SPACE NAVIGATION AND FLIGHT DYNAMICS

20-MAY-2015

MESSENGER Navigation Orbit Reconstruction 3 (ORECON3)

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References:

1. "MESSENGER Navigation Orbit Reconstruction 1 (ORECON1)", Tony Taylor, IOM SNAFD.B/007-14, 1 May 2014.
2. "MESSENGER Navigation Orbit Reconstruction 2 (ORECON2)", Tony Taylor et al., IOM SNAFD.B/014-15, 10 March 2015.

This document describes the reconstruction, by MESSENGER Navigation, of the trajectory/orbit of MESSENGER from 2014/11/26 to end of mission (EOM) on 2015/04/30. The name given by the Navigation team for this reconstruction is ORECON3 (Orbit RECONstruction 3).

Delivery Files

The following files were delivered at

the standard delivery location for reconstructed spacecraft ephemerides.

ORECON3.bsp

This SPICE SPK file contains the reconstructed orbit from 2014/11/26 23:00:00 until 2015/04/30 19:30:00 SCET, TDB. The trajectory ends about 3 minutes after the currently estimated impact time, and contains a phantom periapsis about 26 seconds after Mercury impact. The file contains both the spacecraft ephemeris and the estimated Earth and Mercury barycenter ephemerides (SPK IDs 1 & 3) plus the rest of the DE405 planetary ephemeris bodies. If this file is used in conjunction with the previously delivered ORECON1 and 2 SPK files through the SPICE software "furnsh" function, the files should be loaded in order of delivery, ORECON1 to 3, so that later deliveries override the 1-hour overlap with earlier ones. (Note that this is opposite the ordering that would be used for the same result if merging files through SPICE program "spkmerge".)

ORECON3_Sigmas.m

This file, in Matlab script format, contains the formal 1-sigma solution uncertainties corresponding to the orbit data of ORECON3.bsp. A detailed description of the tabular data and coordinate system is given in the header.

ORECON3_Apses.m

This file, also in Matlab format, contains an array of all periapsis times in calendar string format, and another array of all apoapsis times. These were generated from ORECON3.bsp.

Gravity

Because of the inability to estimate high-order gravity coefficients discussed below, no gravity solution is delivered with ORECON3.

The files delivered are in the same styles and formats as the previous deliveries of References 1 and 2. Much of the discussion in this document is limited to the specifics of this delivery to avoid unnecessary repetition.

The orbit determination setup was the same as for ORECON1 and ORECON2 with the following added procedure:

> Beginning 2015/03/11, because of increasing stress on the filter due to larger unmodeled gravity field accelerations at low altitudes, *a priori* sigmas on the estimated impulses at periapses were increased from 0.5 mm/s per component to 1.0 mm/s.

This will be discussed in more detail in section **Orbit Uncertainties** below.

Comparison with Operations Trajectories

Figures 1 and 2 show the differences at periapses and apoapses between the reconstructed orbit and the current mission design reference trajectory, which consists of orbits from the operations deliveries of the navigation team. The standard deviations of differences for the radial (R) direction, 32 m for periapses and 37 m for apoapses, are about twice the ORECON2 results—still relatively small. Standard deviations for the other two directions, transverse (T) and normal (N), are slightly smaller and are comparable with those for ORECON2.

Figures 3 and 4 show the Mercury Sun-centered ephemeris differences between reconstruction and JPL planetary ephemerides DE405 and DE423. As for ORECON3, the periodic fluctuations in the R and HxR directions in Figure 3 (DE405) are mostly absent from the comparison with DE423, indicating that the reconstruction for those two directions are in reasonably good agreement with the later delivered JPL ephemeris (which, not coincidentally, included data from the three MESSENGER Mercury flybys). Differences in the out-of-plane direction, H, are much larger, as expected from the geometry.

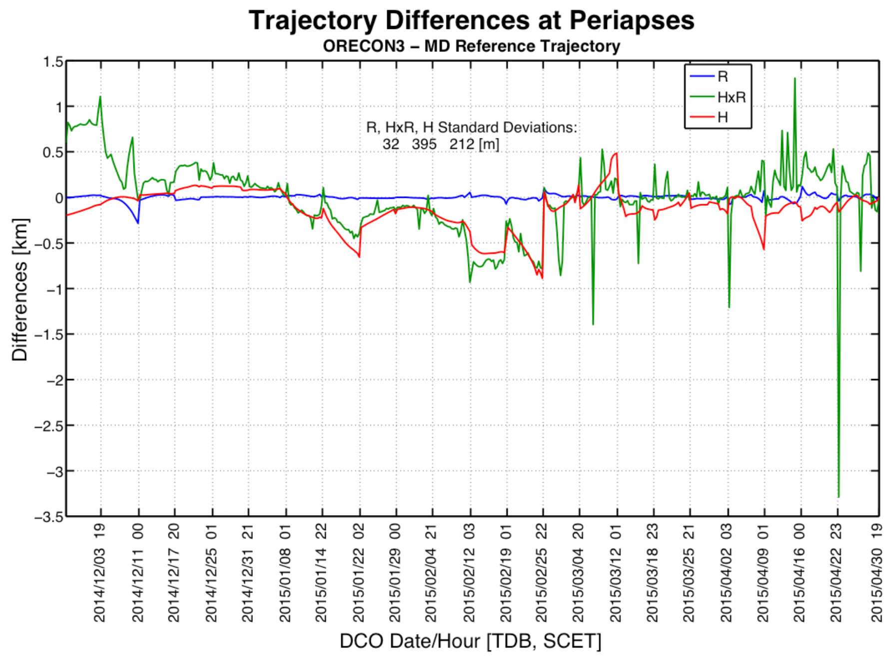

Figure 1: Trajectory differences at periapses in RTN system (R, HxR, H). DCO (Data Cut Off) date/hour is labeled for every ~7-day data arc.

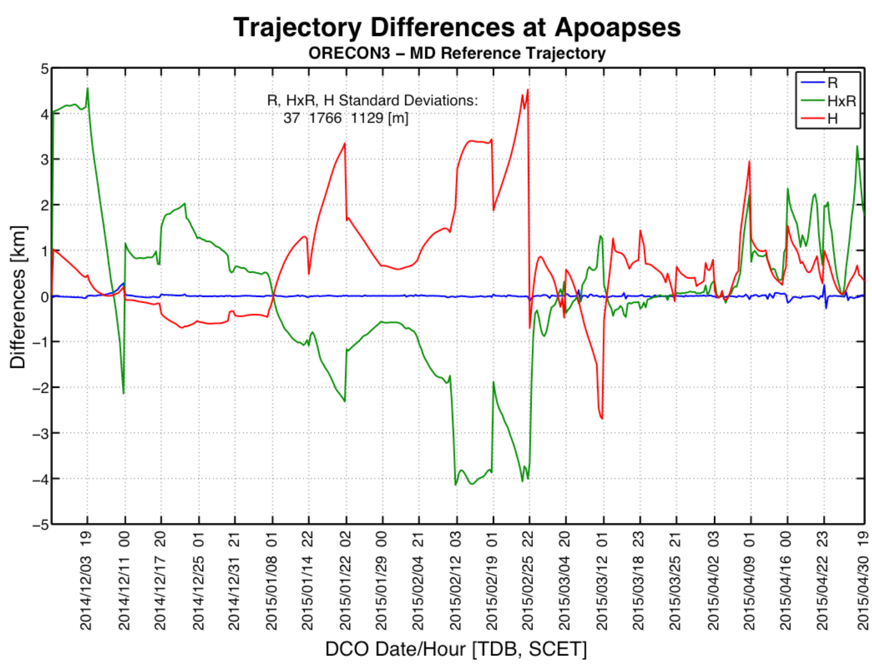

Figure 2: Trajectory differences at apoapses in RTN system (R, HxR, H).

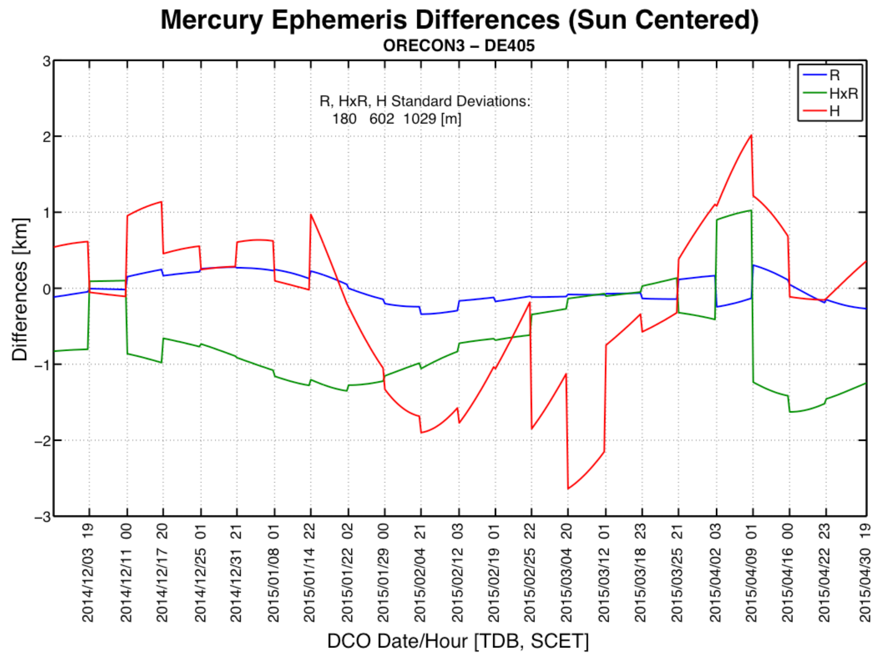

Figure 3: Mercury orbit differences between ORECON3 and DE405.

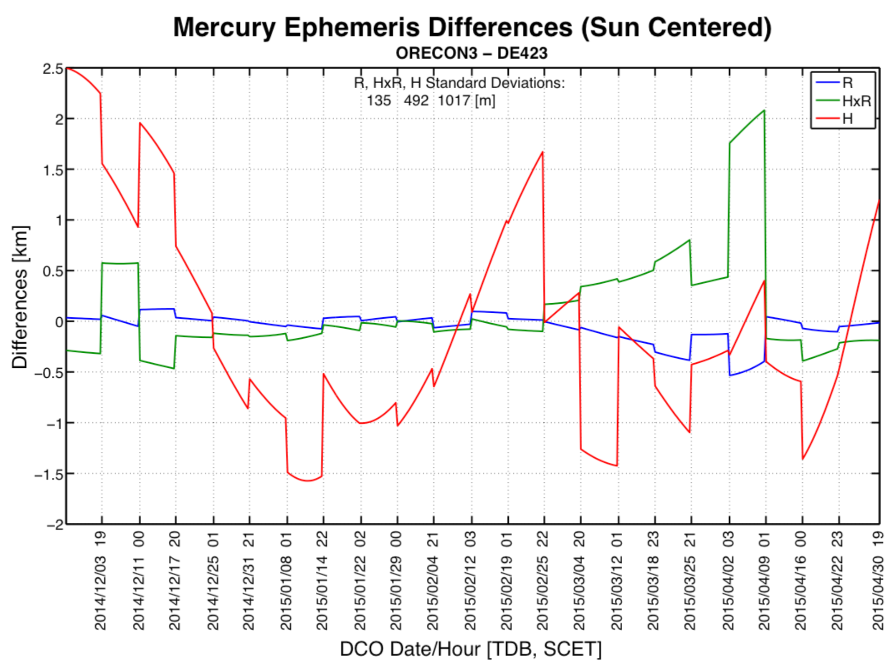

Figure 4: Mercury orbit differences between ORECON3 and DE423.

Apsis Times

Figure 5 shows excerpts from the ORECON3_Apses.m file containing periapse and apoapse times. These were determined from the ORECON3 SPK file using standard Matlab and SPICE/MICE scripts.

```
%!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
% ORECON3_Apses.m
% Created: 13-May-2015 14:27:47 by ApsisTimeGen.m
% Comments:
%   Foreground SPK: ORECON3.bsp
%   Background SPK: None
%   Last periapsis, at 30-APR-2015 19:27:35.247 TDB, is a phantom,
%   about 26 seconds after the currently estimated impact.
% Spice Files:
%     /Users/aht/Content/Technical/spice/naif0010.tls
%     /Users/aht/Content/Technical/spice/ORECON3.bsp
% Begin: 26-NOV-2014 23:00:00. TDB
% End  : 30-APR-2015 19:29:00. TDB
%   450 periapsis times
%   450 apoapsis  times
% Column 1:  Times
% Column 2:  Count
% Column 3:  Hours since previous
% Column 4:  Days  since first

 sPerTimes = [   % Periapsis times.
   '27-NOV-2014 03:50:10.712 TDB'    %     1   0.000000  0.000000
   '27-NOV-2014 12:02:57.036 TDB'    %     2   8.212868  0.342203
   '27-NOV-2014 20:15:43.381 TDB'    %     3   8.212874  0.684406
   .....
   '30-APR-2015 02:45:04.673 TDB'    %   448   8.354251  153.954791
   '30-APR-2015 11:06:20.019 TDB'    %   449   8.354263  154.302885
   '30-APR-2015 19:27:35.247 TDB'    %   450   8.354230  154.650978
  ];


 sApoTimes = [   % Apoapsis times.
   '26-NOV-2014 23:43:47.713 TDB'    %     1   0.000000  0.000000
   '27-NOV-2014 07:56:34.028 TDB'    %     2   8.212865  0.342203
   '27-NOV-2014 16:09:20.353 TDB'    %     3   8.212868  0.684406
   ....
   '29-APR-2015 22:34:28.069 TDB'    %   448   8.354244  153.951856
   '30-APR-2015 06:55:43.415 TDB'    %   449   8.354263  154.299950
   '30-APR-2015 15:16:58.715 TDB'    %   450   8.354250  154.648044
  ];
```

Figure 5: Excerpts of tabular data from ORECON3_Apses.m containing calendar string times for periapses and apoapses generated from the SPK delivery file.

Orbit Uncertainties

Excerpts from the ORECON3_Sigmas.m file are shown in Figure 6. The uncertainties are formal 1-sigma values. Figures 7 and 8 were plotted from the data in that file. Figure 7 is a low detail "grand view" of the entire span of ORECON3 and the geometries that influenced the orbit determination both negatively and positively. Some other influences (not shown) include the amount of data in each orbit determination (OD) data arc and how much of it is at periapses. The figure illustrates that the "Poor Earthline Angle" geometry is bad for determining spacecraft downtrack position (HxR), but better for determining out-of-plane (H). Figure 8 is a zoom into the grand view for more detail, showing the last few days leading to impact at the EOM. Table 1 gives the criteria used to plot the geometry influences of those figures.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% ORECON3_Sigmas.m
% 12-May-2015
% MAP FRAME: View frame 1 (inertial)    MAP CENTER: Mercury
% TRANSFORM: Cartesian    MAP STATES: Msgr
% Column names:
% DCO_TIME   MAP_TIME   R   V_HxR   SIG(R)   SIG(HxR)   SIG(H)
% Column descriptions:
% (Times in seconds past J2000 [SCET, TDB])
%   1: DCO_TIME: Data Cut Off times, each solution
%   2: MAP_TIME: Output (computation) times
%   3: R:        Radial distance [km]
%   4: V_HxR:    Velocity along HxR direction [km/s]
%   4:           where H = orbit pole
%   5: SIG(R):   1-sigma position along R   [km]
%   6: SIG(HxR): 1-sigma position along HxR [km]
%   7: SIG(H):   1-sigma position along H   [km]
%   8: MAP_TIME: As a commented time string
% Map files and sigma scaling factors are commented
% at the beginning of each solution data arc.
%
% Periapsis/apoapsis output times (corresponding to
% minimum/maximum values in the R column) are accurate
% to about +/-0.05 seconds due to rounding errors.
% (The non-time values in each row, however, were computed at
% exact periapsis/apoapsis times limited only by
% solution errors.)
% Other output times are centered in 15 minute steps
% for +/- 2 hours around periapses and 1 hour steps
% around apoapses.
%
 Sigs = [
% /nav/msgr/od/gravity/2014/141203/150317_aht_v2/output/map5.txt.3
% Sigma scale factor = 1.5
   470905200   470317427.700      13199.142    0.734649   0.040    0.775    0.204  % 2014/11/26 23:43:47.700 TDB
   470905200   470321027.730      12638.568    0.767224   0.034    0.747    0.226  % 2014/11/27 00:43:47.730 TDB
   470905200   470325010.680      10609.938    0.913910   0.059    0.631    0.213  % 2014/11/27 01:50:10.680 TDB
   ....
   470905200   470727754.000      12641.532    0.766681   0.028    1.743    0.173  % 2014/12/01 17:42:34.000 TDB
   470905200   470731354.030      13202.174    0.734119   0.026    1.839    0.248  % 2014/12/01 18:42:34.030 TDB
   470905200   470734953.970      12641.529    0.766672   0.025    1.778    0.292  % 2014/12/01 19:42:33.970 TDB
% /nav/msgr/od/gravity/2014/141203/150317_aht_v2/output/map6.txt.3
% Sigma scale factor = 1.5
   470905200   470738937.010      10612.589    0.913242   0.022    1.512    0.291  % 2014/12/01 20:48:57.010 TDB
   470905200   470739837.040       9915.243    0.977470   0.022    1.418    0.280  % 2014/12/01 21:03:57.040 TDB
   470905200   470740736.980       9114.242    1.063375   0.021    1.309    0.264  % 2014/12/01 21:18:56.980 TDB
   ....
   483694200   483693155.280       3257.329    2.928281   0.034    0.757    0.130  % 2015/04/30 19:12:35.280 TDB
   483694200   483694028.960       2438.745    3.911062   0.040    0.578    0.103  % 2015/04/30 19:27:08.960 TDB
   483694200   483694055.220       2437.859    3.912463   0.041    0.579    0.110  % 2015/04/30 19:27:35.220 TDB
 ];
```

Figure 6: Excerpts of tabular data from ORECON3_Sigmas.m containing times, radial distance, transverse velocity, and formal 1-sigma values for position uncertainties relative to Mercury center.

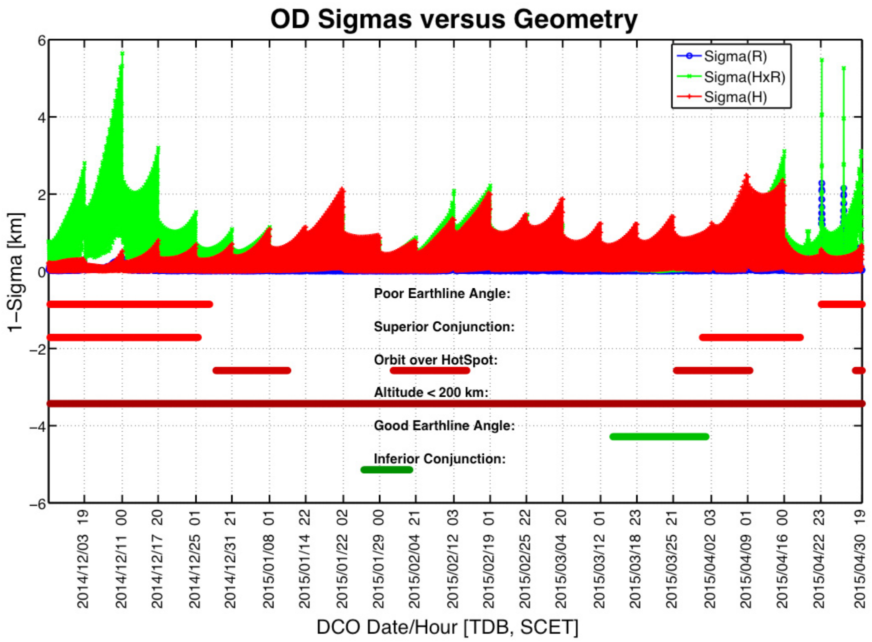

Figure 7: RTN 1-sigma (formal) uncertainties with geometry influences indicated. Red spans indicate negative influences, green positive. Brighter colors indicate more influence than darker ones.

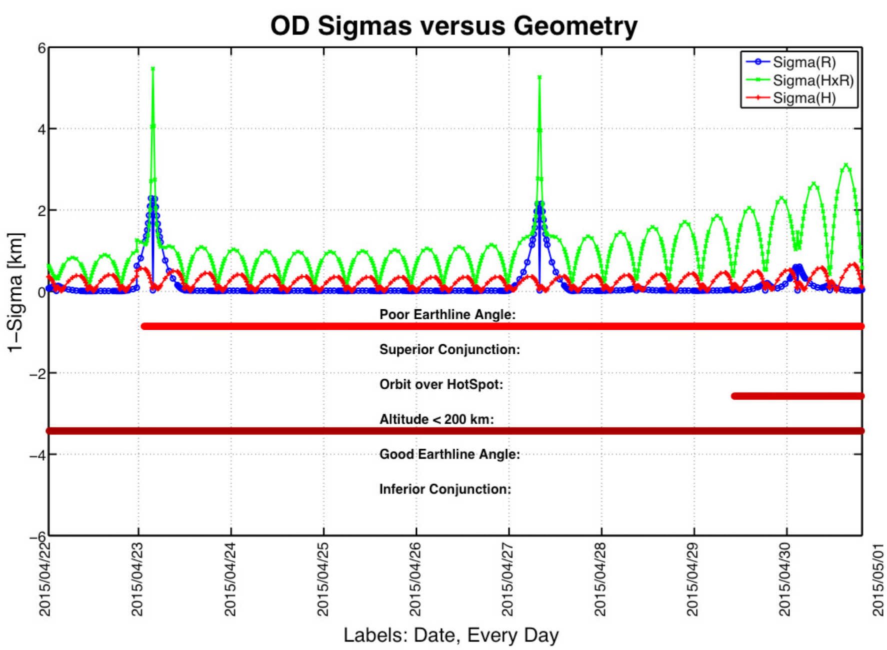

Figure 8: RTN 1-sigma (formal) uncertainties approaching EOM.

Table 1: OD Geometry Influences

Geometry	Criteria
"Poor Earthline Angle"	Earth Vector > 60° from orbit plane
"Superior Conjunction"	SEP < 10° and SPE < 90°
"Orbit over HotSpot"	Sun vector < 30° from orbit plane.
"Altitude < 200 km"	Periapsis altitude < 200 km
"Good Earthline Angle"	Earth vector < 15° from orbit plane
"Inferior Conjunction"	SEP < 10° and SPE > 90°

Because of the inability to estimate gravity coefficients much beyond degree and order 20 (for both practical and software reasons), for data arcs beginning 2014/08/06, radiometric tracking data was deleted when the spacecraft was below 200 km (i.e., near periapsis) and estimated impulsive delta-Vs at every periapsis. This reduced large stresses on the filter, manifested as signatures on the data residuals and large estimated parameter excursions.

The cost of relieving this large mismodeling was the smaller mismodeling induced by approximating the effects of a complicated low-altitude gravity field with simple impulsive delta-Vs. Because of this, a minimum scale factor of 1.5 was applied to all the estimated sigmas delivered with ORECON2 and ORECON3 after 2014/08/06. This was intended to make the uncertainty of results after that date compare well with the earlier formal 1-sigma results, albeit using an empirical correction, but using the best means of correction known.

As the spacecraft proceeded to even lower periapsis altitudes in 2015, stresses again built up and were addressed by raising the a priori sigma of the impulsive maneuvers from 0.5 to 1.0 mm/s beginning with data arcs starting 2015/03/11 and later. This again relieved stress, but traded off large mismodeling with smaller, although increased, mismodeling. The default scale factor was raised to 2.0 on that date.

Table 2 shows scale factors larger than 1.5 which were applied to the sigmas in ORECON3, both as a result of increasing the impulsive a priori and for other reasons. These corrections were similarly subjective.

Table 2: Sigma Scale Factors other than 1.5

Sigma Scale Factor	Data Arc Ending [Date/Hour]
2.0	2015/01/22 02
2.0	2015/02/25 22
3.0	2015/03/04 20
2.0	2015/03/12 01 – 2015/04/02 03
2.5	2015/04/09 01
2.5	2015/04/16 00
2.0	2015/04/22 23
3.0	2015/04/30 19

Now that everything in ORECON3_Sigmas.m is scaled to be on the same formal 1-sigma basis (subjectively), there comes the usual question: What are the *real* sigmas? The answer, as briefly touched on in Reference 1, is still that a scale factor of 2 to 3 would likely be appropriate.

Summary

We delivered files for the third orbit phase reconstruction (ORECON3), covering the interval from 2014/11/26 through the EOM on 2015/04/30. The SPICE SPK file contains both the spacecraft ephemeris and the estimated Earth and Mercury barycenter ephemerides, plus the remainder of the DE405 planetary body ephemerides over the same time span. Associated files include 1-sigma formal uncertainties for the trajectory, and periapsis and apoapsis times.