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A novel signal processing approach for LEO space debris based on a fence-type space surveillance radar system ☆

Jian Huang [a], Weidong Hu [a], Mounir Ghogho [b], Qin Xin [c,*], Xiaoyong Du [a], Weiwei Guo [a]

[a] ATR Key Lab, College of Electronic Science and Engineering, National University of Defense Technology, Changsha, Hunan 410073, PR China

[b] School of Electronic and Electrical Engineering, The University of Leeds, UK

[c] Faculty of Science and Technology, University of the Faroe Islands, Torshavn, Faroe Islands

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Abstract

The increase in space debris can seriously threaten regular activities in the Low Earth Orbit (LEO) environment. Therefore, it is necessary to develop robust, efficient and reliable techniques to understand the potential motions of the LEO debris. In this paper, we propose a novel signal processing approach to detect and estimate the motions of LEO space debris that is based on a fence-type space surveillance radar system. Because of the sparse distribution of the orbiting debris through the fence in our observations, we formulate the signal detection and the motion parameter estimation as a sparse signal reconstruction problem with respect to an over-complete dictionary. Moreover, we propose a new scheme to reduce the size of the original over-complete dictionary without the loss of the important information. This new scheme is based on a careful analysis of the relations between the acceleration and the directions of arrival for the corresponding LEO space debris. Our simulation results show that the proposed approach can achieve extremely good performance in terms of the accuracy for detection and estimation. Furthermore, our simulation results demonstrate the robustness of the approach in scenarios with a low Signal-to-Noise Ratio (SNR) and the super-resolution properties. We hope our signal processing approach can stimulate further work on monitoring LEO space debris.

Keywords: Signal detection; Parameter estimation; LEO debris surveillance; Fence-type radar systems; Sparse reconstruction

1. Introduction

LEO debris, the amount of which has been steadily increasing, presents serious risks to existing space systems. Many efforts had been made to use a fence-type radar system for LEO debris surveillance (Hu et al., 2006, 2007; Huang et al., submitted for publication; Khakhinov et al., 2009; Michal et al., 2005; Montebugnoli et al., 2009; Schumacher et al., 1998). This type of radar system forms a "fence-like" electromagnetic area that can have an extremely large coverage area and is a promising alternative for capturing high-speed LEO objects compared to phased-array radar and optical telescope surveillance systems. A well-known fence radar system is the US Naval Space Surveillance System (NAVSPASUR), which transmits single-frequency, continuous-wave signals and forms a 0.02° beamwidth in the latitudinal direction and a geocentric 50° width in the longitudinal direction. NAVSPASUR has been shown to be capable of detecting LEO debris with inclinations larger than 33°, including approximately 80% of the space objects in the United States Space Command (USSPACECOM) catalogue database (Schumacher et al., 1998). The Graves in France is also a new fence-type radar system that consists of four phased-array radars with each

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* Corresponding author. Tel.: +298 352575.
E-mail addresses: huangjian@nudt.edu.cn (J. Huang), wdhu@nudt.edu.cn (W. Hu), m.ghogho@ieee.org (M. Ghogho), qinx@setur.fo (Q. Xin), xydu@nudt.edu.cn (X. Du), weiweiguo@nudt.edu.cn (W. Guo).

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of them forming an electromagnetic fence with a 10°–30° beamwidth in elevation and 8° in azimuth. With the individual beam scanning in a pre-arranged sequence, this system can cover the entire range of 180° in azimuth (Michal et al., 2005). Currently, there exist several other fence-type surveillance radar systems such as the Italian Medicina space target surveillance system (Montebugnoli et al., 2009) and the Russian Irkutsk ISR (Khakhinov et al., 2009). In Hu et al. (2006, 2007), a double-fence radar system was investigated for LEO debris surveillance that can form a V-shaped electromagnetic beam in the latitudinal direction, unlike the typical fence-type radar systems mentioned previously (Huang et al., Submitted for publication).

The fence-type surveillance radar system is well known for its high efficiency in detecting LEO space debris. In general, the success ratio of space debris surveillance heavily depends on the performance of the signal detection and the parameter estimation in the radar system. However, the accelerated motion of orbiting debris with respect to the radar leads to a frequency modulation at the Doppler frequency and consequently shortens the coherent accumulated time interval, especially for high carrier frequencies.

In addition, because of the limitation of hardware devices for the antennas, the electromagnetic fence usually spreads very wide in the longitudinal direction while remaining quite narrow in the latitudinal direction. This results in a short time window for space debris to cross the fence. For instance, the time duration on average for space debris to cross the electromagnetic fence in NAVSPASUR is approximately 0.1 s (Knowles et al., 1982), which poses a significant challenge to the detection and estimation procedures in a fence-type radar system. Recently, a substantial amount of work has been conducted on signal processing for space debris surveillance systems. In Markkanen et al. (2002, 2005), a generalized match function (GMF)-based method was proposed for signal detection in the EISCAT radar. In Maccone (2007), a fast Karhunen-Loève transform was proposed to improve the signal detection performance in the Medicina bistatic radar. In Isoda et al. (2006), a signal detection method based on coherent accumulation with a linear frequency modulation (LFM) of the transmitted signal was successfully applied to the Kamisaibara radar. The signal models used in the different surveillance radar systems are not required to be exactly the same; thus, the mechanisms used to determine the optimal signal detection and parameter estimation can be significantly different.

Based on the observation of the sparsity, i.e., only a few pieces of space debris can cross the electromagnetic fence in a very short time interval, we can formulate the space debris motion parameter estimation problem as a sparse signal reconstruction one with respect to an over-complete dictionary that will be constructed later.

The sparse signal reconstruction approach has been successfully applied in a variety of applications such as radar imaging (Cetin, 2001). Moreover, this approach can achieve high accuracy in motion parameter estimation as well as a good super-resolution and robustness, especially for the low SNR scenarios. Sparse signal reconstruction represents the signal as a linear combination of the minimum number of generated elements. A crucial step in sparse signal reconstruction is to construct an appropriate over-complete dictionary, which is problem-dependent. For the estimation of the space debris Direction of Arrival (DOA) θ, radial velocity v and acceleration a, the dictionary can be constructed on a grid with all possible velocities v and accelerations a for each possible DOA; *i.e.*, a three-dimensional space can be defined on the grid. Nevertheless, we further exploit the fact that there exists an implicit relationship between the DOA and the radial acceleration by considering the physical orbital motion constraints. This enables us to construct the dictionary using only a two-dimensional $\theta - v$ space, which significantly reduces the size of the dictionary.

The remainder of the paper is structured as follows. Section 2 introduces the system models for space debris, which includes the general signal model, the sparse property, the orbital constraints and the discrete signal model. An inverse problem formulation based on sparse signal reconstruction is presented in Section 3, and the simulation results are provided in Section 4 to demonstrate the effectiveness of our proposed approach. Finally, Section 5 presents our conclusions.

2. Observation model

2.1. Signal model of space debris

A fence-type radar normally transmits single-frequency, continuous-wave signals (Hu et al., 2006, 2007; Huang et al., Submitted for publication; Khakhinov et al., 2009; Michal et al., 2005; Montebugnoli et al., 2009; Schumacher et al., 1998). Here, it should be noticed that according to the specific fence-type radar system being studied, the single-frequency, continuous-wave (CW) signal is slightly modulated by a pseudo-noise (PN) code to obtain the range measurement. However, during the short time for signal processing, the signal model can be assumed equivalent to the unmodulated CW signal after demodulation, i.e., $r(t) = \exp(j2\pi f_0 t)$, where f_0 is the carrier frequency. The backscattered signal at a specific time t by the debris is then given by:

$$s(t) = b_0 \cdot r(t - \tau(t)) \tag{1}$$

where b_0 is the signal amplitude, which is assumed to remain constant over the short duration required for the debris to cross the fence, and τ is the time delay. When a piece of debris crosses the fence, its slight jerk can be neglected. However, the acceleration should be considered because of its influence and the impact on the performance of the signal detection and accumulation (Yuan and Hu, 2009), especially for high carrier frequencies (e.g., a replacement for NAVSPASUR is being developed that will use S-band