 3.05t^2), \qquad 0 \leq t \leq 10\ seconds \tag{3}$$

As a result, the required computations per hypothesis trial significantly drops down to N = 6 million MACs at an audio frequency f_a = 10kHz. This is 200 times lower than the direct approach at intermediate sampling rates.

An extensive investigation indicates that tighter control of the allowable Doppler error may allow a much lower audio rate than on order of kilohertz. The difference in frequency is the key in generating the audio samples at a lower rate. The close the predicted trajectory, the lower is the allowable AF.

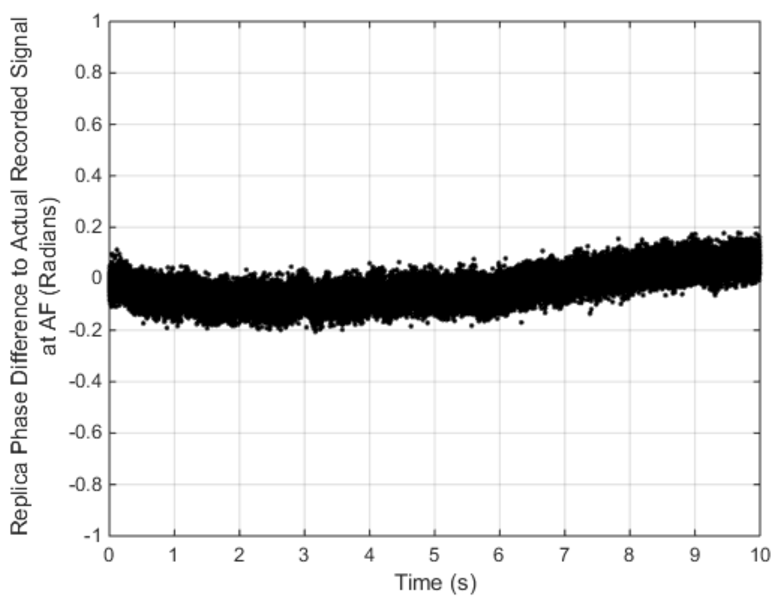

Fig. 7. Phase Error Corrected at AF

We now investigate the effect of the along track error of the anticipated signal from the actual trajectory. Due to the non-linear change in Doppler over the observation period, the signal received from a target which doesn't exactly match the anticipated track makes a non-uniform difference in frequency with the local replica. For a local replica that has a 1ms delay relative to the actual signal received the two Doppler frequencies are shown in Fig. 8. This is indicative of an along-track error of order 7m for LEO targets.

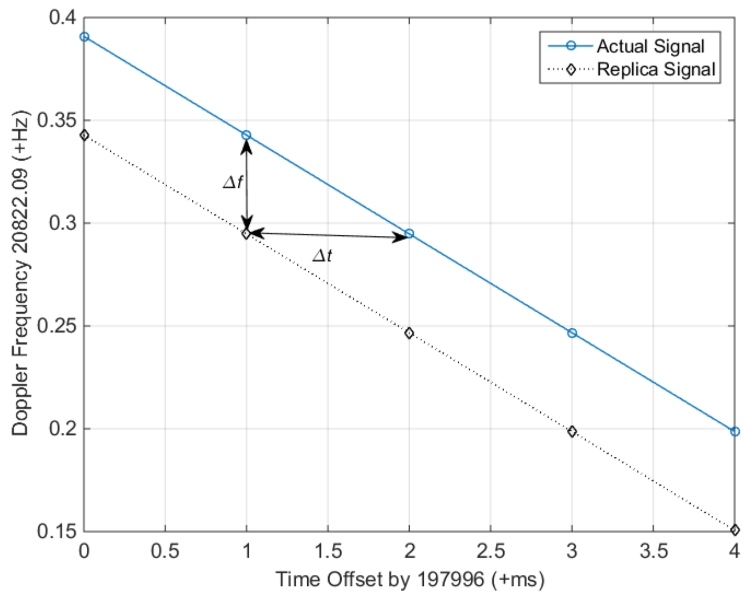

Fig. 8. Doppler Frequency of the Actual and Replica Signal

Over the whole period of observation the difference between the two signals in frequency again shows a non-uniform pattern and illustrated in Fig. 9.

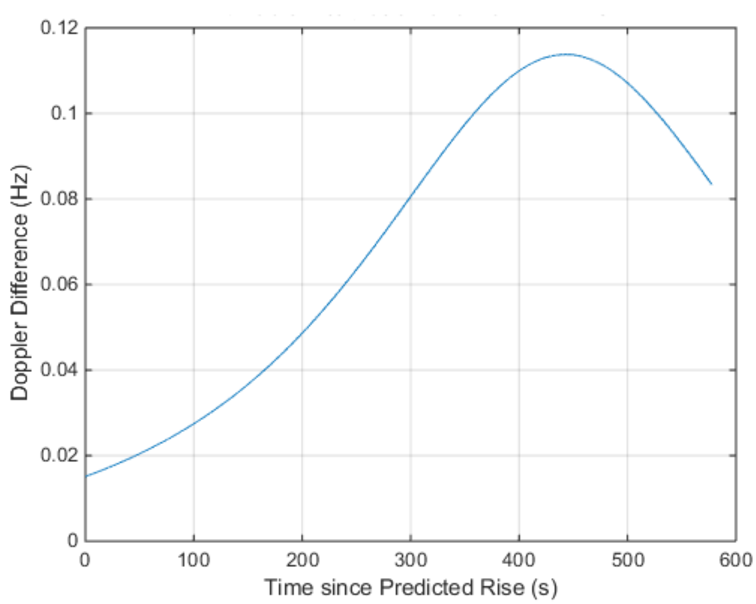

Fig. 9. Doppler Frequency Difference between the Actual and Replica Signal

It is readily apparent that the difference in frequency changes non-linearly over the time of observation. Therefore, for down sampling from intermediate frequency to audio frequency preserving important information can be lower using this feature. To deal with this nonlinear change in Doppler without substantial loss, the integration and dump (I&D) operation is refined. Rather than a constant, short integration period, we propose here that a variable integration duration be used. The duration being chosen according to the Doppler change between the received and local signals. The duration of integration is selected based on the accumulated phase shift between the two signals. Considering that the two signals are initially synchronized in phase but differ in frequency by Δf, then during an interval Δt they develop a total phase difference $\Delta\varphi$ where,

$$\Delta\varphi = \Delta t \times \Delta f \tag{3}$$

or in more general calculus,

$$\varphi = \int_0^{\Delta t} f(t).\,dt \tag{4}$$

Fig. 10 shows that the total accumulated phase shift can be thought of as the area under the frequency difference curve shown in Fig. 9, where we are proposing that the integration duration Δt be chosen such that this area is constant and suitably small.

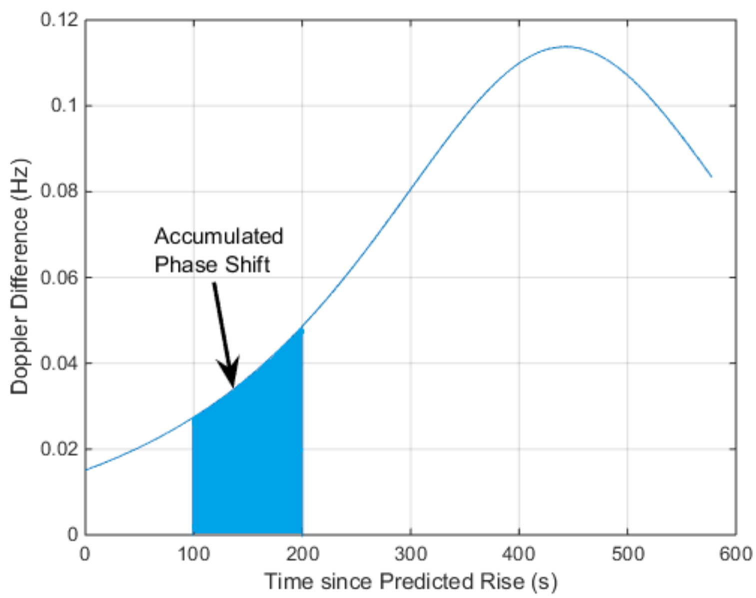

Fig. 10. Accumulated Phase Shift between Two Signals

Therefore, using an integration period of constant and short span to keep the phase error between the received signal and the replica approximately constant over the integration period becomes obsolete. Now, the I&D period will be longer where the frequency difference is negligible and it will be shorter where the difference is larger. The length of integration is actually a function of acceptable integration loss in the correlation outcome. Later, it will be shown that the total number of I&D operations, and hence the computational cost of running a large number of target hypotheses can be substantially reduced from the constant duration case, with negligible loss of detection performance. Fig.11 shows the variation of integration duration for I&D operation based on accumulated phase shift of 0.5 cycles in each I&D period.

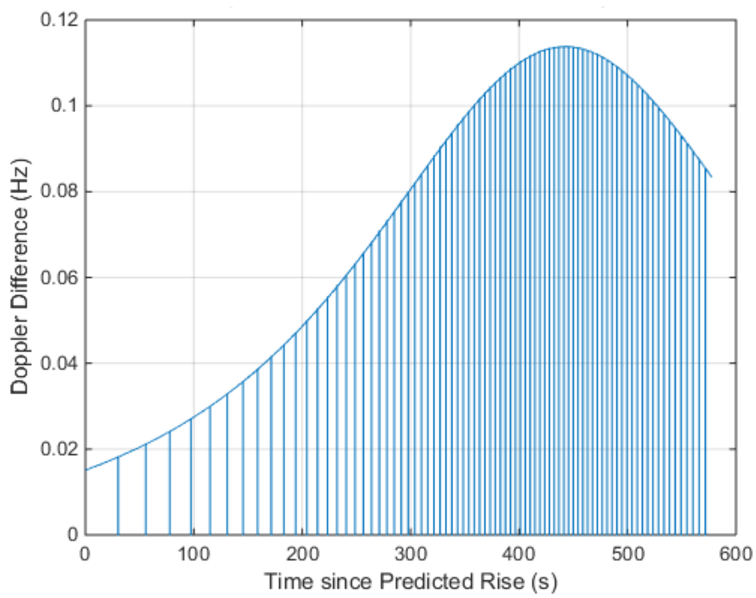

Fig. 11. Variable Integration Length over the Nonlinear Differences, Each Area Represents 0.5 Cycles Accumulated Phase Error

As shown in fig. 11, the proposed system has the longest coherent integration periods where the Doppler frequency difference is smallest. This allows the integration period to be extended without substantial increase in integration loss due to phase error. Integration loss in reducing the sample rate cannot be recovered by later processing steps, thus the selection of the threshold for the accumulated phase is crucial.

The processing cost for each hypotheses trial *N* reduces significantly due to this novel calculation method. The computational cost of each alternate trajectory hypotheses is based on the number of phase adjustment and accumulation operations, and therefore depends heavily on the frequency offsets between the actual and the estimated signals. Larger frequency differences result in smaller I&D steps and therefore greater computational cost. This is because the audio frequency is the result of the difference between the two signals involved in correlation. A zero difference means perfect correlation and thus no additional computation for correction. A large frequency difference between the actual target and the estimated replica requires more corrections in the final processing step. Ensuring this calculation has a modest and acceptable cost is necessary to allow the intended radar system to be viable. Applying the phase correction technique at AF as discussed above results in computational cost as shown in Fig.12. It shows that the computational cost increases at an approximately linear rate with predicted trajectory having an along track timing error up to 20ms, or around in along track range error 140m.

The cost of generating each trajectory hypothesis therefore increases linearly with its offset from the estimated trajectory used to create the audio band version of the received signal. Therefore searching multiple trajectories located some distance from the audio replica is best achieved by creating a new, more appropriate audio replica, and then searching a small distance from that new replica. Taken to the limit, successively partitioning the search region naturally suggests itself as a means to reduce the search cost to a minimum.

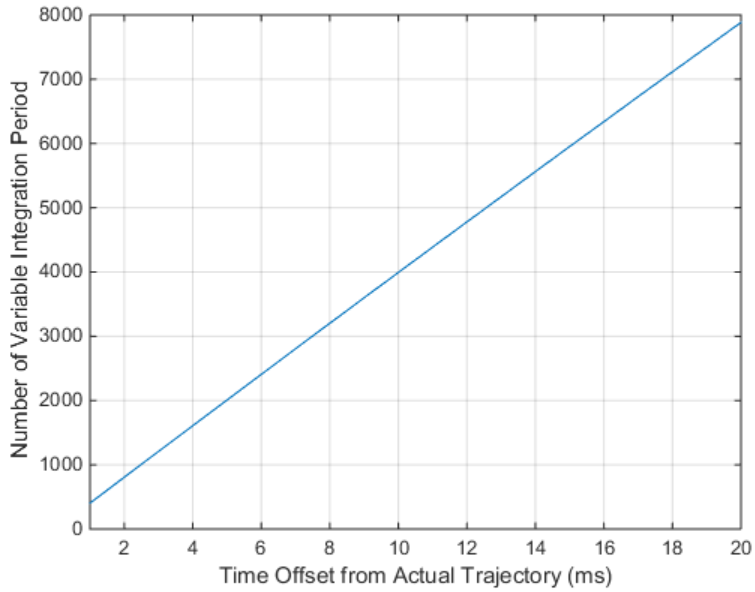

Fig. 12. Linear Growth of Integration points with Time Offset as Predicted

6. CONCLUSION

Space debris, especially in Low Earth Orbit, requires regular tracking to maintain accurate orbital information. The risk of space debris to satellite operations is rising, so highly accurate tracking or debris is necessary. This paper reported progress on the development of a debris detection system using GNSS satellites as emitters of opportunity in a bistatic radar. The weak GNSS signals reflected from LEO debris should be detectable but the processing cost of directly implementing the large number of matched filters to accommodate a sufficiently large search volume is computationally unattractive. Here we improved on the previously proposed approaches to minimize the computational cost of searching an uncertainty region around the expected debris location.

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