RECOVERY OF BENNU'S ORIENTATION FOR THE OSIRIS-REX MISSION. E. Mazarico[1], D. D. Rowlands[1], T. J. Sabaka[1], K. M. Getzandanner[1], D. P. Rubincam[1], J. B. Nicholas[2], M. C. Moreau[1], M. Daly[3], O. S. Barnouin[4], and D. S. Lauretta[5]. [1] NASA Goddard Space Flight Center, Greenbelt, MD, USA (erwan.m.mazarico@nasa.gov); [2] Emergent Space Technologies Inc., Greenbelt, MD, USA; [3] Centre for Research in Earth and Space Science, York University, Toronto, ON, Canada; [4] John Hopkins University Applied Physics Laboratory, Laurel, MD, USA; [5] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA.

Introduction: The Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer (OSIRIS-REx) mission is a NASA New Frontiers mission with the primary objective to return an asteroid sample [1]. Launched on September 8, 2016, it will rendezvous with near-Earth asteroid (101955) Bennu in August 2018. Before sample acquisition, OSIRIS-REx will survey Bennu in great detail to select a scientifically compelling sampling site and to thoroughly understand the shape and dynamics of Bennu and ensure mission success. While the general shape of Bennu has been characterized by ground-based radar observations [2], laser altimetry and camera observations by OSIRIS-REx will yield topographic models of extreme resolution. The long-wavelength gravity field of Bennu will be characterized from the radio tracking of the spacecraft by the NASA Deep Space Network (DSN) ground stations. The orientation dynamics of Bennu also need to be characterized to high accuracy in order to meet the navigational requirements to execute the sampling maneuver. Here, we describe our efforts to demonstrate through a comprehensive simulation that even in the presence of complex rotational dynamics, data returned from the suite of instruments carried by OSIRIS-REx is sufficient to achieve these objectives.

Planetary Orientation: The transformation between the Bennu-fixed frame and inertial space is required for navigation and science e.g. to geolocate instrument data collected at various times onto Bennu's surface. Following IAU convention, the rotation transformation at any epoch is described by three angles: right ascension α, declination δ, and prime meridian location W. Though not arbitrary, the time history of those three angles can vary in complexity. To good approximation, major planets have simple rotations (fixed α and δ, and W linear in time). Longitudinal librations (e.g., Mercury [3]) can be represented by an additional series of periodic terms on W. Simple nutation and precession can also be represented by analytical periodic terms on α and δ.

A wobble state means that there is a rotation about all three body-fixed axes, that the position of the instantaneous spin axis is changing in the Bennu-fixed frame, and that this instantaneous spin axis would trace out an ellipse centered at Bennu's body-fixed Z axis with a given period. From the equations of motion, the wobble period is related to the spin period and the Bennu moments of inertia, and is expected to be ~43 hours for Bennu given current knowledge.

While planetary orientation can be, and has typically been in previous space geodesy work, represented analytically by a simple set of parameters describing constant, linear, and periodic terms in α, δ, and W, this is not well adapted to Bennu. Specifically, the exact period of the wobble would then need to be prescribed but is currently unknown at the required accuracy level. Instead, a full dynamic approach is preferred in which the equations of motions are integrated and used to estimate initial state and inertia tensor (12 total).

We performed dedicated, focused simulations and showed that the Bennu shape and its moments of inertia limit how well a simple analytical model can describe the actual time history of orientation, that is, how quiet and simple Bennu's spin can be. The discrepancies can reach the level of accuracy desired for the OSIRIS-REx sampling event (~1 meter due to uncertainties in the orientation), which further justifies the need to adopt the dynamical approach.

A potential difficulty is related to the linearity and stability in the estimation of the 12 orientation state parameters. Focused simulations demonstrated robustness to small errors in diagonal moments of inertia values as long as the off-diagonal elements are significantly smaller (that is, if we are approximately in the geodetically-prefered principal axes frame).

Orbit Determination: To perform the orientation recovery simulations, and to support the mission during Bennu encounter, we used the GEODYN orbit determination and geodetic parameter estimation software developed and maintained at NASA GSFC. GEODYN has been used for a large number of Earth and planetary missions to analyze numerous types of spacecraft tracking data. Accurate force and measurement models allow the precise reconstruction of spacecraft orbits and the estimation of parameters of interest (e.g., Bennu ephemeris, gravity field coefficients, orientation).

One distinctive feature of GEODYN is the capability to simultaneously analyze radio tracking, imagery such as landmarks, and laser altimetric ranges. Thanks to OSIRIS-REx's capable payload, we are able to leverage all these measurements. For both imagery and altimetry, GEODYN is able to model and analyze undifferenced and differenced data. Image landmark measurements [4] are undifferenced as a single image observation and prior knowledge of landmark positions are sufficient to compute observation residuals. Similarly, individual altimetric ranges to a prescribed shape can be used as undifferenced geodetic measurements.

Altimetric crossovers used at Mars [5] and the Moon [6] are an example of differenced measurements. Another differenced measurement type planned for use at Bennu with OSIRIS-REx is the altimetric constraint introduced by [7], which describe the spatial relationship between two individual altimetric measurements. Differenced imagery data ('landmark crossovers') are constraints to have two Bennu-fixed vectors to identical image features intersect, with no need for prior knowledge of this feature's position.

Simulation of Wobble Recovery: We performed comprehensive simulations based on a realistic operations scenario [8]. We focused on a 3-day period during Orbital Phase B, immediately prior to the initiation of the sampling event, because that is the critical phase for the knowledge of Bennu's orientation. The DSN tracking schedule resulted in ~1900 Doppler observations, and imaging and altimetry were acquired at 42 epochs. These 42 images provide ~820 landmark observations and ~730 landmark crossovers. Altimetry data during these scans were decimated from the expected firing rate, but still provided ~275,000 altimetric ranges, and ~30 altimetric constraints.

Realistic errors were introduced, with significantly perturbed gravity coefficients, biased spacecraft panel reflectivities (used to model solar radiation pressure), 1-m Gaussian errors on landmark coordinates, spacecraft attitude errors, and 30-arcsec 150s-periodic roll and pitch errors on OLA scan errors. We also imposed errors on the initial orientation state, which featured a large 1° wobble. These large systematic effects make for a realistic simulation.

Results and Implications for Spin State Recovery and Geolocation Accuracy: The iterative solutions converged well, reducing the measurement residuals. To assess the performance of the orientation recovery, one can either compare the recovered time history of the three orientation angles, or compare the geolocation error of surface features. The distinction may appear subtle but is important. Indeed, to successfully acquire a sample, OSIRIS-REx requires good relative geolocation knowledge, regardless of biases. if both spacecraft and Bennu have biased estimates.

While the astrometric (inertial) performance is better with downweighted undifferenced measurements, the geolocation performance degrades. Similarly, better geolocation performance is obtained when upweighting the undifferenced data. This can be explained by the fact that the mean errors in orientation angles for the pole of Bennu are compensated in large part by similar, correlated errors in the absolute inertial orientation of the OSIRIS-REx orbit plane (Figure 1).

From our simulation results, we find geolocation errors that meet the <1m requirement, with typical RMS numbers of 30-40 cm (and maximum up to 90 cm). These exhibit a dependence on site latitude, with best performance near the equator.

Conclusions: Our comprehensive simulation demonstrated that the simultaneous use of all tracking data collected by OSIRIS-REx allows precise determination of Bennu's orientation which can ensure successful sampling. With the goal to minimize the geolocation errors, especially important for the sampling, the undifferenced landmark and direct altimetry data types provide a stronger tie to the asteroid frame. This important finding will be used during operations at Bennu. More details on the simulation can be found in [9].

References: [1] Lauretta D.S. et al. (2017) *Sp. Sci. Rev.* [2] Nolan M.C. et al. (2013), *Icarus*, 226. [3] Margot J.-L. (2009), Celest. Mech. Dyn. Astr., 105. [4] Konopliv A.S. et al. (2015), Icarus, 240. [5] Lemoine F.G. et al. (2001), JGR, 106. [6] Mazarico E. et al. (2012), J. Geod., 86. [7] Mazarico E. et al. (2010), J. Geod., 84. [8] Getzandanner K. et al. (2016), 39th AAS GNC, 16-103. [9] Mazarico E. et al. (2017), *J. Geod*.

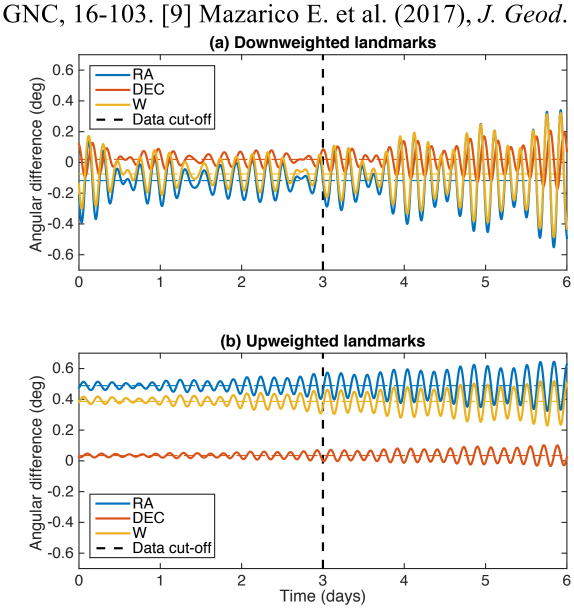

Figure 1. Errors in the orientation angles (α, δ, W) with radio, altimetry, and landmark data (downeighted in **a**; upweighted in **b**). The correlation between α and W leads to biases. After the data cut-off date, the prediction performance degrades slowly. Downweighting the landmarks yields better average orientation angles. But the geolocation performance is better with upweighted landmarks, thanks to orbit plane errors partially compensating the inertial pole position errors.