National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Stardust-NExT: Lessons Learned from a Comet Flyby Mission

Aron Wolf, Tim Larson, Paul Thompson, Tim McElrath, Shyam Bhaskaran, Steve Chesley, Ken Klaasen, Allan Cheuvront

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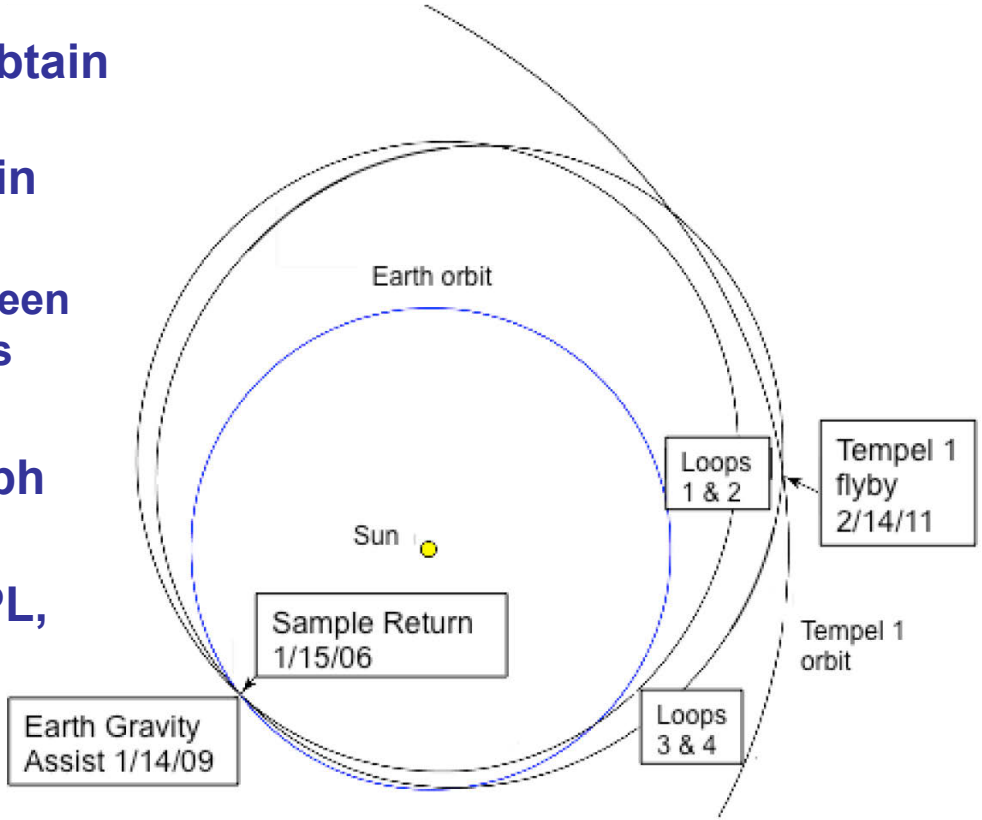
Cornell University

LOCKHEED MARTIN

Project Overview

- **Stardust extended mission to obtain additional science at Tempel 1 (target of Deep Impact mission in 2005)**
  - **Examine surface changes between successive perihelion passages**
  - **Image Deep Impact crater site**
- **Principal Investigator: Dr. Joseph Veverka, Cornell University**
- **Implementing organizations: JPL, LMSS**
- **Instruments:**
  - **Navigation camera (NAVCAM),**
  - **Comet Interstellar Dust Analyzer (CIDA)**
  - **Dust Flux Monitoring Instrument (DFMI)**



Science Baseline and Performance Floor

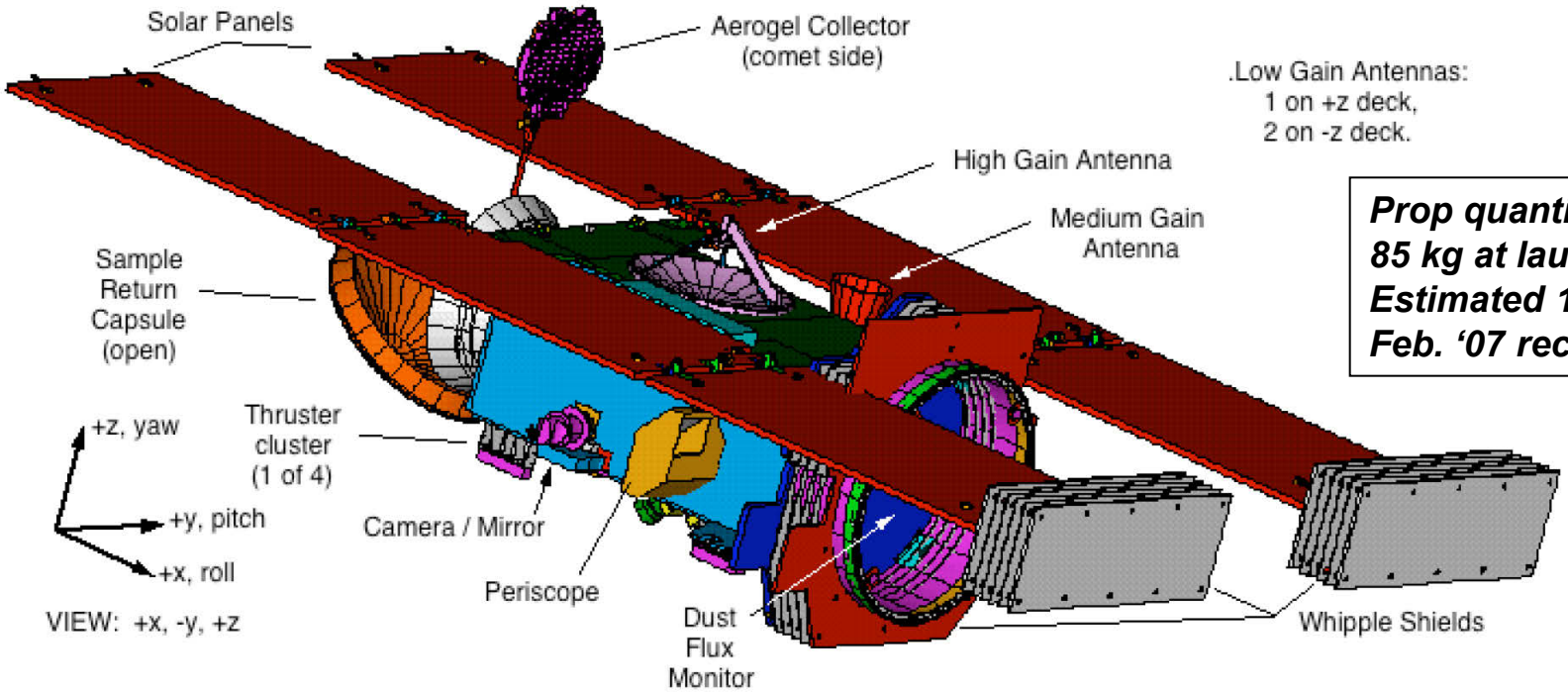
Performance floor:

- **Return at least one stereo image pair at a resolution of 20 m/pxl or better.**
- **Image at least 25% of the hemisphere seen by Deep Impact at 80 m/pxl or better.**

Science Baseline:

- **Achieve Performance Floor**
- **Obtain imaging data:**
  - **Complete sequence of 72 high-resolution images near closest approach (40 at better than 80 m/pxl; best at 12 m/pxl)**
  - **Coma and rotation monitoring images on approach over 60 days.**
- **Obtain CIDA and DFMI data around closest approach.**

Spacecraft



Prop quantity:
85 kg at launch,
Estimated 17.1 kg after Feb. '07 recontact

- **3-axis stabilized configuration with unbalanced thrusters**
  - **Low-cost way to minimize contamination of comet dust sample collected**
  - **All thrusters fire in nearly the same direction, canted for control about all 3 axes**
- **NAVCAM fixed, boresighted on mirror which rotates 180 deg. to allow S/C to maintain constant attitude while imaging nucleus during flyby**

Autonav System

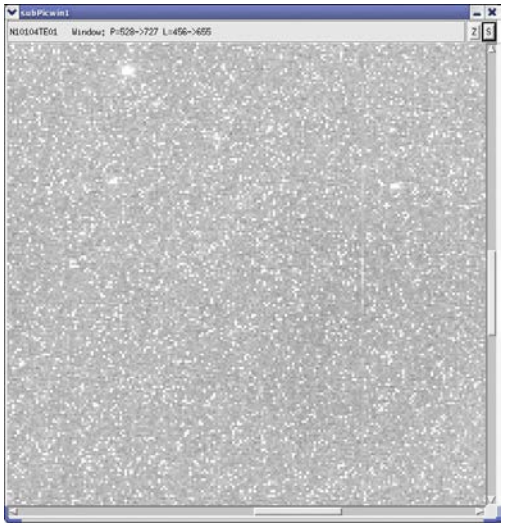
Issue	Autonav function
Ground-based navigation uncertainty too large for accurate determination of the flyby plane (in which scan mirror must sweep to image nucleus) in advance	Determine plane in which scan mirror must sweep to image nucleus (S/C then rolls if needed to put nucleus in mirror plane)
Arrival time uncertainty (±60 sec, 1 sigma) is too large to allow advance determination of scan mirror angles vs. time needed to track the nucleus	Closed-loop tracking of nucleus with mirror during flyby to keep nucleus in FOV

- Demonstrated successfully at Annefrank and Wild 2 during prime mission

- **Operation**
  - Autonav initiated at E-24 min, images taken at 30-sec intervals, used to calculate S/C correct attitude to put comet nucleus in scan mirror plane
  - S/C rolls to put comet nucleus in scan mirror plane at E-5 min
  - Encounter imaging sequence (72 images) started at E-4 min
  - Terminated 90 sec. past nominal encounter time

NAVCAM Performance Issues

- **Contamination of unknown origin observed during prime mission**
  - **Camera bake procedure developed which removed much of the contamination (turn on CCD heater to raise CCD temp to 0-10 deg. C, turn S/C to point radiator to Sun to raise CCD temp to 20-25 deg. C)**
  - **Camera bakes scheduled periodically including four in last 60d before encounter**



Typical unprocessed image

- **Fixed pattern of noisy pixels**
  - **Power-cycling camera reduced fixed pattern noise for several hours; however project imposed limit of 12 power cycles due to concern that NAVCAM would fail to turn on once turned off**

Restricted development funding can lead to insufficient attention to design and quality control => operational issues

Better testing before launch can prevent problems during operations

Effects of Unbalanced Thrusters

- Nonzero DV produced whenever thrusters were fired
- ACS deadbanding (sole means of att ctrl) produced DV that over time had largest effect on trajectory other than gravity
- Changes in predicted trajectory caused by:
  - Addition / deletion of instrument calibrations or other attitude turns (DV order of magnitude ~same as TCM DV)
  - Safings (3 in last 60 days)
  - Deadbanding mismodeling / modeling
- TCM DV not well predicted by traditional tools using formal statistics
  - Corrections at TCMs dominated by non-random events – at every maneuver, correction was > 1-sigma OD error
- Created unusual degree of coupling / dependency between Nav, ACS, Mission Planning, Science

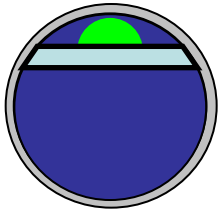
Use of unbalanced thrusters has numerous undesirable consequences and should be avoided on future missions

Estimating Fuel Quantity: PVT vs. PGS, BOL vs. EOL

Beginning of Life

PVT

- gas volume 1 liter; using 1 liter of propellant *doubles* gas volume
- **2% accuracy** of gas volume is 0.02 liter (**≈ 0.02 kg**)



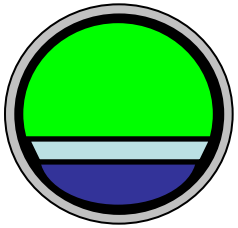
PGS

- Propellant load 1000 kg; using 1 kg of propellant reduces mass by 0.1%; small change in slope of temperature rise
- **10% accuracy of mass is 100 kg**

End of Life

PVT

- gas volume 985 liters; using 1 liter of prop increases volume by 0.1%
- **2% accuracy** of gas volume is 20 liters (**≈ 20 kg**)



PGS

- Propellant load 15 kg; using 1 kg reduces mass by 7%; significant change in thermal response
- **10% accuracy is 1.5 kg**

PGS estimate of prop qty lower by 3kg than PVT, confirmed by end-of-mission burn which depleted all propellant

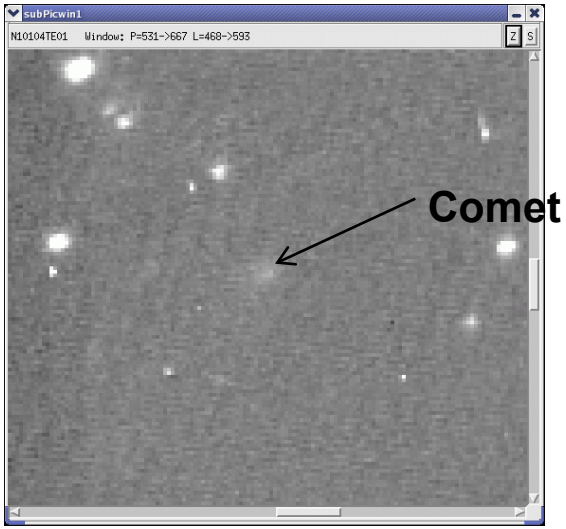
PGS method is more accurate than PVT on a near-empty tank

Propellant Budget Changes

Date	Event	Project response
Summer 2009	PGS testing lowered estimate of remaining prop by 3kg	Reduce max allowed arrival time adjustment to ~8 hr.
Jan. 2010	Decision to delay arrival time by 8 hr at TCM-28 to meet performance floor (and see Deep Impact crater?)	Careful monitoring of prop for remainder of mission
Oct. 2010	Increase in estimated consumption rate in 0.25-deg. deadbands	Deleted NAVCAM calibration
Oct. 2010	S/C safing	Delayed start of science imaging from E-60 to E-40 days
Nov - Dec. 2010	Two more S/C safings	
Dec. 2010 - Jan. 2011	Delay in comet detection (anticipated at E-60d, detection at E-27d)	Delayed TCMs 31 and 32 (prop budget hit) and further delayed start of science imaging to E-7d (savings)

Delayed Comet Detection

- Early science analysis predicted comet would be detectable as early as E-60d
- No detection in initial images despite extensive image processing
- Comparisons with Wild 2 forced revision of previous assumptions relating to comet brightness => revised prediction of detection at E-20d
- Comet detection reported on E-25d

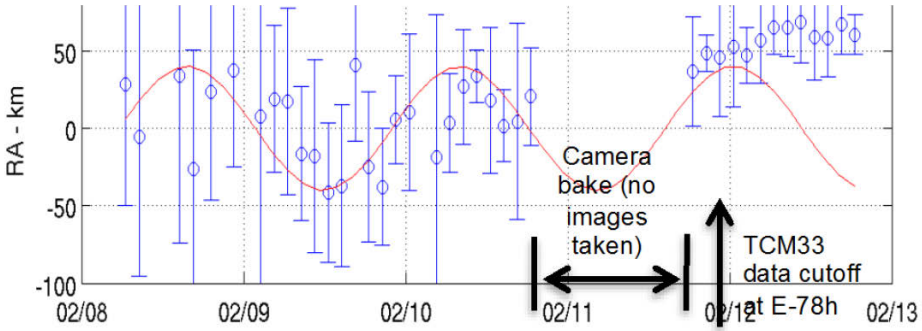


Comet detection image

Check and recheck assumptions that form the basis for mission planning

E-48h Maneuver: Were We Seeing the Nucleus or Not?

- **Variation of optical navigation residuals in last few days looked roughly sinusoidal.. possible center-of-brightness vs. center-of-gravity offset?**
- **Three image sets immediately before data cutoff less noisy, "flatter" ("seeing the nucleus?")**



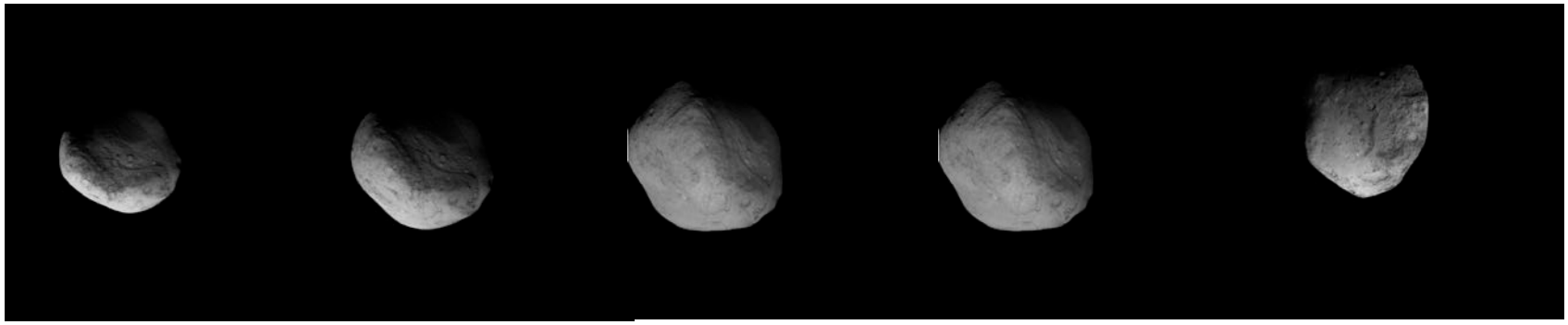
Optical navigation residuals in R.A. over last several days before flyby

- **Images after data cutoff reinforced impression of "seeing the nucleus" but could not be included in O.D. solution due to tight timeline**
- **Designed maneuver assuming the last three points before data cutoff were giving reliable information – this decision turned out to be correct!**

Use as much data as practicable to inform decision making

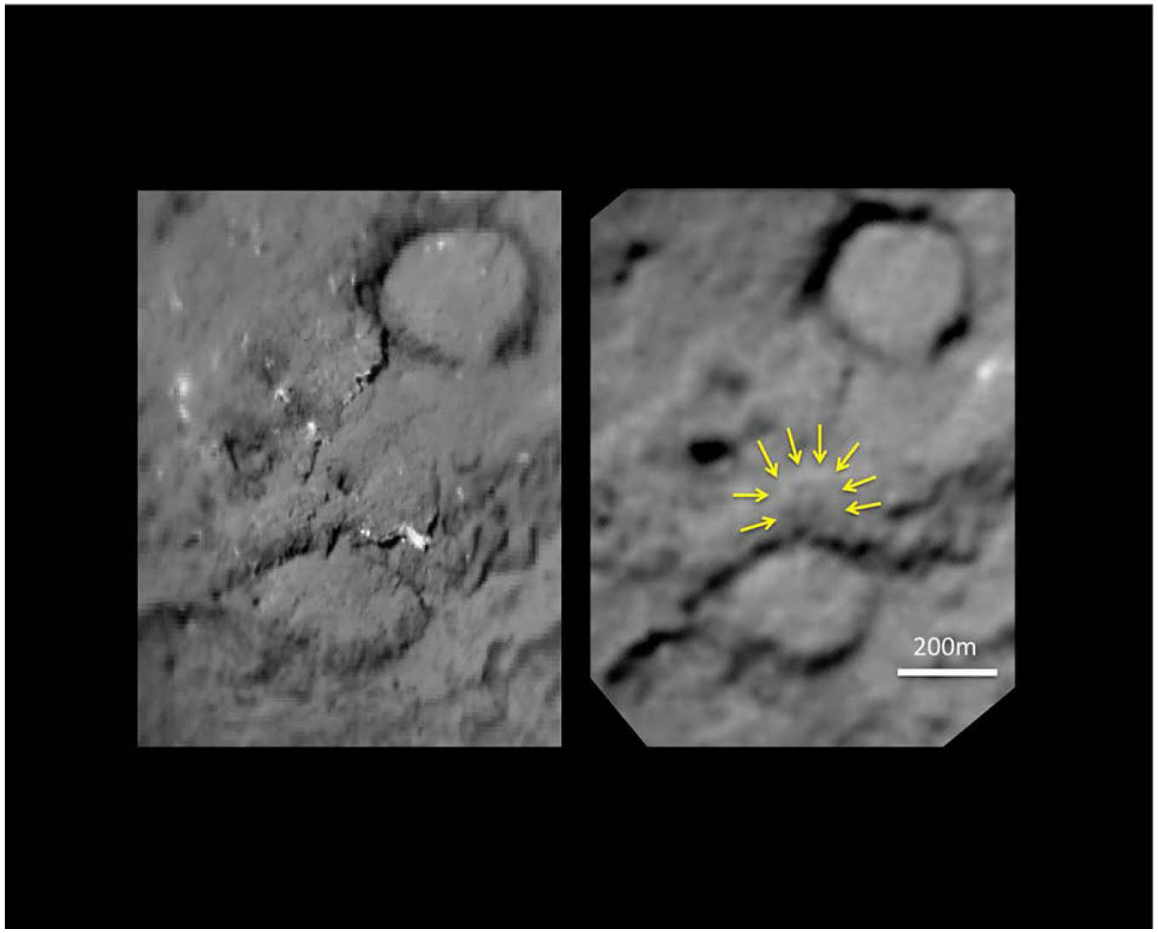
Result: Successful Flyby!

- **Autonav captured nucleus in camera FOV in all 72 images**
  - **Autonav state correction 13 km xtrack, 16 sec time, < 0.5 deg. roll required!**
- **Post-flyby reconstruction showed flyby altitude was 178 km (radius 181 km).. Very close to best possible resolution without exceeding angular rate limit of scanning mirror!**
- **Succeeded in imaging DI impact site (comet rotation predictions turned out to be accurate)!**



An experienced team able to respond with flexibility can be critical to mission success

Find The Crater



Before
(Deep Impact)

After
(Stardust-NExT)

Thank You!