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14. ABSTRACT
This paper reports on the processes of planning, prediction, acquisition, tracking, measurement collection, and measurement reduction as needed to independently document the passage of the space probe by Earth, and to generate tracking data for testing of MITRE mission software under development. Uses the April 10, 2020, the Mercury probe BepiColombo data. Presented at the AAS/AIAA Astrodynamics Specialist Meeting, August 9-13, 2020. Paper and presentation included.

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MITRE TELESCOPE TRACKS BEPICOLOMBO FLYBY

Roger L. Mansfield* and Tim McLaughlin†

On April 10, 2020, the Mercury probe BepiColombo made a planned flyby of Earth. Earth provided, thereby, a gravity assist on this first of a sequence of BepiColombo gravity-assist flybys of planets Earth, Venus, and Mercury toward a goal that the spacecraft orbit Mercury in 2025. Using a custom flyby forecast prepared by registering at the *Heavens-Above* website, the authors obtained predictions of exactly when and where to look to acquire and track the spacecraft during its passage near Earth. This paper reports on the processes of planning, prediction, acquisition, tracking, measurement collection, and measurement reduction as needed to independently document the passage of the space probe by Earth, and to generate tracking data for testing of MITRE mission software under development.

INTRODUCTION

Quoting the European Space Agency (ESA): "BepiColombo is Europe's first mission to Mercury. Launched on 20 October 2018, it is on a seven-year journey to the smallest and least explored terrestrial planet in our Solar System. When it arrives at Mercury in late 2025, it will endure temperatures in excess of 350°C and gather data during its one-year nominal mission with a possible one-year extension. The mission is comprised of two spacecraft: 1) the Mercury Planetary Orbiter (MPO); and 2) the Mercury Magnetospheric Orbiter (Mio). BepiColombo is a joint mission between ESA and the Japan Aerospace Exploration Agency (JAXA), executed under ESA leadership."[1]

The MITRE site in Colorado Springs maintains and operates remotely several satellite-tracking telescopes called the MITRE Telescope Network (MTN). The Pine Park Trail (PPT) telescope is part of this network.

Given a few days advance notice of the BepiColombo flyby, it was determined that the flyby event was well within the capabilities of any telescope in the MTN. However, for convenience

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during the “Stay at Home” order by the Governor of Colorado then in force, it was decided to use the PPT Observatory, which (being situated on private property) could be accessed physically if the need arose, as well as remotely.

News of the imminent BepiColombo flyby was obtained from a post to the SeeSat-L Satellite Observers List on Tuesday, April 7, 2020.[2] Following the suggestion from that post, an account was created at the *Heavens-Above* website, and the PPT Observatory was registered as an observing location.

Table 1. Visibility Predictions for PPT Observatory, Mountain Daylight Time.

Pine Park Trail Observatory, Sensor Number 284

38.994281 deg N. Latitude, -104.640979 deg E. Longitude, 2.250 km above mean sea level

U. S. Mountain Standard Time Zone, -6.00 hours offset from Coordinated Universal Time (UTC)

Time, 2020 April 9	r, km	Magnitude	Altitude, degrees	Azimuth, degrees	Right Ascension	Declination, deg	Constellation	Sun Alt., degrees
23:34:00	27,608	9.6	26.2°	166.8°	12h 40.8m	-23° 33'	Corvus	-38.7°
23:35:00	27,843	9.6	26.6°	167.7°	12h 38.1m	-23° 18'	Corvus	-38.8°
23:36:00	28,082	9.6	27.0°	168.6°	12h 35.5m	-23° 04'	Corvus	-38.9°
23:37:00	28,322	9.6	27.3°	169.4°	12h 32.9m	-22° 50'	Corvus	-39.0°
23:38:00	28,565	9.6	27.7°	170.3°	12h 30.3m	-22° 35'	Corvus	-39.1°
23:39:00	28,809	9.7	28.0°	171.2°	12h 27.9m	-22° 21'	Corvus	-39.2°
23:40:00	29,056	9.7	28.4°	172.0°	12h 25.4m	-22° 07'	Corvus	-39.3°
23:41:00	29,305	9.7	28.7°	172.9°	12h 23.0m	-21° 53'	Corvus	-39.4°
23:42:00	29,556	9.7	29.0°	173.7°	12h 20.7m	-21° 39'	Corvus	-39.4°
23:43:00	29,808	9.7	29.3°	174.6°	12h 18.4m	-21° 26'	Corvus	-39.5°
23:44:00	30,063	9.8	29.5°	175.4°	12h 16.2m	-21° 12'	Corvus	-39.6°
23:45:00	30,319	9.8	29.8°	176.3°	12h 14.0m	-20° 59'	Corvus	-39.7°
23:46:00	30,577	9.8	30.1°	177.1°	12h 11.8m	-20° 46'	Corvus	-39.8°
23:47:00	30,836	9.8	30.3°	177.9°	12h 09.7m	-20° 33'	Corvus	-39.8°
23:48:00	31,097	9.8	30.5°	178.8°	12h 07.6m	-20° 20'	Corvus	-39.9°
23:49:00	31,360	9.9	30.8°	179.6°	12h 05.6m	-20° 07'	Corvus	-40.0°
23:50:00	31,624	9.9	31.0°	180.4°	12h 03.6m	-19° 54'	Corvus	-40.1°
23:51:00	31,890	9.9	31.2°	181.2°	12h 01.7m	-19° 42'	Corvus	-40.1°
23:52:00	32,157	9.9	31.4°	182.0°	11h 59.7m	-19° 29'	Corvus	-40.2°
23:53:00	32,425	9.9	31.5°	182.8°	11h 57.9m	-19° 17'	Corvus	-40.3°
23:54:00	32,695	10.0	31.7°	183.6°	11h 56.0m	-19° 05'	Crater	-40.4°
23:55:00	32,966	10.0	31.9°	184.4°	11h 54.2m	-18° 53'	Crater	-40.4°
23:56:00	33,238	10.0	32.0°	185.2°	11h 52.4m	-18° 41'	Crater	-40.5°
23:57:00	33,511	10.0	32.2°	186.0°	11h 50.7m	-18° 30'	Crater	-40.6°

Table 1 shows the BepiColombo flyby visibility predictions for PPT.

TELESCOPE SYSTEM HARDWARE AND SOFTWARE

The PPT Observatory has a single telescope mount with the following configuration: Celestron CGEM-DX mount with two co-aligned, electro-optical instruments. The first electro-optical instrument is comprised of a Vixen ED103S 103mm f/7.7 refractor and a QHY-174M-GPS camera (0.8 x 0.5 degrees field of view [FOV]). The second electro-optical instrument is comprised of a Nikkor 85mm f/1.4 lens with an Andor Zyla 4.2PLUS 4.2 Megapixel CMOS camera (9x9 degrees FOV).

Figure 1. Mount and Telescope Configuration for the PPT Observatory.

Figure 1 illustrates the equipment. Telescope control was accomplished using a custom telescope control program. This program supports multiple tracking modes. For normal earth-orbiting satellites, a Two-Line Element Set (TLE) is used to drive the telescope in a rate-tracking mode. In this mode, the telescope will follow the satellite, and the stars will streak through the FOV. Given the short notice of the flyby (and in the absence of TLE), the mount was controlled in sidereal-rate tracking mode. Updates were sent to the telescope every few minutes to move to a specified right ascension (RA) and declination (DEC) position and sidereal-rate tracking mode was selected.

For the narrow field of view (NFOV) system (0.8x0.5 degrees FOV), the target appears as a streak and the stars as stationary point sources. Each NFOV image collected was automatically time stamped by the QHY-174M-GPS camera. Images were stored in a Flexible Image Transport System format, which consolidates the image data with all pointing and timing auxiliary data.

Each of the images collected was registered to the star field using Astrometry.net software. This software returns the exact coordinates (RA and DEC) of the center of the image and a plate model. The image is then processed with Source Extractor software to find the centroid of the streak. The streak centroid is converted to a J2000 RA/DEC using the plate model. Aberration corrections are then applied to the RA and DEC J2000 coordinate measurements before referring them to the true equator and mean equinox of date to feed the orbit determination process.

The wide field of view (WFOV) images were processed slightly differently. Target detection was accomplished by differentiating images to find the moving target. Using WFOV and this technique, the target would have been detected with up to 4.5 degrees of pointing error. For this case, the target was exactly where predicted; therefore, no search was required. The images were then passed to registration using Astrometry.net, and the detected coordinates were determined in a similar method as described above.

TRACKING AND MEASUREMENTS

The PPT Observatory collected 129 metric observations over 17 minutes during BepiColombo's Earth flyby.

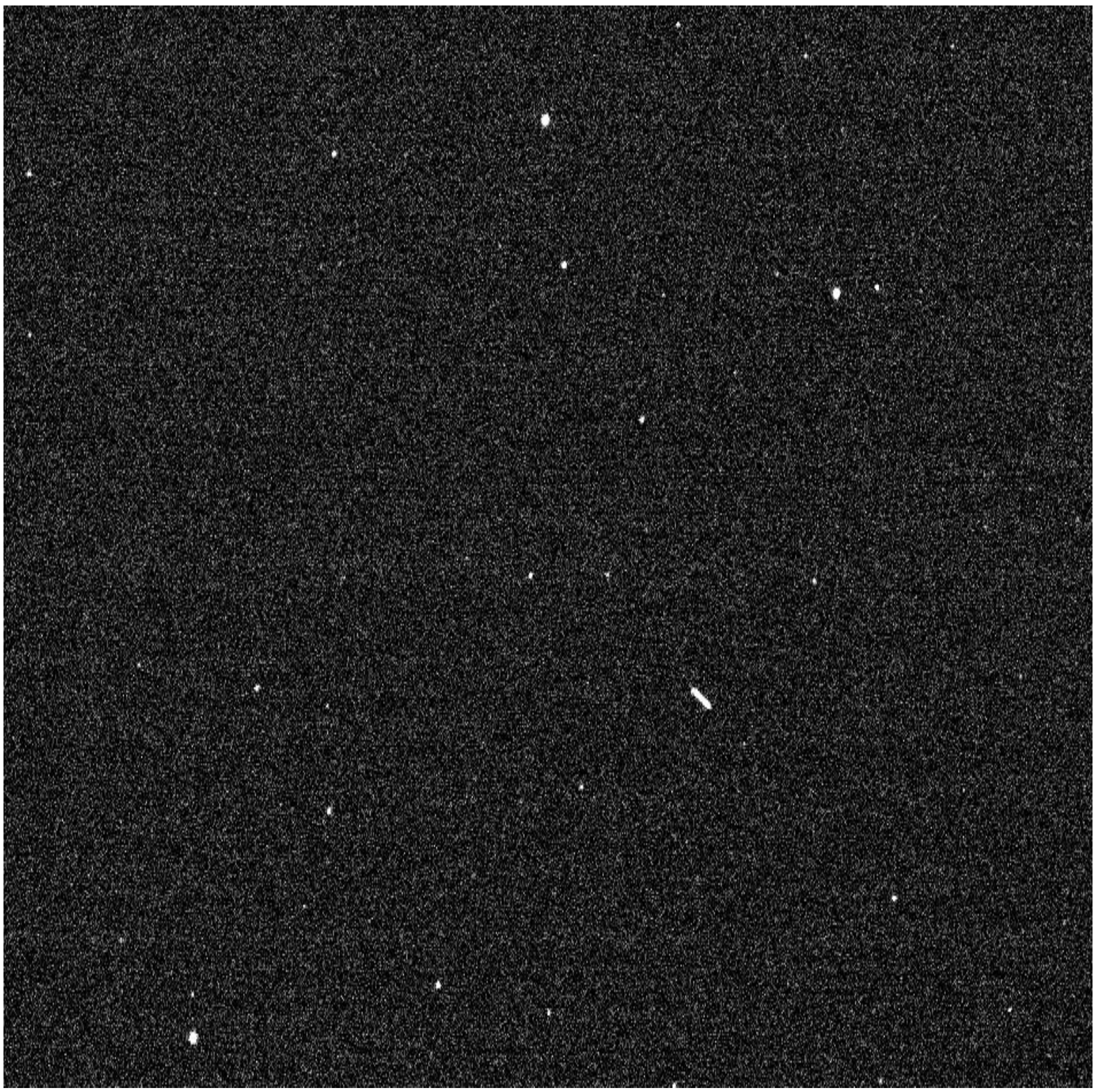

Figure 2. Snapshot from Movie of BepiColombo Flyby of April 10, 2020 (GMT date) as Imaged from the PPT Observatory. Short Streak is BepiColombo.

Figure 2 shows a snapshot of the movie taken during the observation collection process.

Table 2. Observations of BepiColombo on April 10, 2020 (UTC).

Time hh mm ss.sss	DEC deg	Rt Ascen. hh mm ss.s	Ob Num	Time hh mm ss.sss	DEC deg	Rt Ascen. hh mm ss.s	Ob Num
5 37 32.020	-22.8217	12 32 32.3	1	5 41 30.019	-21.8981	12 22 53.0	24
5 37 40.020	-22.7936	12 32 11.8	2	5 41 38.020	-21.8645	12 22 34.1	25
5 37 48.020	-22.7602	12 31 51.1	3	5 41 54.020	-21.8048	12 21 57.2	26
5 37 56.020	-22.7271	12 31 31.4	4	5 42 07.019	-21.7563	12 21 27.1	27
5 38 04.019	-22.6974	12 31 10.7	5	5 42 15.019	-21.7238	12 21 08.1	28
5 38 13.019	-22.6602	12 30 48.8	6	5 42 43.020	-21.6186	12 20 04.1	29
5 38 21.019	-22.6304	12 30 28.0	7	5 42 51.020	-21.5901	12 19 45.7	30
5 38 53.020	-22.5048	12 29 09.5	8	5 43 00.020	-21.5536	12 19 25.3	31
5 39 01.020	-22.4723	12 28 49.9	9	5 43 08.019	-21.5244	12 19 07.9	32
5 39 09.019	-22.4441	12 28 30.0	10	5 43 16.019	-21.4958	12 18 49.6	33
5 39 17.019	-22.4121	12 28 10.5	11	5 43 24.019	-21.4671	12 18 32.1	34
5 39 25.019	-22.3794	12 27 50.8	12	5 43 53.020	-21.3550	12 17 26.1	35
5 39 33.020	-22.3463	12 27 32.3	13	5 44 09.019	-21.2964	12 16 51.1	36
5 39 41.020	-22.3180	12 27 12.5	14	5 44 19.019	-21.2573	12 16 28.9	37
5 39 50.020	-22.2811	12 26 50.3	15	5 44 27.019	-21.2302	12 16 11.5	38
5 39 58.020	-22.2482	12 26 30.5	16	5 45 06.019	-21.0857	12 14 46.2	39
5 40 10.019	-22.2034	12 26 01.4	17	5 45 26.019	-21.0113	12 14 02.4	40
5 40 18.019	-22.1702	12 25 42.7	18	5 45 34.020	-20.9799	12 13 45.3	41
5 40 26.019	-22.1417	12 25 23.8	19	5 45 42.020	-20.9523	12 13 28.0	42
5 40 58.020	-22.0186	12 24 07.5	20	5 45 50.020	-20.9246	12 13 10.7	43
5 41 06.019	-21.9865	12 23 48.8	21	5 46 10.019	-20.8496	12 12 28.2	44
5 41 14.019	-21.9583	12 23 30.1	22	5 46 18.019	-20.8217	12 12 12.0	45
5 41 22.019	-21.9265	12 23 11.6	23	5 46 26.019	-20.7941	12 11 54.5	46

Table 2 provides 46 of these observations from the PPT Observatory's data collect; they will be discussed in the next section.

The panchromatic photometry is depicted as a graph of photometric measurement vs. time as shown in Figure 3.

METRIC MEASUREMENT REDUCTION

The 129 observations were input to the MITRE initial orbit determination (IOD) program Herget-UPM (HGM). (The acronym HGM is an abbreviation for "Herget-UPM.") HGM is an improved version of Paul Herget's orbit determination method.[3] (The principal improvement to Herget's original method is the use of a closed-form formula for Gauss' hypergeometric X-function (as a quotient of Stumpff's c-functions) rather than using the X-function as a truncated hypergeometric infinite series. The abbreviation UPM stands for "Uniform Path Mechanics," a universal-variables method attributed to Karl J. Stumpff and William H. Goodyear.)

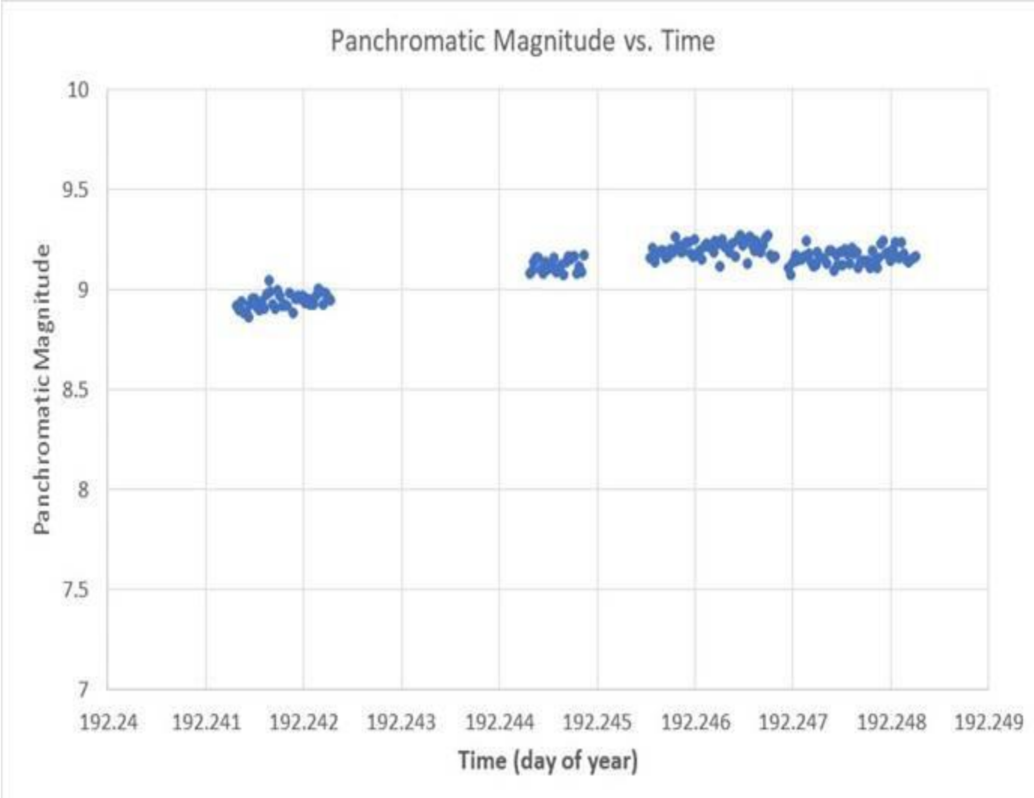

Figure 3. Panchromatic Photometry Measurements of BepiColombo.

With the 129 observations input, HGM yielded an elliptical solution with a root mean square (RMS) error of 69.603 km. This result was suspect on three counts: 1) the solution was expected to be hyperbolic (a flyby path is, by definition, always parabolic or hyperbolic, not elliptical); 2) the high RMS error indicated insufficient modeling of the path perturbations or noisy observations; and 3) HGM took 17 iterations to converge.

HGM's P and Q residuals for the 17th iteration was examined. Five observations were found to be either duplicates or bad.

The P and Q residuals formulas are as follows:

$$P = \rho \cos(\delta)\, \Delta\alpha \quad \text{and} \quad Q = \rho\, \Delta\delta. \tag{1}$$

Here α is right ascension, δ is declination, and Δ denotes the residual in the sense "observed minus computed."

The 5 bad or duplicate observations were deleted leaving 124 good observations, which were then input to HGM, and it yielded a hyperbolic solution in three iterations with a final RMS error of 1.935 km.

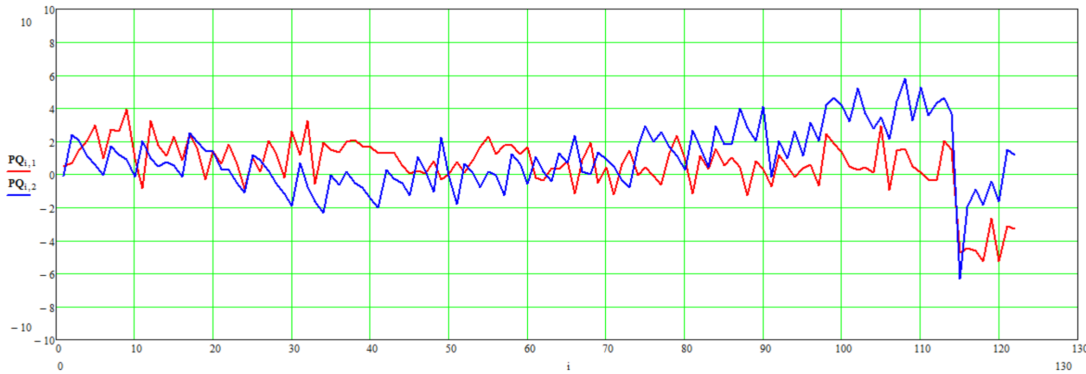

Figure 4. HGM's P (Red) and Q (Blue) Residuals (km) vs. Observation Number i for 122 of 124 PPT Observations.

Figure 4 shows the residuals plot for the third iteration. (There are no residuals for the 1st and 124th observations because their slant ranges are the parameters fitted to the other 122 observations in the HGM algorithm.)

Although HGM yielded a hyperbolic solution, the perigee radius of 4.69227 ER and orbital eccentricity of 5.50175 were known (from the more accurate results provided in the next section) to be too large. Also, Figure 4 shows that the P and Q residuals become much larger toward the end of the data collect; that is, the measurements became "noisier" toward the end of the data collect.

HGM is known to yield its best results when the first and last observations have as little noise as possible. It was noted that observation 92 (i = 91 in Figure 4) had small P and Q residuals. Therefore, it was decided to truncate the observation set used in the metric measurements reduction to 92 observations. Furthermore, to ensure that Table 2 fit on one page, the observation set was further reduced to 46 observations by selecting just the even-numbered observations. Table 3 shows the HGM results with 46 observations.

Unlike the Gauss[4] and Laplace[5] angles-only IOD methods (see Appendix), HGM uses all available observations, not just three (typically, the three chosen are the first, middle, and last). HGM also does a two-parameter least-squares fit, the two parameters being here the slant range estimates for the first and last observations. The HGM least-squares process adjusts these two estimates until the P and Q residuals associated with the observations are minimized. It should be noted that even though HGM uses all observations, its solution is the result of a two-parameter fit.

To get a true, six-parameter fit and a 6x6 covariance matrix, the MITRE track processing method called Batch UPM Differential Correction (BDC) was used. Results with BDC are also shown in Table 3.

(Note: Further documentation of HGM and BDC as a track processing sequence can be found in Reference 6.)

Table 3. HGM and BDC Results with BepiColombo Flyby Observations Collected at PPT.

Flyby Path, Conic Element or Parameter	Results with HGM, 46 observations	Results with BDC, 46 observations
Perigee radius, Earth radii	2.80502	2.84028
Orbital eccentricity	1.585649	1.587760
Flight time, perigee to epoch, min	82.76441	82.98398
Orbital inclination, deg	159.91224	159.75680
Rt ascension of asc node, deg	149.42737	149.67420
Argument of perigee, deg	249.10349	249.87760
RMS error, km	0.819	0.146

(HGM = hgm8.exe, BDC = bd4.exe. Epoch is at time of last observation.)

TRACK PROCESSING RESULTS WITH MINOR PLANET CENTER OBSERVATIONS

Seven observatories contributed to the Minor Planet Center (MPC) a total of 42 observations of BepiColombo, which were given the preliminary designation “2020 GL2.” See Reference 7 for these observations. See Reference 8 for the MPC’s identification of 2002 GL2 as the space probe BepiColombo.

Table 4. BepiColombo Flyby Results With 42 MPC Observations.

Flyby Path, Conic Element or Parameter	Results with Gh1/Ghc	Results with Gd1/Gdc	Results from Reference 9
Perigee radius, Earth radii	2.96499	2.97613	(not specified)
Perigee height, km	12,533	12,604	12,677
Orbital eccentricity	1.7494	1.7527	(not specified)

Mathcad worksheets analogous to HGM (IOD) and BDC were previously developed to work with MPC observations of close approaches to Earth by minor planets. The results from these two worksheet pairs, designated as Gh1/Ghc (Geocentric Herget Initiation/Geocentric Herget Iteration) and Gd1/Gdc (Geocentric DC Initiation/Geocentric DC Iteration) are summarized in Table 4.

(It should be noted at this point that the Mathcad worksheets Gh1/Ghc and Gd1/Gdc also provide two-body, universal variables solutions [i.e., UPM solutions].)

The differences in Table 4, column 2 vs. Table 4, column 3 are attributed to the fact that the Gh1/Ghc worksheets constitute a preliminary IOD method giving a two-parameter fit (estimates of slant range at first and last observation times), whereas the Gd1/Gdc worksheets constitute a full, six-parameter fit (position and velocity). Much higher values of perigee height and orbital eccentricity were obtained using the Gauss and Laplace angles-only methods with the first, middle, and last observations in the PPT observation data collect (see Appendix).

The perigee height in Table 4, column 3 agrees with the value in Table 4, column 4 to within 73 km. This is an indication that the Gd1/Gdc solution with 42 MPC observations is quite good. It is presumed that the orbital eccentricity reported in Table 4, column 3 is also comparably good, since it was not specified in Reference 9.

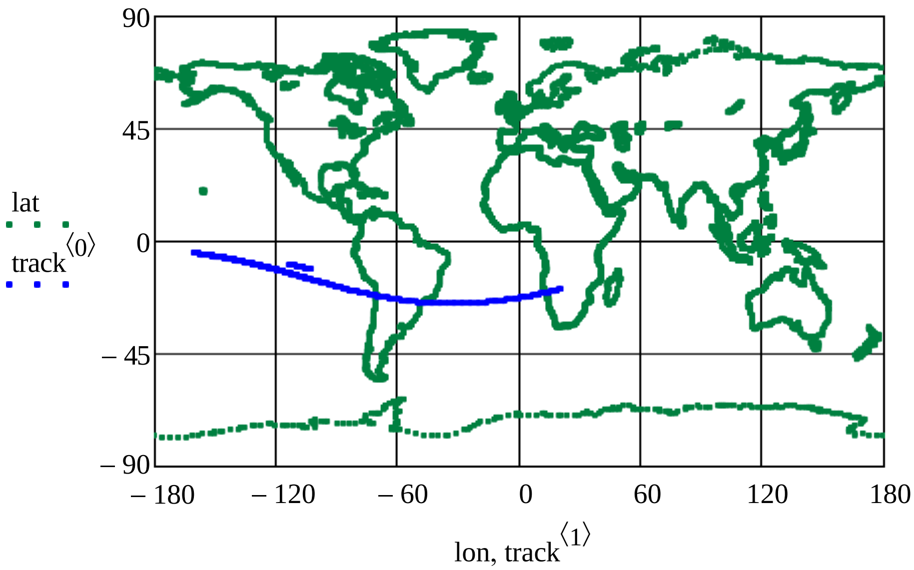

Figure 5. Ground Trace Points/Paths for BepiColombo Flyby.

(Longer blue trace generated using Gd1/Gdc solution with 42 MPC observations. Shorter blue trace generated using BDC solution with 46 PPT observations.)

Figure 5 plots ground trace points calculated using the BDC-computed path with 46 PPT observations vs. the Gd1/Gdc-computed path with 42 MPC observations. Since the computed path elements differ in perigee height and eccentricity, it is not surprising that the ground traces do not coincide perfectly.

Since the ground traces do not coincide perfectly, how do we explain that the perigee radii and eccentricities reported in Table 3 are lower than those in Table 4? Our explanation is that the results in Table 3 were based upon a single observatory, PPT, doing a data collect over 17 minutes. Whereas, the results in Table 4 are based upon seven observatories doing data collects over approximately three days and the MPC doing the data reduction in the heliocentric equatorial J2000 reference frame, with planetary perturbations and antedating of the observations for light-time.

Finally, in view of the shortness of the PPT data collect (17 minutes), it is remarkable that any solution was obtained over the fit span of this single-sensor observation collection.

Our principal goal in this data analysis was to verify that PPT was indeed observing BepiColombo by virtue of these facts: a) we found it exactly where *Heavens-Above* predicted; b) the object was indeed in a hyperbolic trajectory quite close to the path predicted using the MPC observations; and c) the measured photometric magnitudes agree well with the visual magnitudes predicted by *Heavens-Above.*

CONCLUSIONS

Observations taken at the PPT Observatory on April 10, 2020, provided valuable single-sensor, short-arc test cases with which to validate MITRE IOD and differential correction programs.

Due to viewing constraints, only the outbound leg of BepiColombo's hyperbolic flyby path could be tracked, and since the data collect was only 17 minutes long, the BDC orbital solution in Table 3, column 3 is preliminary rather than definitive.

Nevertheless, tracking by the MTN Observatory at PPT has generated high-quality observations, which (upon reduction) confirm that BepiColombo safely flew past Earth in a hyperbolic trajectory of path eccentricity significantly greater than 1 on April 10, 2020.

REFERENCES

[1] European Space Agency, BepiColombo. (See https://sci.esa.int/web/bepicolombo/.)

[2] Text of Alexandre Amorim post to SeeSat List:

From: Alexandre Amorim via Seesat-l <seesat-l@satobs.org>

To: “seesat-l@satobs.org” <seesat-l@satobs.org>

Sent: Tuesday, 7 April 2020, 12:08:14 PM MDT

Subject: BepiColombo flyby

Dear friends:

In 9-10 April we have BepiColombo spacecraft flyby.

More information: https://heavens-above.com/Flyby/Flyby.aspx?lat=-27.5949&lng=48.5482&loc=Florianópolis&alt=30&tz=EBST

(Customize ephemeris for your site.)

[3] R.L. Mansfield, “Preliminary Determination of the Geocentric Earth Flyby Path of Asteroid 2012 DA14,” *24th AAS/AIAA Space Flight Mechanics Meeting,* Santa Fe, New Mexico, 28 January 2014.

[4] H.D. Curtis, *Orbital Mechanics for Engineering Students,* (Elsevier, Second Edition 2009), Section 5.10, Gauss method of preliminary orbit determination.

[5] P.R. Escobal, *Methods of Orbit Determination,* (Krieger Publishing Company, Malabar, Florida, reprint 1976, w/corrections of original John Wiley & Sons, Inc. First Edition 1965), Section 7.4, The Method of Laplace.

[6] R.L. Mansfield and G.J. Der, "Reconstruction of the 1801 Discovery Orbit of Ceres via Contemporary Angles-Only Algorithms," *Advanced Maui Optical and Space Surveillance Technologies (AMOS) Conference 2016*, held in Maui, Hawaii USA, 20-23 September 2016.
(See https://www.amostech.com/TechnicalPapers/2016/Poster/Mansfield.pdf.)

[7] Minor Planet Electronic Circular MPEC 2020 GL96 (heliocentric orbital solution for object 2020 GL2), *Minor Planet Center,* 13 April 2020.

[8] Minor Planet Electronic Circular MPEC 2020-G97 (deletion of object 2020 GL2 as a minor planet, since it is a space probe that originated from Earth), *Minor Planet Center,* 13 April 2020.

[9] C. Magnafico, V. Mangano, J. Benkhoff, and J. Zender, "BepiColombo Earth Flyby," *European Space Agency*, 10 April 2020.

(See https://www.cosmos.esa.int/web/bepicolombo-flyby/earth-flyby.)

[10] Nautical Almanac Office, U.S. Naval Observatory, *Astronomical Almanac for the Year 2020,* Washington, DC 20392, p. B13.

[11] Defense Mapping Agency, "Department of Defense World Geodetic System 1984 - Its Definition and Relationships with Local Geodetic Systems," DMA Technical Report 8350.2, 30 September 1987 (Second Printing).

APPENDIX: GAUSS AND LAPLACE RESULTS WITH THREE PPT OBSERVATIONS

Since gravity-assist flybys of Earth are relatively rare, the opportunity is taken below to provide textbook-quality test cases using 3 of the 46 PPT observations in Table 2 in the body of the paper.

Table A1. Gauss and Laplace Solutions with Three PPT Observations.

Flyby Path, Conic Element or Parameter	Results with Gauss Method	Results with Laplace Method
Perigee radius, Earth radii	3.7970478	3.815775
Orbital eccentricity	3.081167	3.100476
Flight time, perigee to epoch, min	69.30437	69.22275
Orbital inclination, deg	157.99485	157.95515
Rt ascension of asc. node, deg	148.50744	148.54260
Argument of perigee, deg	262.93391	263.18509

(Epoch is at time of middle observation.)

Table A1 shows the results of using Gauss' method, as documented in Reference 4, and Laplace's method, as documented in Reference 5, with 3 of the 46 angles-only observations given in Table 2. The 3 observations chosen are the 1st, 24th, and 46th.

In calculating the values in Table A1, the mean right ascension of Greenwich at January 0.0 UTC, 99.13616 degrees, was taken from Reference 10. Earth's rotation rate with respect to the moving equinox, 360.98564736 degrees per mean solar day, was taken from Reference 11.

Table A2 shows the astrodynamic constants used in the Gauss and Laplace solutions. They were taken or derived from values in Reference 11.

Table A2. WGS-84 Constants Adopted with Gauss and Laplace Methods.

Astrodynamic Constant	Description
a_e = 6378.137 km	Earth's mean equatorial radius
f = 1/298.27	Oblate spheroidal flattening factor
k_e = 0.07436685037	Gaussian gravity constant, $ER^{3/2}$ / min

The HGM solution given in Table 3 exhibits a perigee radius of approximately 2.8 Earth radii. The Laplace and Gauss solutions in Table A1 both exhibit perigee radii of approximately 3.8 Earth radii.

The perigee radius exhibited in Table 4 (approximately 3.0 Earth radii) is based upon a differential correction with the 42 observations reported to the MPC. It is believed to be the best possible estimate of perigee radius, given the available data.

Thus, the HGM solution using 46 PPT observations is better than both the Gauss and Laplace solutions using just three observations. This comparison illustrates a strength of HGM: using all available observations (not just three) better estimates the perigee radius of BepiColombo’s hyperbolic Earth flyby path. Similar comments apply to the orbital eccentricity.

MITRE Telescope Tracks BepiColombo Flyby AAS 20-537

Roger L. Mansfield, Principal Astrodynamicist
Tim McLaughlin, Principal Sensors Systems Engineer

Virtual Presentation for
AAS/AIAA Astrodynamics Specialist Meeting
August 9-13, 2020

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Introduction

- **ESA/JAXA Mercury Probe BepiColombo flew by Earth on April 10, 2020**
  - Will be flying by Venus and Mercury now before settling into Mercury orbit in 2025
  - See ESA website (https://www.cosmos.esa.int/web/bepicolombo-flyby/earth-flyby) for an excellent pre-flyby summary
- **MITRE's Pine Park Trail (PPT) telescope tracked BepiColombo**
  - Registered PPT observatory at *Heavens-Above* pre-flyby and generated visibility predictions
  - Predictions posted less than a day in advance for remotely-operated tracking
  - *Heavens-Above* predictions were "spot on"

MITRE Telescope Network (MTN) Satellite Tracking Sites

- **United States Air Force Academy (USAFA)**
  - MITRE Observatory Experiment (MOE)
  - Participated in North-South data collect from Vicuna, Chile and USAFA during total solar eclipse of 2019 (2 July)
- **Black Forest (North of Colorado Springs)**
  - Pine Park Trail (PPT) Observatory
  - Tracked Northrop Grumman's Mission Extension Vehicle 1 (MEV-1) to rendezvous with Intelsat 901 during January-March 2020
- **Tokyo, Japan**
  - MITRE Telescope Tokyo (MTT) also used to track Northrop Grumman's MEV-1 to rendezvous with Intelsat 901 during January-March 2020

Why Did PPT Observatory Track BepiColombo Flyby?

- **Demonstrate MITRE's mastery of electro-optical systems technology**
  - On small-aperture telescopes, for tracking space objects out to geosynchronous Earth Orbit (GEO)
  - Using a combination of custom and commercial off-the-shelf hardware and software
- **Independently document safe passage of BepiColombo by Earth**
  - Spacecraft penetrated Earth's vicinity to a perigee height of approximately 2.0 Earth radii
  - Above highly-congested Earth-orbital regime (LEO)
- **Generate test cases for MITRE mission applications**
  - Share tracking data and analyses with space community

PPT Telescope System Hardware and Software

- **Two co-aligned optical assemblies on Celestron mount**
  - **Optical Assembly 1:**
    - Vixen ED103S 103mm f/7.7 refractor and a QHY-174M-GPS camera (0.8x0.5 degrees NFOV)
    - NFOV (Narrow Field of View): target streaks and stars are stationary in image
    - Astrometry.net used for star registration in images
    - Images time-stamped via GPS camera
  - **Optical Assembly 2:**
    - Nikkor 85mm f/1.4 lens with an Andor Zyla 4.2PLUS 4.2 Megapixel CMOS camera (9x9 degrees WFOV)
    - Wide Field of View (WFOV): moving target detected by differentiating images
    - Astrometry.net used for star registration in images
    - See next page for image of telescope hardware

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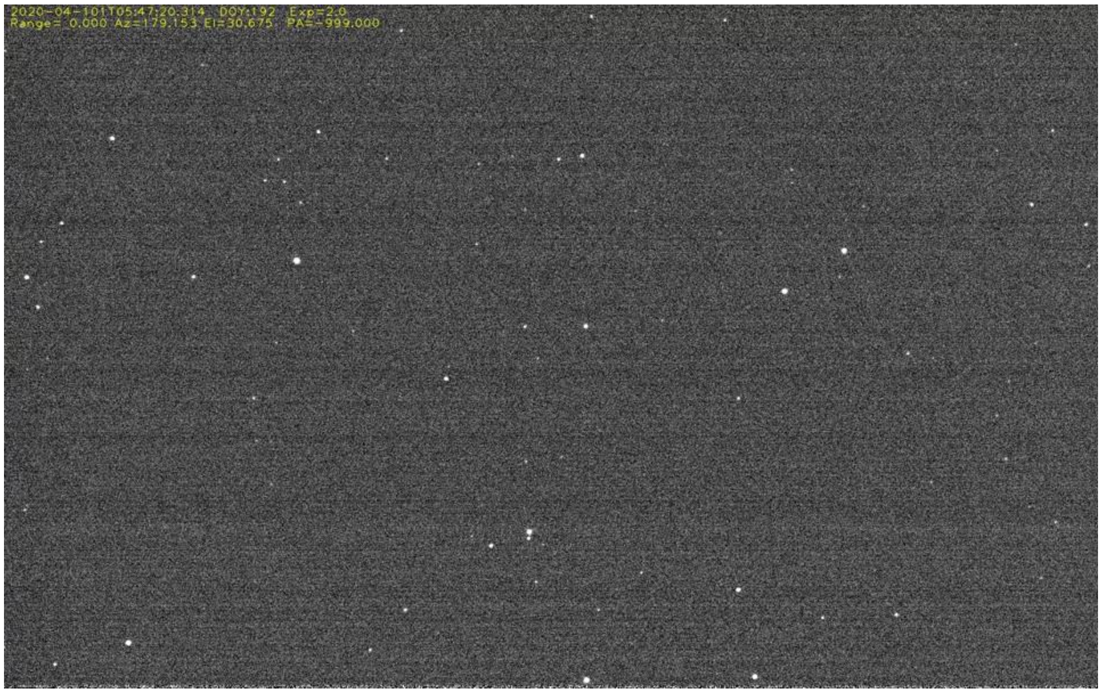
PPT Telescope Mount and Optical Assemblies

Source: MITRE

Celestron CGEM-DX Mount and Telescope Configuration for the PPT Observatory

Video of BepiColombo as Tracked by PPT Observatory



Source: MITRE

Sky conditions were hazy over PPT Observatory. BepiColombo was acquired in constellation Corvus (the Crow) and passed into constellation Crater (the Cup). BepiColombo was tracked for 17 minutes. Moon was low above southeastern horizon about three nights past full.

Metric and Photometric Measurements

Table 2. 46 PPT Observations of BepiColombo on April 10, 2020 (UTC)

Time hh mm ss.sss	Dec. deg.	Rt. Ascen. hh mm ss.s	Ob. Num.	Time hh mm ss.sss	Dec. deg.	Rt. Ascen. hh mm ss.s	Ob. Num.
5 37 32.020	-22.8217	12 32 32.3	1	5 41 30.019	-21.8981	12 22 53.0	24
5 37 40.020	-22.7936	12 32 11.8	2	5 41 38.020	-21.8645	12 22 34.1	25
5 37 48.020	-22.7602	12 31 51.1	3	5 41 54.020	-21.8048	12 21 57.2	26
5 37 56.020	-22.7271	12 31 31.4	4	5 42 07.019	-21.7563	12 21 27.1	27
5 38 04.019	-22.6974	12 31 10.7	5	5 42 15.019	-21.7238	12 21 08.1	28
5 38 13.019	-22.6602	12 30 48.8	6	5 42 43.020	-21.6186	12 20 04.1	29
5 38 21.019	-22.6304	12 30 28.0	7	5 42 51.020	-21.5901	12 19 45.7	30
5 38 53.020	-22.5048	12 29 09.5	8	5 43 00.020	-21.5536	12 19 25.3	31
5 39 01.020	-22.4723	12 28 49.9	9	5 43 08.019	-21.5244	12 19 07.9	32
5 39 09.019	-22.4441	12 28 30.0	10	5 43 16.019	-21.4958	12 18 49.6	33
5 39 17.019	-22.4121	12 28 10.5	11	5 43 24.019	-21.4671	12 18 32.1	34
5 39 25.019	-22.3794	12 27 50.8	12	5 43 53.020	-21.3550	12 17 26.1	35
5 39 33.020	-22.3463	12 27 32.3	13	5 44 09.019	-21.2964	12 16 51.1	36
5 39 41.020	-22.3180	12 27 12.5	14	5 44 19.019	-21.2573	12 16 28.9	37
5 39 50.020	-22.2811	12 26 50.3	15	5 44 27.019	-21.2302	12 16 11.5	38
5 39 58.020	-22.2482	12 26 30.5	16	5 45 06.019	-21.0857	12 14 46.2	39
5 40 10.019	-22.2034	12 26 01.4	17	5 45 26.019	-21.0113	12 14 02.4	40
5 40 18.019	-22.1702	12 25 42.7	18	5 45 34.020	-20.9799	12 13 45.3	41
5 40 26.019	-22.1417	12 25 23.8	19	5 45 42.020	-20.9523	12 13 28.0	42
5 40 58.020	-22.0186	12 24 07.5	20	5 45 50.020	-20.9246	12 13 10.7	43
5 41 06.019	-21.9865	12 23 48.8	21	5 46 10.019	-20.8496	12 12 28.2	44
5 41 14.019	-21.9583	12 23 30.1	22	5 46 18.019	-20.8217	12 12 12.0	45
5 41 22.019	-21.9265	12 23 11.6	23	5 46 26.019	-20.7941	12 11 54.5	46

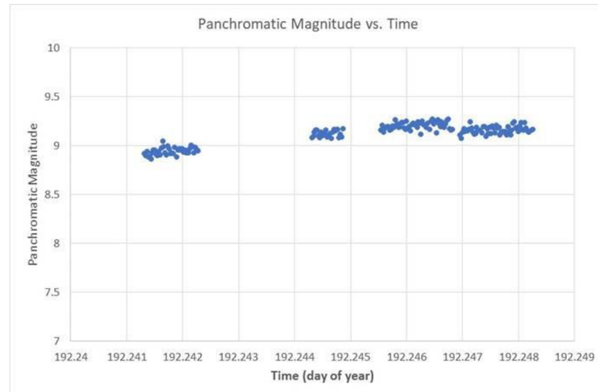


Figure 3. Panchromatic Photometry Measurements of BepiColombo

Summary: 17 minutes total of metric and photometric observations. Only first nine minutes of metric obs were actually used. (Next slide shows why.)

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P and Q Residuals in HGM Preliminary Orbit Determination

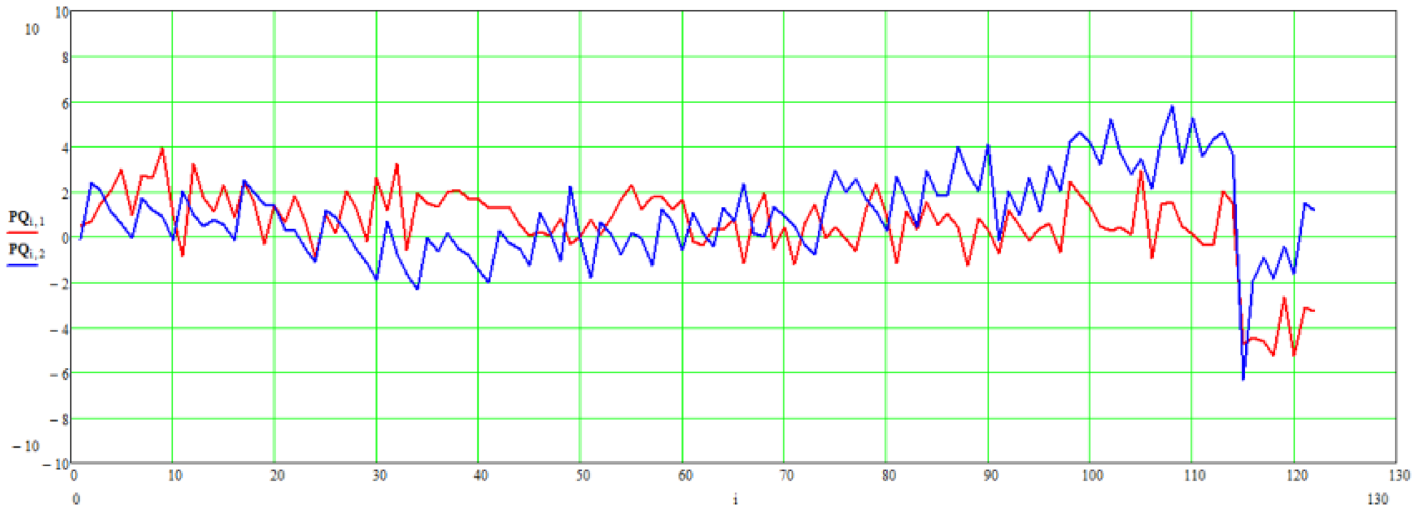

Figure 4. HGM's P (red) and Q (blue) Residuals (km) vs. Observation Number i for 122 of 124 PPT Observations.

The P and Q residuals formulas are as follows: P = ρ cos(δ) Δα and Q = ρ Δδ.

Here α is right ascension, δ is declination, and Δ denotes the residual in the sense "observed minus computed."

Observations truncated after observation 92 due to later obs being noisier. Truncation cut total time span of observations from original 17 minutes down to nine minutes.

HGM and BDC Solutions

Table 3. HGM and BDC Results with BepiColombo Flyby Observations Collected at PPT.

Flyby Path, Conic Element or Parameter	Results with HGM, 46 observations	Results with BDC, 46 observations
Perigee radius, Earth radii	2.80502	2.84028
Orbital eccentricity	1.585649	1.587760
Flight time, perigee to epoch, min	82.76441	82.98398
Orbital inclination, deg	159.91224	159.75680
Rt. ascension of asc. node, deg	149.42737	149.67420
Argument of perigee, deg	249.10349	249.87760
RMS error, km	0.819	0.146

(HGM = hgm8.exe, BDC = bd4.exe. Epoch is at time of last observation.)

HGM used 46 observations but performed a two-parameter fit (range estimates for first and last observations). BDC did a true six-parameter fit (position and velocity at time of last observation) and provided a 6x6 covariance matrix.

So BDC solution is more accurate and provides more information.

Measurement Reduction, 42 Minor Planet Center (MPC) Observations

Table 4. BepiColombo Flyby Results with 42 MPC Observations.

Flyby Path, Conic Element or Parameter	Results with Gh1/Ghc	Results with Gd1/Gdc	Results from [9]
Perigee radius, Earth radii	2.96499	2.97613	(not specified)
Perigee height, km	12,533	12,604	12,677
Orbital eccentricity	1.7494	1.7527	(not specified)

BepiColombo observations reported to MPC over span of three days provided a means to assess quality of PPT observations taken over span of 17 minutes.

MPC received 42 observations of BepiColombo during 10-13 April 2020 as the Mercury probe was outbound from Earth's vicinity.

At first detection, BepiColombo was designated as asteroid 2020 GL2. When observer P. Birtwhistle informed the MPC that the object was actually the ESA/JAXA Mercury probe BepiColombo, the MPC delisted the "asteroid" from its minor planet database.

Ground Trace Plots

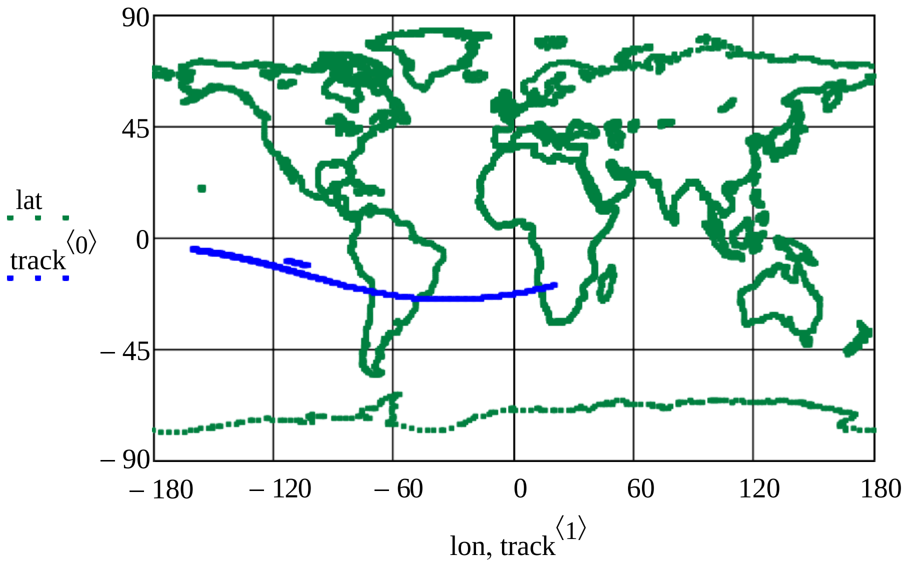

Figure 5. Ground Trace Points/Paths for BepiColombo Flyby

Longer blue trace was generated using Geocentric DC Initiation/Geocentric DC Iteration (Gd1/Gdc) solution with 42 MPC observations spread out over three days.

Shorter blue trace was generated using Batch UPM Differential Correction (BDC) solution with 46 PPT observations spread out over nine minutes.

Appendix: Gauss and Laplace Solutions

Table A1. Gauss and Laplace Solutions with Three PPT Observations.

Flyby Path, Conic Element or Parameter	Results with Gauss Method	Results with Laplace Method
Perigee radius, Earth radii	3.7970478	3.815775
Orbital eccentricity	3.081167	3.100476
Flight time, perigee to epoch, min	69.30437	69.22275
Orbital inclination, deg	157.99485	157.95515
Rt. ascension of asc. node, deg	148.50744	148.54260
Argument of perigee, deg	262.93391	263.18509

(Epoch is at time of middle observation.)

The HGM solution given in Table 3 in the body of the paper exhibits a perigee radius of approximately 2.8 Earth radii. The Laplace and Gauss solutions in Table A1, above, both exhibit perigee radii of approximately 3.8 Earth radii.

The perigee radius exhibited in Table 4, approximately 3.0 Earth radii, is based upon a differential correction with 42 observations reported to the MPC. It is believed to be the best possible estimate of perigee radius, given the available data. So the HGM preliminary solution is better than the Gauss and Laplace solutions because it characterized perigee radius better. Similar comment for eccentricity.

Summary

- **PPT observations of BepiColombo provided valuable test cases**
  - Single-sensor, short-arc
  - Useful to test MITRE IOD and differential correction programs
- **Data collect was only 17 minutes in duration**
  - And only the outbound leg of BepiColombo's hyperbolic flyby path was tracked
  - So the BDC orbital solution in Table 3, column 3 is **preliminary** rather than **definitive**
  - But the BDC solution quite good, despite the fact that the 46 observations actually used only span the first nine minutes of the 17-minute data collect
- **Tracking of the BepiColombo Earth flyby by the MTN observatory at PPT**
  - Generated high-quality metric observations, which, upon reduction, confirm that BepiColombo safely flew by Earth in a hyperbolic trajectory
  - Provided photometry indicating the BepiColombo spacecraft had a visual magnitude of approximately 9.0, as expected

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Questions?

Thank you for attending!

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