SERENDIPITOUS GEODESY FROM BENNU'S SHORT-LIVED MOONLETS

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ABSTRACT

The Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx; or OREx) spacecraft arrived at its target, near-Earth asteroid (101955) Bennu, on December 3, 2018. The OSIRIS-REx spacecraft has since collected a wealth of scientific information in order to select a suitable site for sampling. Shortly after insertion into orbit on December 31, 2018, particles were identified in starfield images taken by the navigation camera (NavCam 1). Several groups within the OSIRIS-REx team analyzed the particle data in an effort to better understand this newfound activity of Bennu and to investigate the potential sensitivity of the particles to Bennu's geophysical parameters.

A number of particles were identified through automatic and manual methods in multiple images, which could be turned into short sequences of optical tracking observations. Here, we discuss the precision orbit determination (OD) effort focused on these particles at NASA GSFC, which involved members of the Independent Navigation Team (INT) in particular. The particle data are combined with other OSIRIS-REx tracking data (radiometric from DSN and optical landmark data) using the NASA GSFC GEODYN orbit determination and geodetic parameter estimation software.

We present the results of our study, particularly those pertaining to the gravity field of Bennu. We describe the force modeling improvements made to GEODYN specifically for this work, *e.g.*, with a raytracing-based modeling of solar radiation pressure. The short-lived, low-flying moonlets enable us to determine a gravity field model up to a relatively high degree and order: at least degree 6 without constraints, and up to degree 10 when applying Kaula-like regularization. We can backward- and forward-integrate the trajectory of these particles to the ejection and landing sites on Bennu. We assess the recovered field by its impact on the OSIRIS-REx trajectory reconstruction and prediction quality in the various mission phases (*e.g.*, Orbital A, Detailed Survey, and Orbital B).

DATA

Orbital A [Jan. 1, 2019 to Feb. 28, 2019]
- 33202 Doppler and 10848 Range
- 187512 landmark observations
- 33288 image constraints

Orbital B [Jun. 28, 2019 to Aug. 5, 2019]
- 24501 Doppler and 5508 Range
- 73866 landmark observations
- 186003 image constraints

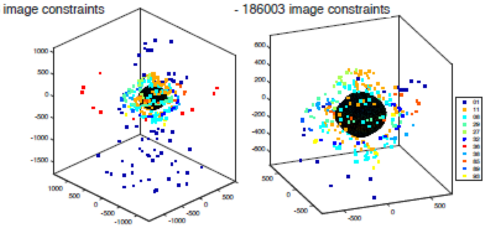

Fig. 1. Positions of particles at observation times in the Bennu-fixed frame

The identification of particles from the NavCam images is a complex process detailed in Liounis et al. (2019). OREx team members validated the 'tracklets' (short series of non-star identifications appearing consistent between NavCam images).

References: Lauretta et al. (2019), OSIRIS-REx Discovery of Particle Ejection from Active Asteroid (101955) Bennu, *Science*, doi:10.1126/science.aay3544 ; Liounis et al. (2019), Autonomous Detection of Particles and Tracks in Optical Images, submitted, *ESS*, arXiv 1911.04449

MODELING

We used the GEODYN orbit determination and geodetic parameter estimation software developed and maintained at NASA GSFC. It has been used over decades for a wide variety of geodetic studies at Earth, the Moon, Mars, Mercury, Ceres, and asteroids (e.g., Eros). The state-of-the-art force and measurement modeling enables the integration of the spacecraft trajectory and estimation based on a wide variety of measurement types. Typical tracking observations are radiometric Doppler and Range from NASA Deep Space Network (DSN) ground stations, but given the weak gravity field of Bennu, they are supplemented by optical measurements derived from NavCam images.

For the OSIRIS-REx mission, additional measurement types were developed and improved. The altimetric ranges from the OSIRIS-REx Laser Altimeter (OLA) can be used as "direct altimetry" by comparison to a pre-defined shape model, or as differenced measurements of co-registered profiles or scans.

GEODYN also has a 'multi-satellite' capability, where multiple bodies can be considered. The co-estimation of OSIRIS-REx and the moonlets allows the consistent computation of partial derivatives for the Bennu geophysical parameters, such as gravity. The image landmark observation was modified to allow "satellite-to-satellite" optical measurements, the only tracking data constraining the particle dynamics. The physical properties of these particles are unknown, and it is desirable to minimize the number of empirical parameters used to fit the optical data. The solar radiation pressure (SRP) modeling was substantially improved, with raytracing against the Bennu shape (mesh with ~800k triangles) rather than a simple spherical umbra/penumbra model (Fig. 2). The Sun is discretized into 100 sources to account for its size and for limb darkening. With these changes, we can successfully fit orbits for a large number of particles with only a SRP scale factor (a proxy for the albedo and area-to-mass ratio), in addition to the initial state (no empiricals or stochastics).

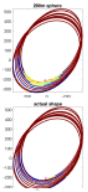

Fig. 2. Differences in solar flux incident on a particle (red=full Sun).

ORBIT FITS

The initial analysis of the particle observations involved "manual" fitting of individual short observation spans ('tracklets') with GEODYN. We also leveraged the work by JPL, UoA, and KinetX which related some of the small tracklets in longer segments, and added to these linkages. The trajectories estimated over these initial short time periods were backward- and forward-integrated to identify potential earlier and later sightings of the same particle in the tracklet database. This was done both by computing orbit differences and by finding observations near the path of the converged particle in the OREx frame (Fig. 3). This helped strengthen the orbit determination (Fig. 4) and lengthened the period of observation for key particles which increased their orbit's sensitivity to Bennu's higher-degree gravity field (Fig. 5). Other particles were on ballistic trajectories and re-impacted Bennu about half an orbit after ejection (Fig. 6).

Later, we used an Extended Kalman Filter to obtain initial state estimates for each tracklet (Liounis et al., 2019). Although non-spherical gravity and non-unity solar radiation scale factors were not considered, this typically proved beneficial to the stability and convergence of the higher-fidelity batched least-squares OD process.

Fig.7 shows the particles estimated during the OrbA mission phase. While OREx flew at <1-km radius in OrbB, many of these particles flew at altitudes <200m for extended periods, some making close approaches within 10-20m of the surface.

These particles also have varied orbit inclinations (Tab. 1) and provide valuable, complementary information to OREx's polar orbits.

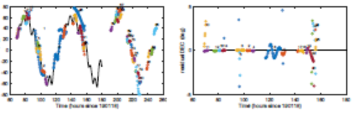

Fig. 3. Example of linkage-finding by propagating a trajectory converged with a few tracklets. The particle observations are compared to that trajectory in RA/DEC space (RA not shown here) to identify potential later sighting of the same particle (e.g., 8-9-17-18-19-22).

GRAVITY SOLUTIONS

In addition to the benefits of particle orbits to understand Bennu as an active asteroid (Lauretta et al., 2019), their low altitude makes them well-suited to provide gravity information not available to the OSIRIS-REx spacecraft in its higher-altitude orbits.

After converging the orbits of individual moonlets from the OREx NavCam observations, we created a single data arc containing the OREx spacecraft and all moonlets. The arc was reconverged and partial derivatives were computed for the dynamical and geometric parameters. Several inversions were performed to assess the strength and robustness of the solution.

We find that the gravity inversion does not require regularization ('Kaula') up to degree ≥6, indicating good spatial coverage (Fig.5). A 6x6 solution was used by the GSFC IV&V team during OrbB operations and was found to perform better in prediction performance than the previous gravity-from-shape (i.e., constant density) field.

Adding a constraint and making use of the Variance Component Estimation procedure to find optimal weights between the various datasets, we obtain the 10x10 gravity field solution shown in Fig. 8. The computed field degree strength is ≥7 and up to 10 in limited regions. The errors predicted from the resulting covariance can be mapped to support for instance studies of density variations.

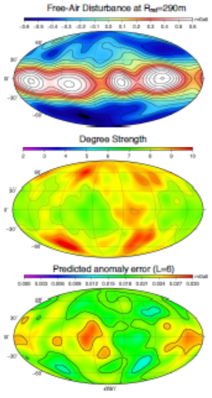

Fig. 8. Mapped gravity field, degree strength, and anomaly error for the 10x10 gravity field solution.

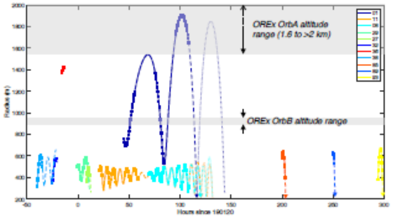

Fig. 7. Time series of orbit radius for a number of OrbA moonlets. Observation times are indicated by a square symbol on the trajectories.
[reconstructed = solid; propagated = dashed]

ID	sma	ecc.	inc.	asc.node
OrbA	1829.495	0.155	89.025	28.867
1	1022.199	0.327	90.090	307.591
8	415.864	0.075	82.797	309.961
11	381.740	0.315	82.697	322.195
38	473.534	0.417	15.551	128.539
32	492.310	0.289	15.010	96.791
36	857.100	0.633	89.059	5.496
29	474.406	0.112	15.622	58.329
27	372.271	0.353	83.951	324.511
85	357.535	0.809	28.845	0.917
89	321.454	0.983	142.943	176.795

Tab. 1. The moonlets observed in OrbA have a variety of orbit inclinations, which benefits the determination of individual gravity coefficients.

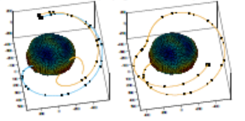

Fig. 4. Due to the line-of-sight nature of the observations, orbit fits can be quite sensitive to the initial state and to the amount of optical data used. [inertial frame]

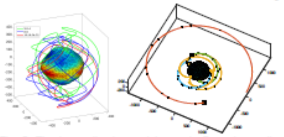

Fig. 5. The longer-lived moonlet sample Bennu's gravity field at much lower altitude than safely accessible by OREx. [Bennu-fixed frame]

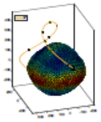

Fig. 6. Example of a very short-lived moonlet. [Bennu-fixed frame]