Validation of a Low-Thrust Mission Design Tool Using Operational Navigation Software

Jacob A. Englander [1] Jeremy M. Knittel [1]
Ken Williams [2] Dale Stanbridge [2]
Donald H. Ellison [3]

[1] Goddard Space Flight Center

[2] KinetX Aerospace Inc.

[3] University of Illinois at Urbana-Champaign

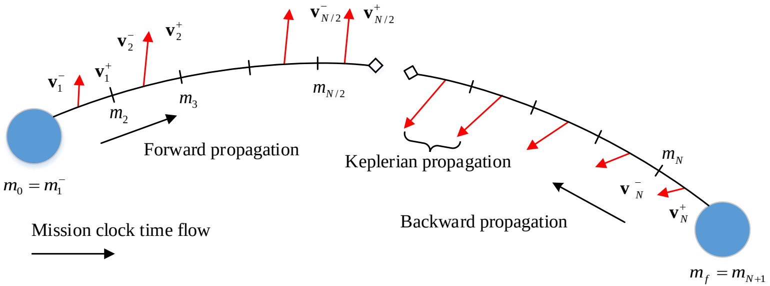
February 9, 2017

Outline

- Medium-fidelity trajectory design
- Bridging the gap to proposal submission
- Finite-burn low-thrust trajectory model
- Application: Nauplius-Odysseus Tour Mission
- Trajectory verification with MIRAGE
- Small body approach navigation
- Summary

Medium-Fidelity Mission Design

- Several toolsets exist for preliminary design of missions utilizing solar-electric propulsion (SEP)
  - EMTG, MALTO, PaGMO, GALLOP
- Most use bounded-impulse models, Keplerian propagation and other approximations to allow for rapid high-level mission/system trades
- Produce accurate mass budgets
- Solution topologies generated typically only roughly resemble the final flight-grade trajectory



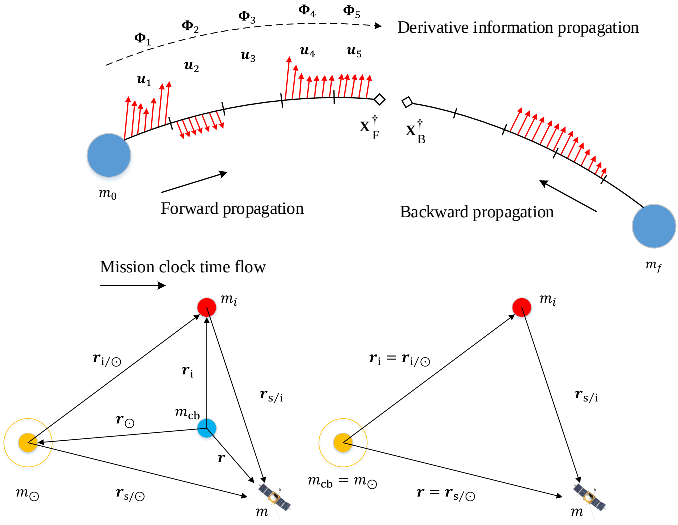
Bridging the Gap to Proposal Submission

- Proposal submission (Discovery, New Frontiers etc.) requires a higher fidelity solution
- Tools such as Copernicus and Mystic can provide the required accuracy for low-thrust trajectories...not always available to proposal teams
- A stepping stone is required...medium-high fidelity
- Finite-burn + patched conic model → FBLT model
  - integrate equations of motion
  - include third-body gravity and solar radiation pressure

$$\ddot{\mathbf{r}} = -\frac{G\left(\cancelto{0}{m} + m_{\mathsf{cb}}\right)}{r^2}\frac{\mathbf{r}}{r} - \sum_{\mathsf{i}} G\, m_{\mathsf{i}} \left(\frac{\mathbf{r}-\mathbf{r}_{\mathsf{i}}}{\|\mathbf{r}-\mathbf{r}_{\mathsf{i}}\|^3} + \frac{\mathbf{r}_{\mathsf{i}}}{r_{\mathsf{i}}^3}\right) + \frac{C_r A_s K \phi}{c\, r_{s/\odot}^2}\frac{\mathbf{r}_{s/\odot}}{r_{s/\odot}} + \frac{D\, T}{m}\mathbf{u}$$

$$\dot{m} = -\|\mathbf{u}\|\, D\, \dot{m}_{\mathsf{max}}$$

Finite-burn low-thrust model



MIRAGE

- Multiple Interferometric Ranging Analysis using GPS Ensemble
- Licensed version of the Double-Precision Trajectory and Orbit Determination Program (DPTRAJ/ODP)
- Originally developed at JPL to support high-fidelity orbit determination, trajectory propagation and maneuver planning.
- Flight heritage from 1970s-present
- Used to navigate NEAR, Stardust, Genesis at JPL
- Used at KinetX for MESSENGER, New Horizons and OSIRIS-REx
- Most relevant to this work, Deep Space 1 (SEP)
- Now used to validate EMTG

KINETX AEROSPACE

Application: Nauplius-Odysseus Tour

- Trojan asteroid mission used to benchmark EMTG-MIRAGE workflow
- "Trojan Tour and Rendezvous" acceptable New Frontiers 4 Announcement of Opportunity
  - Visit 2+ Trojan bodies including a rendezvous and extended stay
- Flyby of 9712 Nauplius (magnitude +10.7)
- Rendezvous with 1143 Odysseus (magnitude +7.93)

Option	Value
Launch window open date	1/1/2024
Launch window close date	12/31/2024
Flight time upper bound	12 years
Arrival condition at Nauplius	flyby
Arrival condition at Odysseus	rendezvous
Launch vehicle	Atlas V 551
Launch asymptote declination bounds	$[-28.5, 28.5]$ (Kennedy Space Center)
Post-launch coast duration	60 days
Pre-flyby coast duration	30 days
Post-flyby coast duration	30 days
Solar array P_0	40 kW
Solar array coefficients γ_i	$[1, 0, 0, 0, 0]$
Spacecraft power coefficients $a_{s/c} - c_{s/c}$	$[0.8, 0, 0]$
Propulsion system	2 NEXT in "high-Thrust" mode
Throttle Logic	minimum number of thrusters
Duty cycle	90%
Power margin	15%
Number of segments per phase	40

Application: Nauplius-Odysseus Tour

- Force model assumptions for EMTG-MIRAGE comparison
- Earth, Mars, Jupiter gravity and SRP

Category	Model	Notable Details
Planetary ephemerides	DE433	**Available bodies (SPICE ID):** SUN (10), MERCURY BARYCENTER (1), MERCURY(199), VENUS BARYCENTER (2), VENUS (299), EARTH BARYCENTER (3), EARTH (399), MOON (301), MARS BARYCENTER (4), MARS (499), JUPITER BARYCENTER (5), SATURN BARYCENTER (6), URANUS BARYCENTER (7), NEPTUNE BARYCENTER (8), PLUTO BARYCENTER (9) **Time span (ET or TDB):** 1899 DEC 04 00:00:00 - 2050 OCT 17 00:00:00
Gravity	Sun, Earth and Jupiter only μ [$\mathrm{km}^3/\mathrm{s}^2$]	$\mu_\odot = 1.32712440041939\mathrm{E}{+}11$ $\mu_\oplus = 3.98694790080000\mathrm{E}{+}05$ $\mu_♃ = 1.26686510964000\mathrm{E}{+}08$
Solar radiation pressure	Spacecraft bus	$A_s = 114.1\ \mathrm{m}^2$ $C_r = 1.0$ $\phi = 1.015242216\mathrm{E}{+}08\ \frac{\mathrm{kg\ km}^3}{\mathrm{m}^2\mathrm{s}^2}$ equivalent to solar luminosity $L_\odot = 1360\,\frac{\mathrm{W}}{\mathrm{m}^2}$

Application: Nauplius-Odysseus Tour

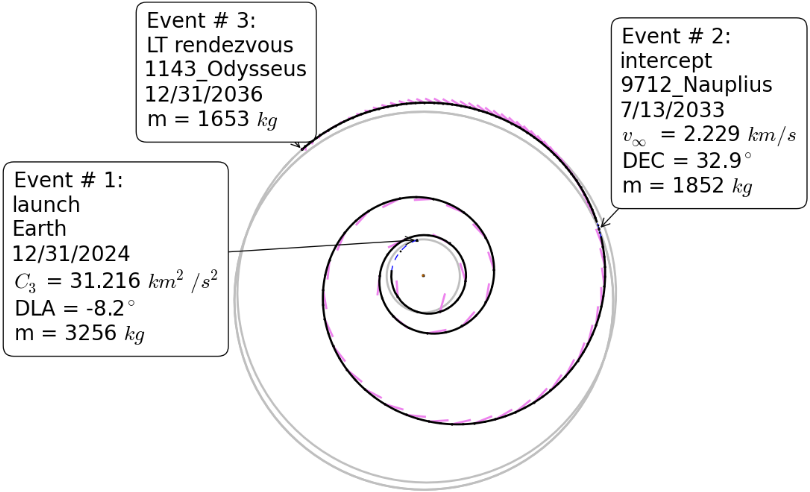


Figure: Optimal trajectory to Nauplius and Odysseus, from EMTG

Trajectory Verification with MIRAGE

- EMTG $\rightarrow$ MIRAGE trajectory conversion performed
  - Validates EMTG's physics engine
  - Create database for performing orbit determination, covariance analysis and trajectory prediction/management for flight operations
- MIRAGE takes EMTG segments (including thrust profile/direction) and models as long finite-burns
- SEPV module searches for Δv to match EMTG state history at the end of each segment

Maximum discrepency	Earth-Nauplius	Nauplius-Odysseus
Position (m)	87.3	350.0
Velocity (m/s)	1.17	0.09
Mass (g)	742	541

- 1.17 m/s velocity discrepency due to thruster on/off...final difference 15.0 cm/s!
- Earth-Nauplius Δv difference: 2.24 m/s out of 17.34 km/s
- Nauplius-Odysseus Δv difference: 14 mm/s out of 1.63 km/s
- All well within operational tolerances

Trajectory Verification with MIRAGE

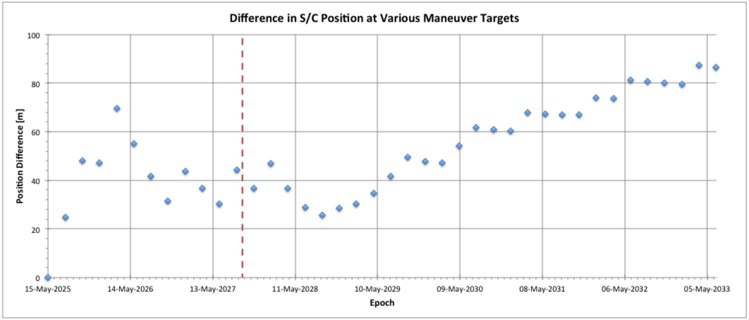


Figure: Differences in propagated spacecraft position of MIRAGE relative to EMTG for the Earth-Nauplius phase. Red lines indicate thruster on/off events.

Small Body Approach Navigation

Approach navigation begins 90 days prior to closest approach (N-90).

- Deep space network (DSN)
  - radiometric tracking
  - provides line-of-sight range and range rate measurements (Doppler)
  - N-90 to N-60: three eight-hour passes per week
  - N-60 to encounter: one eight-hour pass per day
- Delta differential one-way range (DDOR)
  - doubly-differenced very long baseline interferometry (VLBI)
  - information about s/c motion normal to the line-of-sight vector
  - N-90 to encounter: Two east/west and two north/south baselines per week
- Optical navigation (OpNav)
  - In-situ optical sensing, improve body-spacecraft position knowlowedge
  - Update small body's ephemeris, de-correlate s/c state estimate
  - Vital for precision required for hyperbolic B-plane targeting
  - N-60 to N-45: three image sets per week (eight images per set)
  - N-45 to encounter: one image set per day

Small body approach navigation

- Nauplius flyby:
  - Optical navigation (OpNav) observing campaign begins at N-60 days
  - Goal: deliver spacecraft to B-plane aim-point within 1σ error ellipse
  - Trajectory correction maneuver (TCM) may be used if OD solution confidence is high enough
  - TCM opportunities are scheduled at N-60, N-30, N-7 and N-3 days
  - s/c and Nauplius OD solutions continuously refined
  - Late ephemerides updates allow for a final TCM opportunity at N-3 days
    - only used in case of emergency (e.g. satellite discovered around Nauplius)
  - Chemical propulsion necessary as SEP lacks control authority this late
- Odysseus rendezvous:
  - Relative speed is only 0.1 km/s at O-60 vs. 2.224 km/s at N-60
  - Odysseus $4\times$ larger than Nauplius, subtends 100 pixels at O-60
  - Cross-track motion uncertainties can be reduced much farther, lower closest-approach of 400 km
  - Chemical propulsion not required, can be fully SEP

Small body approach navigation: Challenges

- OpNav vital to refine OD solution
- Earth-based observations have large uncertainties for small bodies
- In-situ OpNav is also challenging:
  - body size (diameter 33 km $\pm$ 4 km)
  - low albedo (0.083)
  - unknown shape
  - solar phase angle (46-49 degrees)
  - moving platform with some instabilities
  - pointing knowledge errors
- OpNav imager angular resolution is 5μrad/pixel
- Nauplius subtends $>$ pixel only 34 days prior to encounter
- Nauplius apparent magnitude is $< +10$ at only N-40 days
- Parallax is only observable very late, so flight time-to-go uncertainty only appreciably reduced after N-10 days

OpNav Image

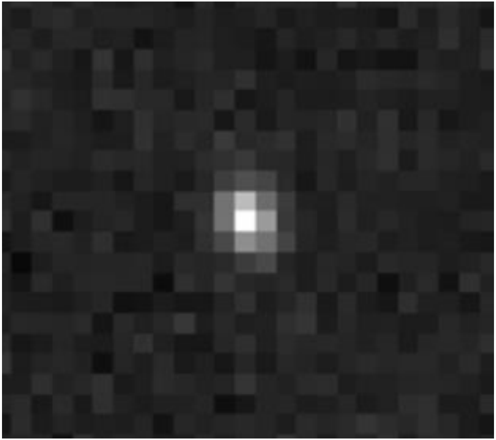


Figure: Simulated image of Nauplius 30 days from closest approach.

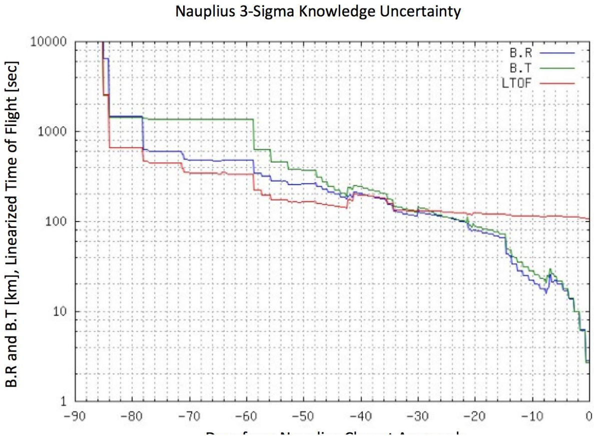


Figure: Spacecraft position 3σ uncertainty on Nauplius approach.

Nauplius Image Size

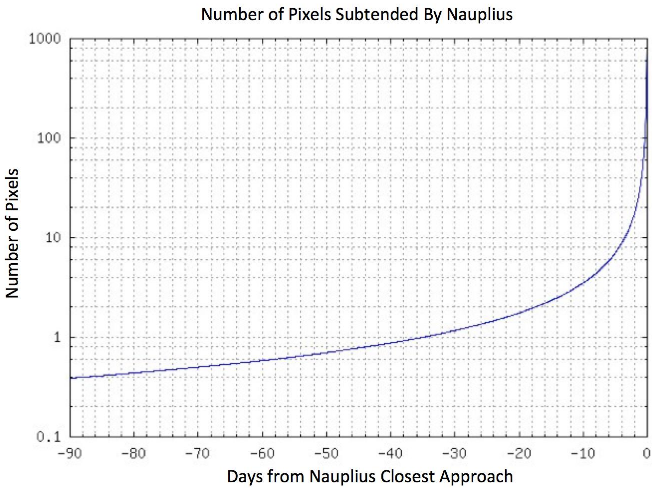


Figure: Number of pixels subtended by Nauplius on approach.

Summary

- EMTG's finite-burn low-thrust model bridges the "fidelity gap" between bounded-impulse patched conic and fully flight-ready trajectories
- Allows for rapid generation of trajectories suitable for proposal or flight design
- Notional mission to Trojan asteroids Nauplius and Odysseus
  - MIRAGE used to validate trajectory produced by EMTG
  - Developed concept-of-operations for OpNav during target approach
- Discrepancies fall well within operational uncertainty limits
- OpNav analysis $\rightarrow$ low-velocity flyby of Nauplius and rendezvous with Odysseus achievable
- Analysis also shows that a higher-thrust TCM is required after last pre-flyby OpNav update
- This can be accomplished with attitude control system thrusters

Thank You