ARTICLE IN PRESS

Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research xxx (2014) xxx–xxx

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

An analysis of very short-arc orbit determination for low-Earth objects using sparse optical and laser tracking data

J.C. Bennett [a,b,*], J. Sang [c], C. Smith [b], K. Zhang [a]

[a] The Satellite Positioning for Atmosphere, Climate and Environment (SPACE) Research Centre, School of Mathematical and Geospatial Sciences, RMIT University, GPO Box 2476, Melbourne, Victoria 3001, Australia

[b] EOS Space Systems Pty. Ltd., Mount Stromlo Observatory, Cotter Road, Weston Creek, Australian Capital Territory 2611, Australia

[c] School of Geodesy and Geomatics, Wuhan University, 129 Luoyu Road, Wuhan 430079, China

Received 16 July 2014; received in revised form 15 October 2014; accepted 16 October 2014

Abstract

The requirement to regularly track an increasing number of objects will result in straining existing tracking networks. This paper investigates the orbit prediction capability of an orbit determination process using very short-arc optical and laser debris tracking data for objects in low-Earth orbits. An analysis is carried out to determine the reduction in orbit prediction accuracy when tracking data over 5 s from each pass is only available for an orbit determination.

The results show that the reduction in accuracy is not extensive and good orbit predictions are still possible when using only 5 s of data from the beginning of each pass. The results are achievable due to an accurate ballistic coefficient estimation and accurate tracking data. The dependence of the results on the perigee altitude of the objects is obvious, indicating modelling error of the atmospheric mass density in lower orbits remains the dominant source of error.

Keywords: Short-arc orbit determination; Sparse; Debris

1. Introduction

The near-Earth orbit environment has become progressively cluttered from over 50 years of space operations. Due to the large number of objects, particularly in the low-Earth orbit (LEO) environment, providing reliable orbital information for these objects is a challenging task. The most comprehensive publicly accessible source of orbital data is in the form of two-line element (TLE) sets available through Space-Track.org (https://www.space-track.org). Orbital information is imperative for space situational awareness, particularly for conjunction assessments.

Studies into the population growth of objects in the near-Earth orbit environment have been numerous since Kessler and Cour-Palais (1978) predicted the onset of a collisional cascade (the *Kessler Syndrome*), where collisions become the dominant source of new debris. The instability in some LEO orbits as seen in the modelling studies (Liou and Johnson, 2006, 2008; Rossi et al., 2009; Bennett and Sang, 2011), has sparked in-depth investigations into mitigation and remediation scenarios to stabilise the environment (Braun et al., 2013; Inter-Agency Space Debris Co-ordination Committee, 2013; Liou, 2013; Mason

* Corresponding author at: The Satellite Positioning for Atmosphere, Climate and Environment (SPACE) Research Centre, School of Mathematical and Geospatial Sciences, RMIT University, GPO Box 2476, Melbourne, Victoria, 3001, Australia. Tel.: +61 2 6222 7905; fax: +61 2 6288 2853.

E-mail addresses: james.cameron.bennett@rmit.edu.au (J.C. Bennett), jzhsang@sgg.whu.edu.cn (J. Sang), csmith@eos-aus.com (C. Smith), kefei.zhang@rmit.edu.au (K. Zhang).

http://dx.doi.org/10.1016/j.asr.2014.10.020
0273-1177/

Please cite this article in press as: Bennett, J.C., et al. An analysis of very short-arc orbit determination for low-Earth objects using sparse optical and laser tracking data. Adv. Space Res. (2014), http://dx.doi.org/10.1016/j.asr.2014.10.020

et al., 2011; Phipps, 2014; Stupl et al., 2013; White and Lewis, 2014).

The uncertainty in debris orbit prediction (OP) yields unreliable conjunction assessments which could result in unexpected collisions with operational spacecraft. For example, considering two-body dynamics, the semi-major axis is related to the orbital period through Kepler's third law. An error in the semi-major axis determined from observations results in orbital period error which means that as the prediction period increases, the error in the calculated orbit increases. Regular tracking is required to reduce this error growth. Departing from two-body dynamics, the two main sources of orbit estimation error are incomplete modelling of the perturbing forces acting on the object and sensor measurement error (Vallado, 2007, Ch. 10). Obtaining the true orbit is unlikely when fitting data corrupted with measurement error. The orbit error reduces as the tracking data precision increases. Therefore, highly accurate tracking data is one of the necessities for debris OP accuracy and is necessary to protect space assets.

Currently, the debris laser tracking system located at EOS Space Systems on top of Mount Stromlo, Canberra, requires an accurate track from the optical tracking system before the laser is fired. This limits the system operation to two terminator sessions per day due to the need for the debris target to be sun-illuminated and visible from the ground station. Efforts are underway to extend the system capability to operate outside of terminator – *unaided laser ranging*. A benchmark OP accuracy requirement for unaided laser ranging is set to 20 arc-seconds pointing error, although this is yet to be experimentally verified. Until non-terminator tracking is realised, the system is operational for approximately 4 h a day. This operation time is reduced if weather conditions are not clear. The azimuth and elevation data collected from the optical tracking system has been shown to have approximately 1.5 arc-second root-mean-square (RMS) error. The debris laser ranging system range accuracy is better than 1.5 m RMS error (Sang and Smith, 2011; Sang et al., 2012).

Optimally tasking the laser tracking is a well-constrained problem involving pass duration, geometry, the number of objects to track, telescope slew time, etc. There are multiple ways to optimise an individual tracking session based on specific campaign needs, for example, higher priority may be assigned to objects based on a predefined mission-related hierarchy, limited tracking opportunities, or objects with elements likely to quickly degrade. If the requirement for the pass duration can be minimised, the number of objects that can be tracked during a session increases. Tasking a network of stations is more complicated and is considered in detail by Arregui et al. (2012). In this paper, the focus is to minimise the tracking data requirement rather than optimising the session operation. Any reduction in tracking load of a single station should readily extrapolate to a reduced load in a station network. The goal is to reduce the tracking data requirements without too much loss of OP accuracy in a data sparse situation (i.e. 2 passes) for low LEO debris objects – where atmospheric drag effects are the dominant source of orbit perturbations.

If the data required to achieve a certain OP accuracy can be reduced, this has important benefits in the maintenance of a space debris catalogue. Although not considered in this paper, the buildup of a catalogue of objects is not a simple process and involves many problems including: data association, track correlation, and initial orbit determination (IOD), often from sparse and short-arc data with no a priori orbital information (Milani et al., 2011; DeMars et al., 2012). Orbit and detection constraints can be used to define *admissible regions* (Tommei et al., 2007) and candidate solutions found by sampling. Milani et al. (2012) provide a large-scale simulation study on the creation and maintenance of a space debris catalogue for low-Earth debris objects (above 1100 km perigee altitude) using a network of optical tracking stations. It is found that it would take 2 months to build up a catalogue containing 98% of the objects they considered.

Good OP accuracy has been achieved using sparse optical and laser tracking data of debris objects from a single station (Bennett et al., 2013; Sang and Bennett, 2014; Sang et al., 2014). Together with the accurate observational data, the key to the OP accuracy achievements is the accuracy of the ballistic coefficient determined using a newly-developed method which uses long-term TLE data (Sang et al., 2013). Sufficient OP accuracy for laser debris orbit manoeuvre is achievable, as shown in Bennett et al., 2013.

In what follows, an orbit determination (OD) study is performed to determine if there is any extra benefit in short term OP accuracy in using full passes of optical and laser tracking data versus a scenario where only very short-arc data is available. The situation considered throughout is one of sparseness – the likely scenario when dealing with debris tracking data.

Two OD variants are considered: (1) Initially a least squares OD procedure is used to fit the full pass data; (2) The process is repeated with only 5 s of data from the beginning of each pass used in the OD. The tracking data observations can be taken as 1D – range only; 2D – angles only; and 3D angles and range together. A comparison is made between the OPs from the two OD variants using 3D observations to determine the potential loss of accuracy when using only a small fraction of each pass. The 5 s OD variant is then analysed comparing fitting 3D observations with fitting 1D and 2D data to determine the importance of 3D positioning in short-arc OD. The use of TLE-generated positions as supplemental observations is also analysed to enhance the 5 s 1D and 2D fitting procedure OP accuracy.

In the absence of "true" orbits, the accurate optical and Debris Laser Ranging (DLR) tracking data that falls after the OD period (i.e. *not* used in the OD fitting) is used to determine the accuracy of the OP for the two OD variants. The tracking data distribution used in this work will be presented first, followed by the OD/OP study. The results of