Streak detection and analysis pipeline for space-debris optical images

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Abstract

We describe a novel data-processing and analysis pipeline for optical observations of moving objects, either of natural (asteroids, meteors) or artificial origin (satellites, space debris). The monitoring of the space object populations requires reliable acquisition of observational data, to support the development and validation of population models and to build and maintain catalogues of orbital elements. The orbital catalogues are, in turn, needed for the assessment of close approaches (for asteroids, with the Earth; for satellites, with each other) and for the support of contingency situations or launches. For both types of populations, there is also increasing interest to detect fainter objects corresponding to the small end of the size distribution.

The ESA-funded StreakDet (streak detection and astrometric reduction) activity has aimed at formulating and discussing suitable approaches for the detection and astrometric reduction of object trails, or streaks, in optical observations. Our two main focuses are objects in lower altitudes and space-based observations (i.e., high angular velocities), resulting in long (potentially curved) and faint streaks in the optical images. In particular, we concentrate on single-image (as compared to consecutive frames of the same field) and low-SNR detection of objects. Particular attention has been paid to the process of extraction of all necessary information from one image (segmentation), and subsequently, to efficient reduction of the extracted data (classification).

We have developed an automated streak detection and processing pipeline and demonstrated its performance with an extensive database of semisynthetic images simulating streak observations both from ground-based and space-based observing platforms. The average processing time per image is about 13 s for a typical 2k-by-2k image. For long streaks (length >100 pixels), primary targets of the pipeline, the detection sensitivity (true positives) is about 90% for both scenarios for the bright streaks ($SNR > 1$), while in the low-SNR regime, the sensitivity is still 50% at $SNR = 0.5$.
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1. Introduction

During the past decades, the near-Earth space has become densely populated by man-made objects. It has been estimated that our space activities have left behind a population (active satellites as well as debris) of over 700,000 objects larger than 1 cm (from ESA's MASTER model,[2] Flegel et al. (2011)). To have a realistic understanding of this highly dynamic population – its size and orbital distribution, frequency of collisions etc. – constant monitoring of the objects is required. Observations are being carried out with both ground-based and space-based instrumentation. When observing from ground, optical telescopes are best suited for high-orbiting debris (e.g., geostationary orbits, GEO), while radars can detect debris on low-Earth orbit regime (LEO, below 2000 km). However, there is an increasing interest in applying ground-based optical systems also to LEO objects, to complement the use of radars (e.g., Milani et al. (2012)). On the other hand, as ground-based sensors have a detection limit of centimeters (LEO) to decimeters (GEO), space-based monitoring has been considered to assess the population of small debris objects (e.g., Flohrer et al. (2005)). For optical surveys of space debris, different observing scenarios have been applied and suggested (see, e.g., Schildknecht et al. (2004, 2006) and Valtonen et al. (2006)). While specific (object) tracking techniques can be applied to make the objects appear point-like or as short trails in the exposures, e.g., typical for GEO observations, the general survey scenario is always a "track-before-detect" problem, resulting in trailed objects, or streaks, of arbitrary lengths in the acquired images.

We present results from an ESA-funded StreakDet (streak detection and astrometric reduction) activity, which has aimed at formulating and discussing suitable approaches for the detection and astrometric reduction of trailed objects (streaks) in optical observations, as well as developing and evaluating prototype implementations. The main application targets for the processing pipeline were observations from optical LEO surveys, as well as from space-based optical surveys. The study was further restricted to single-image detections, as compared to rather a typical approach with consecutive frames of the same field, to support the detection of LEO objects, which are characterized by short pass duration and short field-of-view (FOV) crossing times which makes obtaining consecutive images (often referred to as a "tracklet") or even images from the same pass challenging. A major focus in the algorithm development has been on the low-SNR processing, i.e., faint and typically, small objects, but also on the efficiency of computation on current and near-future space-based platforms.

The currently available, mature image-processing algorithms for detection and astrometric reduction of optical

data cover objects that cross the sensor FOV comparably slowly, that is, nearly point-like objects, or within a rather narrow range of angular velocities, resulting in streaks with predefined lengths. In addition to the routine algorithms for processing point-like objects, several considerations for streak-like objects are also available, including rather complete processing pipelines such as the Apex II image processing package (see, e.g., Kouprianov (2008)), Pan-STARRS Image Processing Pipeline (IPP) and Moving Object Processing System (MOPS), or the TAROT software (Laas-Bourez et al., 2009). However, the existing algorithms are typically restricted by one or more assumptions on the observing scenario (e.g., use of object tracking, i.e., assuming star streaks with predefined length and orientation), on the detected objects (e.g., GEO targets producing streaks with predefined length), or require multiple images of the target. In the case of the survey system currently running at ESA's Optical Ground Station (OGS), the algorithm is not designed and optimized to find faint streak-like features. In particular, some of the challenges identified in the objectives of the StreakDet study have not yet been properly addressed. For the LEO and space-based surveys considered, objects typically produce long, potentially non-linear (curved) and non-uniform (discontinuous) streaks, in short, complex streak morphologies, requiring specific algorithms to identify the streaks in the acquired images.

To meet the objectives in the StreakDet framework, we have considered the processing to consist of two major phases: *segmentation*, robust low-SNR extraction of all necessary information (features) from one image, and subsequently, *classification*, the characterization and efficient reduction of the extracted data. The third and last phase of the basic pipeline, *astrometric and photometric reduction* consist of more routine-like tools for coordinate and magnitude conversions. We discuss the adopted approach in more detail in Section 2.1 and review some existing approaches for the two main phases, some of which have served as a starting point for our algorithm development (Section 2). The prototype pipeline is complemented with potential post-processing steps in terms of orbital validation (Section 3.1) and classification method using training data (Section 3.2). In Section 4, we demonstrate the performance of the prototype using both semisynthetic and real observations of space debris. We give our conclusions in Section 5.

2. Processing pipeline

2.1. About the adopted approach

Segmentation. A common difficulty in all astronomical image analysis is the detection of very low-SNR objects, whether space debris, asteroids, or, e.g., Low Surface Brightness (LSB) galaxies. Solving this problem is the main aim of segmentation: to separate unknown or transient objects from an image containing a large number of known