Tracking non-cooperative low earth orbit objects using GNSS satellites as a multi-static radar

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Abstract

Space debris is a growing hazard since space activity and the amount of space debris are both increasing. If the risks posed by space object collisions cannot be mitigated, this will hinder the future use of space. Accurate knowledge of the trajectory and behavior of satellites and debris is required to mitigate collision risks as the density of space objects increases. This requires space object tracking systems that are both affordable and scale well for very large numbers of objects under observation. Wide field of view, all-weather, passive systems scale well for reliable surveillance of very large numbers of objects. Global Navigation Satellite System (GNSS) satellites have been proposed as potential illuminators of opportunity to track Low Earth Orbit (LEO) debris, paired with ground-based receivers in a bistatic arrangement. In this paper, we discuss the signal characteristics used in these observations, the results of recent relevant laboratory-based experiments, simulation work performed in preparation for on-orbit experiments of these techniques, and our plans for the development of a system capable of tracking LEO debris to enhance space situational awareness.

Introduction

Space debris is an existing and growing problem for active satellites and future space missions. Since the first ever space mission, Sputnik 1, up to now, the number of tracked objects as small as 10 cm is catalogued as 43,931 (Kelso, 2018). Most of these objects are existing inactive satellites and their fragments. This large amount of debris increases the collision probability. Moreover, the current rate of space operation indicates that the number will 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. Even with a mitigation plan, the same number can be reached in the next 200 years (Wormnes et al., 2013).

In a space debris report provided by NASA, the number of orbital space objects (including small pieces) is more than 500,000 with speed up to 28,000 Km/h (Garcia, 2017). With this high speed, tiny space debris as big as 10cm in any dimension can cause much damage to the active satellites or spacecrafts. Debris larger than 10cm are tracked and catalogued by ground-based radars and telescopes. Hence, collisions could be avoided using a thrust to the spacecraft. Debris with size less than 1 cm are numerous and their effect can be blocked by the shield because the masses are small and their destructive capability is weak (Fu et al., 2008). The debris of our interest with a diameter between 1 and 10 cm at low Earth orbit (LEO) are mostly out of the coverage of existing tracking facilities, and cannot be blocked by shielding. Detecting and obtaining orbital information of LEO debris

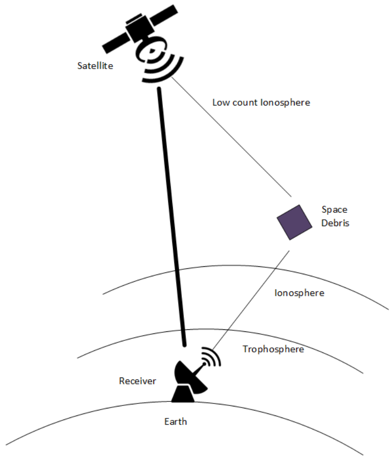

Figure 1: Illustration of direct and debris-scattered signal concept

using space-based radar are promising to provide a guarantee of spacecraft security to enhance space situational awareness (LU et al., 2006).

These days, it is a matter of great concern that collisions can be the main source for new debris, which will lead the space environment into a state with unacceptable risk for future operations. In this paper, we summarize the concept of bistatic tracking of space debris using Global Navigation Satellite System (GNSS) satellites. We present the multipath GPS signal of interest and its difference from the direct ones. The opportunity and proof that the debris-scattered signal is detectable in the presence of other interference sources are discussed. Then, the current lab-based experiments and plan to demonstrate the proposed method using cooperative objects, here a CubeSat, is presented.

GPS as Bistatic Radar

Apart from navigation and standard positioning, GPS has a wide range of applications and radar is considered as one of the potential applications in tracking space debris. Early research shows that GPS satellites can be used as transmitters to collect information about LEO debris (Mahmud et al., 2015). GPS satellites are flying in medium earth orbit (MEO) at an altitude of 20,200 km on average. The target, for instance, any LEO debris, is orbiting in a range of 400 – 2,000 km from the Earth surface. Thus, most of the radio signals collected will be of forward scattered signals. Our target space debris is mostly smaller than GPS wavelengths (20cm). The key element here is that the forward scattered signal has a known phase relationship with the incident signal. Thus, it eliminates the uncertainty that generally limits the coherent integration period of radar. Obtaining a long coherent integration is difficult. However, it is shown previously that the computational cost can be minimized and achieving such integration is possible too (Mahmud et al., 2016c). Figure 1 illustrates the concept of the bistatic configuration of GPS satellites to track LEO debris. It shows the two versions of the GPS signal, the direct and the debris-scattered signals. In the later section, we discuss the differences between these two signals and the proposed method to detect the debris-scattered signal.

Debris-Scattered Signal

We consider GPS as radar to track LEO debris where a terrestrial receiver receives a direct signal, comes from a satellite without any obstruction, as well as an 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 the receiver end. However, the debris-scattered signal is even weaker than the direct signal on the order of hundreds in dB scale (Benson, 2014). This weak signal at the receiver often faces the near-far problem where the strong signals dominate it. It is noted that in 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. Following the calculation of Doppler frequency shift, it is found that the maximum value for GPS direct signal is around ±5kHz, whereas for debris-scattered GPS signal it is ±37kHz (Mahmud et al., 2016d). Figure 2 shows an illustration of the case where the difference in the frequency range for two signals are clear. Figure 3 shows that the local replica created based on the predicted Doppler frequency correlates with the desired signal while the correlation with the direct signal appears as random noise (Mahmud et al., 2016b). Over the observation period of nearly 10 minutes, the Doppler shift for the direct satellite signal remains almost constant, however, for 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. During the real-time signal detection, we extract the information of navigation data and C/A code.

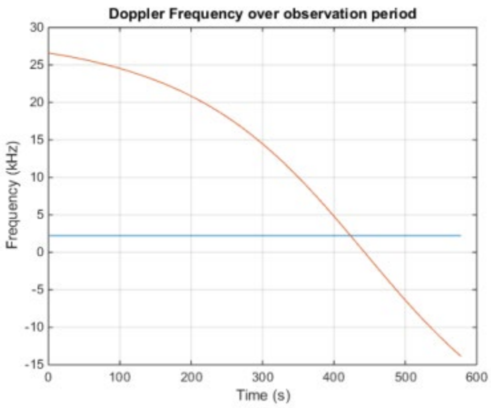

Figure 2: Doppler Frequency for Direct and Debris-Scattered GPS Signals (Mahmud et al., 2016d)

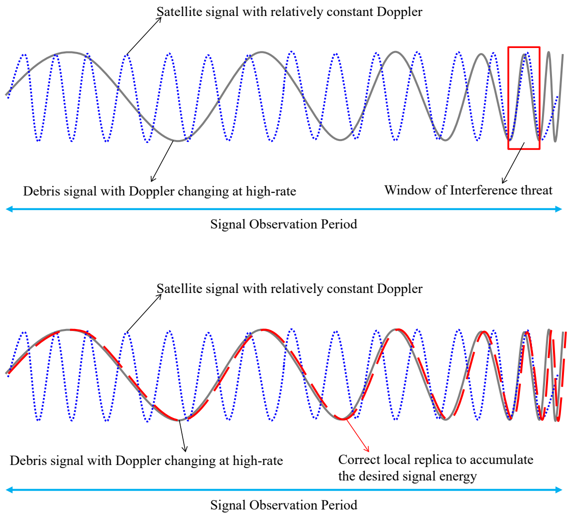

Figure 3: Correlation rejection for interfering signals such as direct GPS signal (Mahmud et al., 2016c)

After a full 10 seconds of data received, we use the previously extracted information to remove the transition effect in the acquisition. The only uncertainty remains is the Doppler frequency which we need to search during detection. A novel signal processing technique has been developed and simulated to confirm that the computational cost associated with extended coherent integration can be reduced to an affordable level (Mahmud et al., 2016a).

Concept Demonstration using Proxy Scatterer

A simplified link budget analysis (Mahmud, 2017) shows that the required signal gain can be achieved through different sources and one of those is the receiving antenna. It has been mathematically showed that for GPS signals a receiver array of 1,000,000 individual elements can achieve 60dB of gain (Mahmud, 2017). Building such a big receiver system is highly expensive and is not feasible before confirmation of other processing gains. Hence, an alternative approach has been taken into consideration to use a CubeSat with GPS repeater onboard as proxy debris to validate the proposal. Figure 4 illustrates the concept of using a CubeSat with GPS repeater to demonstrate the method of tracking LEO debris using GPS satellites as emitters of opportunity. The Royal Australian Air Force (RAAF) in cooperation with the University of New South Wales (UNSW) Canberra is in progress to carry out small satellite demonstrations to develop expertise in satellite technology. M1 CubeSat is a part of this project. It is carrying a GPS repeater onboard that receives GPS signal at 1575.42MHz and retransmits at 2400MHz. Thus, the retransmitted signal is much stronger and can be detected in any terrestrial compatible receiver in the conventional approach. However, a better Signal-to-Noise (SNR) can be achieved through regenerating the signal instead of

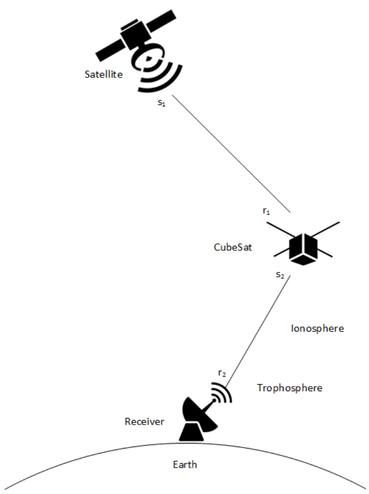

Figure 4: CubeSat with GPS repeater imitating LEO Debris

retransmitting. A pilot tone can also be added to confirm the signal detection and to make the CubeSat tracking easy. All these operations can be controlled and manipulated remotely through some programming changes as the repeater is software defined. Hence, any customization in radio configuration is possible according to the purpose.

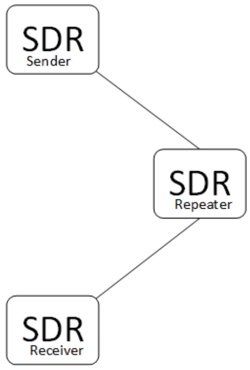

Figure 5: Lab set up to replicate the CubeSat based GPS repeater

Repeater Configuration and Ground based Test

To test the performance of the GPS repeater at the ground, a testbed with three different configurations was set at the lab. In the first experiment, the transmission of the device has been tested with carrier only and modulated signal with Pseudorandom noise (PRN) Code. Secondly, a static transmitter-repeater-receiver configuration was set and the performance of the repeater is tested using a carrier and modulated signals. In the third phase, the repeater was tested to receive and retransmit the GPS signal. In all configurations, transmitter and receiver are separated by 10m distance from each other and carrier frequency for the transmitter was 1575.42MHz and for the receiver was 2400MHz. Figure 5 shows the block diagram of the ground testbed to analyse the performance of the M1 repeater. The M1 repeater was set to receive the signal at 1575.42MHz and retransmit it at 2400MHz where applicable. In each experiment, all transmitted and repeated signals were successfully detected at the receiver. The retransmitted GPS signal in the third configuration couldn't be detected due to the extremely noisy received signal. Figure 6 shows the experimental results confirming the detection of the target signal at the receiver through M1 replica board. The concept here is to test the repeater with the signal of interest (GPS). The test at the

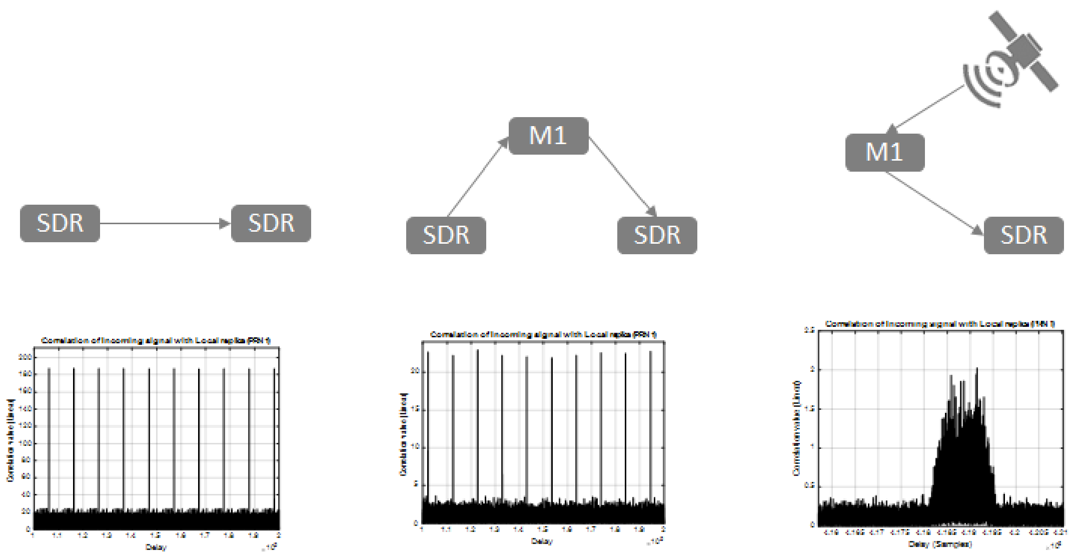

Figure 6: Experimental results ensuring signal detection at receiver through M1 repeater. Retransmitted GPS signal was noisy and couldn't be detected in this experiment.

ground-based experiment lacks only the dynamics i.e., the Doppler profile, while the M1 board will be on orbit. However, the behaviour due to fast movement on orbit is known and the effects on the signal profile are expected.

Conclusion

Space debris is a serious threat to active satellites and future space missions. The impact on low Earth orbit is high with less accurate information about debris. The available technologies are not capable enough to support safety at an acceptable stage. In this paper, we summarize the concept of tracking LEO debris using GPS signals as emitters of opportunity. Our investigation shows that due to extremely low power debris-scattered GPS signal, detection requires a long coherent integration to accumulate sufficient energy. Overcoming the integration limiting factors, extended dwell time is achievable with prior information provided to the receiver. Having a large Doppler shift associated with the debris-scattered signal correlation gain at a detectable range is possible in the presence of strong direct signals. To validate the plan a CubeSat based GPS repeater is proposed as proxy scatterer to replicate small low Earth orbit debris. Existing and future CubeSat missions of RAAF in cooperation with UNSW Canberra brings the opportunity to demonstrate the concept. This alternative is affordable in terms of cost and resource availability to conduct necessary experiments for proof of concept.

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