Enhancing space situational awareness using passive radar from space based emitters of opportunity

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***Abstract*— Space debris is a growing hazard to space users. Debris trajectories must be accurately predicted to maintain safe space access. Accurate predictions are premised on precise knowledge of the current trajectory, and a detailed understanding of disturbances that affect the future trajectory. Both tasks are facilitated by accurate and timely tracking of debris. It is possible to track space debris using radar and telescopes, yet both are expensive and result in unacceptable trajectory projections due to limitations on both accuracy and update frequency. In this paper we consider the performance budget necessary to augment debris tracking by passive radar, initially using Global Navigation Satellites as emitters of opportunity.**

space debris; gnss; gps; bistatic radar; space situational awareness.

I. Introduction

There is a large and growing quantity of space debris [1]. This space debris poses a risk to space operations, since although much of the debris is very small, the relative impact velocities are many thousands of meters per second. Detailed knowledge of space debris trajectories, commonly discussed under the umbrella of Space Situational Awareness (SSA) is necessary to manage risks to space operations. Orbital objects are tracked by various sensor systems, but the tracking precision and update rates, as well as uncertainty in subsequent dynamic disturbances means that uncertainty in SSA predictions is unacceptable. A need exists for an affordable method of enhancing SSA, in spite of the growing number of orbiting objects.

Accurately predicting the orbits of space debris is difficult because the quantity of objects to be tracked and cost of the tracking systems. Together these limit the rate at which observations of the trajectory of orbiting objects can be made. This in turn leads to extended periods where the location of space debris is predicted rather than measured. Although dynamic disturbance forces are small, the errors in predicted trajectory can grow substantially between updates based on infrequent measurements from scarce sensors.

In this paper we investigate the feasibility of tracking space debris by low-power scattering of space-based radio sources. The space debris tracking problem is unusual in that the target field is very sparsely populated, and the trajectory of the objects to be tracked is very well known. Coupled with extremely stable illumination signals this means that very long coherent integration periods should be attainable, and over such processing intervals all other co-frequency signals will appear random. Further, the tracking sensor output does not need to be a traditional detection of a target at high SNR, rather an indication of the likelihood of the debris being on certain trajectories should be sufficient to improve the maximum likelihood estimate of a kinematic tracker (eg Kalman Filter), to maintain adequate SSA.

II. Space Debris as a Radar Target

Because we consider tracking space debris by observation of scattered radio signals we are actually describing a form of bistatic radar. The illuminator is a space-borne radio transmitter, in our case a Global Navigation Satellite System (GNSS) satellite such as GPS. The radio signal from these satellites has very precisely controlled timing, and their trajectories are also very precisely controlled and tracked [2]. The signal characteristics are publically documented [3], and for our purposes comprise a Direct Sequence Spread Spectrum (DSSS) signal at a chip rate of 1.023 Mcps on a 1575.42 MHz carrier. The illumination pattern of these Medium Earth Orbit (MEO) satellites covers approximately a third of the surface of the Earth. In general, objects in Low Earth Orbit will also be illuminated, as would objects beyond LEO, subject to some readily apparent geometric constraints.

The wavelength of L1 GNSS signals is approximately 20 cm, and here we initially focus on tracking of debris marginally smaller than the wavelength of the radar, notionally placing the debris signature in the Rayleigh region. We consider the forward scattering case, whereby the debris lies nominally on a path between the emitter and the observer. The advantage of this arrangement is that the phase change of the scattered signal is constant, and the angle over which scattering can be observed is also well documented. The expected Radar Cross Section (RCS) of the target of projected area A is given by Babinet's Principle as [4]:

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

We consider three cases, the first where the object is small relative to the radiation wavelength, a second where the object is of the same dimension as the wavelength, and the third where the object is large relative to the radiation wavelength. For a small object of several centimeters in each dimension the RCS is likely to be of the order of -20 dB re 1m^2, but we reinforce that the scattered radio signal will have a highly predictable phase change relative to the illumination source, thus the RCS will be free from scintillation although we do concede that scintillation due to other propagation effects may occur. For an object of approximately the same dimension as the wavelength the null to null beamwidth of the forward scattered power approaches 180° and the RCS approaches:

$$\lim \sigma_{D\to\lambda} = \frac{4\pi^3\left(\frac{D}{2}\right)^4}{\lambda^2} = \frac{\pi^3\lambda^2}{4} = -5.5\text{dB re }1\text{m}^2 \quad (2)$$

For a large object the forward scatter RCS is larger, but the diffraction pattern is more complex and the power is focused over a narrower angle – both of which limit the coherent integration period. For comparison we consider a nominal large target of 10 m^2 (10 dB re 1 m^2) RCS, noting this would be a complex scatterer, processing for which we defer to future work.

III. A LINK BUDGET

We assume the receiver is one or more low-cost units stationary on the Earth's surface. A patch antenna and simple GNSS front-end chip such as the MAX2769 [5] would appear eminently suitable. A relatively large number of these units, driven from a single local oscillator, and with the output of the I&Q 1-bit A/D conversion being collected by a FPGA/DSP chip could produce a cost-effective receiver array. Each element of the receiver array is capable of observing the GNSS satellite signal direct arrivals (order 10 sv's), as well as the weaker, indirect arrival scattered from the space debris (order 10 sv's times *D* pieces of debris), all buried under noise and observable only by suitable processing using the correct DSSS codes, code delay and Doppler rate for each sv-debris pair. These observations are relatively immune to clock errors, since the local clock bias at any time can be observed relative to the direct arrival GNSS signals.

The signal power S_D received by such a system for the direct path of length R_{GNSS} from a signal source of power $EIRP_{GNSS}$ into an antenna of effective aperture A_{Erx} and suffering losses of L – such as a 3dB polarization loss, is given by:

$$S_D = EIRP_{GNSS} \times \frac{1}{4\pi R_{GNSS}{}^2} \times A_{Erx} \times \frac{1}{L} \quad (3)$$

And for the indirect path via space debris of RCS σ is given by:

$$S_I = EIRP_{GNSS} \times \frac{1}{4\pi R_{GNSS\to SD}{}^2} \times \sigma \times \frac{1}{4\pi R_{SD\to RX}{}^2} \times A_{Erx} \times \frac{1}{L} \quad (4)$$

Assuming that the path loss to the LEO debris is approximately equal to the path loss to the Earth's surface ($R_{GNSS} \approx R_{GNSS}-S_D$), that losses L remain the same on the two paths, the difference in signal level would be:

$$\frac{S_I}{S_D} = \sigma \times \frac{1}{4\pi R_{SD\to RX}{}^2} \quad (5)$$

The GPS C/A-code signal, is well documented [3], and with a typical antenna and GNSS receiver effective noise temperature the SNR in a 2 MHz bandwidth is approximately -21.5 dB [6] before processing gains. The SNR of the received signal into a typical GNSS receiver before processing gains from the indirect path, as scattered from debris 1000 km from the receiver is shown in table I.

TABLE I. APPROXIMATE BISTATIC SIGNAL LEVEL RECEIVED

RCS (re 1m2)	***SNR at typical receiver***
-20	-21.5-20-11-120=-172.5dB
-5.5	-21.5-5.5-11-120=-158dB
10	-21.5+10-11-120=-142.5dB

In the next section we examine how the SNR can be improved.

IV. IMPROVING WEAK SIGNAL TRACKING

Although the expected SNR is very poor, there are numerous opportunities for improvement. Firstly we consider multiple receive elements, then we consider the integration period, then we examine how low the SNR from each signal source can be while still remaining useful. Finally we point to opportunities for further improvement.

Using multiple receive elements *N* results in *N* coherent observations with independent noise. This provides for up to *N* times improvement in SNR. We note that simple beamforming at the receiver array may not be optimal, and that coherent blending of the signals over long observation periods may require each receive element to apply a different time (Doppler) adjustment based on geometry of the illumination source trajectory, debris trajectory and array layout. In a modern processing device such calculations are not inconceivable, especially at 1-bit amplitude, and it is likely that suitable piecewise linear approximations exist. Provided the receive elements can be fabricated at low cost, then relatively large arrays should be possible. With the use of sub-arrays and intermediate stages of processing, extension of observation systems to a thousand or more elements is possible. For illustration we use improvements in apparent signal level of 30 to 60 dB due to receiver arrays. We also note that since the processing is done in software on a receive signal only, multiple objects can be tracked with the same antenna array, simply by adding software (or firmware) processing channels. Thus this approach can utilize the same array for tracking as many visible objects as desired, with the processing load scaling linearly with the number of tracks to be generated.

The direct and scattered signals are extremely stable over time, excepting for the kinematic effects. The kinematic effects are understood to extremely high precision – the uncertainty is only the uncertainty in the debris trajectory – so it is possible for the receiving system to create a very precise replica of the expected scattered signal from the debris. Using this as a matched filter in the receiver means that a very long coherent integration period can be used. We anticipate this integration period could be minutes in duration. This is not to say that we will accurately predict the code and carrier on the scattered path for that duration, rather, we expect the prediction to act as a coherent matched filter for that duration – meaning that the actual scattered signal arriving will differ in both phase and phase rate (Doppler frequency) from the prediction. We initially assume that the path length of the indirect path is known accurately relative to the chip length of the DSSS code on the GNSS signal (300m for GPS), although if this is not the case, then early and late replicas could be used at a linear increase in processing cost. Returning to examine the output of the matched filter, we should expect to see a matched filter output that cycles between the I and Q channels at a rate corresponding to the error between the matched filter and the actual received signal. A Fast Fourier Transform (FFT) on the filter output resolves this in frequency space, and thus the difference between the estimated debris path and the actual path may be observed. The phase component of the frequency space representation may also contain useful information.

The concept of the energy contained in the received signal from the debris all falling into a single Doppler bin is premised on the Doppler shift being constant over the observation duration. The signal results from two bodies that are both moving at thousands of meters per second relative to the receiver, so this is not guaranteed, however the deviation from the prediction is expected to be very small, so a linear approximation may very well hold, and in any case suitable transforms could be used. As with range errors greater than the chip length, an additional k matched filters could also be used, although the computational cost may scale more poorly than for a FFT.

Given the chip rate of C/A-code is 1,023,000 chips per second, the processing gain achievable in one second is approximately 60 dB, and in one minute is approximately 78 dB. A non-coherent integration may also be applied over successive coherent windows, although the gain would not scale as well. We note that LEO debris may be observable from a single location for the order of ten minutes, depending on the orbit altitude and trajectory.

Finally, we are not limited to observation of a single illumination signal on each piece of debris. At any given time there are approximately ten GPS satellites visible. Future GNSSs such as Galileo and Beidou-2 will further increase the number of illuminators. Further, each satellite emits on the order of ten signals, all of which are synchronized with each other, so at the cost of additional complexity, a further 20-25 dB of improvement might be attained.

Potential processing gains above the single antenna SNR projected earlier for a conservative and an optimistic processing case are:

$$30(N)+78\text{ (1 minute)}+0.7\times10\text{ (minutes)}+10\text{ (sv's)} = 125\text{dB} \quad (6)$$

$$60(N)+78\text{ (1 minute)}+10\text{ (minutes)}+25\text{ (sv's)} = 173\text{dB} \quad (7)$$

The resulting SNR achieved is postulated in table II below, using the three RCS cases described earlier, and the two processing gains above.

TABLE II. BISTATIC SIGNAL LEVEL AFTER PROCESSING

	SNR at typical receiver		
RCS (re 1m^2)	G_p=0dB	G_p=125dB	G_p=173dB
-20	-172.5dB	-48.5	-0.5
-5.5	-158dB	-33	15
10	-142.5	-17.5	30.5

We highlight that to obtain maximum benefit from a long coherent processing interval the signal must be stable (ie have a constant or zero frequency offset) relative to the matched filter. This means that not only must the phase of scattered radio signal be predictable, but the cumulative effect of ionospheric delays (refraction) must also be considered. We believe that the former constraint is achievable, at least for small objects, and the ionospheric delay is predictable to this level to support broad area carrier phase measurements. Regardless, the SNR after processing is likely to be low – most likely below unity. In a later section we examine how such observations might be useful.

The cost in computational power to obtain the levels of processing gain may be high. As an estimate we note that for a linear operation – for example a single correlator of sufficient length to achieve 153 dB of processing gain the number of multiply and accumulate operations is M:

$$M = 10^{5.3} \approx 2 \times 10^{15} \quad (8)$$

A single commodity FPGA/DSP module [7], could undertake of order 31.5×10^9 high precision multiply and accumulate (MAC) operations per second, or 1060 processor minutes for the required 2×10^{15} operations to obtain the processing gain proposed against a single piece of debris. The commodity board discussed draws no more than 20 W and costs €159. Thus obtaining 153 dB of processing gain (excluding antenna, downconversion and sampling operations and infrastructure) has a capital cost of €120/fix/day (or over 5 year life €0.16/fix) and an energy cost of 0.35 kWh/fix. These estimates obviously ignore many additional costs, but also ignore the potential for much of the processing to be highly efficient. For example early stage correlations are a simple 1-bit XOR so don't need a 14 bit multiplier and 48 bit accumulator, and late-stage processing may use an FFT for NlogN scaling. In summary, costs are not intended to be definitive, but rather give an indication that the processing and energy costs do not seem prohibitive.

V. LIMITS ON INTEGRATION GAIN

In order for a coherent integration gain to be achieved it is necessary for the received signal to have a constant phase (or for FFT binning a constant rate of phase change) relative to the synthesised Local Oscillator (LO). We are proposing to generate a LO that tracks the phase and code of the indirect reflected path, but that calculation must produce a phase stable (or phase-rate stable) replica of the expected signal. Effectively the LO acts as a matched filter. Possible issues are: non-predictable variation in the phase of the RCS, instability in the physical LO at the receiver unit, untracked instability in the emitter, non-predicted (and non-linear) wander in the geometry, ionospheric delay variations (manifesting as phase variability and multipath fading), tropospheric variations and the time that the object is usefully above the horizon.

Non-Predictable Variation in RCS Phase: Using a forward scatter wave from small objects (size<wavelength) should result in a well behaved signature, with a 180° phase change directly forward following Babinet's principle.

Instability in Receiver LO: For simplicity the Local Oscillator used for downconversion of the GNSS direct and indirect signals (prior to matched filtering) should be consistent across any receiver array. If this is not the case a correction will need to be applied to each sub-array (where a sub-array shares a LO). There is an opportunity to use the direct signal arrivals as the time-synchronisation for the processing of the indirect signals. We note that there is a short delay between the direct arrival and the indirect arrival, generally less than 5 ms (1500 km). Because a GNSS direct solutions corrects for absolute clock errors, it is the stability of the local clock that is important, not the absolute accuracy (which will be derived from the GPS solution). The LO stability problem does not appear challenging.

Non-predicted, Non-linear Wander in Geometry. The trajectory of GNSS emitters is well documented [2] and observed on a continual basis. The trajectory of objects to be tracked is generally not as well known, however over time this project and others seeks to improve this tracking accuracy. We believe that the tracking accuracy will be sufficient that the deviation of the observed trajectory from the anticipated trajectory (and hence indirect path length) is within one code length (300m for C/A-code) and approaches predictable offset in observed frequency. Thus a set of long correlations (meaning downshift to very low frequencies in I and Q), and an operation similar to a complex FFT will project the tracking error onto the frequency and phase domain representation.

Emitter Stability: We believe that GNSS satellite transmitters will provide suitable phase stability for our purposes. As a last resort instabilities in the emitter signals can be tracked from the ground simultaneously with the indirect signals and corrected, with the typical path difference of order 5 ms removing most difficulties faced.

Ionospheric models: Ionospheric models used in most GNSS systems are thin shell approximations of Total Electron Count (TEC) at 350 km altitude that simply calculate a point of penetration. However when TEC varies substantially with altitude these fail. Given the widespread availability of Real-Time_Kinematic data for sub-wavelength survey operations, it is apparent that conditions resulting in failure of the thin shell model are not the norm. An opportunity appears to exist in using tomography for fine-grained study of ionospheric properties (ie scintillation or wavefront analysis rather than global variation) through an array of very high-rate CORS stations at selected spacing, or perhaps a radio-telescope array. Initial steps in this direction are discussed in [8].

Tropospheric effects: Delays in arrival of GNSS signals due to tropospheric effects are localized and frequency insensitive. Appropriate adjustments for tropospheric effects should be available from local measurements of GNSS direct path signals as applied to the known geometry of the indirect path signals.

Observation Duration: For illumination of LEO objects from MEO emitters via forward scatter (+/-90deg) the LEO object must (i) be above the horizon and (ii) be illuminated from behind. We note that the time above the horizon is typically of order 10 minutes. Further analysis is premised on orbit altitude, offset from tracking station zenith, the mask angle required and the exact limit (and roll-off in RCS) of the forward scatter angle. In the interim we will use 10 minutes as a typical integration time, noting that it may prove optimistic, but that some objects will achieve (approximately) this exposure time.

VI. Using Low SNR Tracking Outputs

There are signals other than the scattering from the space debris present in the received signal. However over the processing interval their code and Doppler are uncorrelated with the matched filter used to predict the expected debris signal. Thus the detection problem should resemble a single signal in Gaussian noise – the competing signals (such as direct arrivals and echo's from other debris) being randomly spread by the matched filter that is tailored to the range and Doppler of the fast moving debris.

The power and processing budget indicates that the signal to noise ratio is likely to remain low, even after the matched filter. However the aggressive SNR budget provides hope that a useful signal might be obtained. To be useful however, a means to utilize a low SNR (possibly less than unity) must be developed. The outputs of the processing should be viewed not as an attempt to decide on which range-doppler resolution cell (bin) the debris is in, rather the energy in each range-doppler bin is related to the likelihood that the debris is in that bin. These probability functions should then be used to refine the estimated kinematic model of the debris, which in turn informs future observations.

VII. Proofs of Concept

It is apparent from the power and SNR budgets presented earlier that a large receiver array is required for adequate performance. In addition there are several uncertainties to be clarified.

The phase stability and RCS of the forward scattering from space debris can be confirmed using radio-telescope arrays such as the Australian Square Kilometer Array Pathfinder (ASKAP) [9], deliberately tracking the expected trajectory of known pieces of debris could be used in place of the postulated array of unity gain simple receivers. Such systems may provide an improvement of around 166 dB {as NF=-10 dB, $G=4\pi*0.7*4000m^2/(0.2^2)$=59 dB, DSSS C/A = 60 dB, integration time=60x10=27 dB, #svs=10=10 dB, =166dB, for a

SNR of 8 dB against a target of dimension 0.2m square}. This is through use of a large aggregate capture area (4000 m^2 physical area) and low noise receivers. The advantage of such risk reduction tasks is that while they utilize expensive resources, these resources already exist and the processing can be performed in non-real time.

Simulation and modelling can shed light on many of the challenges apparent, especially in predicting the signal arriving at each array element, and validating processing approaches.

The ability of low-cost generic GNSS front-end units to track weak signals that have different kinematics to the direct path from the transmitting satellites can be demonstrated by tracking small GNSS repeaters located hundreds of meters to kilometers from the receiver(s). The geometry of the signal path via the repeater is different to the direct arrival, and path length changes by up to twice the spacing between the repeater and the receiver during the approximately four hours during which each GNSS satellite is typically visible. Such activities will confirm the ability to undertake extremely long coherent integration of GNSS derived signals, and that extremely weak signals can be actually be recovered from proposed 1-bit ADC and low-cost front ends.

VIII. Conclusion

In this paper we have proposed a receive-only method of tracking space debris. The technique is insensitive to time of day and weather, thus providing observation of any object above the horizon. The use of commodity receiver units offers the opportunity for very large, yet affordable and durable arrays. By using a staring array, and processing the collected signals using matched filters for each piece of debris, the front-end (and infrastructure) costs are insensitive to the number of objects to be tracked, while the processing cost grows linearly with the number of tracks.

However the signal power scattered by small space debris is very low, and the path losses from the debris to the Earth's surface are large. Substantial processing gain will therefore be required to achieve adequate performance. We have discussed techniques whereby it may be possible to obtain useful information from such low received power levels, and proposed some activities that may start to reduce uncertainties.

A system such as that proposed may track many pieces of debris in parallel at all times of day or night and in all weather. In addition, the affordability of such a system may allow for deployment of multiple sensor arrays around the globe, providing frequent observation of debris and resultant regular updates of debris trajectory, thereby providing a substantial improvement to Space Situational Awareness.

IX. References

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