The Ephemeris of Asteroid (101955) Bennu from OSIRIS-REx Approach Data.

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Introduction: OSIRIS-REx is a sample return mission to near-Earth asteroid (101955) Bennu [1]. Our contribution to the OSIRIS-REx radio science investigation includes the estimation of the accurate trajectory of Bennu, the hazard assessment of a possible collision between Bennu and Earth, and the modeling of the Yarkovsky effect acting on Bennu [2].

Before launch in September 2016, we delivered JPL solution 76 as the baseline ephemeris of asteroid Bennu to be used for OSIRIS-REx operations [3]. JPL solution 76 was based on ground-based measurements from 1999 to 2013: 478 optical, 22 delay, and 7 Doppler observations. This wealth of data provided extremely strong constraints on the trajectory of Bennu, resulting in formal 1σ ephemeris uncertainties smaller than 10 km for the Approach phase of OSIRIS-REx.

After about two years of cruise, the OSIRIS-REx spacecraft first imaged Bennu on 2018 August 17 and optical navigation measurements [4] have been regularly collected since then. These spacecraft optical measurements represented the first opportunity since 2011 to significantly improve our knowledge on the trajectory of Bennu. The new solution (JPL 103) incorporates spacecraft observations and is reported here.

Synthetic astrometric observations: We fit the OSIRIS-REx radiometric [5] and optical navigation data from 2018 August 15 to 2018 October 29 using JPL's Mission Analysis, Operations, and Navigation Toolkit Environment [6]. Our goal was to generate three synthetic astrometric observations of Bennu from the OSIRIS-REx spacecraft. Therefore, we split the data arc in three disjoint arcs separated by the first two Asteroid Approach Maneuvers.

For each data arc, we estimated the position and velocity of the spacecraft, the ephemeris of Bennu, solar radiation pressure scale factors, impulsive ΔV for small-burn events, and polynomial stochastic accelerations $\sim 3\times10^{-12}$ km/s^2. We adopted large a priori uncertainties in the estimated parameters to make the solutions from each of the disjoint arcs as independent as possible. In particular, we scaled the a priori uncertainty of the JPL 76 ephemeris solution by a factor of 1000 and therefore ensured that the information on the Bennu ephemeris coming from each arc was independent of any prior knowledge.

For each arc, we selected an epoch around the middle of the arc, computed the nominal light-time–corrected, line-of-sight direction from OSIRIS-REx to Bennu, and projected the Bennu positional covariance into the corresponding plane-of-sky. Figure 1 shows this plane-of-sky mapping on 2018 September 07 (first arc). Finally, we converted the three mappings to synthetic plane-of-sky angular measurements, which are reported in Table 1.

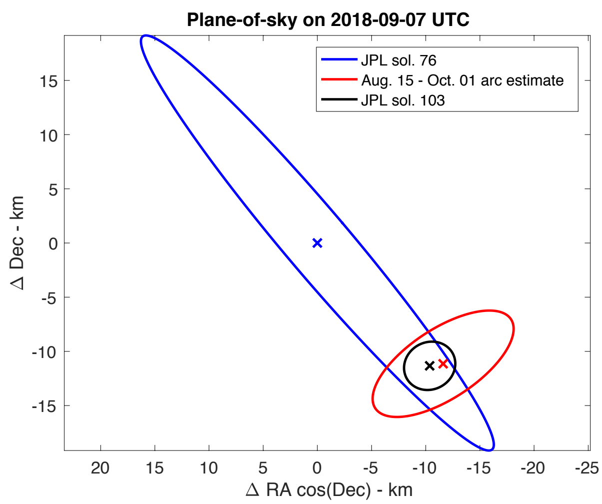

Figure 1. Projection of the Bennu ephemeris and 3σ uncertainty onto the 2018 September 07.0 UTC plane-of-sky as seen from the nominal OSIRIS-REx position. The line of sight is light-time–corrected.

Updated Bennu ephemeris: Since the delivery of JPL solution 76, we updated the ground-based observational dataset with eleven additional astrometric positions, for a total of 489 ground-based optical measurements. The resulting data arc goes from 1999 September 11 to 2018 May 15. To this dataset we applied the more recent star catalog debiasing and weighting schemes [7,8], though we retained some weights and outlier rejections that we had previously set manually [3]. Finally, to this optical dataset and the three radar apparitions, we added the three synthetic observations of Table 1.

The updated ephemeris (JPL solution 103) corresponds to a 2σ correction relative to JPL solution 76. The most statistically significant corrections are in eccentricity, inclination, time of perihelion, and argument of perihelion. On the other hand, both semimajor axis and the Yarkovsky drift are within the 1σ uncertainties of JPL solution 76. In particular, the revised Yarkovsky estimate does not materially affect previous estimates of the density and mass of Bennu [2].

Figure 1 compares JPL solutions 76 and 103 in the OSIRIS-REx plane-of-sky on 2018 September 07, while Fig. 2 shows the radial, transverse, and normal trajectory differences. The largest trajectory difference through the rest of the mission is 31 km and solution 103 reduces the Bennu ephemeris 3σ uncertainties through the rest of the mission to less than 11 km.

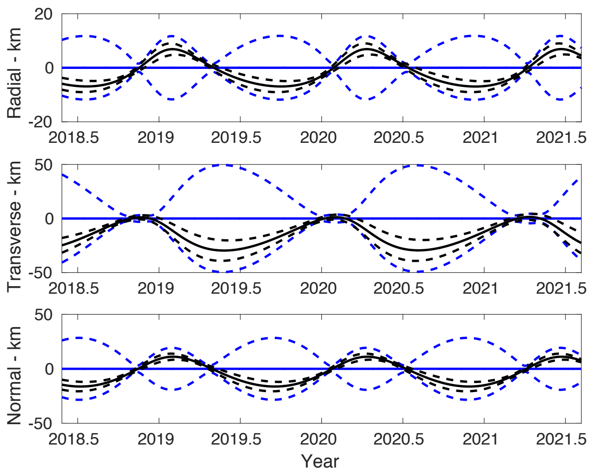

Figure 2. Trajectory differences between JPL solution 76 (solid blue line) and solution 103 (solid black line). Dashed lines correspond to 3σ uncertainties.

Implications for the impact hazard assessment: A refined hazard assessment will be performed later in the mission when even tighter and more conclusive ephemeris constraints will be available. Here, we performed a linear mapping of JPL solution 103 to the 2135 close approach. The close approach distance goes from 150,000 km to 300,000 km (3σ range), while the value of the Opik ζ coordinate [9] is ζ_{2135} = 190,000 ± 90,000 km (3σ uncertainty). While some of the possible impacts found by [2] appear to be ruled out, some kilometer-sized keyholes persist within the core of the distribution.

References: [1] Lauretta et al. (2017) *Space Science Reviews, 212*, 925–984. [2] Chesley et al. (2014) *Icarus, 235,* 5–22. [3] Chesley and Farnocchia (2013) *JPL Technical Report,* IOM 343R-13-001. [4] Owen (2011) *AAS Spaceflight Mechanics Conference,* 11-215. [5] Thornton and Border (2003) *Radiometric Tracking Techniques for Deep-Space Navigation*. [6] Evans et al. (2018) *CEAS Space Journal, 10,* 79–86. [7] Farnocchia et al. (2015) *Icarus, 245*, 94–111. [8] Veres et al. (2017) *Icarus, 296*, 139–149. [9] Valsecchi et al. (2003) *A&A, 408*, 1179–1196.

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Table 1. Synthetic astrometric positions of Bennu relative to the nominal OSIRIS-REx position. The uncertainty in RA uncertainty is multiplied by cos(Dec). The OSIRIS-REx X, Y, and Z coordinates are relative to the geocenter and are in the equatorial J2000 reference frame.

Time UTC	2018-09-07.0	2018-10-08.0	2018-10-22.0
RA (hms)	17 50 55.124	17 49 08.532	20 26 44.175
Dec (dms)	-09 04 04.99	-09 20 47.29	-22 49 20.41
$1\sigma_{RA}$ (″)	0.36	3.67	106
$1\sigma_{Dec}$ (″)	0.27	3.12	75.3
Correlation of RA and Dec	-0.66	-0.95	-0.97
OSIRIS-REx X (km)	-43784303.392	-4093092.403	18985529.722
OSIRIS-REx Y (km)	-93008364.473	-114254805.813	-115915374.340
OSIRIS-REx Z (km)	-58470953.387	-60708385.658	-57623056.604