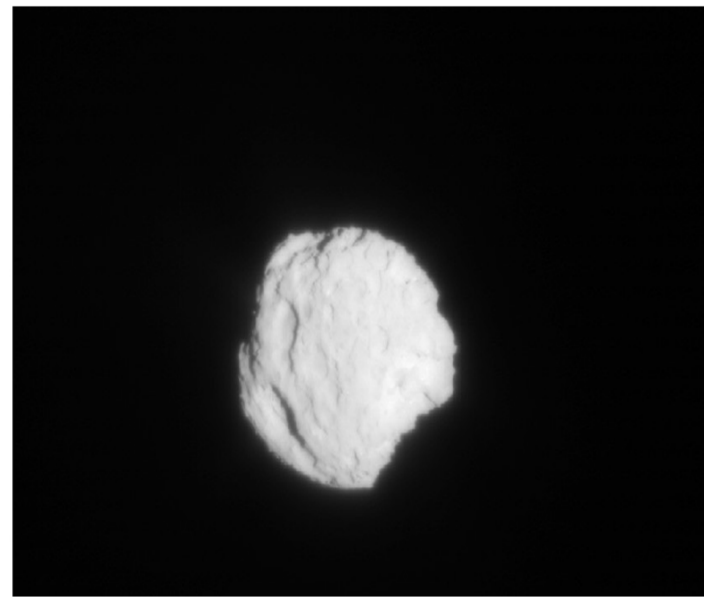# Autonomous Navigation for Deep Space Missions

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Background on Deep Space Navigation

- Spacecraft have visited 8 planets, asteroids and comets
- Navigation (determining where the spacecraft is at any given time, controlling its path to achieve desired targets), performed using ground-in-the-loop techniques
  - Data includes 2-way radiometric (Doppler, range), interferometric (Delta-Differential One-way Range), and optical (images of natural bodies taken by onboard camera)
  - Data received on the ground, processed to determine orbit, commands sent to execute maneuvers to control orbit
- Current capabilities can achieve highly accurate results, for example:
  - km level targeting accuracies for satellite flybys on Cassini mission
  - 10s of km landing ellipses on Mars
- Need still to keep increasing performance for future missions

Drawbacks to Ground-based Navigation

- Long round-trip light time (many minutes to many hours), depending on where the spacecraft is in Solar System
- Time needed to process the data by analysts
  - Orbit determination and maneuver calculations
  - Analyze results
  - Convene meetings to make decisions and implement decisions
  - Generate sequence commands and uplink them to spacecraft
- Lag time between the last navigation update and implementing maneuvers can typically take 8 or more hours to over a week. As a result:
  - Loss of some science, for example, to precisely point instruments at a target cannot use latest navigation knowledge
  - Loss for mission parameters, such as increased use of fuel as the orbit information has become stale during turnaround time to implement maneuvers

Onboard Autonomous Navigation

- A self-contained, onboard, autonomous navigation system can:
  - Eliminate delays due to round-trip light time
  - Eliminate the human factors in ground-based processing
  - Reduce turnaround time from navigation update to minutes, down to seconds
  - React to late-breaking data
- At JPL, we have developed the framework and computational elements of an autonomous navigation system, called AutoNav
  - Originally developed as one of the technologies for the Deep Space 1 mission, launched in 1998
  - Subsequently used on three other spacecraft, for four different missions
  - Primary use has been on comet missions to track comets during flybys, and impact one comet

AutoNav Data

- In principle, can use same data as ground-based navigation (radiometric and optical)
  - Radiometric data requires other information, such as media calibrations, for Earth-based data, or location of other spacecraft for spacecraft-to-spacecraft data
- More straightforward to use entirely self-contained data, so current AutoNav based on using optical data only
  - Future versions can include other self-contained data, such as lidar
- Optical data basics
  - Images are taken of a natural body, either from distance or close-up
  - Center-of-figure of the body is found using a centroiding method
  - Centroid location provides line-of-sight vector to that body (angular measurement)
  - Time series of LOS vectors can be input to a least-squares filter to estimate spacecraft position and velocity
  - Inertial pointing direction of camera provided by stars in image

AutoNav Overview

- All steps performed in ground-based navigation transferred to spacecraft
- Involves 3 steps – (1) image processing, (2) orbit determination, and (3) maneuver planning and execution
- Image processing
  - Camera system includes the lens focusing light onto CCD array
    - Size of CCD pixels, camera focal length, determine image resolution
    - Number of pixels determines total camera field-of-view
    - Incoming light convolved with camera pointspread function to get image
  - Determining center-of-figure location of natural body
    - Unresolved objects – body extends less than a pixel. Use Gaussian or other function as template to correlate with image. Location of maximum correlation is centroid location.
    - Resolved objects – body extends greater than a pixel. Use moment algorithm to determine center-of-brightness

AutoNav Overview (cont.)

- Orbit determination
  - Numerical integration of dynamic equations of motion/ force modeling
    - Ground navigation uses very high fidelity models of forces acting on spacecraft since radiometric data is very accurate, and processing speed not an issue
    - Onboard computers not as fast, and rapid turnaround is important, so force models not as detailed
      - Include central and 3rd body point mass gravitational accelerations, simple solar pressure model, impulsive Delta-V. Onboard thruster activity accumulated by IMUs also included in integration
      - Low-thrust (e.g., ion propulsion system) modeled as linear polynomials
  - Least-squares estimation
    - Difference observed values of data against predicted values (based on predicted spacecraft trajectory) to get residuals
    - Perform least squares fit - adjust parameters of trajectory to minimize the residuals until only random noise remains
    - Result is reconstruction of past spacecraft trajectory, which can also be propagated into future to get predicted path

AutoNav Overview (cont.)

- Maneuver planning and execution
  - If predicted path based on latest OD does not meet mission requirements, maneuvers must be implemented to correct course
  - Current AutoNav can control low-thrust (ion propulsion system) or standard impulsive delta-v (chemical systems)
  - Low-thrust
    - Long burns (many hours to many days), controlled by adjusting linear polynomials representing thrust direction, and duration of burn
    - Adjustments are linear corrections to pre-planned directions and duration
  - Impulsive delta-v
    - 3 parameters of impulse (cartesian components of delta-v) adjusted to control 3 targeting parameters (cartesian or B-plane target location)
    - targeting parameters in linear regime around reference trajectory
  - Full optimization and/or redesign of reference trajectory currently not supported

AutoNav Overview (cont.)

- Data editing
  - AutoNav performs same functions as ground navigation process, but must be done robustly
    - Large outliers in data set, whether random or systematic, would seriously corrupt OD solution if not removed
    - Editing on ground done by human in-the-loop – provides very good filter for bad data, especially systematic errors
  - Optical data used by AutoNav is relatively sparse (e.g., 1 data point every 15-60 sec)
  - Onboard process is to store a series of data, then analyze it statistically for outliers
    - If not enough data accumulated, OD update is not performed
    - Philosophy is that it is better to stay with a known, stale solution, rather than update orbit with potentially bad data
  - Parameters for editing outliers mission specific and decided on from results of many hundreds of Monte Carlo simulation runs

AutoNav Overview (cont.)

- Flyby target tracking
  - Due to rapid turnaround needed during fast flybys of small bodies, specialized version of AutoNav created for this purpose
  - Uses lower fidelity set of dynamics, fewer parameters and inputs/outputs for speed
  - Updates spacecraft position only. Velocity assumed to be good enough not to need updating
  - Initiated in the tens of minutes before closest approach

Mission Results

- 5 missions using 4 different spacecraft have used AutoNav during the mission
    - Deep Space 1 (cruise and flyby of comet Borrelly)
    - Stardust (flyby of asteroid Annefrank and comet Wild 2)
    - Deep Impact (Impactor and Flyby spacecraft imaging for comet Tempel 1)
    - EPOXI (flyby of comet Hartley 2)
    - Stardust NExT (flyby of comet Tempel 1)
- Flyby mission parameters

Mission/Target	Flyby Radius (km)	Flyby Velocity (km/s)	Approach Phase (deg)
DS1/Borrelly	2171	16.6	65
STARDUST/Anne frank	3076	7.2	150
STARDUST/Wild 2	237	6.1	72
DI/Tempel 1	500/0	10.2	62
EPOXI/Hartley 2	694	12.3	86
STARDUST NExT/Tempel 1	182	10.9	82

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Deep Space 1

- 1st mission in NASA's New Millennium Program
  - Goal was to test advanced technologies as part of a demonstration mission
  - DS1 had 12 technologies, among which included:
    - AutoNav
    - Ion propulsion system
    - Miniature Integrated Camera and Spectrometer (MICAS)
- Mission overview
  - Launch on October 1998
  - Fly by asteroid Braille on July 1999
  - Sole onboard star-tracker used to provide s/c attitude fails on August 1999. Results in long period where spacecraft in safe-mode while mission was redesigned to use MICAS camera as substitute star tracker. Long hibernation period results in dropping planned comet Wilson-Harrington flyby
  - Flyby of comet Borrelly on September 2001

Deep Space 1 (cont.)

- Original plan was to have AutoNav control interplanetary cruise and asteroid/comet flybys

- Initial results from camera images, however, showed several unforeseen issues with MICAS
  - Images heavily corrupted by stray light
  - Sensitivity of camera not as good as expected
  - Camera distortions unusual and difficult to model

- Much of AutoNav software had to be reprogrammed to accommodate camera issues and so validation of cruise results delayed until June 1999, 8 months after launch and only 2 months before Braille encounter

- Results in late June and early July indicated that orbit estimates as good as can be expected, but not as good as pre-flight analysis predicted, due to lingering camera performance issues

- Maneuver planning and execution occurred as planned,
  - OD had to be "seeded" from the ground in certain cases due to degraded perfomance
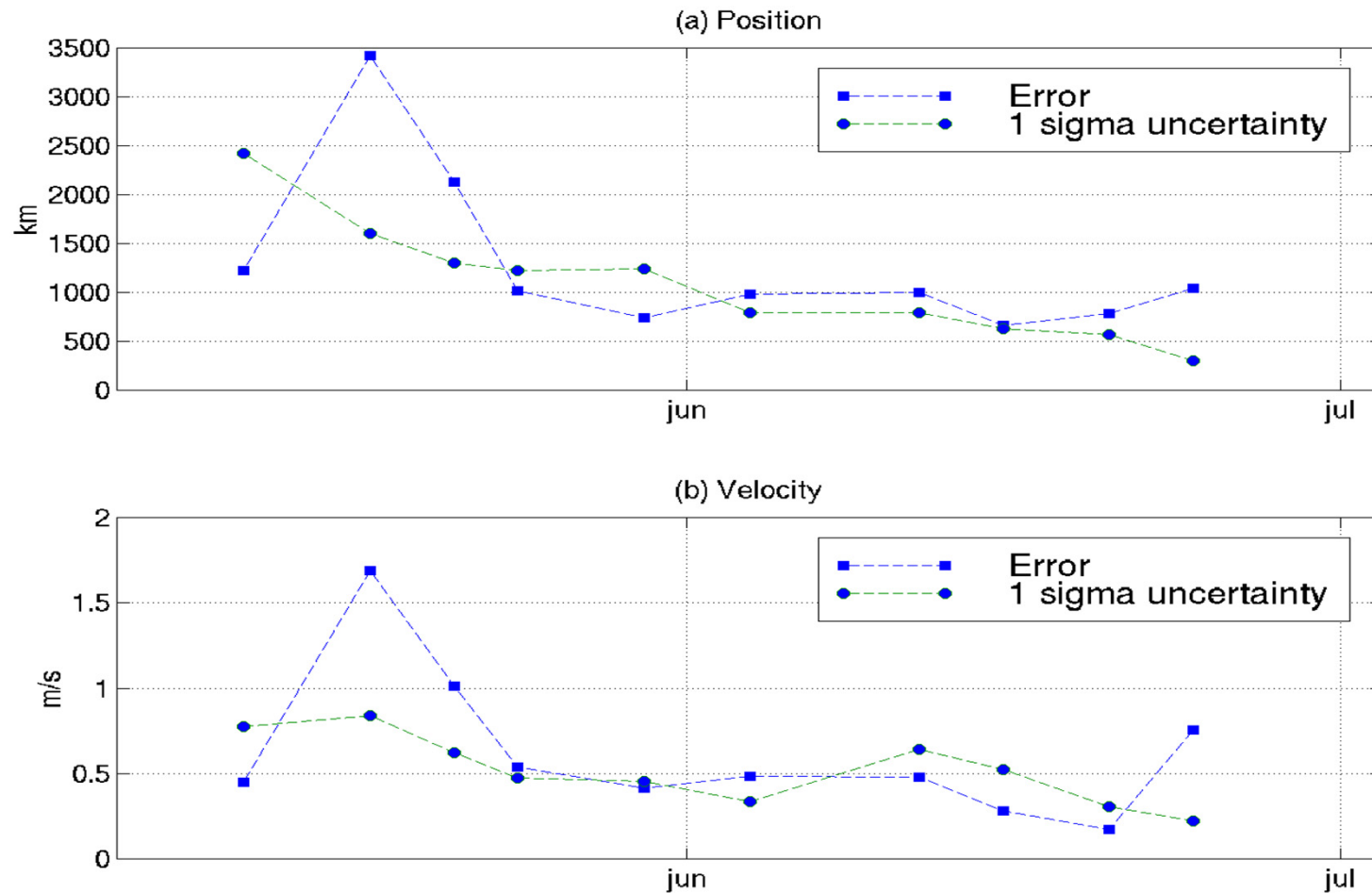
Deep Space 1 (cont.)

- Braille flyby also problematic
  - Flyby tracking mode initiated 30 minutes prior to closest approach
  - In 1st image taken, asteroid was too dim to be detected, but random cosmic-ray induced noise was above threshold and mistaken as the target
  - Since filter updated orbit solution after every image, 1st update produced incorrect orbit, and so subsequent pointing of camera was erroneous
  - Remainder of images never had asteroid in camera FOV, so all close approach images were lost
- Lessons learned
  - Wait for data to accumulate, and not perform OD estimates until sufficient data to perform error checking has been taken
  - Use robust error detection to mitigate against unwanted signal corrupting solution
  - Careful camera calibration to predict signal levels and exposure setting very important

- Following Braille encounter, AutoNav in control of cruise navigation until August star tracker failure. Since AutoNav required attitude information from star tracker, had to fly remainder of cruise using ground-based navigation

- Borrelly encounter on September 23, 2001
  - Lessons from Braille encounter applied, and new software uploaded by June 2001
  - Flyby tracking initiated 32 minutes prior to closest approach
  - AutoNav performed successfully, tracking Borrelly until E- 2.5 min, when slew rate exceeded spacecraft capability
  - Nucleus captured in 46 out of 52 image shuttered, resulting in best image at 46 m resolution on surface

Stardust

- 4th mission of NASA's low cost, PI led Discovery Program
- Primary goal of mission was to fly through coma of comet Wild 2 and return samples to Earth. Second goal was to capture high resolution images of comet nucleus during flyby
- Launch on February 1999
- Opportunistic flyby of asteroid Annefrank on November 2002
  - Provided engineering test case of spacecraft operations at flyby, including test of AutoNav
- Wild 2 flyby on January 2004
- Sample returned successfully to Earth in January 2006
- Cruise, comet approach, and Earth return all done using standard ground-based radiometric and optical navigation techniques

Stardust (cont.)

- Flyby version of AutoNav used for both Annefrank and Wild 2 encounters

- Annefrank
  - High phase (150 deg) approach phase resulted in no ground-updates to target relative position at initiation of AutoNav
  - AutoNav started at E-20 min and tracked asteroid through encounter
  - Successful test increased confidence for Wild 2 encounter

- Wild 2 encounter
  - AutoNav initialized at E-30 min with ground-based target-relative information accurate to 5 km crosstrack, 2000 km (or, equivalently, 50 seconds) in downtrack direction
  - Data accumulated for 20 min, 1st OD update at E-10 min.
  - AutoNav initiated roll at E-4 min to align camera boresight rotation plane with flyby plane
  - End result successfully centered comet for approach, flyby, and departure

Stardust (cont.)

Deep Impact

- DI was the eight mission in NASA's Discovery Program
- Goal of mission was to impact the comet Tempel 1 with one spacecraft while imaging the impact event with another
- Flyby/Impactor combo launched on January 12, 2005
- Cruise for 6 months
  - Cruise and approach to comet performed using standard ground-based radiometric an optical navigation techniques
- Impactor released from Flyby spacecraft at E-1 day. Flyby performs burn to slow down so that the impact can be observed prior to passing through closest approach
- Modified full-up version of AutoNav used on both Impactor and Flyby
  - Impactor needed maneuver implementation to autonomous guide itself to impact site
  - Flyby version kept identical to Impactor version to minimize and simplify testing

Deep Impact (cont.)

- Impactor AutoNav
  - Initiated at E-2 hours with pre-release target-relative navigation knowledge
  - Images taken at 15 sec intervals
  - Data accumulated for 10 min, the 1st OD update
  - Maneuvers times pre-planned at E-90, 35, and 12.5 min. Delta-V vector computed and implemented onboard
  - Image processing used "scene analysis" to direct spacecraft to impact site that was both lit, and biased towards the limb where the Flyby spacecraft made its overflight
- Flyby AutoNav
  - Initiated at E-2 hours with post-release navigation knowledge
  - Used same image and OD cadence as Impactor, but no maneuvers performed
  - Used knowledge of expected impact time to update time of rapid image sequencing start to capture event
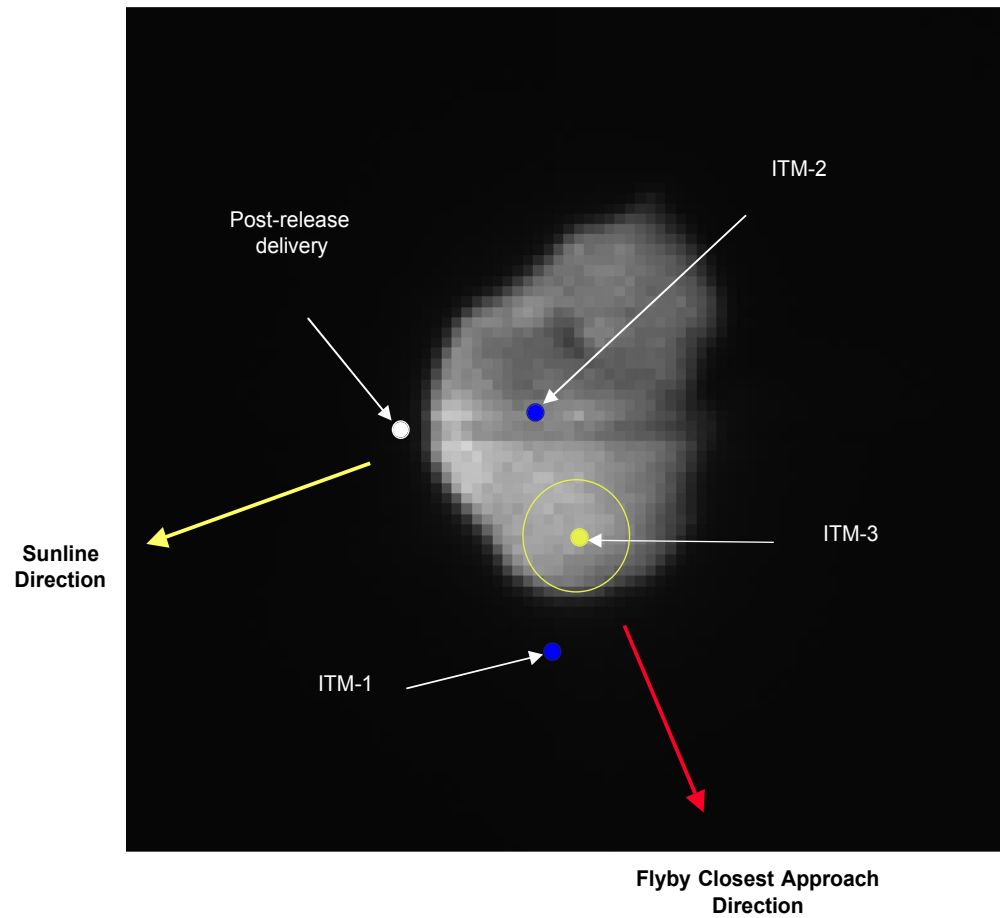
EPOXI and Stardust NExT

- EPOXI was the follow-on mission for DI, selected as Discovery Mission of Opportunity in August 2007
  - Healthy Flyby spacecraft following Tempel 1 encounter sent to encounter comet Hartley 2
  - Following 3 year cruise with 4 Earth flybys, rendezvous with Hartley 2 occurred on November 4, 2010
  - Goal was to image Hartley 2 using visible and IR detectors
- Stardust NExT was the follow-on mission for Stardust, also selected as Discovery Mission of Opportunity in August 2007
  - Stardust main spacecraft healthy after release of sample canister probe to Earth
  - Crater created by DI was not able to be imaged due to dust from the Impactor obscuring view, strong desire to see what crater was formed
  - Stardust sent to comet Tempel 1, marking 1st time a comet was imaged from 2 different spacecraft at 2 different times
  - Goal was to image crater location, and any more of Tempel 1 that was feasible

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- EPOXI AutoNav
  - DI software used unchanged.
  - Desire to image comet through approach, flyby, and departure resulted in some new twists due to interaction with attitude control system knowledge and errors (DI stopped imaging about 70 sec prior to closest approach)
  - Encounter imaging was successful, but leftover data from DI resulted in unforeseen offpoint at closest approach
    - Resulted in discovery of large particles being ejected from nucleus
- Stardust NExT AutoNav
  - Stardust software used unchanged
  - Desire for high resolution images resulted in decision to flyby at altitude that was limit of spacecraft's capability to track
  - AutoNav successfully tracked, although closest image slightly clipped
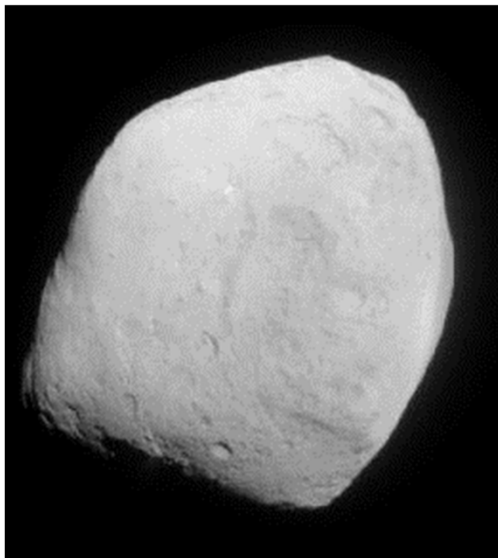
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Future of AutoNav

- 2nd generation AutoNav development ongoing at JPL. New capabilities:
  - VML based interface to allow easier access to parameters and settings
  - Merging attitude dynamics to provide 6DOF capability
  - Addition of landmark tracking data type for terrain relative navigation in the proximity of a solar system body
- Potential future uses for AutoNav
  - Asteroid deflection – terminal guidance for high speed impact already demonstrated. Enhancements would allow for greater variability in approach velocity and target sizes
  - Small body/Lunar pinpoint landing – numerical simulations indicate AutoNav capable of delivering lander to less than 3 m accuracies for small bodies and 20 m for the moon
  - Aerobraking – maintain safe aerobraking corridor at Mars
  - Outer plane satellite tour – rapid turnaround navigation to take advantage of delta-v and mission time savings in complex dynamical environment