EPOXI

Extrasolar Planet Observation and Characterization (EPOCh) and Deep Impact eXtended Investigation (DIXI)

EPOXI Trajectory and Maneuver Analyses

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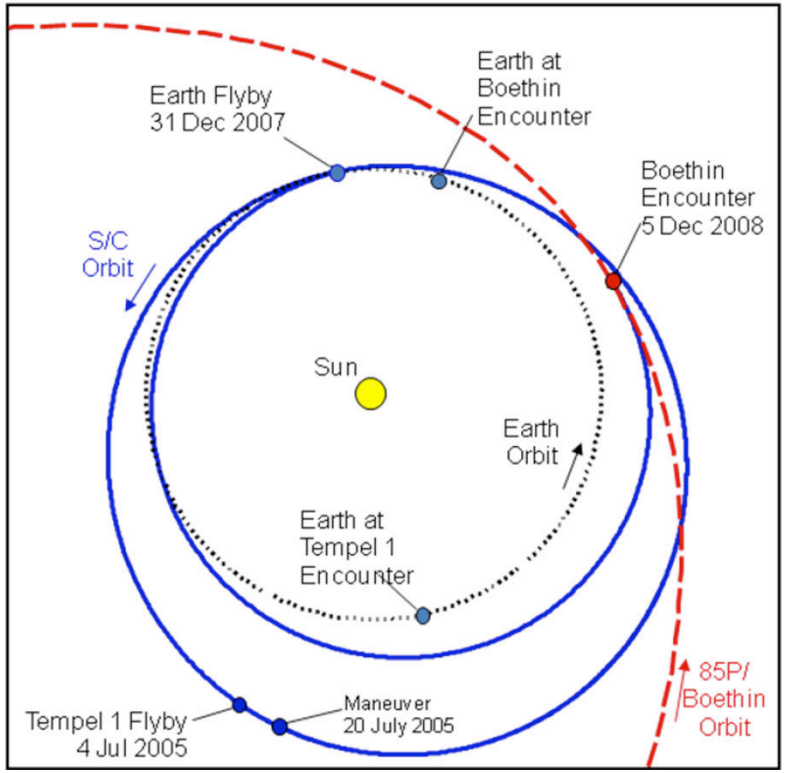
Preliminary Trajectories

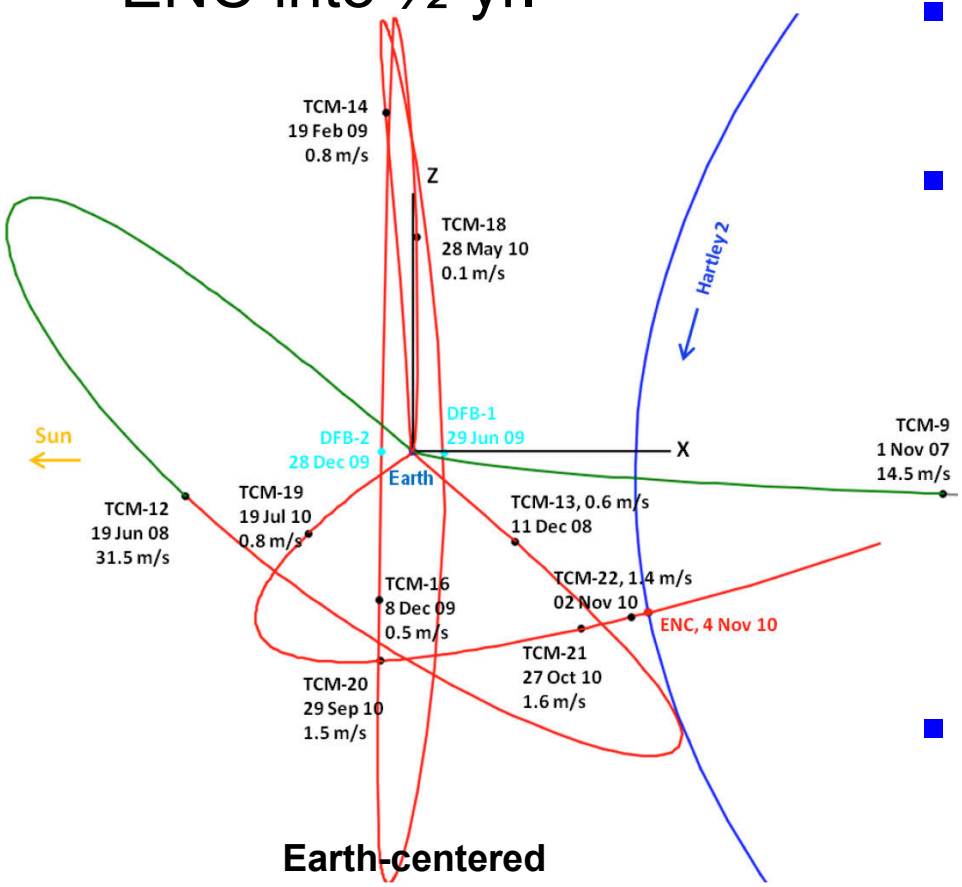


- DI Trajectory
  - Launched into ~1.5-yr period orbit w.r.t. Sun for encounter with Temple 1 in ½ yr.
  - Shortly afterwards TCM-8 (97 m/s) performed for expected <u>encounter with Boethin</u> in 3 yrs.
- EPOXI Mission
  - Awakened in Sep'07.
  - Boethin not recovered.

- TCM-9 (14.5 m/s) performed for <u>backup trajectory to Hartley 2</u>.
- Phase angle (Sun-comet-s/c) on approach too low (~70º).
- <u>Alternate trajectory to Hartley 2</u> found with better phase angle but with a long Earth eclipse.

Final Reference Trajectory

- Convert the leg from EGA-2 to 3 into a 1½-yr Earth loop w/ 2 distant Earth flybys(DFB-1 & 2) and the leg from EGA-3 to ENC into ½-yr.



Earth-centered
Sun-Earth Rotating Frame

- TCM-12 (31.5 m/s) into the final reference trajectory.
- The leg from EGA-2 to 3 remains in a narrow region above and below Earth w.r.t. the Ecliptic
  - Sun range ~1 AU (backup traj < 0.885 AU where 0.88 AU minimum for thermal reason).
- Converting the leg from EGA-3 to ENC into ½-yr achieves the phase angle of ~86º.

Statistical ΔV Analyses

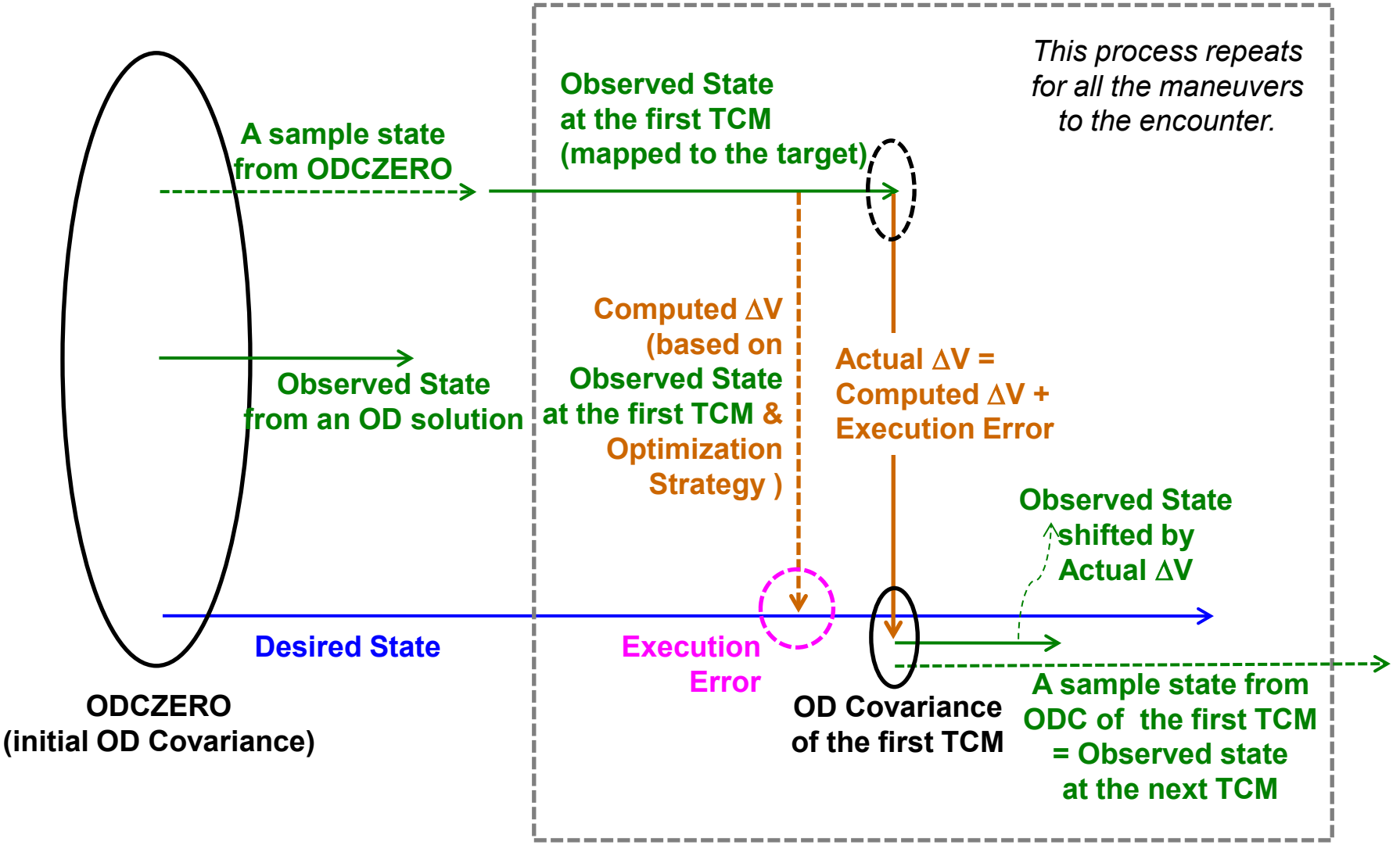
- Due to a few reference trajectory updates, we had to ensure each reference trajectory had enough fuel / ΔV remaining.
  - In the beginning, 70 m/s of ΔV capability for Boethin trajectory.
  - TCM-9 (14.5 m/s) to target Hartley 2 (56 m/s remaining).
  - TCM-12 (31.5 m/s) to insert into the final reference trajectory (less than 25 m/s remaining).
  - Final reference trajectory longer and more complicated:
    - Two additional EGAs and DFBs
    - Comet ephemeris uncertainty

- Statistical ΔV analysis estimates the ΔV requirement via Monte Carlo simulation using OD covariance matrix.

OD Covariance

- Correlated covariance matrix for the s/c state
  - Determined at the data cutoff (DCO) of each maneuver and
  - Mapped to the next significant encounter target.
- Simulated Doppler and range radio data, the optical navigation data, desats, *a priori* uncertainties of all estimated and considered parameters, etc. are input to a standard filter to estimate the spacecraft state and map it and its uncertainty to the next encounter event.

OD Covariance Propagation



Monte Carlo Simulation using OD Covariance

- The OD covariance propagation cycle repeats for all maneuvers until the comet target is reached.
- The above process repeats for at least 5,000 randomly independent cases.
- The statistics of the actual ΔVs are gathered together to yield the mean, the sigma, and the expected percentile values of each individual TCM as well as the total TCMs.
- JPL Mission Design & Navigation Section software LAMBIC (Linear Analysis of Maneuvers with Bounds and Inequality Constraints) was used to perform the statistical ΔV analyses.

Statistical ΔV Analyses Results

- Performed statistical ΔV analyses at various points and at least once prior to each major reference trajectory update to ensure ΔV capability to complete the mission.
- For example,
  - The final reference trajectory update prior to TCM-12, we had about 56 m/s ΔV capability allocated for maneuver.
  - Using LAMBIC, we estimated ΔV95 for the final reference trajectory to be 47 m/s optimally or at most 53.5 m/s in the worst condition (vectorization for all future maneuvers)
  - With the delivery dispersion up to 5-6 km at 1-σ in **B•R** & **B•T**.
  - Thus, we were able to conclude that the fuel allocated for maneuver was sufficient to complete the entire mission at least with a ΔV 95% confidence level.

Estimating vs Considering Hartley 2 Ephemeris Uncertainty

- Sample case done over 1 year before the encounter where we compared two different ways of reckoning the Hartley 2 ephemeris uncertainty to ensure ΔV capability:

  A. Estimate the Hartley 2 ephemeris at TCM-19 and propagate the uncertainty to TCM-20 (the method used up to this point, but the estimated uncertainty may be too optimistic).

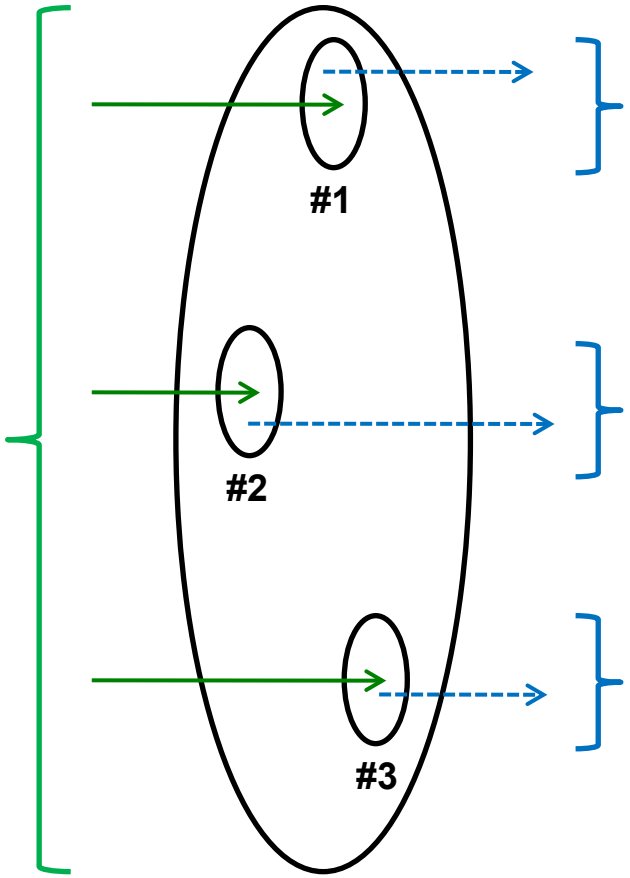
TCM	ODC Name	σ(B.R), km	σ(B.T), km	Remark
19	ODC19A	6119	925	Estimate H2 Eph
20	ODC20A	147	139	Estimate parameters

  B. Consider the Hartley 2 ephemeris uncertainty at TCM-20 via an *a priori* comet covariance when the optical navigation data is available (closer to what is expected via optical navigation data)

TCM	ODC Name	σ(B.R), km	σ(B.T), km	Remark
19	ODC19B	325	531	Not Estimate H2 Eph
20	ODC20B	6118	771	Consider H2 Eph uncertainty

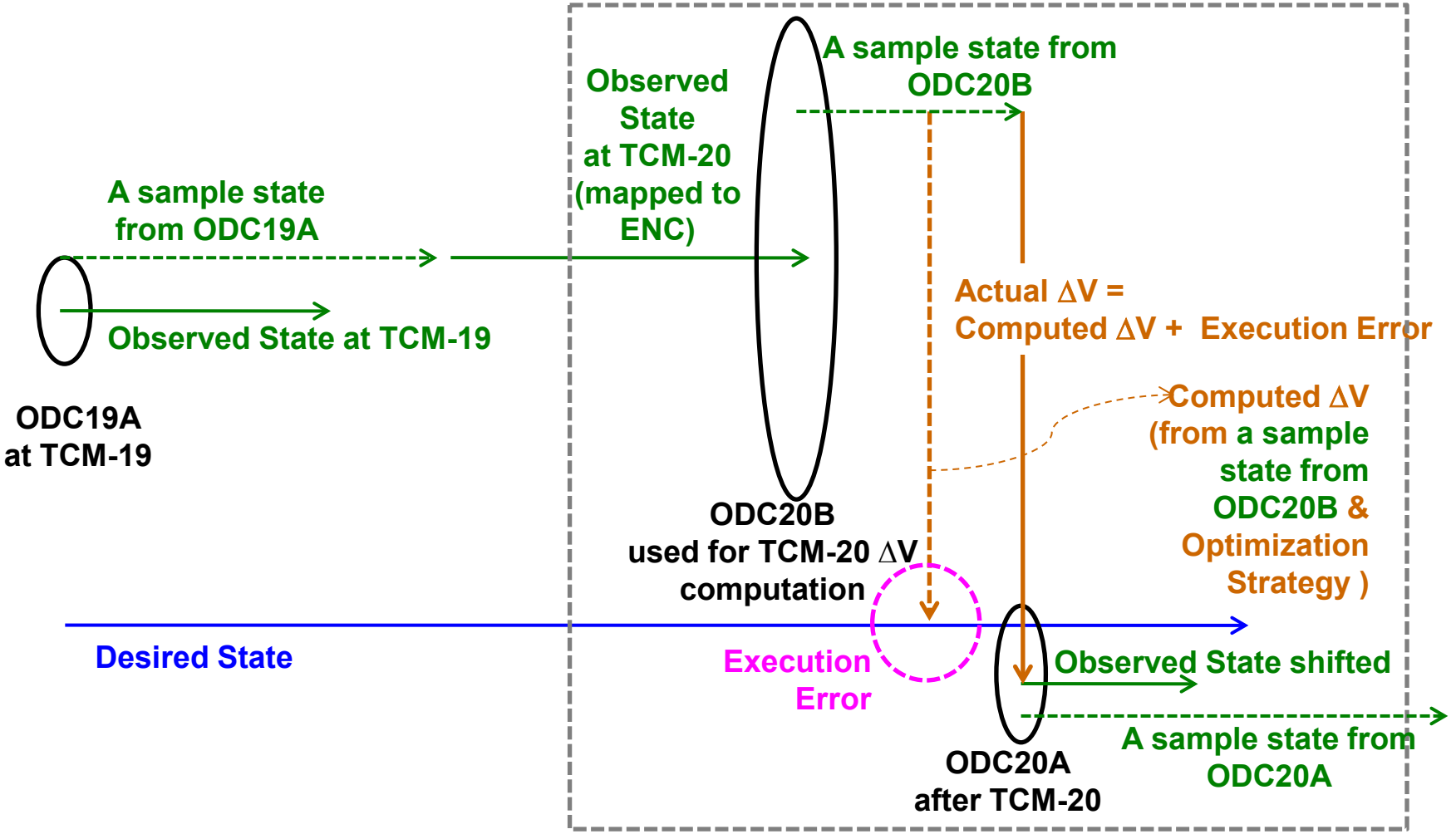
ODC20B

ODC20B, an *a priori* Hartley 2 ephemeris uncertainty, fully resolved at TCM-20 optically, for example, either #1, #2, or #3, etc.



Normal/estimated OD uncertainty, ODC20A, unused for the computation of TCM-20 DV but used to sample from each observed state. These will be observed states for TCM-21.

A Priori OD Covariance Propagation



Statistical ΔV Estimating Hartley 2 Ephemeris at TCM-19

- This was simulated using OD covariances: ODC19A + ODC20A.
- LAMBIC produced the following satisfactory result:

TCM	Mean (m/s)	1-σ (m/s)	ΔV90 (m/s)	ΔV95 (m/s)	ΔV99 (m/s)	OD Covariance Used	Remark
16	0.73	0.54	1.49	1.77	2.31	ODC16	ODCZERO Used initially
17	0.09	0.06	0.17	0.22	0.31	ODC17	
18	0.45	0.30	0.87	1.03	1.36	ODC18	
19	4.20	2.49	7.34	8.65	12.09	ODC19A	Estimate Hartley 2 Ephemeris
20	2.35	1.74	4.79	5.71	7.51	ODC20A	
21	0.42	0.25	0.77	0.91	1.19	ODC21	
22	0.44	0.31	0.88	1.04	1.38	ODC22	
Total	8.69	3.18	12.77	14.34	18.10		

Statistical ΔV Considering Hartley 2 Ephemeris Uncertainty at TCM-20

- This was simulated using OD covariances: ODC19B + ODC20B.
- Had to "rewire" LAMBIC to make it work with an *a priori* OD covariance:

TCM	Mean (m/s)	1-σ (m/s)	ΔV90 (m/s)	ΔV95 (m/s)	ΔV99 (m/s)	OD Covariance Used	Remark
16	0.73	0.54	1.49	1.77	2.31	ODC16	initial ODCZERO
17	0.09	0.06	0.17	0.22	0.31	ODC17	
18	0.45	0.30	0.87	1.03	1.36	ODC18	Pre-EGA-3
19	4.20	2.49	7.34	8.65	12.09	ODC19B	Not estimate Hartley 2 Ephemeris
20	2.36	1.74	4.81	5.73	7.52	OCD20A	ODC20B added *a priori*
21	0.42	0.25	0.77	0.91	1.19	ODC21	
22	0.44	0.31	0.88	1.04	1.38	ODC22	
Total	8.69	3.18	12.78	14.34	18.14		

Other Maneuver Design Analyses

- We updated the reference trajectory with JPL trajectory optimization s/w CATO for every maneuver.
- Avoiding Vectorization of TCM
- Analyses useful for determining a cancellation of TCM
  - ΔV contour map
  - Maneuver solution w/ or w/o a TCM

Conclusion

- Due to a few updates to the reference trajectory, statistical ΔV analyses had to be performed at various times to ensure that we had enough ΔV to complete the mission.
- Strategies were developed to address the challenges and perform maneuver design efficiently with much automation, which led to a successful Hartley 2 encounter.

NASA
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EPOXI

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