MRD 150- Bennu Ephemeris

Data Product Overview

This data product is responsive to MRD-150 (2.14.1) Measure the Yarkovsky acceleration of Bennu with a SNR ≥400.

This document discusses only the Bennu ephemeris aspect of MDR-150. Other aspects are covered elsewhere, for example:

- Yarkovsky measurement
- Bennu pseudo-ranging measurements
- Bennu planetary encounters and impact hazard analysis

The "Bennu ephemeris" data product will consist of an SPK file containing Bennu's trajectory information.

Overview
This data product is used for navigation, science value, and long-term science.

Inputs:

Bennu pseudo-ranging data product

Time to produce will be on the order of days to complete the analysis and the associated report.

Data Product Structure and Organization
This data product is delivered as an SPK file.

Data Format Descriptions
The Bennu ephemeris file will be delivered in an SPK file format, which contains Chebyshev polynomial coefficients.
See
ftp://ssd.jpl.nasa.gov/pub/eph/small_bodies/orex/asteroid/IOM_343R-13-001.pdf
(copy downloaded 2016-03-10 here)

Data Product Generation

This product development will be led by Co-I Steve Chesley through the Radio Science Working Group.

The Bennu ephemeris will be generated at JPL through a least-squares orbit determination process using the Bennu pseudo-ranging data product.

Multiple versions of the products may be generated in case of:

- Significant change in spacecraft orbit

Data Product Validation
Verification will be ascertained by analyzing the output from the ephemeris reconstruction by RSWG and DEWG.

Data Flow
See

ftp://ssd.jpl.nasa.gov/pub/eph/small_bodies/orex/asteroid/IOM_343R-13-001.pdf

(same file as above) for more details.

Standards used to generate data product
Any standards will be discussed in the report.

JET PROPULSION LABORATORY **INTEROFFICE MEMORANDUM**
IOM 343R-13-001
February 5, 2013

TO: Distribution

FROM: Steven R. Chesley, Davide Farnocchia (JPL Solar System Dynamics, 343R)

SUBJECT: Asteroid 101955 (1999 RQ36) Ephemeris Delivery, JPL Solution 76

This memorandum documents the initial ephemeris file delivery for asteroid 101955 (1999 RQ36) in support of the OSIRIS-REx mission. JPL orbit solution 76 fits 478 optical measurements over the interval 1999–2013, as well as a total of 22 radar delay and 7 Doppler measurements in September 1999, 2005 and 2011. Solution 76 includes an estimate of a non-gravitational acceleration on 1999 RQ36 known as the Yarkovsky effect, which is the recoil acceleration from thermal re-emissions of absorbed solar radiation. Formal uncertainties during the planned approach phase of OSIRIS-REx are under 10 km.

Introduction

The OSIRIS-REx asteroid sample return mission is scheduled for launch in September 2016, and approximately two years later it will begin its approach to the target asteroid 101955 (1999 RQ36). The mission plan calls for the spacecraft to be in the vicinity of the asteroid from rendezvous in October 2018 until asteroid departure in March 2021, although proximity operations are expected to end after the first sample collection attempt in July 2019.

Efforts at optical acquisition of 1999 RQ36 by OSIRIS-REx are scheduled to start 2018-Aug-15. Mission requirements call for acquisition no later than 2018-Sep-10, which is 21 days before the first rendezvous maneuver AAM-1.

1999 RQ36 is a near-Earth asteroid with an effective diameter of 493 meters. The asteroid has experienced a series of encounters with the Earth in recent years, starting with the discovery apparition in 1999, when it approached to within 0.015 au of the Earth. This was followed by progressively more distant approaches every six years, and at each encounter radar delay measurements from Earth were successfully received. With this well-distributed set of high precision position measurements, the orbit is tightly constrained and the effect of tiny accelerations on the asteroid becomes important to model. For example, the Yarkovsky effect is detected with better than 1% precision, and the relativistic perturbations due to the Earth monopole have a significant effect on the trajectory.

Orbit Determination

The current orbital solution is JPL 76 and is detailed in Table 1. Solution 76 is based on 478 ground-based RA/DEC observations, as well as 22 radar delay and 7 Doppler measurements from the Arecibo and Goldstone radar observatories.

Astrometry. The treatment of the radar data is according to the observer-assigned uncertainty estimates[1], but the statistical treatment of the optical astrometry is not as straightforward. The de-biasing algorithm developed by Chesley et al. (2010), was used to minimize the effect of systematic errors associated with zonal errors in reference star catalogs. The weighting scheme described by Chesley et al. (2010) was also used, although considerable care was dedicated to identifying and removing statistical outliers in the set of optical astrometry, leading to the elimination of 91 data points considered discordant with the mass of the observations.

As discussed below, the selection of outliers does have a statistically significant effect on the ephemeris. To explore this sensitivity, we have generated for comparison four additional orbital solutions with a variety of automatic outlier rejection parameter settings. These are summarized in Table 2, which shows the solution number and the χ_{rej} parameter value used in the algorithm described by Carpino et al. (2003), and the number of outliers rejected in the solution. Below we discuss the dependency of the ephemeris prediction on the outlier rejection approach.

Dynamical Model. The 1999 RQ36 orbit is estimated based on an extraordinarily refined dynamical model. The dominant forces on the asteroid come from the point-mass gravitational perturbations of the Sun, Moon, eight planets, and Pluto. The positions of these bodies are taken from DE424 (Folkner, 2011), which also defines the reference frame of the 1999 RQ36 ephemeris. Relativistic perturbations are applied from the Sun, Moon and eight planets based on the EIH formulation (e.g., Moyer, 1971). While the relativistic perturbation of the Sun is often crucial in fitting asteroid orbits, this is the first case where the relativistic perturbation of the Earth affects the ephemeris in a statistically significant way. Other small perturbations in the force model include point-mass perturbations from 25 main-belt asteroids, the J_2 spherical harmonic term in the geopotential, and direct solar radiation pressure (assumed area-to-mass ratio 3.07×10^{-6} m^2/kg). Finally, the Yarkovsky effect is perhaps the most interesting and informative perturbation in the force model.

There are three numerical models at hand for the Yarkovsky effect. The lowest fidelity model applies a transverse acceleration of the form $a_T = A_2 r^{-d}$ where A_2 is an estimated parameter, r is the heliocentric distance, and d is strictly in the range 0.5–3.5, but for most NEAs the value is in the range 2-3 (Farnocchia et al., 2012). For the known physical characteristics of 1999 RQ36, $d = 2.75$. This model neglects out-of-plane and radial accelerations, as well as some finer details in the transverse acceleration such as hysteresis, but it captures the key aspects of the Yarkovsky effect, is computationally fast and requires no information on the physical properties of the asteroid and thus is the most generally applicable. The next step up in fidelity is termed the Linear Model,

[1]The radar astrometry and uncertainty can be viewed at `http://ssd.jpl.nasa.gov/?radar`.

Table 1: Post-fit summary of asteroid 101955 (1999 RQ36) JPL Orbit Soln. 76.

```
 Object: Minor Planet 101955 (1999 RQ36)
 Ref. Solution: 76
 Producer: Steven R. Chesley
 Planetary Ephemeris: DE424
 Small Body Ephemeris: SB424-RQ36
 No. Observations:    507
 Observation Arc: 1999-Sep-11.4 to 2013-Jan-20.1

 ---- Optical Residuals ----      RA        Dec      Total
 Mean weighted residual         0.000     0.062     0.062
 RMS, unweighted                0.275     0.238     0.257
 RMS, weighted                                      0.248
 Normalized RMS                                     0.266
 No. optical observations:   478 used and   91 deleted.

 ----- Radar Residuals -----     Delay   Doppler   Radar+Opt
 Normalized RMS                 0.170     0.229     0.264110
 No. Delay observations: 22 used and   0 deleted.
 No. Doppler observations:  7 used and   0 deleted.

 ---- Corrected Elements (J2000):  Solution 76
   Epoch  2455562.50000 = 2011 Jan  1.00000
                          Post-Fit Std.Dev.
 EC   0.2037451146135014    2.123081E-08 d
 QR   0.8968943569669300    2.390158E-08 au
 TP   2455439.1419464422    3.025935E-06 d    2010 Aug 30.64195
 OM     2.06086819910204    6.531279E-08 deg
 W     66.22306886293201    9.685025E-08 deg
 IN     6.03493867976381    4.721372E-08 deg
 A     1.126391025571644    4.111300E-11 au
 P     436.6487279241047    2.390600E-08 d    1.19545811633719 yr
 RHO    957.452515773391    5.070551E+00 kg/m^3

Legend (angles WRT J2000 Ecliptic):
 EC - Eccentricity
 QR - Perihelion distance (au)
 TP - Perihelion Passage Time
 OM - Longitude of Ascending Node (deg)
 W  - Argument of perihelion (deg)
 IN - Inclination (deg)
 A  - Semimajor axis (au)
 P  - Orbital Period (days/years)
 RHO- Asteroid Bulk Density (kg/m^3)
```

Table 2: Outlier Rejection Test Solutions

Solution No.	Outlier Criterion	No. Rejected
81	$\chi_{rej} > 3$	3
82	$\chi_{rej} > 2$	15
84	$\chi_{rej} > 1.5$	24
83	$\chi_{rej} > 1$	51
76	Manual	91

which assumes a linearized heat transfer model on a homogeneous sphere with known spin state (Vokrouhlický et al., 2000). This model does include radial and out-of-plane accelerations, and also allows inferences for physical parameters, but for typical spheroidal asteroid shapes the key assumptions (sphericity and linearity) introduce errors of a few percent in the acceleration and several percent in the derived physical quantities.

Our highest fidelity Yarkovsky model is produced in collaboration with D. Vokrouhlický of Charles University in Prague. This model uses the shape model of Nolan et al. (2012) in a fully nonlinear, finite-element heat transfer model, with shadowing and re-absorption. The technique computes the thermal evolution over several orbital periods until it has stabilized, and then produces a look-up table of thermal recoil acceleration $\vec{a}_Y$ as a function of orbital anomaly. This look-up table is interpolated in the orbit propagation and estimation process to derive the acceleration at any point in the orbit. One shortcoming of this approach, which is important for 1999 RQ36, is that the look-up table is computed for a frozen orbit, and so strictly applies only to the assumed semimajor axis a and eccentricity e. An enhancement to the model developed for the OSIRIS-REx mission was to make additional runs with varied orbital elements, which allowed construction of a table of partial derivatives $\partial\vec{a}_Y/\partial(a, e)$ from finite differences. This allowed us to correct the acceleration for off-nominal orbital elements during the trajectory propagation. The estimable parameter associated with the nonlinear Yarkovsky model is the bulk density ρ, identified as `RHO` in the associated file deliveries.

Ephemeris Predictions

As mentioned above, the OSIRIS-REx mission requirements call for an optical detection of 1999 RQ36 by 2018-Sep-10, at which point the asteroid should be at a range of approximately 1 million km. The Radial-Transverse-Normal (RTN) position uncertainties in the Soln. 76 ephemeris prediction at that time will be (3.3, 3.8, 6.9) km. These are formal, one-sigma uncertainties. In the spacecraft plane-of-sky the uncertainty ellipse has a semimajor axis 8.3 km and a semiminor axis of 0.9 km oriented 50° North of East in the RA-DEC frame. The OSIRIS-REx plane-of-sky presentation is depicted in Fig. 1, where Soln. 76 is placed at the origin, and a variety of other solution predictions are also depicted. The predictions based on the three Yarkovsky models described above differ by only a kilometer or so, with the Linear and Nonlinear models falling within a few

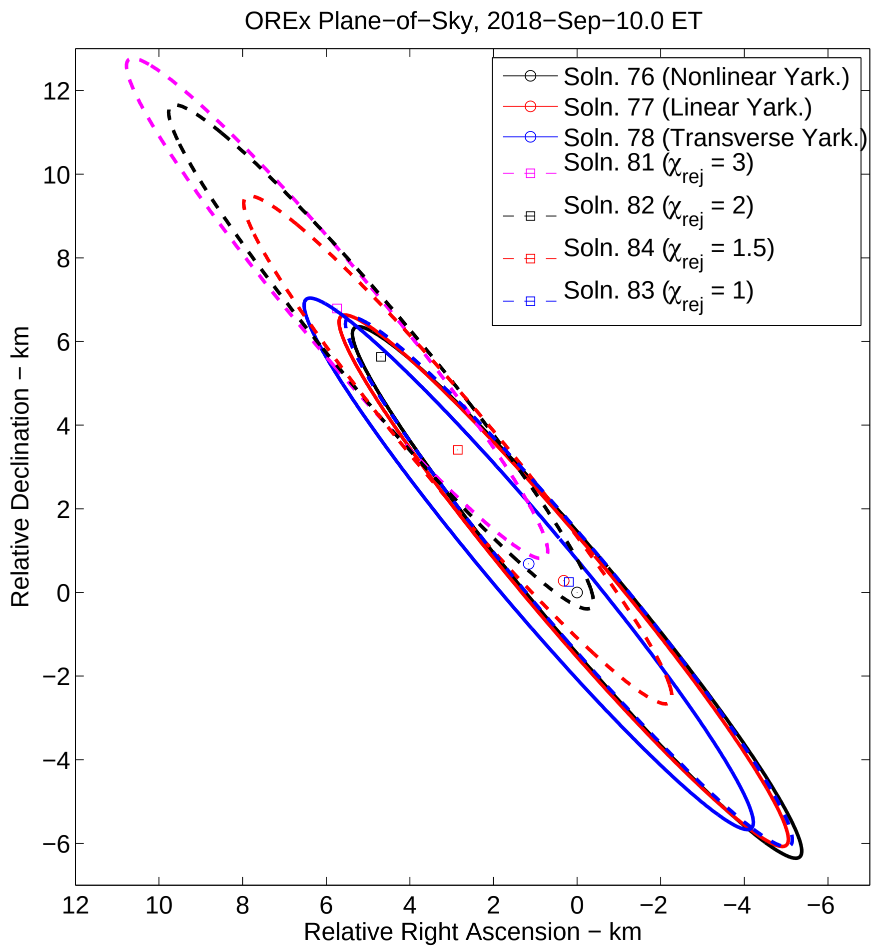

Figure 1: 1999 RQ36 position and uncertainty in the OSIRIS-REx plane of sky at 2018-Sep-10. The various solutions reflect the effect of different models for the Yarkovsky effect and different criteria for identifying statistical outliers.

hundred meters of each other.

The importance of careful handling of statistical outliers is reflected in Fig. 1, where the solutions are seen to progress steadily towards Soln. 76 as progressively more stringent requirements are placed on the outlier selection. These solutions can be cross-referenced with Table 2. The most inclusive approach to outliers (Soln. 81) places the prediction just over 1 sigma from the Soln. 76 prediction; however, even a cursory inspection of the data indicates that numerous spurious points remain in the fit for that solution. While the manual outlier rejections in Soln. 76 are rather more aggressive than even the most stringent automatic selections (Soln. 83), the separation between these two solutions is slight, and both are very well constrained by the observational data, with 478 and 518 optical observations, respectively. Most of the movement in the plane-of-sky predictions due to outlier treatment can be traced to a small handful of observatories with significantly biased observations. In most cases the manual approach deletes the entire contribution from a problematic observatory, rather than only those that are clearly discordant with the bulk of the data.

The formal uncertainties stated here do not capture the possible effects of mismodeling, either in the force model or the observational error model, either of which can in some cases increase the dispersions by perhaps a factor of two. While this problem is dramatically more severe for comets, in the present case we are pushing the force model fidelity and observational accuracy to unprecedented levels, which means that possible mismodeling of small perturbations still leaves some potential for statistically significant effects. For this reason any OSIRIS-REx mission operations that rely critically on the 1999 RQ36 ephemeris accuracy should apply safety factors of 2-3 to the ephemeris uncertainties stated here.

Ephemeris and Partial Derivatives Files

All of the following files and documentation are available from the JPL Solar System Dynamics (SSD) FTP server

`ftp://ssd.jpl.nasa.gov`

in the directory

`pub/eph/small_bodies/orex/`,

which will be the base directory for OSIRIS-REx file deliveries from SSD. Within the `orex` directory are three sub-directories as follows:

`orex/planet/` This directory includes the ephemeris files and associated documentation for the DE424 planetary ephemeris (Folkner, 2011), which establishes the reference frame for the 1999 RQ36 ephemeris. DE424 is provided in both NIO and SPK formats. The time span of the provided files is from 1964-Jul-12 to 2025-Jan-13, which covers the OSIRIS-REx mission time frame.

`orex/asteroid/` This directory holds the current 1999 RQ36 ephemeris files:

`sb-101955-76.nio.ftp` - Small body ephemeris in NAVIO tranfer format

`sb-101955-76.tsp` - Small body ephemeris in SPK tranfer format

`sbp-101955-76.nio.ftp` - Small body partials in NAVIO tranfer format

`cov-101955-76.txt` - Set III covariance matrix in FORTRAN NAMELIST format

The time span of the ephemeris file is from 2015-Jan-01 to 2023-May-31 and that of the partial file is from 2015-Jan-01 to 2023-Jan-07. The mapping epoch of the covariance and partials files is 2019-Jan-01.0 ET. The Set 3 covariance matrix is listed with reduced precision in Table 3. Full precision can be found in the NAMELIST format file `cov-101955-76.txt`.

`orex/doc/` This directory includes miscellaneous documentation files that may be of use to those using the delivered files. For example, the documentation for the small-body NAVIO ephemeris (Chamberlin, 1998) and partials (Chodas, 1998) files is available in this area.

Table 3: Mapped Set III covariance matrix for Soln. 76. Mapping epoch 2019-Jan-01.0 ET.

	DMW	DP	DQ	EDW	DA	DE	RHO
DMW	2.368578E-15	-7.656335E-16	2.094926E-15	9.263165E-16	2.769659E-18	1.029236E-15	3.096773E-08
DP		2.959484E-16	-7.075602E-16	-3.179315E-16	-1.465742E-18	-3.305542E-16	-4.199398E-08
DQ			1.980158E-15	8.250605E-16	3.206422E-18	9.298667E-16	6.429863E-08
EDW				3.705417E-16	1.311229E-18	4.015102E-16	2.434908E-08
DA					1.271820E-20	1.292911E-18	5.172957E-10
DE						4.524961E-16	1.647036E-08
RHO							2.571048E+01

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