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Analysis of Mono- and Multi-static Laser Ranging Scenarios for Orbit Improvement of Space Debris

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Space debris refers to Earth orbiting objects, which no longer serve any useful purpose. Examples are fragments resulting from collisions, break-ups and explosions, spent upper stages, and decommissioned satellites. The number of space debris objects is rising rapidly, particularly in the very populated LEO regimes, where the density of operational satellites is high. This poses an increasing threat to manned and unmanned space flight. Hence, spacecraft operators are faced with several challenges like conjunction event prediction and close approach assessments, and re-entry follow-up, as well as need precise knowledge on dysfunctional objects, e.g. during contingency situations, and, potentially, for the planning of active debris removal. In this framework, reliable and accurate orbit prediction of space debris is a crucial issue. Currently, the USSTRATCOM maintains the largest space debris objects catalogue with orbital information about the majority of trackable objects. This information is provided in the form of two line elements (TLE), which are for LEO mostly derived from orbit determination using radar-tracking data. These TLEs are basically Kepler parameters and can be used for orbit prediction. However, such predictions tend to be too inaccurate with regard to the challenges named above. Recently, it was shown that laser ranging to space debris targets has the potential to significantly improve the quality of orbit determination giving rise to better predictions in terms of both reliability and accuracy. Detecting the diffusely reflected photons of the transmitting station with several other (passive) stations in multi-static ranging mode proves to be a promising technique to further increase observability of orbit parameters with limited satellite pass durations. Though it is not intended/feasible to use laser ranging for maintaining a catalogue of space debris objects, orbit refinement and even initial orbit determination of selected objects is envisaged and expected to provide valuable support to spacecraft operations.

Our work focuses on the analysis of potential benefits of such multi-static tracking scenarios for orbit prediction based on laser tracking data. We study the cases of only one passive station (bi-static ranging), more than one passive station (multi-static ranging) and ranging simultaneously in both directions (bi-directional ranging). In doing so, orbit refinement with uncertain a-priori information as well as initial orbit determination (without a-priori information) supported by additional telescope angle readings is considered. One of the most relevant challenges of the considered tracking scenarios is clock synchronization between the participating stations, as it directly affects the ranging observations. Moreover, space debris orbit determination and prediction in low Earth orbit is complicated by unknown parameters for nonconservative force modeling due to unknown object geometry, mass and attitude. Hence, parameters such as measurement biases accounting for imperfect time synchronization as well as force model parameters (such as the ballistic coefficient) must be estimated to cope with these difficulties. As the observability of these parameters largely depends on the tracking scenario (e.g. tracking station selection, mono- or multi-static ranging), a-priori orbit information, and observation time (number of passes), we identify requirements on the design of potential tracking campaigns so as to meet necessary orbit prediction accuracies.

The presented work will be based on simulated tracking data. A set of objects representing typical use cases such as collision avoidance, re-entry prediction and contingency scenarios is selected, which serve as the basis for Monte-Carlo simulations. Covariance analyses will facilitate the evaluation of the impact of critical system parameters (e.g. station selection and distribution, clock synchronization accuracy, measurement biases and random errors). We aim to provide a rather general analysis of the abovementioned mono- and multi-static laser ranging scenarios. The comparatively generic and theoretical nature of our simulations shall complement existing work, which mostly focused on laser ranging experiments to particularly suitable objects. Such experiments were primarily meant to study the feasibility of laser-based orbit determination of space debris objects and to test the maturity of the required technology. In contrast, our results shall be useful for ground systems design (e.g. site selection) to support spacecraft operations, which may require accurate orbit determination and prediction of arbitrary objects on demand. Furthermore, the results will be used for campaign planning for the ESA GSTP study "Accurate Orbit Determination of Space Debris with Laser Tracking/Tasking", which is the framework under which our work is performed.