EPOXI

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

Navigation of the EPOXI Spacecraft to Comet Hartley 2

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Background

- On Jul 4, 2005, Deep Impact impactor spacecraft collides with comet Tempel 1, while mother ship flies by and images the impact
- With DI primary mission completed, healthy mother ship has over 70 m/s propellant remaining to use for extended mission, plus working suite of instruments
  - High Resolution Imager (HRI) and Medium Resolution Imager (MRI)
  - Infrared Spectrometer
- Spacecraft performs maneuver in August 2005 which brings it back for an Earth flyby and eventual encounter with comet Boethin in the hope that such a mission will be funded. Spacecraft then put into hibernation mode
- In mid-2007, extended mission for DI funded under NASA's Discovery Mission of Oppurtunity Program
  - Extrasolar Planet Observation and Characterization (EPOCh) uses HRI to observe transit of planets across stars
  - Deep Impact eXtended Investigation (DIXI) to flyby and image Boethin in late 2008 using MRI, HRI, and IR Spectrometer
  - Missions combined into one, with merged name called EPOXI

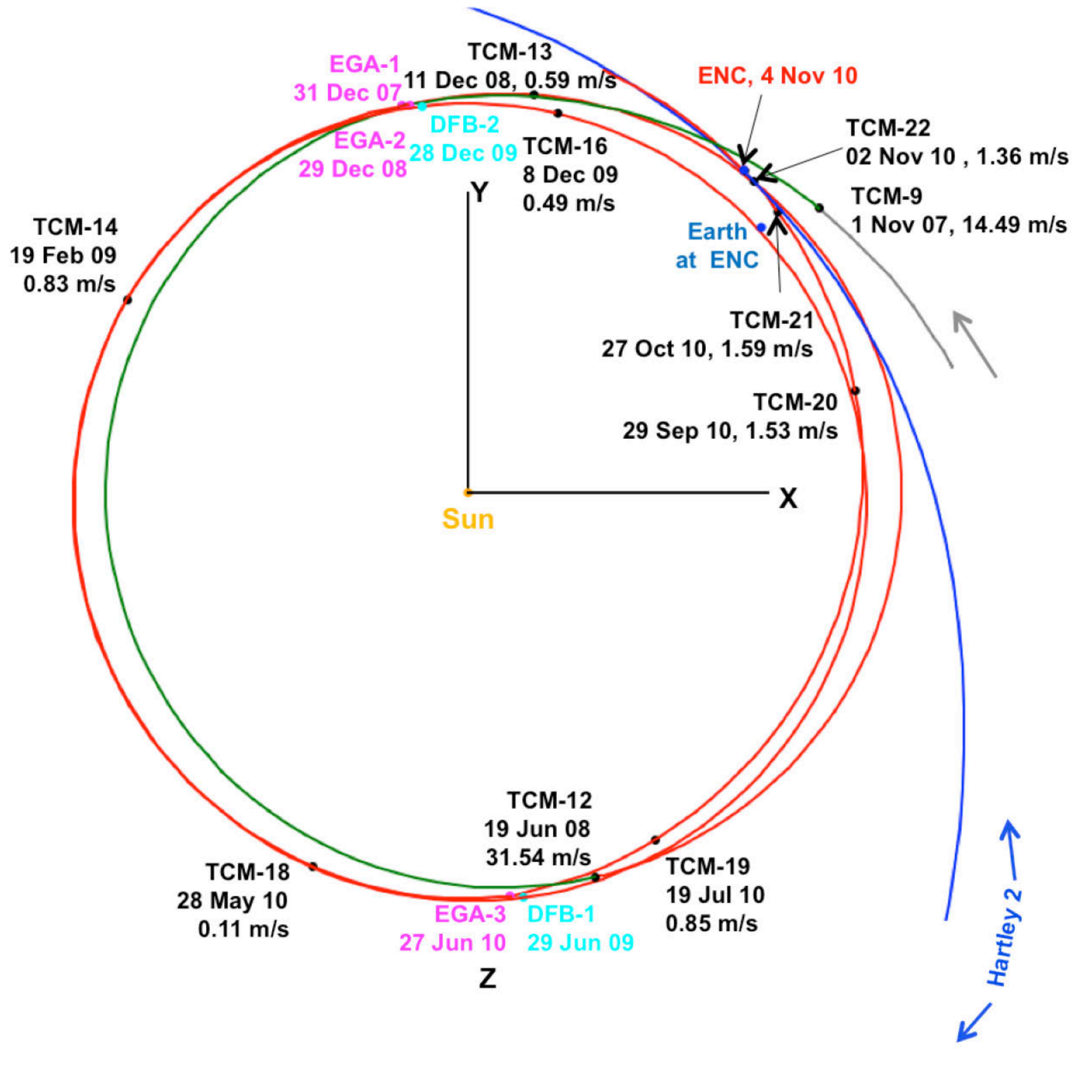
Background (cont)

- On September 24, 2007, command sent to bring spacecraft out of hibernation
- Ground observations to locate comet Boethin unsuccessful, leading to conclusion that Boethin may have broken up
- Decision made in November 2007 to target different comet, Hartley 2
  - Requires immediate maneuver to change upcoming Earth gravity assist in December 2007
  - Longer mission, eventually requiring three Earth gravity assists, 3 year cruise, and encounter in Fall of 2010

Mission Design

- 1st step in flying mission – design reference trajectory which satisfies mission constraints
  - Engineering constraints include available fuel, telecom links, thermal constraints, , battery limitations, mission duration,etc.
  - Science constraints include scientific attractiveness of target, image resolution and smear, lighting geometry before, during, and after encounter etc.
- Search made in Fall 2008 to find alternate comets which satisfy constraints
  - Searched for comets with perihelion distances less than 1.6 AU and arrival dates between January 2008 and January 2011
  - Among available candidates, comet Hartley 2 selected by PI
- Minimum delta-V optimized trajectory found which encounters Hartley 2 on October 11, 2010
  - 1st EGA in December 2007 places s/c in trajectory which stays very near Earth for 2 years, 2nd EGA 1 year later, then 3rd EGA in December 2009 provides boost to arrive at comet
  - Not ideal for science – phase angle on approach not good for IR spectrometer
- Mission redesigned in Spring 2008 (after EGA-1) which shifts EGA-3 six months later and arrives at Hartley 2 on November 4, 2010
  - Alternate trajectory improves phase angle on approach
  - Higher delta-V needed, in particular, a trajectory correction maneuver (TCM) on June 19, 2008, and one additional TCM a month prior to EGA-3
  - Final design has flyby at 700 km radius and relative velocity of 12.3 km/s

Reference Trajectory



Navigation

- Orbit determination – use tracking data to reconstruct the s/c trajectory and predict future course
  - Fit a high fidelity dynamic model of s/c trajectory to tracking data
  - Dynamic model includes following forces
    - Point-mass gravitational attraction of Sun, planets, and Moon
    - Effects of non-spherical gravity field when near a planetary body (70x70 spherical harmonic expansion used for EGAs)
    - Solar radiation pressure
    - Spacecraft propulsive events (TCMs, small force events for momentum wheel desaturations)
    - Comet gravity has negligible effect on trajectory and is not included
- Maneuvers performed to correct the course
  - Deterministic maneuvers designed as part of reference and tweaked as needed
  - Statistical maneuvers have zero a priori values in reference but placed at strategic locations to clean up OD and maneuver execution errors

Navigation (cont)

- Tracking data
  - Radiometric data (2-way Doppler, 2-way range)
    - Provides line-of-sight velocity and distance of s/c to tracking station
    - Used through all mission phases
  - Interferometric (Delta Differential One-way Range, or DDOR)
    - Provides angular measurement of s/c in Earth plane-of-sky
    - Complementary to the information along line-of-sight from radiometric data
    - Used through all mission phases
  - Optical data (image of comet taken from onboard camera against star background)
    - Stars in the frame used to fix the inertial pointing direction of camera boresight
    - Centerfinding on comet used to determine angular position of s/c relative to target
    - Critical for missions to comets due to large uncertainty in ephemeris of comet since this is the only target-relative information available
    - Used only during approach/encounter - measurements start roughly 50-60 days prior to encounter when comet becomes bright enough to detect in camera
    - Initial measurements effect primarily is to correct a priori comet ephemeris. As s/c nears comet, measurements have enough strength to correct both s/c and comet trajectories
- Filter
  - Batch-sequential filter to perform least-squares fit of all data types
  - Ability to estimate bias and stochastic parameters
  - Solution mapped to coordinates of interest (e.g. B-plane), along with associated covariances

Comet Ephemeris

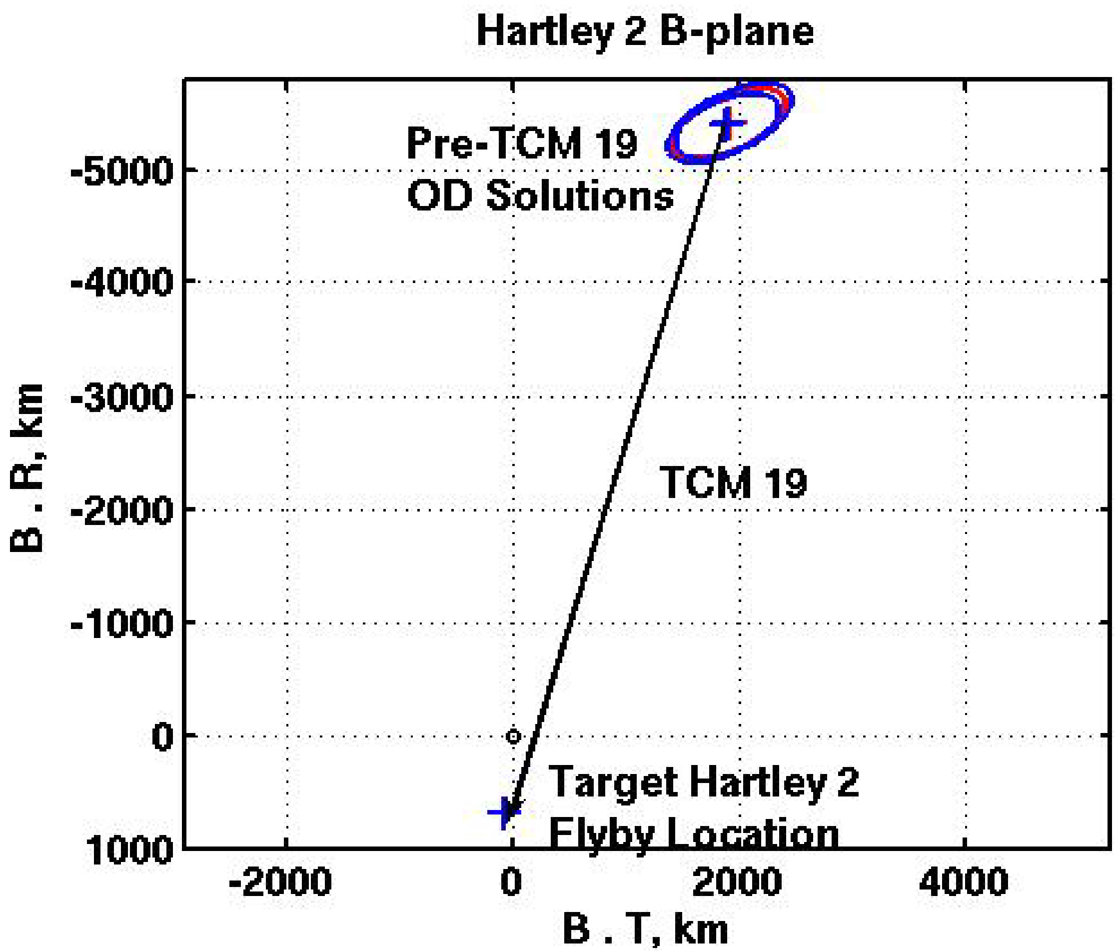
- Knowledge of target body ephemeris a key factor in the implementation of comet encounter missions
- Comet ephemeris modeling
  - Outgassing of volatiles produces unpredictable, and therefore difficult to model non-gravitational force
  - Coma surrounding nucleus obscures location of nucleus, so observations have inherent biases
  - Combination of poor dynamic model with poor measurement model makes ephemeris uncertainties relatively large
- Pre-encounter comet ephemeris
  - Comes from many years of ground observations taken at sporadic intervals from multiple observatories
  - Accuracy of ephemeris from ground-based measurements only sufficient for designing reference mission, but not for precision targeting of flyby
- Approach and encounter comet ephemeris
  - Onboard optical data provides additional data, starting ~2 months before encounter. Accuracy increases as distance to comet decreases
  - Combination of ground and onboard data used to make continual improvements to comet ephemeris during approach
  - Accuracies dependent on many factors, including relative viewing geometries of spacecraft and Earth, resolution of onboard camera, centerfinding ability, behavior of comet
  - Best accuracy for terminal targeting comes when nucleus becomes photometrically detectable from spacecraft which only happens several days from encounter

Cruise Results

- EGA-1 on December 31, 2007
  - TCM 9 (EGA-60 days) and TCM 10 (EGA-30 days, cancelled) used to target flyby
  - Achieved perigee of 21,943.6 km at 19:29:20 UTC, 300 m and 15 seconds from target
  - Accuracy of flyby sufficient to cancel post EGA cleanup maneuver (TCM 11)
- EGA-2 on December 29, 2008
  - TCM 13 (EGA-20 days) used to target flyby
  - Achieved perigee of 49,835.0 km at 21:39:57 UTC, 7 km and less than 1 second from target
  - Post EGA cleanup maneuver canceled
- EGA-3 on June 27, 2010
  - TCM 18 (EGA-30 days) used to target flyby
  - Achieved perigee of 36,875.0 km at 22:03:49 UTC, 16 km and 1.2 seconds from target
  - TCM 19 (EGA+22 days) used to cleanup Earth flyby errors
- No “anomalous delta-V” seen in any of the Earth flybys

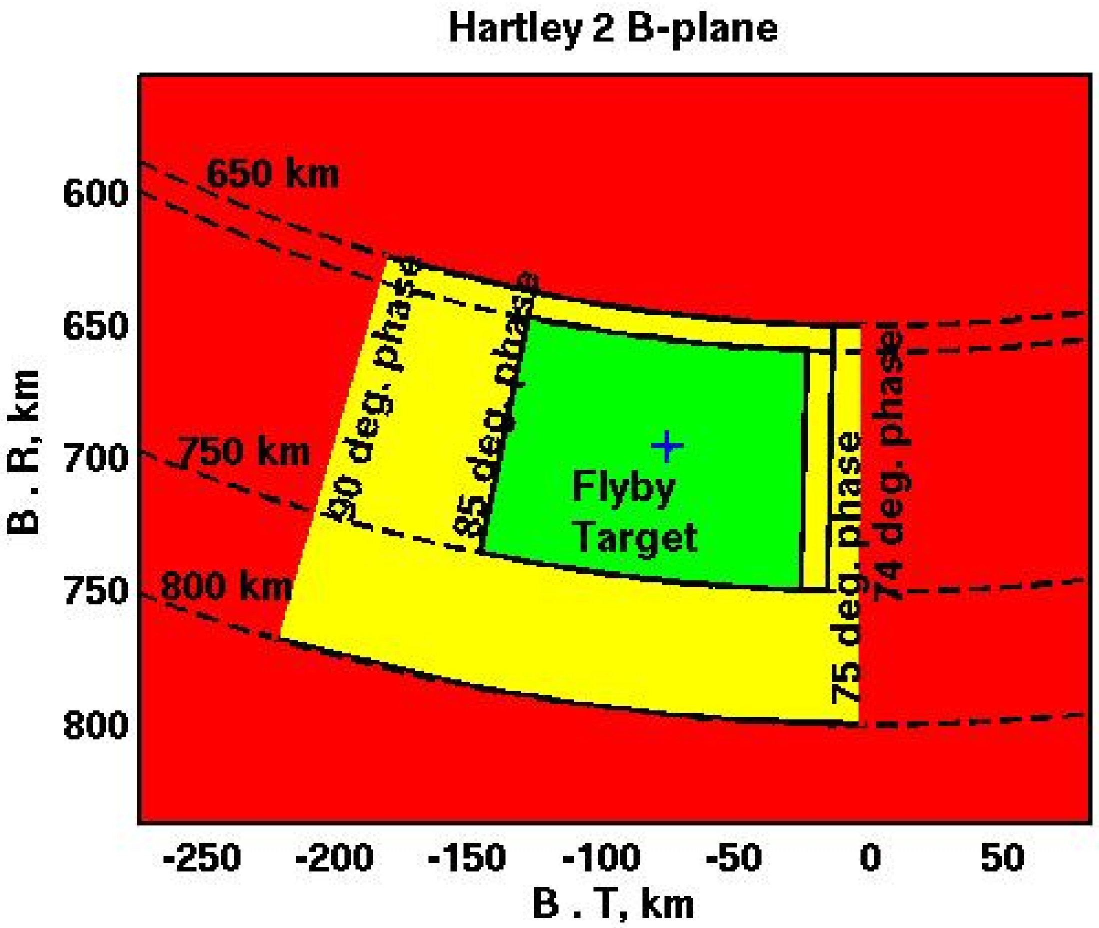
TCM 19

- Hartley 2 ephemeris at time of TCM 19 still based solely on ground observations
- Although EGA-3 accuracy within tolerance, magnification effect of flyby has large effect on post-flyby trajectory which needed corrections



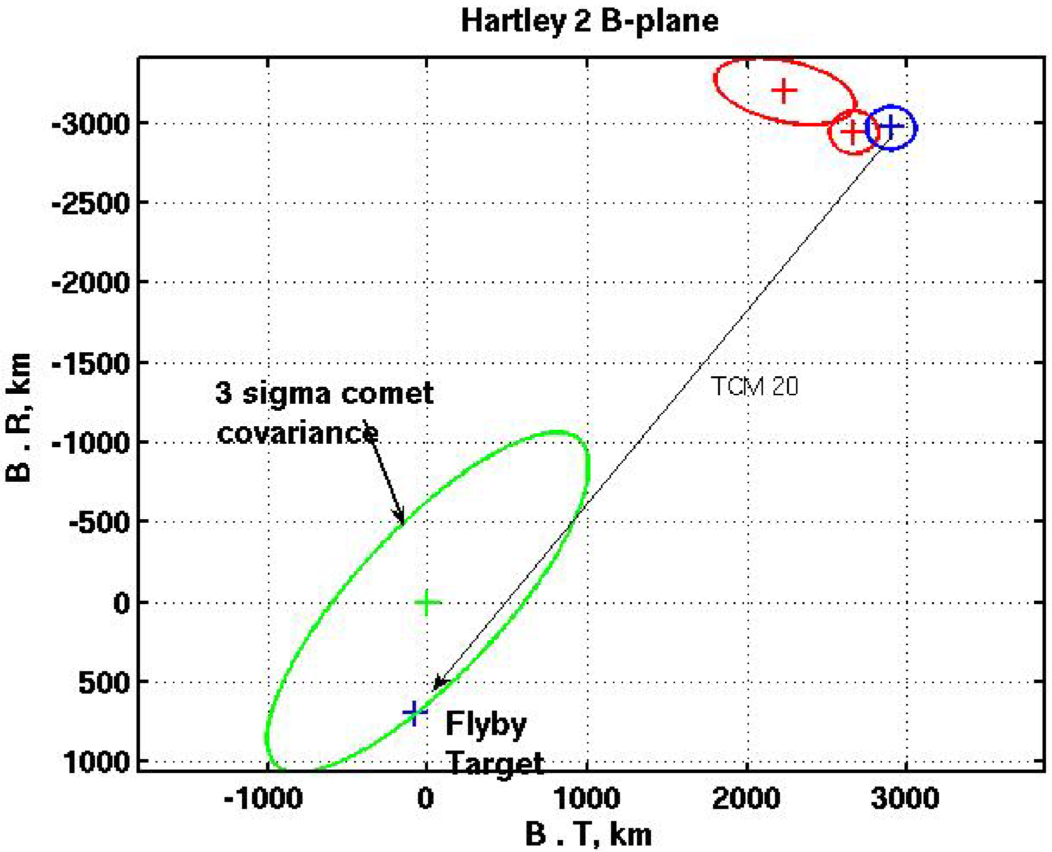
Approach

- Approach strategy was to use 3 TCMs at E-37 (TCM 20), E-10 (TCM 21), and E-2 days (TCM 22) to close in to flyby location
- Flyby location chosen for optimizing science within engineering constraints
  - Distance of 700 km chose for highest resolution within limit of spacecraft slew rate to track comet during flyby
  - B-plane clock angle best for lighting and for IR spectrometer
- Tolerance region for deciding whether or not to implement a maneuver



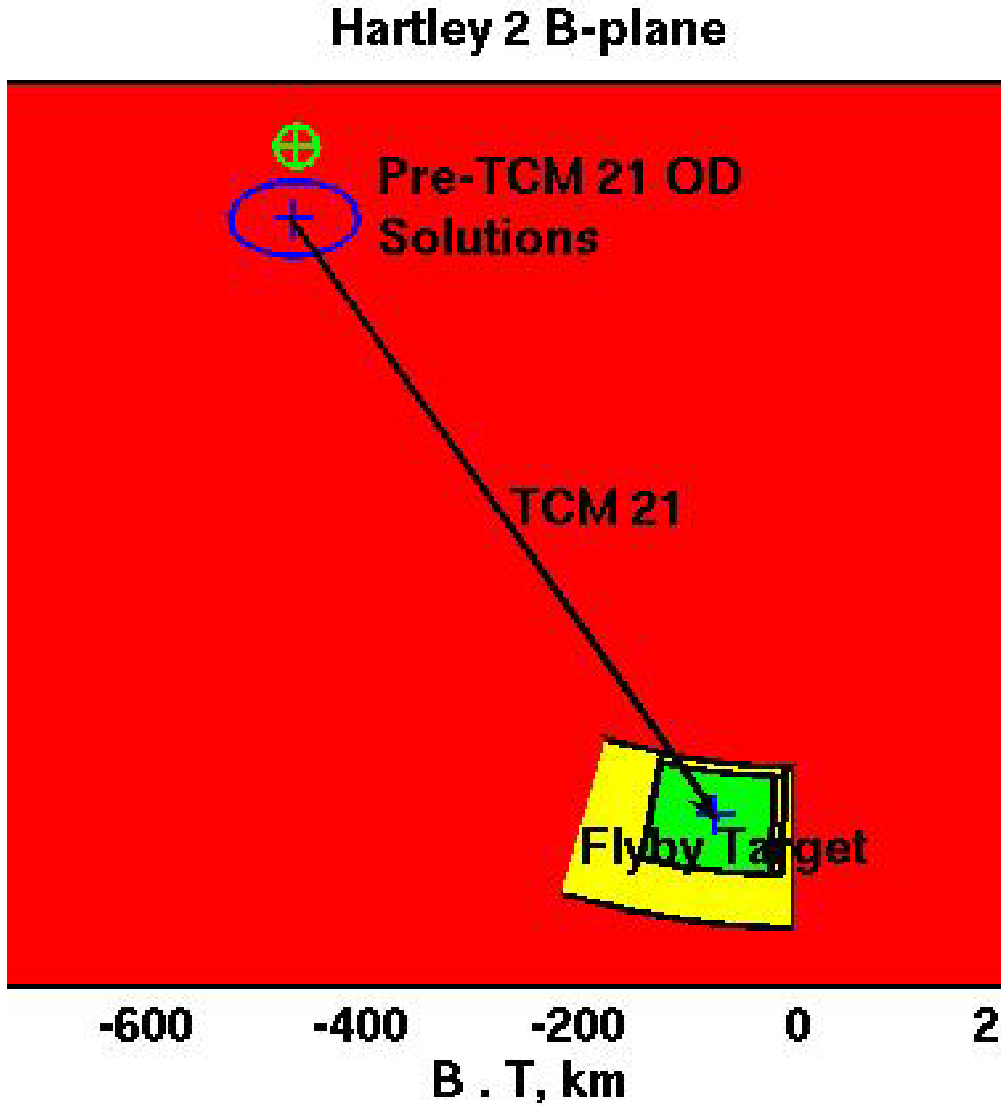
TCM 20 at E-37 Days

- 1st images taken show that comet location much further away than expected
- Solutions for comet ephemeris very unstable
- Source of instability ultimately traced to large outgassing forces acting on relatively small comet
- Choice of which solution to base maneuver on relied as much on intuition as science



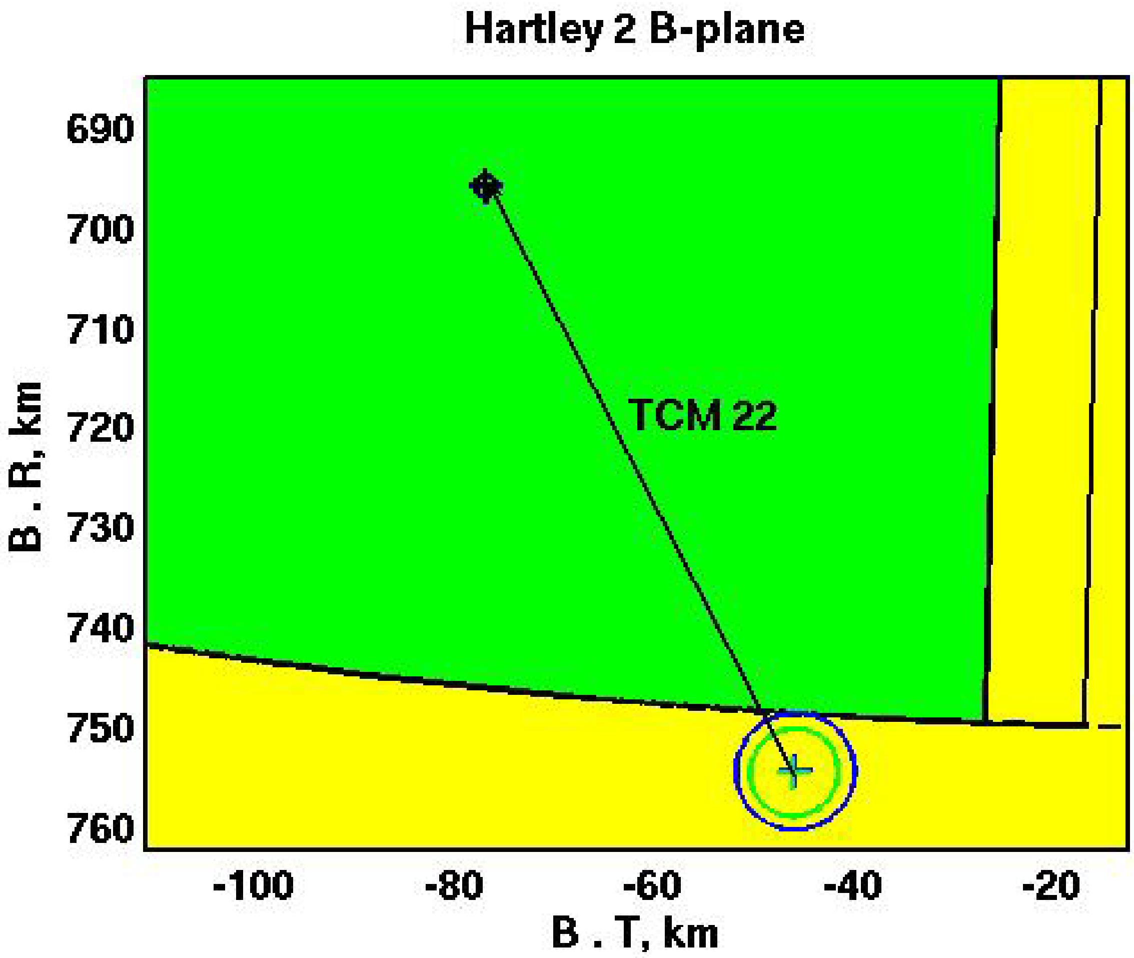
TCM 21 at E-10 Days

- Comet ephemeris still showing high volatility
- TCM 20 maneuver was very accurate
- Remaining error due entirely to comet ephemeris errors
- Inconsistent solutions once again led to using intuition for deciding which solution to design maneuver



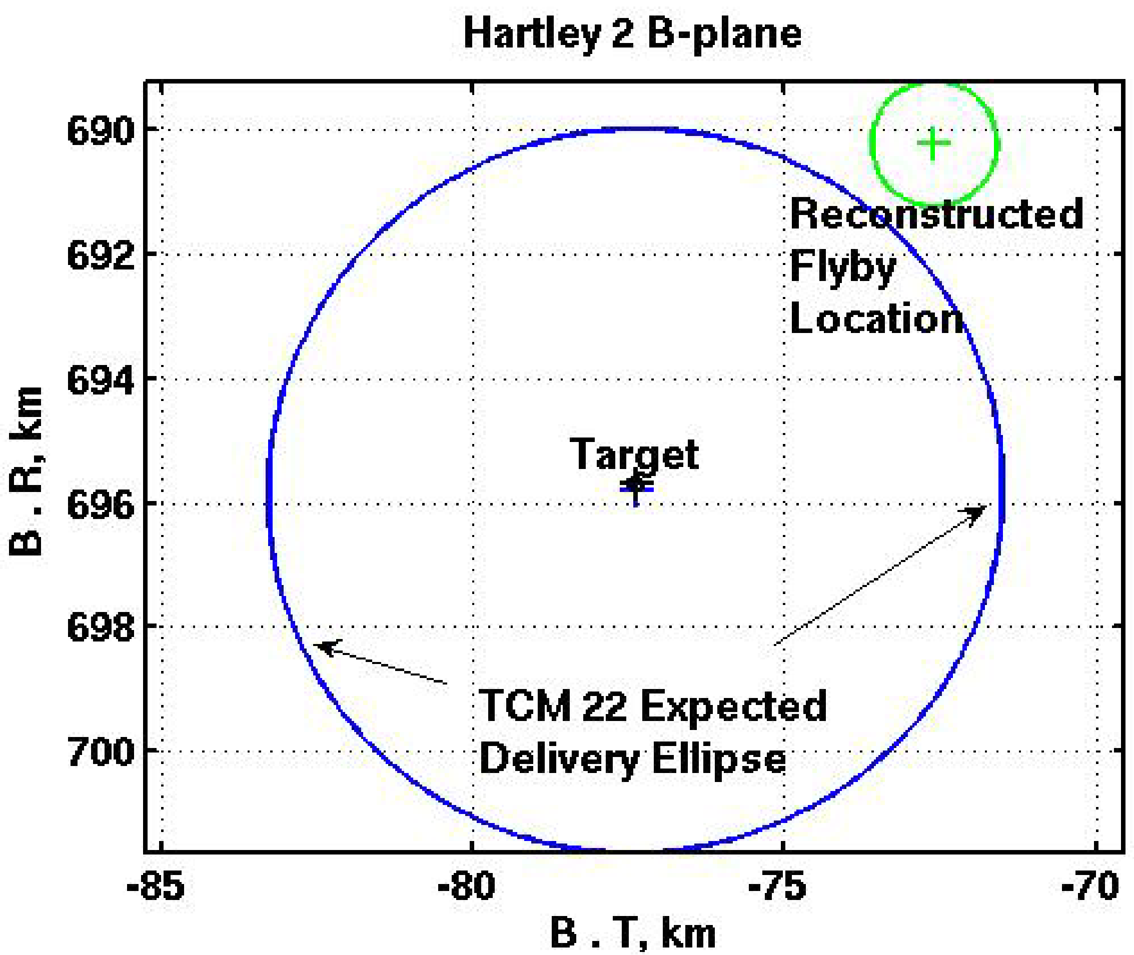
TCM 22 at E-2 days

- TCM 21 performed accurately
- Ephemeris solutions starting to stabilize
  - Optical navigation pictures continually improving in accuracy as comet nears
  - Length of time needed to propagate non-gravitational effects of outgassing on comets shortens, so errors don't have as bad an effect
  - Converging on modeling of comet non-gravs
- Pre-TCM 22 OD solutions just outside green zone
  - PM and PI make joint decision to implement TCM 22



Flyby

- TCM 22 performed accurately
- Expected knowledge of comet-relative state from ground-based navigation not sufficient to keep comet in camera FOV through closest approach
- Onboard AutoNav (used successfully on DI and 2 other missions) used for closed-loop tracking through closet approach
- Post-flyby reconstruction indicated that s/c was delivered to within 6 km of intended target, and 1 sec of intended time, well within science requirements



- Success! 307 out of 307 images taken of nucleus during flyby. All had comet nucleus in MRI FOV.
- Resolution of above image taken at closest approach is about 7 m/pixel.
- Images led to discovery of golf ball size chunks of ice being ejected off surface. Volatiles turned out to be be carbon-dioxide instead of water as originally thought.