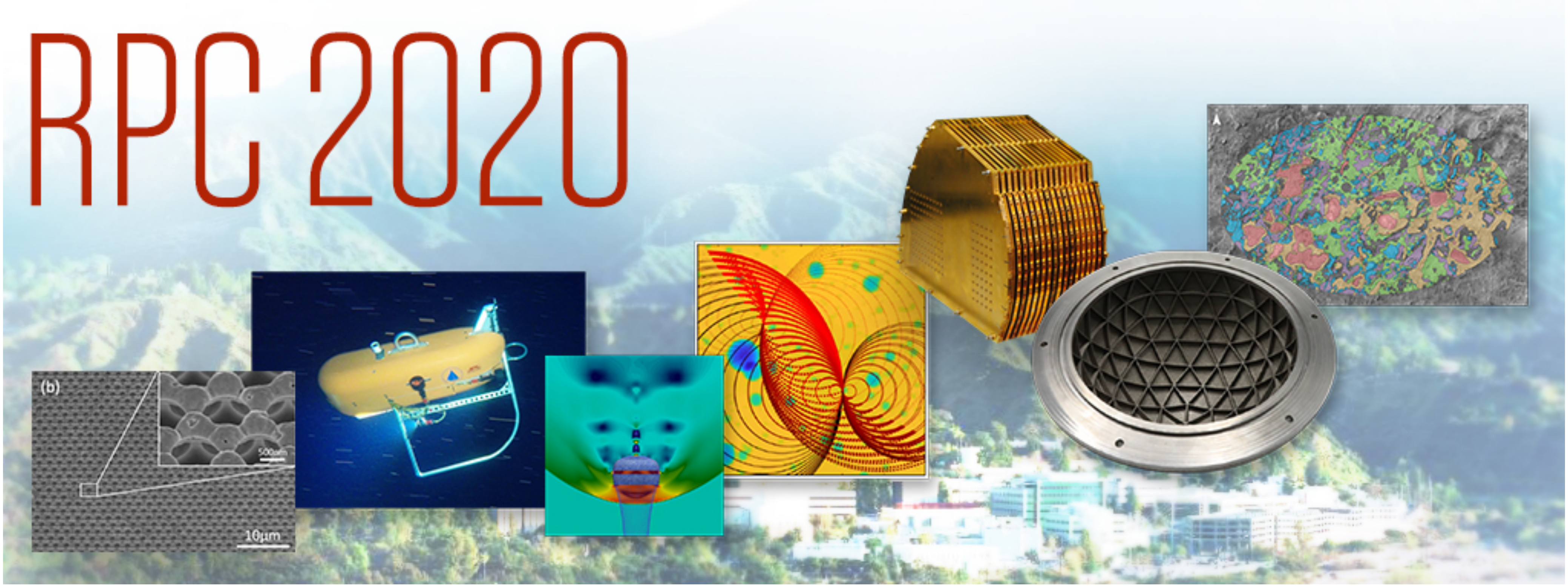

# Virtual Research Presentation Conference

## Autonomous Navigation of Orbiting Satellites Without Ground Tracking or GPS.

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**Program: Strategic Initiative**

Assigned Presentation #20006

**Jet Propulsion Laboratory**
California Institute of Technology

# Tutorial Introduction

**Abstract**

This research intends to advance the usefulness and autonomy of Section 392's Optical Autonomous Navigation (AutoNav) software. First, AutoNav will be integrated with the ASTERIA cubesat FSW. Then it will be flown as a flight experiment to demonstrate that it could be operated on a cubesat form. Next, it will be enhanced to use satellites as optical navigation targets instead of asteroids. Afterwards, a task network will be devised that will operated the AutoNav software from inside the ASTERIA FSW context, replacing the complicated sets of sequenced commands that have driven past instances of AutoNav. This tasknet will be instantiated, scheduled and executed by Section 397's planning and execution software tool, MEXEC. Once working, this tasknet experiment will be integrated with Section 393's fault modeling and reporting tool, MONSID, in order to assess the tasknet responsiveness to reported faults.

# Problem Description

## (Context)

- Two decades ago, JPL was at the forefront of Deep Space autonomous navigation with missions such as Deep Space 1, Deep Impact and Stardust.
    - These missions demonstrated how an AutoNav system can provide low cost navigation with quick turn-around times that cannot be achieved with ground-in-the-loop.
    - Current missions and proposed missions such as DART, OSIRIS-REx, LUCY and CAESAR are all using non-JPL AutoNav systems. When flown missions are used as a metric, JPL is falling behind in the realm of autonomous navigation. To maintain our competitive mission stance we need to advance our capabilities.
    - Recent advances in spacecraft clock technology (DSAC), software radios and higher fidelity optics will soon enable future missions to achieve their goals with highly accurate real-time navigation solutions. JPL needs to expand its AutoNav experience base and mature its AutoNav capabilities in order to be a provider of those future navigation services.

# Problem Description

## (State of the art)

- GPS and/or Air Force tracking reports for Earth orbiting spacecraft provide accuracies of tens of meters and hundreds of meters, respectively.
    - On-board optical navigation for Earth orbiters could theoretically have accuracies at the hundreds of meters level,  with high fidelity optics and spacecraft clocks.
- Terrain Relative Navigation for Asteroid orbiters was provided by navigation teams for Dawn and Osiris-REx missions.
    - On-board optical navigation can be operated autonomously, for long periods of time, for the orbiting case
- Terrain Relative Navigation for asteroid sample collection was provided by an onboard system for the Osiris-REx mission.
    - JPL has often proposed similar systems for use in sample collection proposals, but the system was not deemed technologically ready.

# Problem Description

## (Relevance to NASA and JPL)

- This research will address the Earth orbiting navigation case by developing image processing techniques needed for spacecraft-relative optical navigation.
- This research will address the long-term asteroid orbital navigation case by developing a goal-oriented, re-usable, autonomous task network that enables navigation activities. This can provide a cost savings by reducing the size of operations teams and the complexity of operations processes.
- Follow-on research can build on this research to demonstrate higher technical feasibility for future JPL proposals that require an autonomous navigation capability.

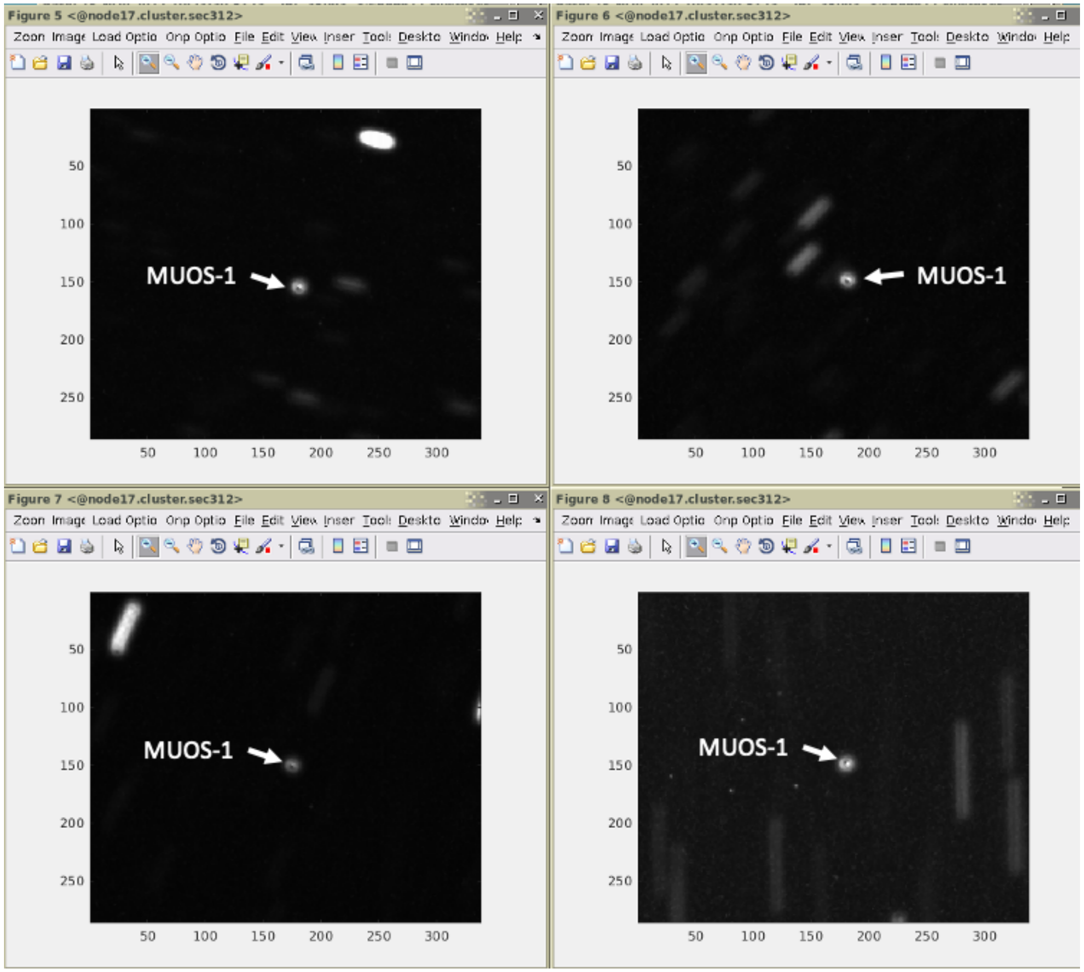
# Methodology

## (AutoNav onboard a CubeSat)

- Experiment description
  - Characterize camera response to geosynchronous satellite and asteroid targets
  - Tune or modify image processing software to register locations of target in imagery
  - Integrate AutoNav FSW with ASTERIA FSW
  - Design scenario and necessary sequenced commands
  - Operate AutoNav onboard ASTERIA
- Innovation, advancement
  - The signal-to-noise ratio from geosynchronous satellites was enhanced by taking long-exposures with non-zero spacecraft attitude rates that kept the target in front of the camera, negating the smearing effects of orbital motion.
  - High fidelity attitude of the midpoint of each camera exposure was determined by processing of the streaked stars in the image

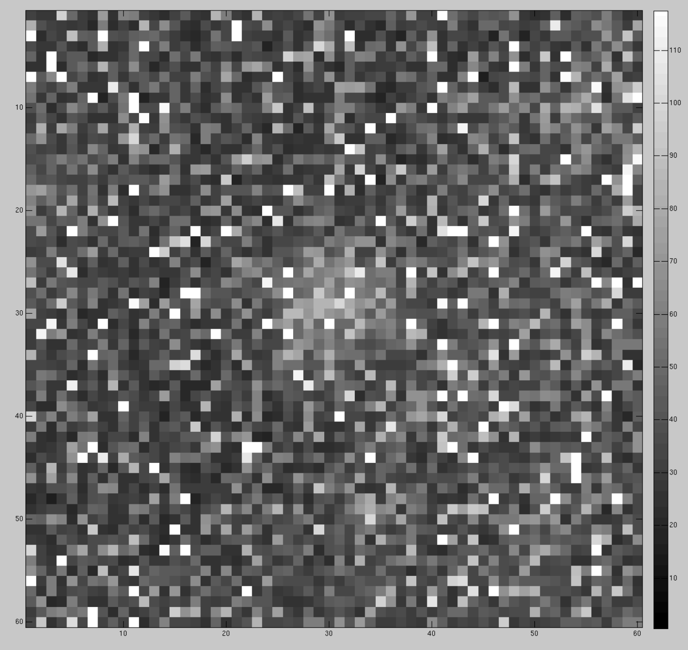
# Onboard images

- Some geosynchronous satellites are relatively bright.
- Shown here is the satellite MUOS-1, clearly seen in these subframes of four images taken in November, 2019
- Signal from streaked stars is visible in each image



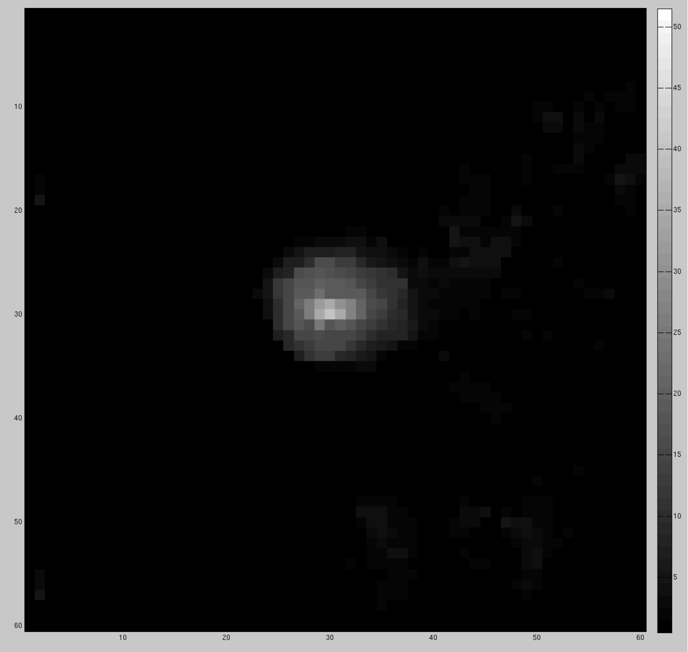
# Onboard images

- Some geosynchronous satellites are relatively dim.
- Shown, the signal from the SUPERBIRD geosynchronous satellite before and after the application of noise, background and hot pixel filters.



Before

After



# Results:

## (AutoNav onboard a CubeSat)

- Accomplishments
  - Satellites are a viable optical target
  - Successful with asteroid tracking, demonstrating AutoNav algorithms can be executed on ASTERIA
  - not successful with satellites because we lost the spacecraft due to an onboard fault before the FSW could be uploaded and executed.
- Significance
  - Demonstrated autonav on a cubesat form, which means limited resources could support autonav activities, although the system computational throughput was stressed, advising a careful selection of flight computer and OS.
  - Demonstrated capability of very stable ACS platform
  - Different signal responses from the different target geosynchronous satellites indicate that an imaging campaign to chararacterize the signal from individual satellites will be needed before a fully robust autonav system can be activated onboard.
- Next steps
  - Perform AutoNav experiments on other imaging-capable platforms in Earth Orbit, as opportunities become available.

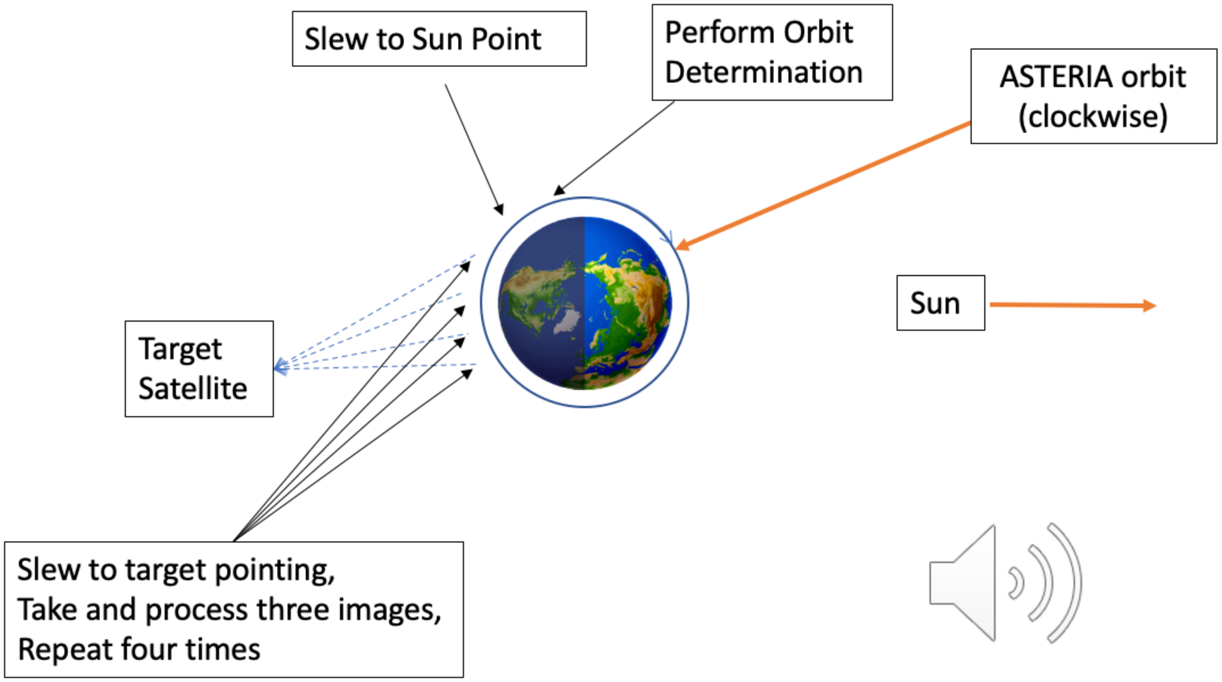
# Methodology

## (Tasknets)

- Experiment description
  - Identify the scenario in which a tasknet would be used in place of a command sequence.
  - Define templates needed to execute the scenario, and the template interactions needed to control task flow
  - Define driving goal: perform AutoNav when confidence in orbital location grows too poor.
  - Develop and use tools to implement tasknet in XML for planner/scheduler software, MEXEC
  - update software to provide image planning details for tasknet instantiation at run-time
  - Define off-nominal scenarios for tasknet to respond to inputs from modeled fault reporting software, MONSID
- Innovation, advancement
  - Task template encoding into XML
  - Single interface that permits AutoNav to provide detail parameters in tasks instantiated by MEXEC

# Orbiting Scenario

- The tasknet scenario was quite similar to the scenario implemented on the vehicle.
- All imaging in eclipse
- Three orbits of imaging
- One target per orbit
- Four attitude changes per orbit
- Three images on each attitude



Slew to Sun Point

Perform Orbit Determination

ASTERIA orbit (clockwise)

Sun

Target Satellite

Slew to target pointing,
Take and process three images,
Repeat four times

# Orbiting Scenario

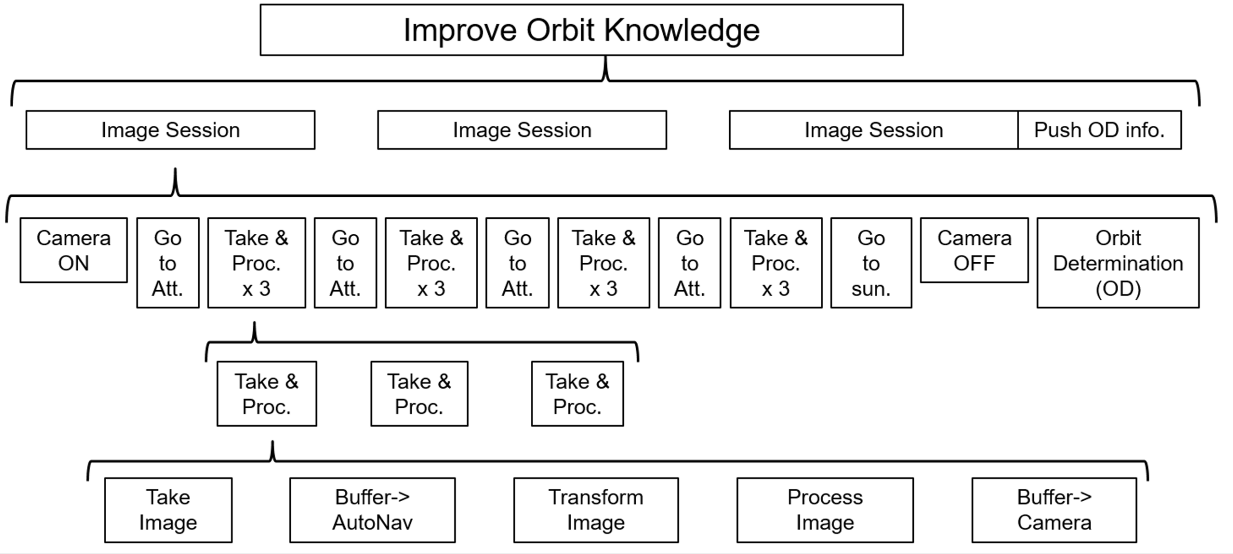

Improve Orbit Knowledge

Image Session

Image Session

Image Session

Push OD info.

Camera ON

Go to Att.

Take & Proc. x 3

Go to Att.

Take & Proc. x 3

Go to Att.

Take & Proc. x 3

Go to Att.

Take & Proc. x 3

Go to sun.

Camera OFF

Orbit Determination (OD)

Take & Proc.

Take & Proc.

Take & Proc.

Take Image

Buffer-> AutoNav

Transform Image

Process Image

Buffer-> Camera

- Abbreviated layout of the tasknet that was constructed to drive AutoNav activities, including attitude changes, camera exposures, image processing and orbit determination. Each of the 245 commands in the full tasknet are instantiated from one of 16 individual task templates that are uploaded into MEXEC as an XML file in a binary format. This one tasknet mimicked the activity directed by a ground sequence with 900 commands.

# Results:

## (Tasknets)

- Accomplishments
  - The ASTERIA FSW that was integrated with AutoNav and MEXEC was able to successfully execute the tasknet.
  - XML inputs and interfaces operated as expected.
  - Off-nominal scenarios executed successfully, using ASTERIA FSW that integrated AutoNav, MEXEC and MONSID
- Significance
  - MEXEC Planner software shown to be capable of *autonomously* re-executing the AutoNav tasknet to improve orbit confidence goal as confidence goal decayed, in perpetuity and without ground intervention
  - Tasknet able to execute appropriately under nominal and fault injected conditions.
- Next steps
  - Continue development of tasknets and tasknet designs for use in potential AutoNav scenarios for future mission proposals

# Publications

a) Kennedy, Brian M., Doran, P., Hughes, Randall S., Hughes, K., Bocchino, R., Lubey, D., Mages, D., Fesq, L.,"Satellite-to-satellite imaging in support of LEO optical navigation, using the ASTERIA cubesat." SPIE Opticsand Photonics Conference, San Diego CA, August 2020.

b) Feather, M.S., and others, "System-Level Autonomy for Spacecraft-a Demonstration", IEEE AeroSpaceConference, Big Sky, MT, 2021.

# References

1) Fesq, L., Beauchamp, P., Donner, A., Bocchino, R., Kennedy, B., Mirza, F., Mohan, S., Sternberg, D., Smith, M.W., Troesch, M, Knapp, M., “Extended Mission Technology Demonstrations Using the ASTERIA Spacecraft,” IEEE Aerospace Conference, Big Sky, MT, March 2019. https://ieeexplore.ieee.org/document/8742020/

2) Broschart, S., Bradley, N., Bhaskaran, S., “A Kinematic Approximation of Position Accuracy Achieved using Optical Observations of Distant Asteroids”, *Journal of Spacecraft and Rockets*, vol. 56, No 5. (2019), pp. 1382-1392.

3) Bradley, N., Olikara, Z., Bhaskaran, S., “Cislunar Navigation Accuracy Using Optical Observations of Natural and Artificial Targets”, *Journal of Spacecraft and Rockets*, vol. 57, No. 4 (2020), pp. 777-792.

4) Riedel, J. E., Bhaskaran, S., Synnott, S. P., Desai, S. D., Bollman, W. E., Dumont, P. J., Halsell, C. A., Han, D., Kennedy, B. M., Null, G. W., Owen Jr., W. M., Werner, R. A., and Williams, B. G. “Navigation for the New Millenium: Autonomous Navigation for Deep Space-1”, Proceedings of the 12th International Symposium on Flight Dynamics, Darmstadt, Germany, June 1997.

5) Mastrodemos, N., Kubitschek, D.G. & Synnott, S.P. Autonomous Navigation for the Deep Impact Mission Encounter with Comet Tempel 1. *Space Sci Rev* **117,** 95–121 (2005). https://doi.org/10.1007/s11214-005-3394-4