KINETX AEROSPACE

SPACE NAVIGATION AND FLIGHT DYNAMICS

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MESSENGER Navigation Orbit Reconstruction 2 (ORECON2)

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Reference:

"MESSENGER Navigation Orbit Reconstruction 1 (ORECON1)", Tony Taylor, IOM SNAFD.B/007-14, 1 May 2014.

This document describes the reconstruction, by MESSENGER Navigation, of the trajectory/orbit of MESSENGER from 2012/04/26 to 2014/11/27. The name given by the Navigation team for this reconstruction is ORECON2 (Orbit RECONstruction 2).

Delivery Files

The following files were delivered to the standard delivery location for reconstructed spacecraft ephemerides.

ORECON2-1.bsp and ORECON2-2.bsp

These two SPICE SPK files contain the reconstructed orbit from 2012/04/26 03:00:00 until 2013/08/14 21:00:00 and 2013/08/14 20:00:00 until 2014/11/27 00:00:00 SCET, TDB. The files contain both the spacecraft ephemeris and the estimated Earth and Mercury barycenter ephemerides (SPK IDs 1 & 3) plus the rest of the DE405 planetary ephemeris. The ephemerides were split between two files because of file length software limitations. If these files are used in conjunction with the previously delivered ORECON1.bsp through the Spice software "furnsh" function, ORECON2_1.bsp has a one hour overlap with the end of ORECON1.bsp and should be loaded after that file so that it overrides the first file during the overlap. Similarly, ORECON2_2.bsp should be loaded after ORECON2_1. (Note that this is opposite the ordering that would be used for the same result if merging files through Spice program "spkmerge".)

ORECON2_Sigmas.m

This file, in Matlab script format, contains the formal 1-sigma solution uncertainties corresponding to the orbit data of ORECON2_1.bsp and ORECON2_2.bsp. A detailed description of the tabular data and coordinate system is given in the header.

ORECON2_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 ORECON2_1.bsp and ORECON2_2.bsp.

The files delivered are in the same styles and formats as for the ORECON1 delivery of the Reference. Much of the discussion in this document will be limited to the specifics of this delivery to avoid unnecessary repetition of the more general discussions of the last delivery document.

The orbit determination setup was the same as for ORECON1 with the following added procedures:

- Beginning 2014/06/04, we used the radio science HGM006prelim gravity field as the nominal for values of degree/order 21x21 to 75x75. Values of GM, J2 and the rest of the parameters up to degree/order 20x20 were estimated as before. This was done because of difficulty with large data residuals at altitudes below 200 km and the impracticality of estimating a complete 75x75 field with the Mirage software.
- Beginning 2014/08/13, because of altitudes below 200 km and the impracticality of estimating gravity parameters beyond 20x20, we deleted data below 200 km altitude and estimated impulsive maneuvers at periapses. The impulsive maneuvers had the effect of "covering" (in a filter sense) for the unmodeled effects of the low altitude field, and greatly reduced stress on the filter.

Comparison with Operations Trajectories

Figures 1 and 2 show the differences at periapses and apoapses between the reconstructed orbit and the mission design (MD) reference trajectory, which consisted of orbits from the operations deliveries of the navigation team. The standard deviations of differences for the radial (R) direction are quite small for both apses, comparable with ORECON1, but substantially larger than ORECON1 for the transverse (T) and normal (N) directions.

Figures 3 and 4 show the Mercury Sun-centered ephemeris differences between reconstruction and JPL planetary ephemerides DE405 and DE423. 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 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. This illustrates why delta-differential one-way ranging (DDOR) data might be of value in determining the precision of Mercury's ephemerides.

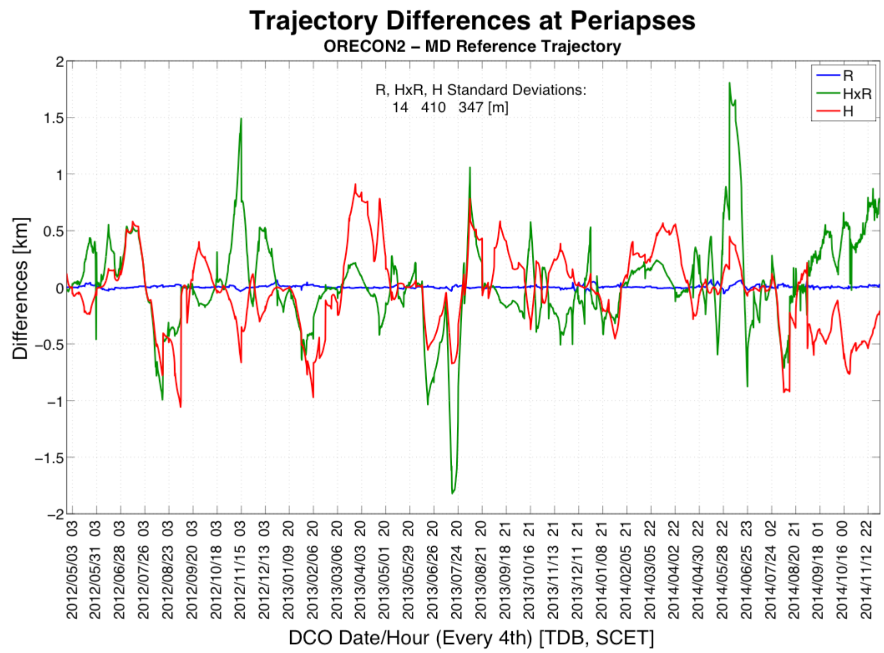

Figure 1: Trajectory differences at periapses in RTN system (R, HxR, H). Seven day data arcs. DCO (Data Cut Off) date/hour is labeled for every 4th data arc.

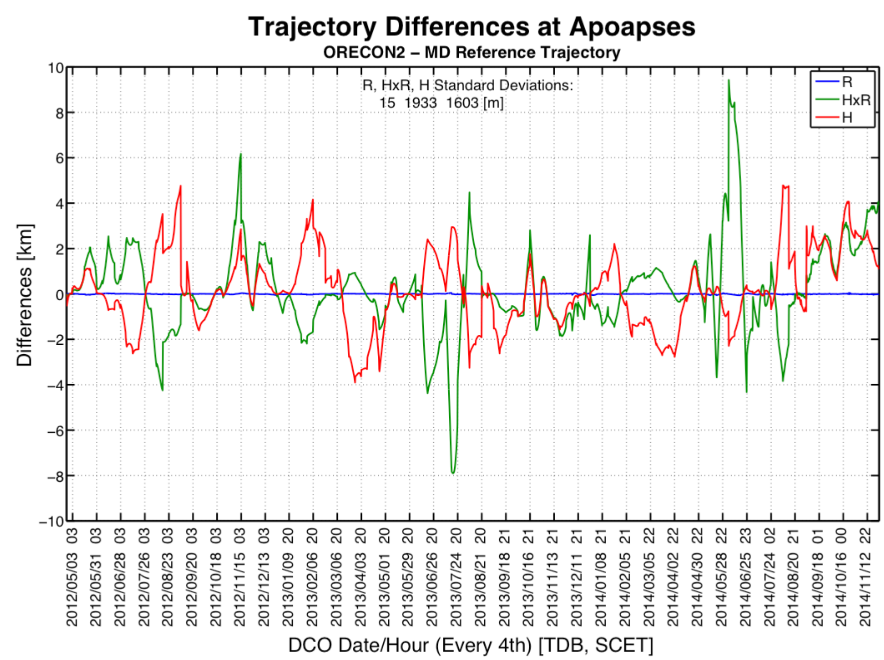

Figure 2: Trajectory differences at apoapses in RTN system (R, HxR, H).

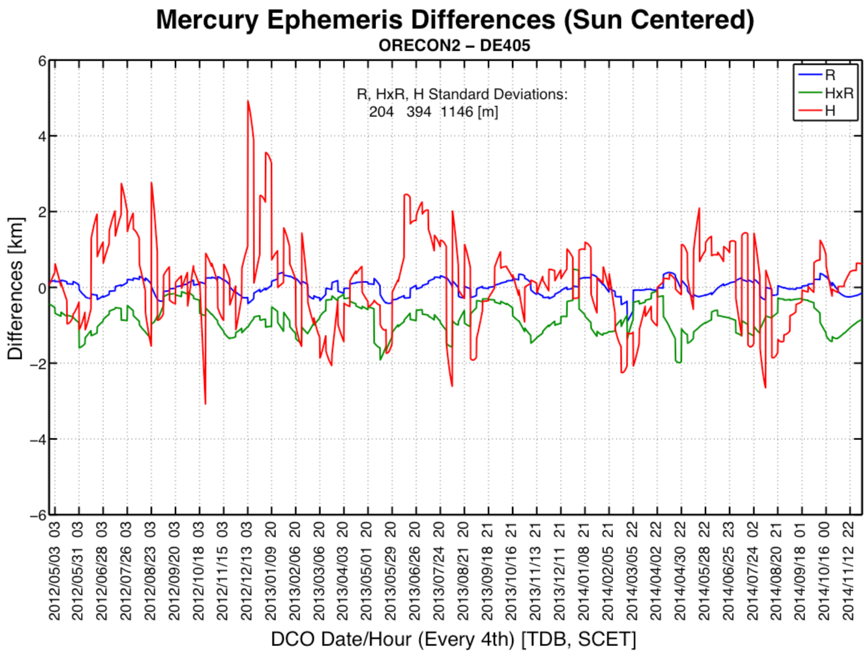

Figure 3: Mercury orbit differences between ORECON2 and DE405.

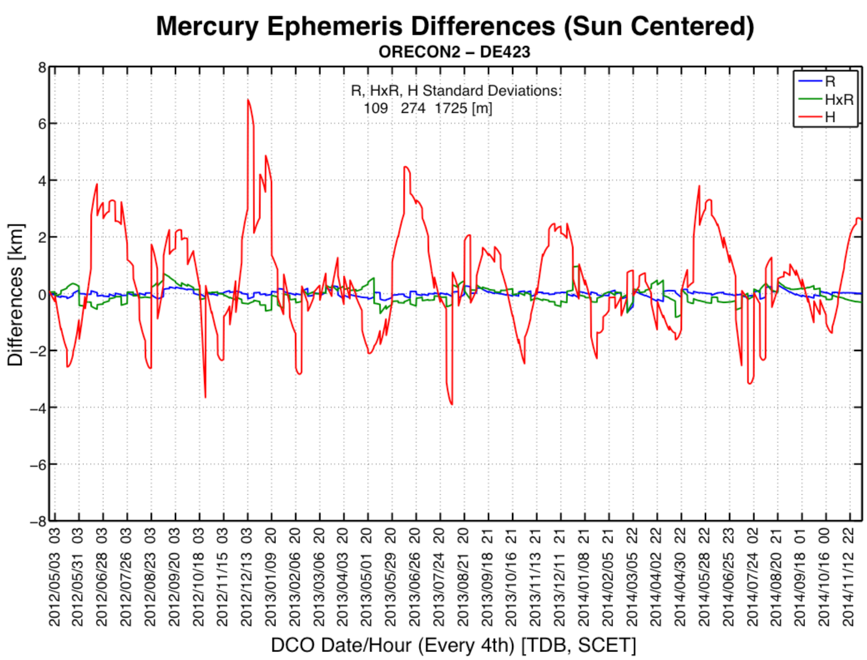

Figure 4: Mercury orbit differences between ORECON2 and DE423.

Apsis Times

Figure 5 shows excerpts from the ORECON2_Apses.m file containing periapsis and apoapsis times. These were determined from the ORECON2 SPK files using standard Matlab and SPICE/MICE scripts.

```
%!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
% ORECON2_Apses.m
% Created: 22-Feb-2015 12:45:45 by ApsisTimeGen.m
% Comments:
%   Foreground SPKs: ORECON1.bsp, ORECON2_1.bsp, ORECON2_2.bsp
%   Background SPK: msgr_20040803_20150430_od411sc_0.bsp
%   End time is DCO of ORECON2 + 1 hour.
% Spice Files:
%     /Users/aht/Content/Technical/spice/naif0010.tls
%     /Users/aht/Content/Technical/spice/AllMDRef_Latest.bsp
%     /Users/aht/Content/Technical/spice/ORECON1.bsp
%     /Users/aht/Content/Technical/spice/ORECON2_1.bsp
%     /Users/aht/Content/Technical/spice/ORECON2_2.bsp
% Begin: 26-APR-2012 03:00:00. TDB
% End  : 27-NOV-2014 00:00:00. TDB
%  2829 periapsis times
%  2830 apoapsis  times
% Column 1:  Times
% Column 2:  Count
% Column 3:  Hours since previous
% Column 4:  Days  since first

 sPerTimes = [   % Periapsis times.
   '26-APR-2012 07:10:05.462 TDB'    %     1   0.000000  0.000000
   '26-APR-2012 15:10:07.701 TDB'    %     2   8.000622  0.333359
   '26-APR-2012 23:10:09.976 TDB'    %     3   8.000632  0.666719
    .....
   '26-NOV-2014 03:11:51.322 TDB'    %  2827   8.212947  943.834559
   '26-NOV-2014 11:24:37.847 TDB'    %  2828   8.212924  944.176764
   '26-NOV-2014 19:37:24.281 TDB'    %  2829   8.212898  944.518968
  ];

sApoTimes = [   % Apoapsis times.
   '26-APR-2012 03:10:04.281 TDB'    %     1   0.000000  0.000000
   '26-APR-2012 11:10:06.509 TDB'    %     2   8.000619  0.333359
   '26-APR-2012 19:10:08.760 TDB'    %     3   8.000625  0.666719
    .....
   '25-NOV-2014 23:05:28.199 TDB'    %  2827   8.212940  943.830138
   '26-NOV-2014 07:18:14.755 TDB'    %  2828   8.212932  944.172343
   '26-NOV-2014 15:31:01.229 TDB'    %  2829   8.212909  944.514548
   '26-NOV-2014 23:43:47.637 TDB'    %  2830   8.212891  944.856752
  ];
```

Figure 5: Excerpts of tabular data from ORECON2_Apses.m containing calendar string times for periapses and apoapses generated from the SPK delivery file.

Orbit Uncertainties

Excerpts from the ORECON2_Sigmas.m file are shown in Figure 6. The uncertainties are formal 1-sigma values. Figures 7–10 were plotted from the data in that file. Figure 7 is "the grand view" of the entire span of ORECON2 and the geometries that influenced the orbit determination both negatively and positively. Some other influences (not shown) would include the amount of data in each orbit determination (OD) data arc and how much of this data is at periapses. Figures 8 and 9 provide zooms of the grand view for more detail, and illustrate, for instance, that when the Earth direction lies close to the orbit plane, the down-track direction (HxR) is well determined while the out-of-plane direction (H) is not well determined. Conversely, when Earth is near 90 degrees from the spacecraft orbit plane, H is better determined than HxR. Table 1, which gives the criteria used to plot the geometry influences of those figures, includes key ranges of angles such as Sun-Earth-probe (SEP) and Sun-probe-Earth (SPE).

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% ORECON2_Sigmas.m
% 21-Feb-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/2012/120502/140612_aht_v2/output/map5.txt.5
% Sigma scale factor = 1.0
   389286000   388681804.280      12753.337    0.779183   0.002   0.019   0.075  % 2012/04/26 03:10:04.280 TDB
   389286000   388685404.310      12177.721    0.816020   0.002   0.019   0.067  % 2012/04/26 04:10:04.310 TDB
   389286000   388689005.460      10367.382    0.958519   0.002   0.016   0.048  % 2012/04/26 05:10:05.460 TDB
   389286000   388689905.490       9693.172    1.025190   0.002   0.015   0.041  % 2012/04/26 05:25:05.490 TDB
    .....
   389286000   389077835.870      10364.575    0.959213   0.002   0.040   0.102  % 2012/04/30 17:10:35.870 TDB
   389286000   389081436.940      12174.558    0.816608   0.002   0.048   0.126  % 2012/04/30 18:10:36.940 TDB
   389286000   389085036.970      12750.094    0.779754   0.002   0.050   0.130  % 2012/04/30 19:10:36.970 TDB
   389286000   389088637.000      12174.568    0.816628   0.002   0.048   0.115  % 2012/04/30 20:10:37.000 TDB
% /nav/msgr/od/gravity/2012/120502/140612_aht_v2/output/map6.txt.5
% Sigma scale factor = 1.0
   389286000   389092238.410      10364.429    0.959265   0.002   0.041   0.082  % 2012/04/30 21:10:38.410 TDB
   389286000   389093138.350       9690.366    1.025995   0.002   0.038   0.071  % 2012/04/30 21:25:38.350 TDB
   389286000   389094038.380       8914.108    1.115344   0.002   0.035   0.058  % 2012/04/30 21:40:38.380 TDB
   389286000   389094938.410       8026.202    1.238732   0.001   0.032   0.044  % 2012/04/30 21:55:38.410 TDB
    .....
   470314800   470308944.300       9912.581    0.978257   0.016   0.971   0.092  % 2014/11/26 21:22:24.300 TDB
   470314800   470309844.240      10609.793    0.913969   0.017   1.041   0.128  % 2014/11/26 21:37:24.240 TDB
   470314800   470313827.630      12638.590    0.767245   0.023   1.249   0.261  % 2014/11/26 22:43:47.630 TDB
   470314800   470317427.660      13199.154    0.734649   0.034   1.311   0.343  % 2014/11/26 23:43:47.660 TDB
 ];
```

Figure 6: Excerpts of tabular data from ORECON2_Sigmas.m containing times, radial distance, transverse velocity, and formal 1-sigma values for position uncertainties relative to Mercury center.

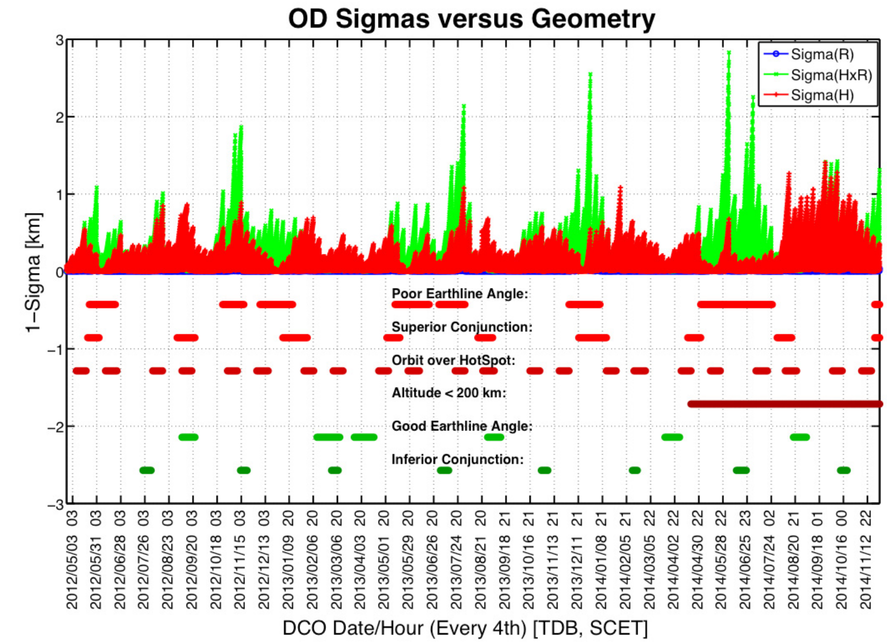

Figure 7: RTN 1-sigma (formal) uncertainties with geometry influences indicated. Red spans indicate negative influences, green positive. Brighter colors indicate more influence than darker ones.

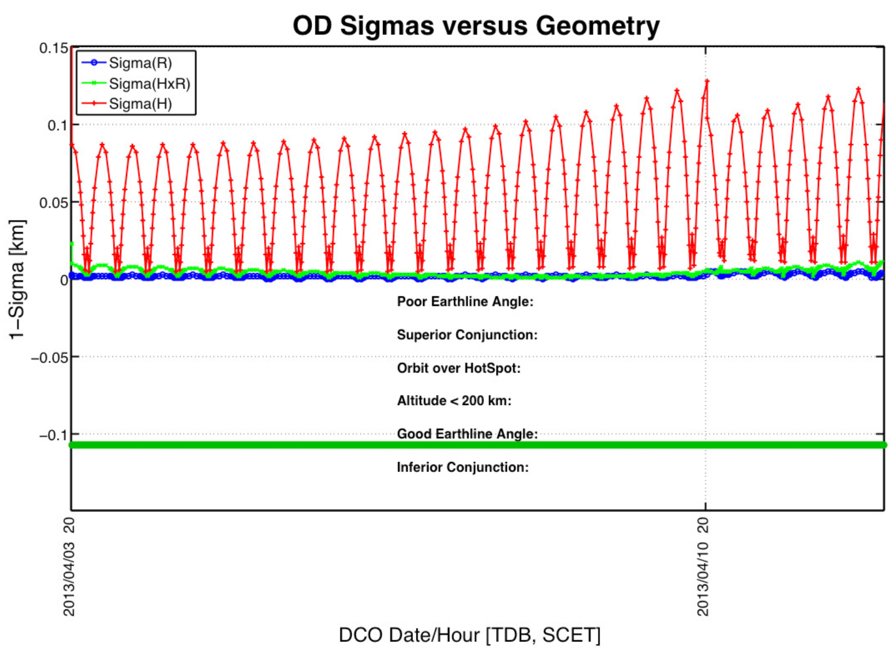

Figure 8: RTN 1-sigma (formal) uncertainties during a span of favorable geometry.

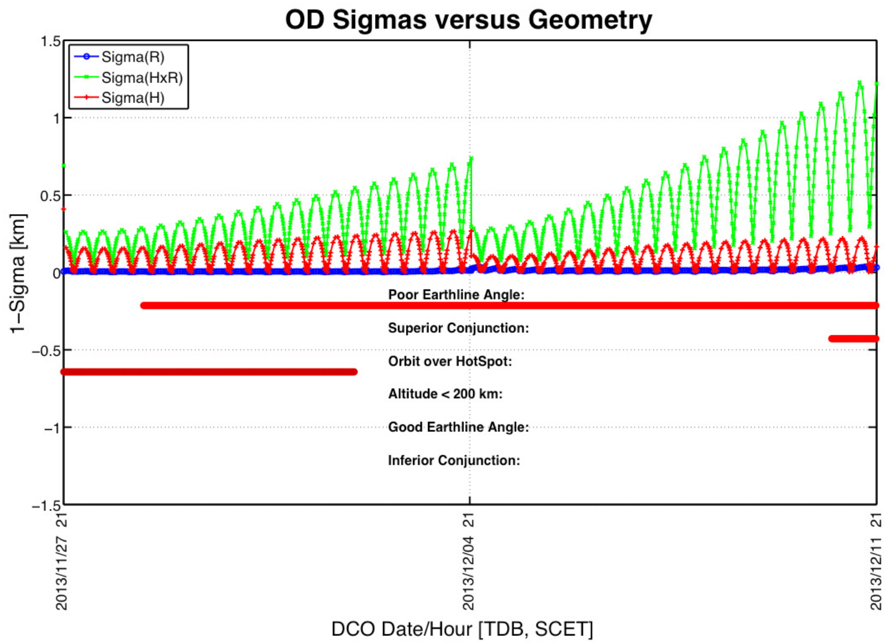

Figure 9: RTN 1-sigma (formal) uncertainties during a span of unfavorable geometry.

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°

Figure 10 shows the effect on the radial uncertainty due to the procedure adopted to delete data below 200 km Mercury-relative altitude and to estimate impulsive spacecraft velocity changes at periapses. That procedure began with the data arc that started on 2014/08/06. Before that time, the radial uncertainties are quite small throughout every data arc. After that time, the radial uncertainties remain small through spans for which there is Doppler data covering periapses, and peak up at periapses through spans for which there is no Doppler data. This illustrates the result of mismodeling a detailed low-altitude gravity field with an impulsive velocity change at each periapsis. The estimated impulses had a priori sigmas of 0.5 mm/s in each direction, and the resulting estimates were typically in the 0.1–0.3 mm/s range, with some excursions to the 0.4–0.7 mm/s region.

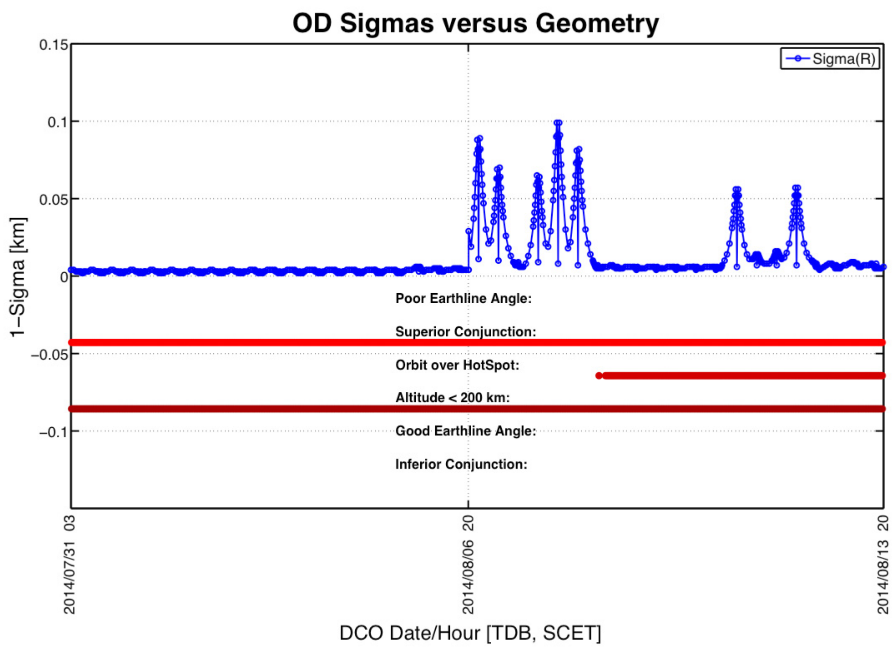

Figure 10: Details of 1-sigma radial uncertainties when deleting data below 200 km and estimating impulses at periapses.

Because of the mismodeling induced by this process, a scale factor of 1.5 was applied to all the sigmas of ORECON2_Sigmas.m 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.

Additionally, scale factors were applied to other data arcs that exhibited symptoms of mismodeling, such as unexplained signatures in the tracking data and estimated parameter excursions indicating a stressed filter. These were similarly subjective. All of the applied scale factors are shown in Table 2.

Table 2: Sigma Scale Factors other than 1.0

Sigma Scale Factor	Data Arc Ending [Date/Hour]
2.0	2012/08/30 03
2.0	2012/09/06 03
2.0	2012/10/25 03
1.5	2013/03/13 20
1.5	2013/04/17 20
2.0	2013/06/19 20
1.5	2013/07/17 20
2.0	2013/07/31 20
2.0	2013/08/07 20
1.5	2013/08/14 20
1.5	2013/12/25 21
2.0	2014/01/29 21
1.5	2014/04/16 22
1.5	2014/05/14 22
1.5	2014/06/04 22
1.5	2014/08/13 20 – 2014/11/26 23

Now that everything in ORECON2_Sigmas.m is on the same formal 1-sigma basis (subjectively), there comes the usual question: What are the *real* sigmas? A scale factor of 2 to 3 is thought to be most appropriate, based on experience.

Gravity

As for ORECON1, a gravity field came out of the reconstruction process of ORECON2 as a byproduct. The gravity field delivery, named MNG05, combines all the Square Root Information (SRI) data from MNG04 (ORECON1) with data from ORECON2 up to 2014/02/05 for a total of 18 rotations of the planet beneath the approximately inertial plane of the orbit since the orbit phase began. There were difficulties producing a realistic gravity field beyond that date as evidenced by the appearance of severe spurious artifacts in gravity contours in the southern hemisphere, probably due to our inability to estimate a field beyond 20x20 for low altitudes. Even the gravity potential contours of MNG05, as seen in Figure 11, exhibit a trace of unrealism in the form of spuriously steep slopes along latitude –25 degrees. These unrealistic rapid changes in gravity potential get much worse if data from the subsequent Mercury inertial rotations, 19-23, are added. Thus, MNG05 may be the last gravity field that the navigation team produces, and should be considered experimental since the agreement with the higher degree terms of the MNG04 gravity field is not very good.

Figure 12 shows the spectrum of the solution, and Figure 13, some of the low-order terms.

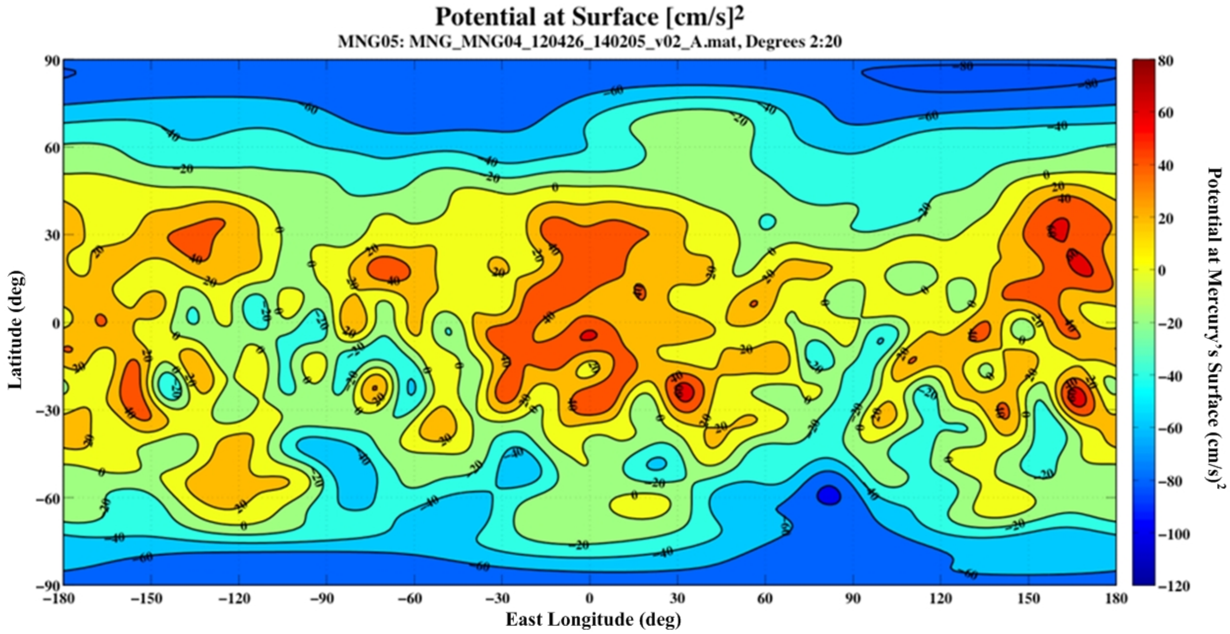

Figure 11: Contours of the gravity potential at the surface on a cylindrical projection.

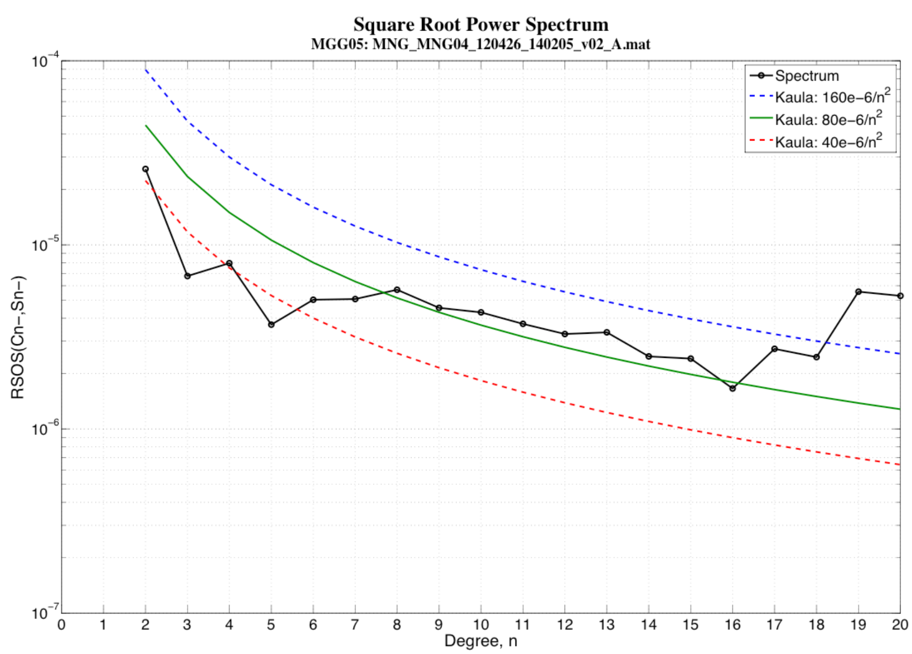

Figure 12: Spectrum of gravity coefficients. Initial Kaula constraint of 80e-6/n^2.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%
% MNG05_C.m
% MNG05
% MESSENGER Navigation Gravity Field for Mercury
% Tony Taylor, KinetX, Inc.
% 26-Feb-2015
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% MNG05_C.m
% Matlab formatted output from Export2CS
% Basis: Export file MNG_MNG04_120426_140205_v02_E.m
% 438 of 438 parameters output.

 NAMES = {
       'GM1'  '1C02_00'  '1C02_01' ...
   '1S02_01'  '1C02_02'  '1S02_02' ...
   '1C03_00'  '1C03_01'  '1S03_01' ...
   '1C03_02'  '1S03_02'  '1C03_03' ...
   '1S03_03'  '1C04_00'  '1C04_01' ...
     ...

 VALUES = [
   2.203187141090345e+04   -2.260740784710829e-05   -1.636069412404097e-08 ...
  -7.197010222216091e-09    1.252488229166967e-05   -2.154818140525441e-08 ...
  -4.703578834637455e-06   -3.523573664231877e-06   -2.595915020185691e-06 ...
   9.640535459287587e-07   -6.413694847619414e-07    6.013118448000784e-07 ...
   1.695675516813831e-06   -5.996659363865358e-06    1.503317220561016e-06 ...
     ...

 SIGMAS = [
   1.856308818197524e-04    1.862663922557718e-09    7.629841674574674e-10 ...
   7.448685678091027e-10    8.151634423340518e-10    8.278288295586527e-10 ...
   4.726872058371977e-09    3.353466008601503e-09    3.211675981797722e-09 ...
   2.487122634547989e-09    2.479526708741663e-09    8.455993007483254e-10 ...
   8.392953042674226e-10    1.643203214508330e-08    1.165638335782170e-08 ...
     ...
```

Figure 13: Excerpts from file MNG05_C.m containing solved-for gravity parameters and 1-sigma uncertainties.

Summary

This delivery includes the second orbit phase reconstruction (ORECON2), covering the interval from 2012/04/26 to 2014/11/27—16 rotations of the planet beneath the orbit. The Spice SPK files contain both the spacecraft ephemeris and the estimated Earth and Mercury barycenter ephemerides, plus the remainder of the DE405 planetary ephemerides over the same time span. Associated files include 1-sigma formal uncertainties for the trajectory, as well as periapsis and apoapsis times.