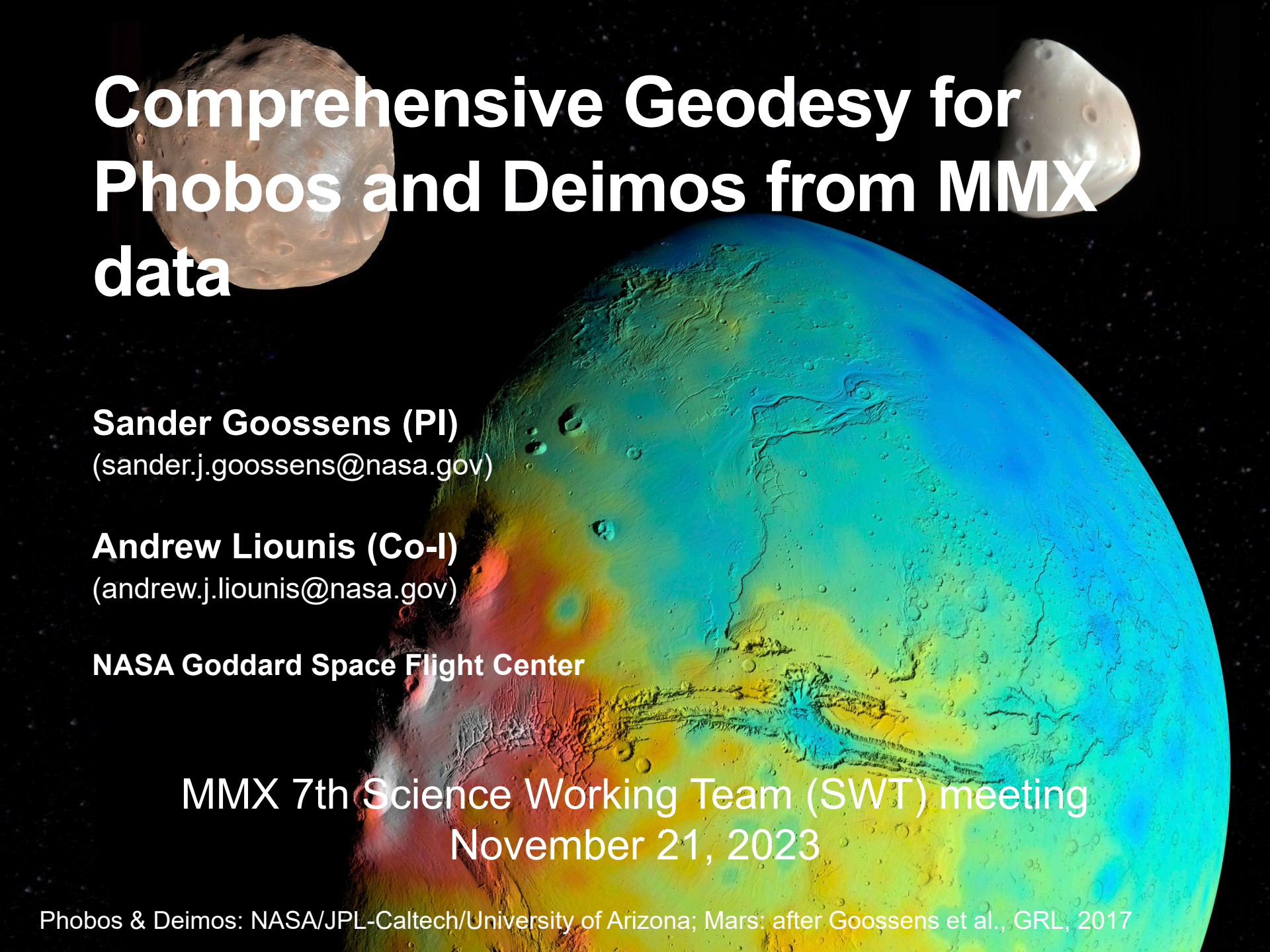




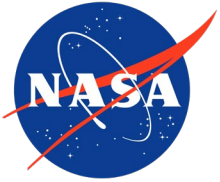
# Comprehensive Geodesy for Phobos and Deimos from MMX data

**Sander Goossens (PI)**  
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**Andrew Liounis (Co-I)**  
([andrew.j.liounis@nasa.gov](mailto:andrew.j.liounis@nasa.gov))

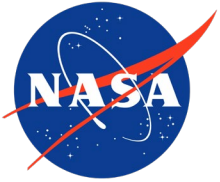
**NASA Goddard Space Flight Center**

MMX 7th Science Working Team (SWT) meeting  
November 21, 2023



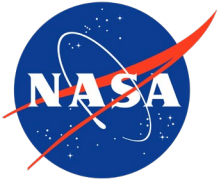
# Overview

- Brief Introduction
- Proposed MMX project:
  - MMX data analysis
  - Shape model verification
  - Interior modeling
- Example from OSIRIS-REx analysis
- Proposed timeline



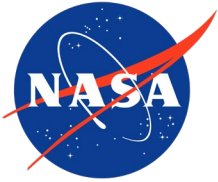
# Brief Introduction

- Obtained PhD in Aerospace Engineering in 2005 from Delft University of Technology, the Netherlands.
- 2003/2004+2005-2011: Fellowships/researcher at National Astronomical Observatory of Japan, for the SELENE mission
- Since 2011 at NASA/Goddard.
  - Civil servant since August 2021



# Research Interests and Mission involvement

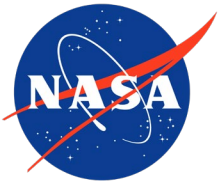
- Research interests:
  - Orbit determination
  - Gravity field determination
  - Interior structure modeling
  - Estimation theory
- Mission involvement:
  - SELENE: gravity and shape
  - GRAIL: gravity and interior modeling
  - MESSENGER: gravity and interior
  - MRO and other Mars data: gravity, structure of the crust
  - OSIRIS-REx: geophysical parameter determination (see later)
  - Juno: participating scientist for extended mission, focus on the flybys of the Galilean moons (Io flyby late December and in February!)



# Andrew Liounis' expertise

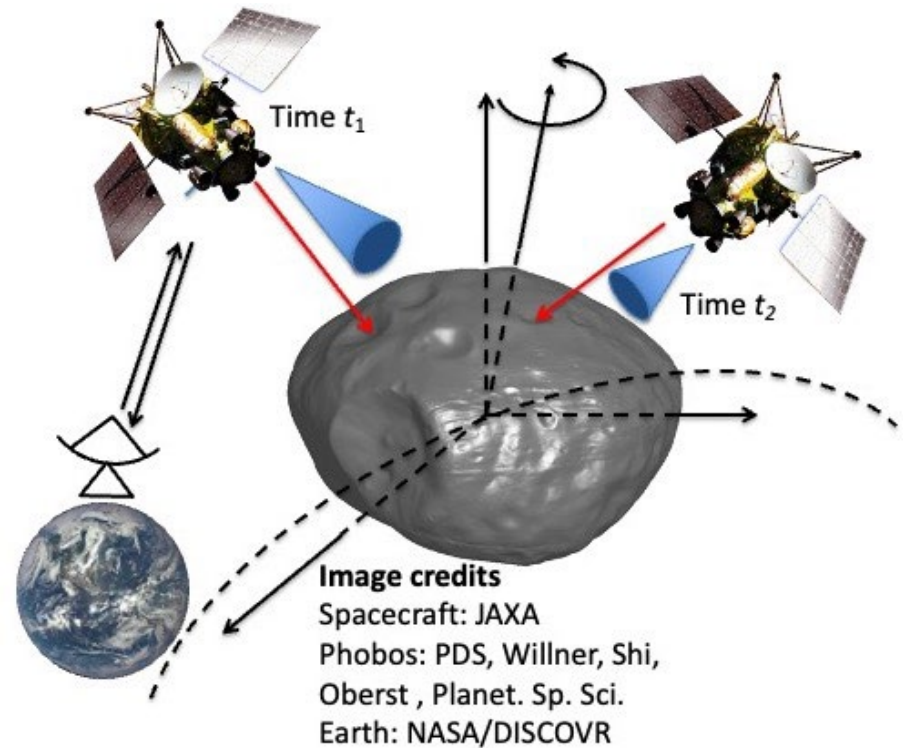
- Obtained MSc in Aerospace, Aeronautical, and Astronautical Engineering from Western Virginia University in 2016
- Since 2016 at NASA/Goddard in the Navigation & Mission Design Branch.
- Author and Maintainer of the open-source Goddard Image Analysis and Navigation Tool (GIANT, [github.com/nasa/giant](https://github.com/nasa/giant))
  - Used extensively for OSIRIS-REx
  - Includes celestial navigation
  - Currently also used for a study of the Saturnian system with Cassini data

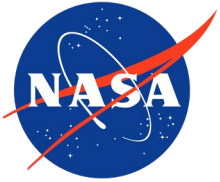
GIANT



# Our MMX project

- Analyze MMX tracking, optical, and lidar data
  - To determine the moons' gravity
  - To determine the moons' rotational state
- Validate shape models
  - Through combined use of different data types
  - By estimating shape model parameters

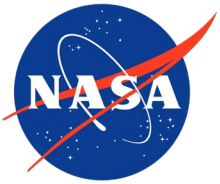




# Rationale

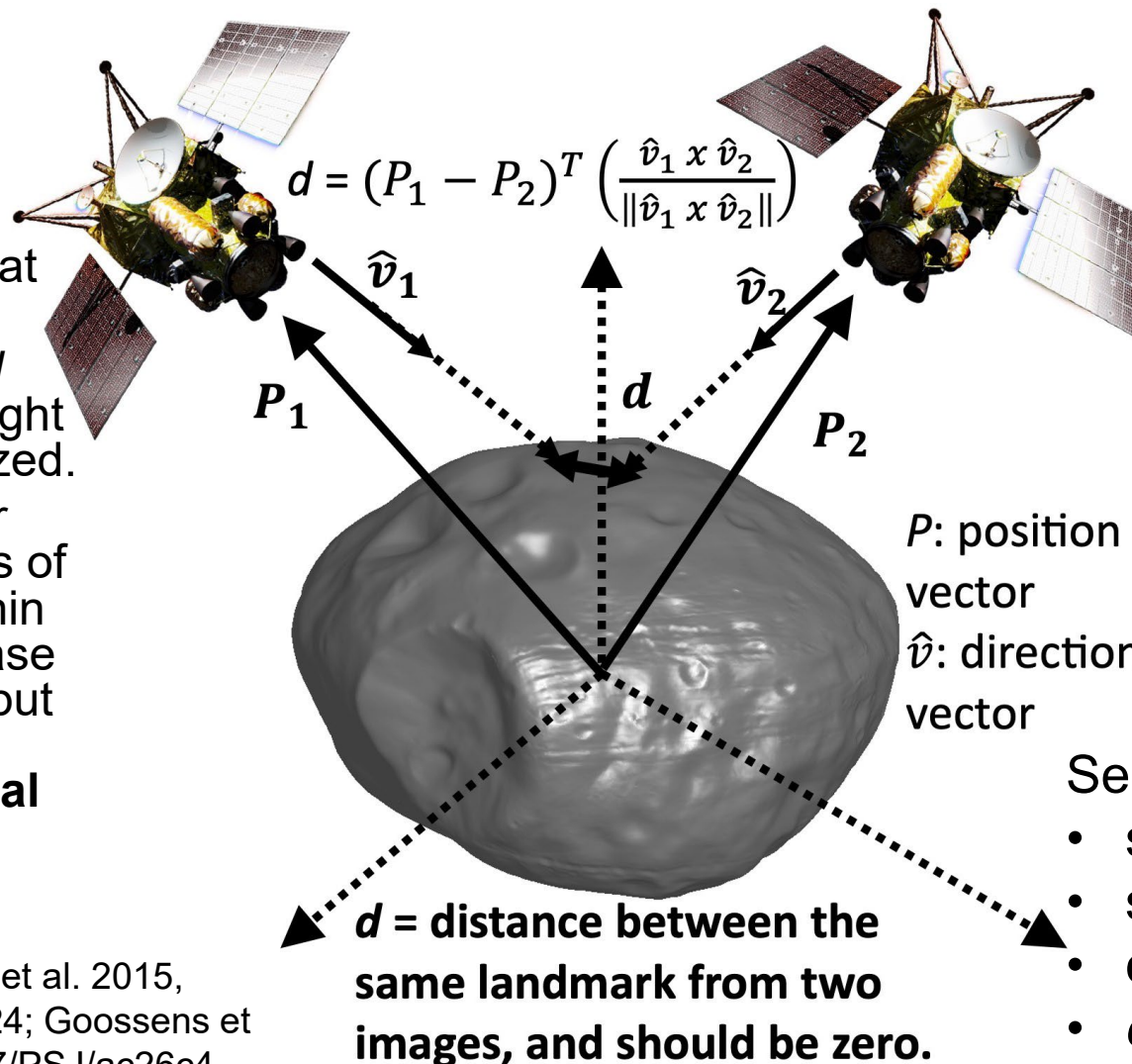
Our analysis will **complement, not duplicate**, the science team's efforts:

- We use **different tools and data types**, which is important to ensure a successful sample return (verification and validation)
- We will provide the science team with precise orbits, gravity models, and rotational parameters.
- Our analysis will also benefit spacecraft operations through the aforementioned products, augmented with updated attitude estimates, and by resolving early mission issues such as scale ambiguities between camera data and lidar data.



# Differential measurements

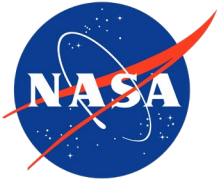
- The same landmark is photographed at different times.
- The distance  $d$  between the sight lines is minimized.
- We use this for pairs of images of landmarks within one orbital phase (intra-phase), but also **between different orbital phases**.



Sensitive to:

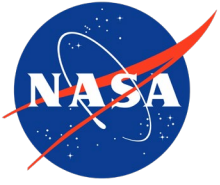
- s/c position
- s/c attitude
- camera model
- *changes* in body orientation

See also: Centinello et al. 2015, doi:10.2514/1.A33224; Goossens et al. 2021, doi:10.3847/PSJ/ac26c4

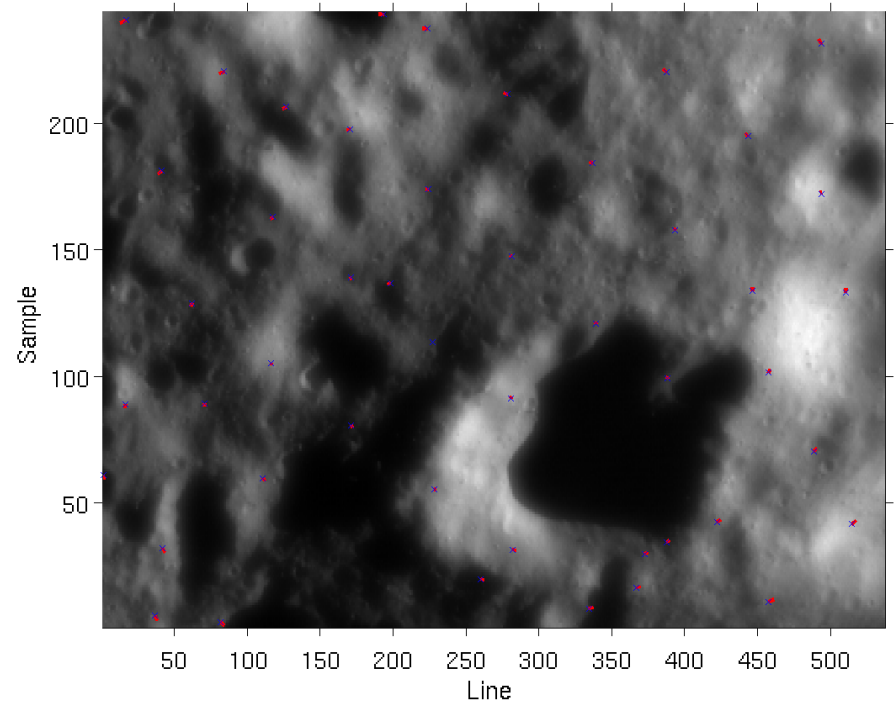
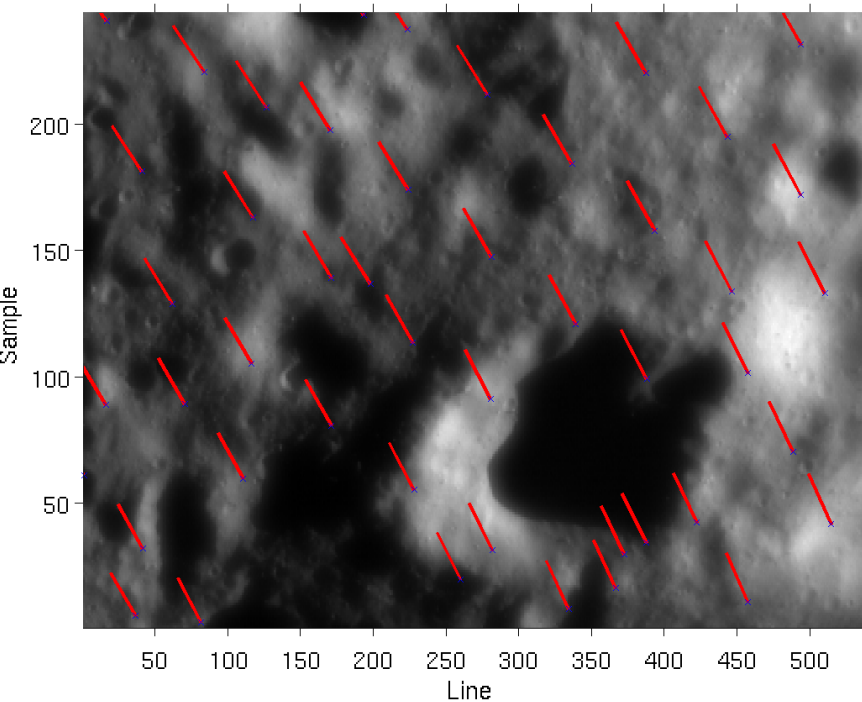


# Shape model verification

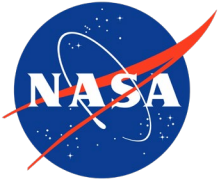
- Through the use of image and lidar data
  - landmarks
  - image constraints
  - direct altimetry
  - altimetric crossovers
- Verification/estimation of scale factors
- Direct estimation of the center-of-figure and center-of-mass offset
  - This does **not** use gravity degree-1 coefficients, which can be problematic when combined with Doppler data.



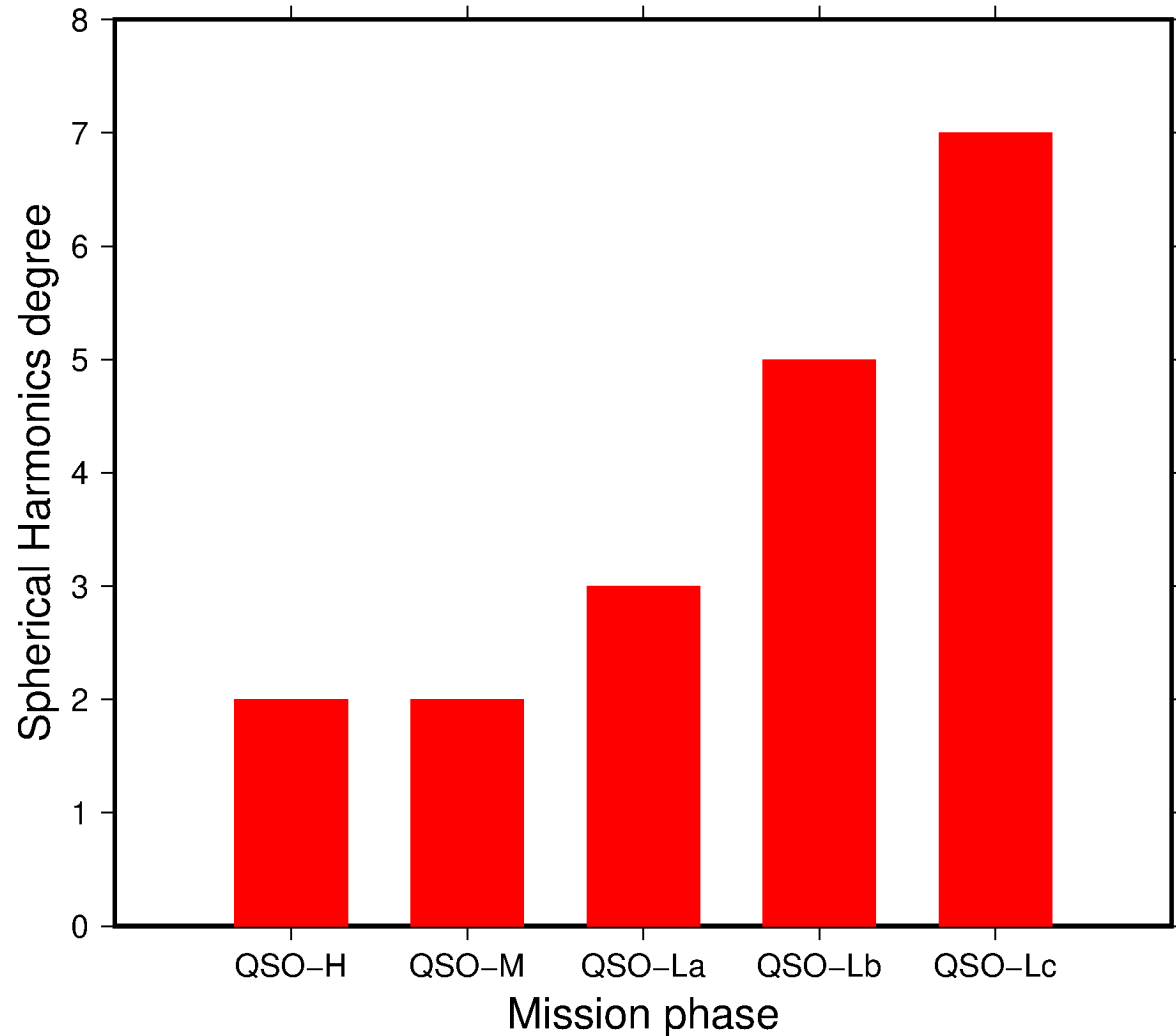
# Example landmark processing

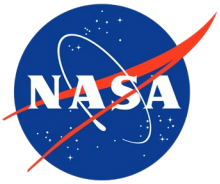


Landmark residuals on Near Earth Asteroid Rendezvous (NEAR) Multispectral Imager image M0131963551F4, before and after spacecraft position estimation.



# Sensitivity to gravity terms

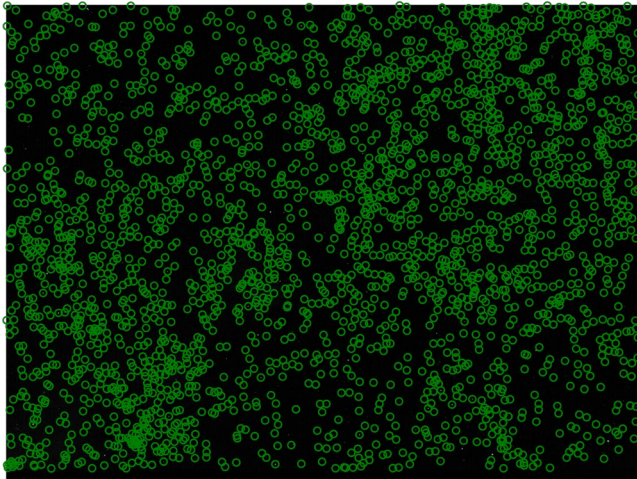




# GIANT capabilities

There are 3 primary types of OpNav: star-based, celestial, and relative.

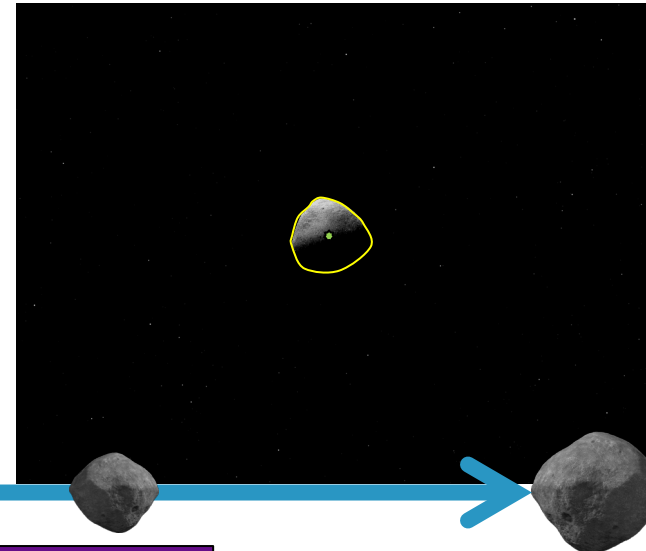
Star based OpNav generates inertial pointing measurements



CelNav produces bearing measurements to a number of objects



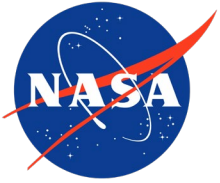
Relative OpNav (RelNav) generates bearing/position estimates to an observed object



Star based

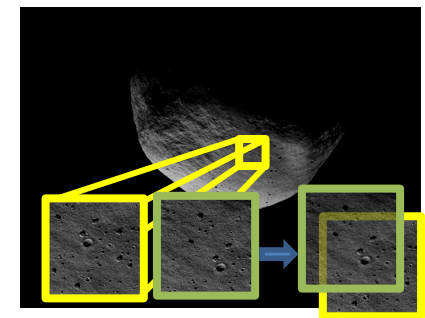
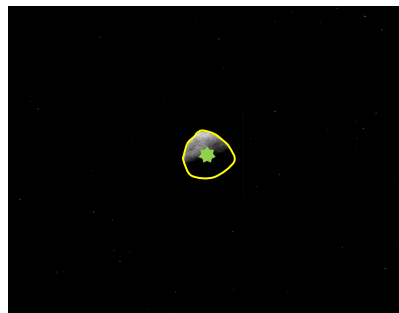
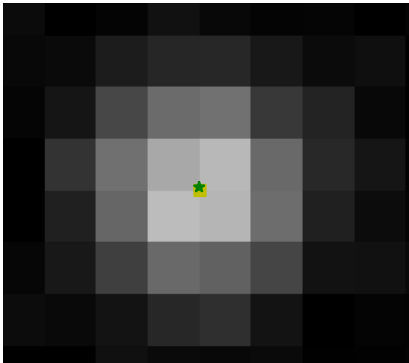
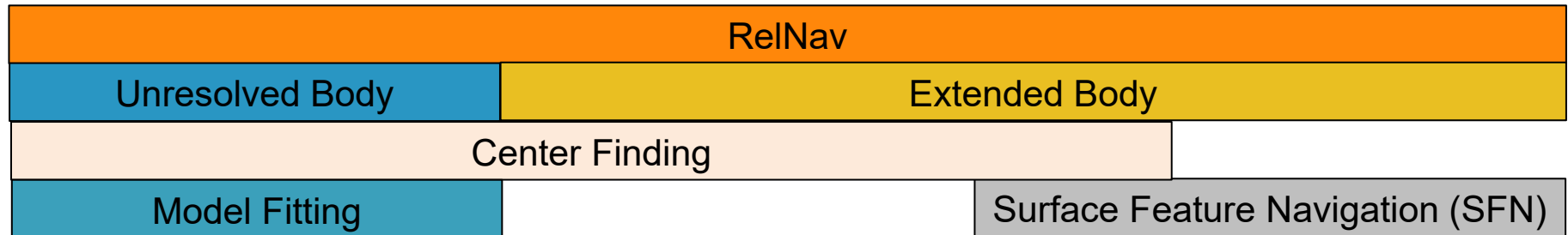
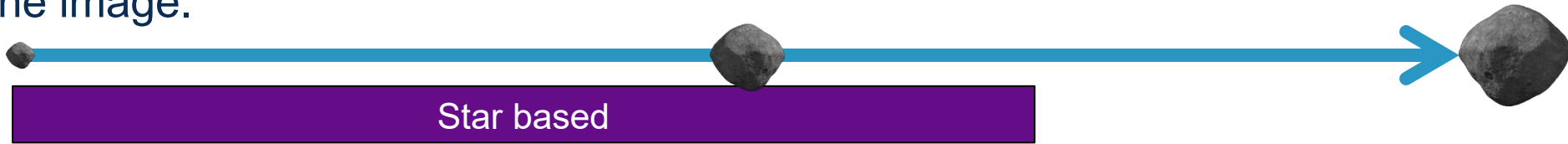
CelNav

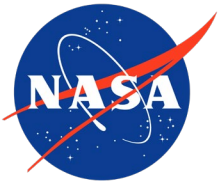
RelNav



# GIANT capabilities

The type of CelNav/RelNav used depends on the apparent size of the body in the image.





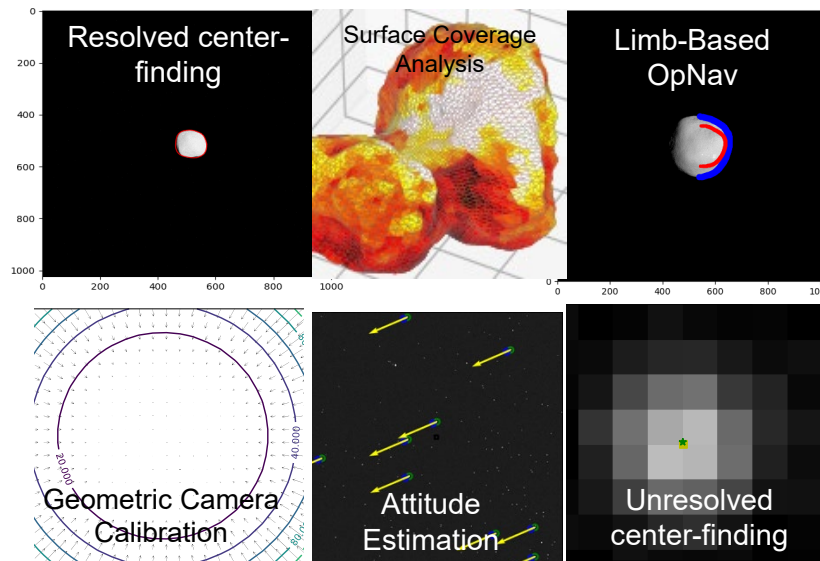
# GIANT capabilities

The Goddard Image Analysis and Navigation Tool is an **open-source, flight proven, broad, extensible, ground software suite** for performing precision optical navigation.

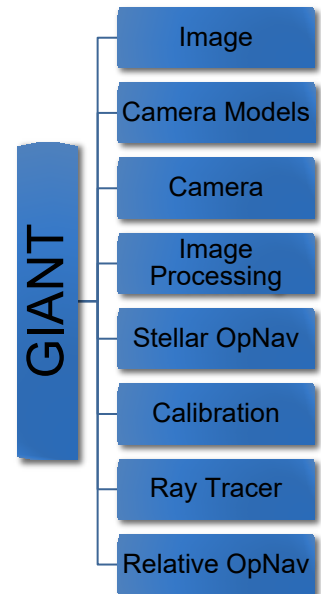
Flight Proven

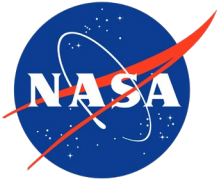


Broad

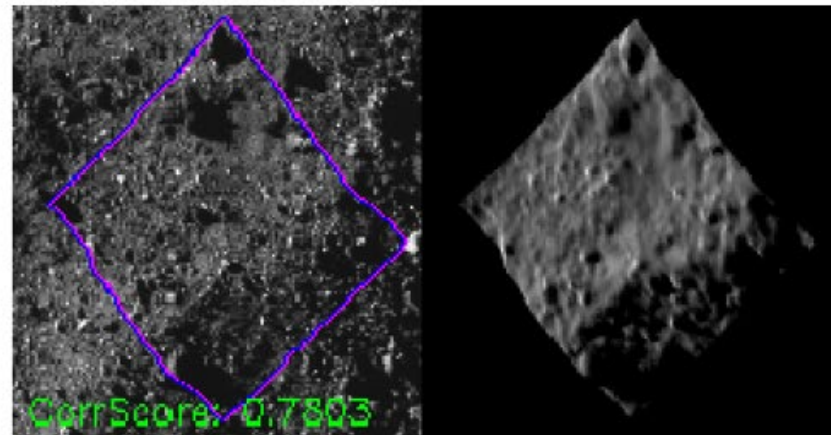
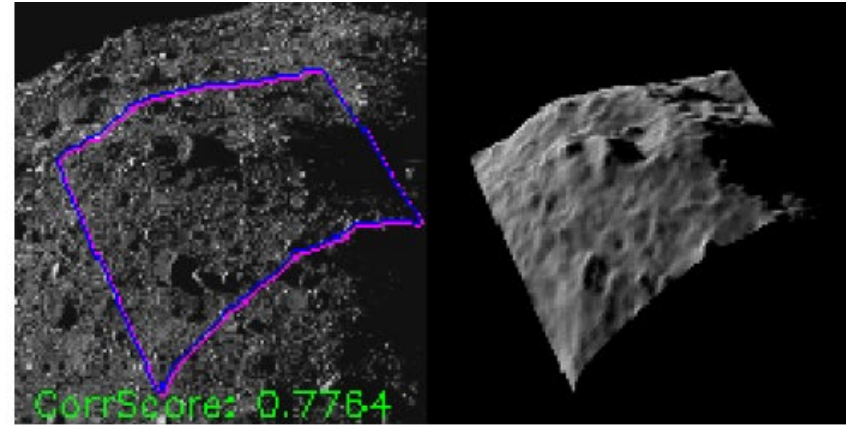
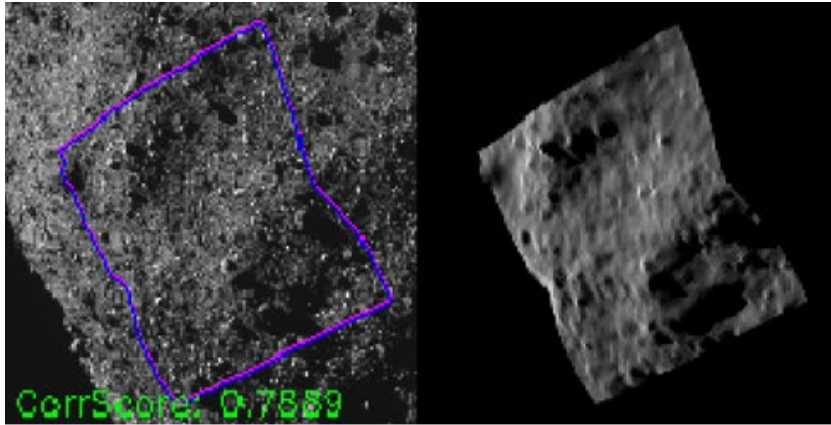


Extensible

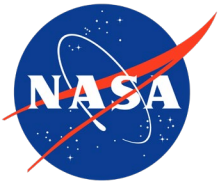




# Examples of capabilities of GIANT

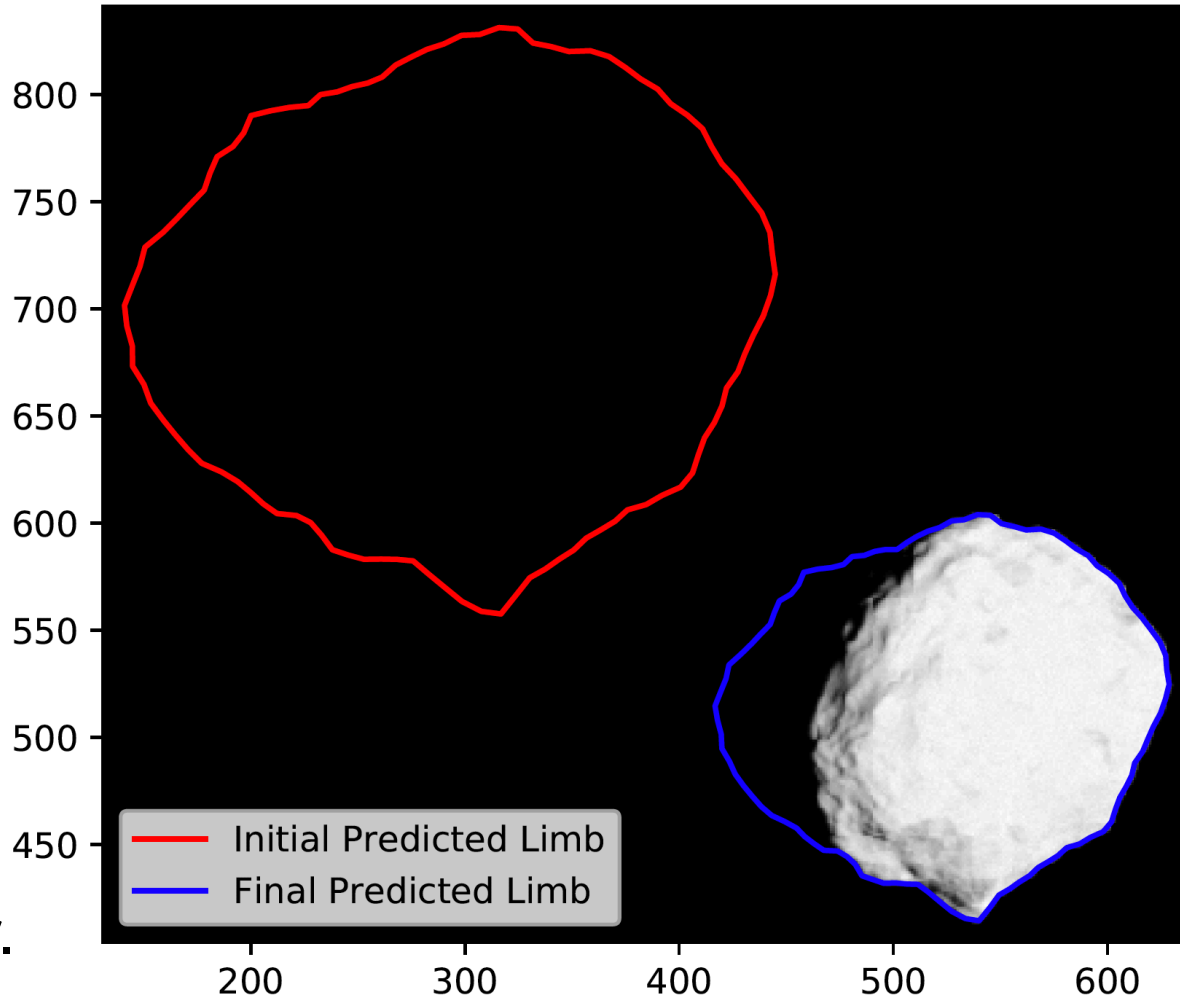


Orbital A sample landmark matches



# Example of limb-based navigation

The final predicted shape for Comet 67P matches scale and position much better.





# An example with OSIRIS-REx

THE PLANETARY SCIENCE JOURNAL, 2:219 (18pp), 2021 December

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**OPEN ACCESS**

<https://doi.org/10.3847/PSJ/ac26c4>



## Mass and Shape Determination of (101955) Bennu Using Differenced Data from Multiple OSIRIS-REx Mission Phases

Sander Goossens<sup>1,2,3,9</sup> , David D. Rowlands<sup>2</sup>, Erwan Mazarico<sup>2</sup> , Andrew J. Liounis<sup>2</sup> , Jeffrey L. Small<sup>2</sup>,  
Dolan E. Highsmith<sup>2,4</sup> , Jason C. Swenson<sup>2</sup>, Joshua R. Lyzhoft<sup>2</sup>, Benjamin W. Ashman<sup>2</sup>, Kenneth M. Getzandanner<sup>2</sup> ,  
Jason M. Leonard<sup>5</sup> , Jeroen L. Geeraert<sup>5</sup> , Coralie D. Adam<sup>5</sup> , Peter G. Antreasian<sup>5</sup> , Olivier S. Barnouin<sup>6</sup> ,  
Michael G. Daly<sup>7</sup> , Jeffrey A. Seabrook<sup>7</sup> , and Dante S. Lauretta<sup>8</sup>

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<sup>3</sup> Center for Research and Exploration in Space Science and Technology (CREST) II, NASA/GSFC, Greenbelt, MD 20771, USA

<sup>4</sup> The Aerospace Corporation, Chantilly, VA 20151, USA

<sup>5</sup> KinetX Inc., Simi Valley, CA 93065, USA

<sup>6</sup> The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA

<sup>7</sup> The Centre for Research in Earth and Space Science, York University, Toronto, ON M3J1P3, Canada

<sup>8</sup> Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA

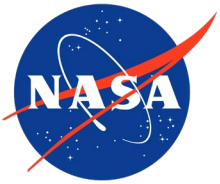
*Received 2021 June 2; revised 2021 September 10; accepted 2021 September 13; published 2021 November 1*

### Abstract

The Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer (OSIRIS-REx) mission collected a sample from the rubble-pile asteroid (101955) Bennu for return to Earth. For the successful Touch And Go sample acquisition maneuver, the shape and mass of the asteroid needed to be known precisely. Here we use a combination of radiometric, image landmark, and laser altimetry data to determine Bennu's mass, shape, and orientation simultaneously and to verify existing models thereof. Our shape determination consists of estimating a scale factor and three frame rotation angles that apply to both the global digital terrain model (GDTM) and the landmark coordinates. We use a data type called image constraints, where we take the difference of the observation of the same landmark in images taken at two different times. We analyze data from two phases of the OSIRIS-REx mission, Orbital B and Recon B, and show that interphase image constraints greatly reduce interdependencies between estimated parameters for mass, GDTM scale, and biases on the altimetry data. This results in an improved solution for the mass and shape relative to considering a single mission phase. We find Bennu's gravitational parameter  $GM$  to be  $4.89256 \pm 0.00035 \text{ m}^3 \text{ s}^{-2}$ , and we find a scale factor of  $1.000896 \pm 0.00036$  for the altimetry-based GDTM. Using the scaled volume, this results in a bulk density of  $1191.57 \pm 1.74 \text{ kg m}^{-3}$ , which is within the uncertainties of previous analyses but more precise.

*Unified Astronomy Thesaurus concepts:* [Small Solar System bodies \(1469\)](#); [Gravitational fields \(667\)](#)

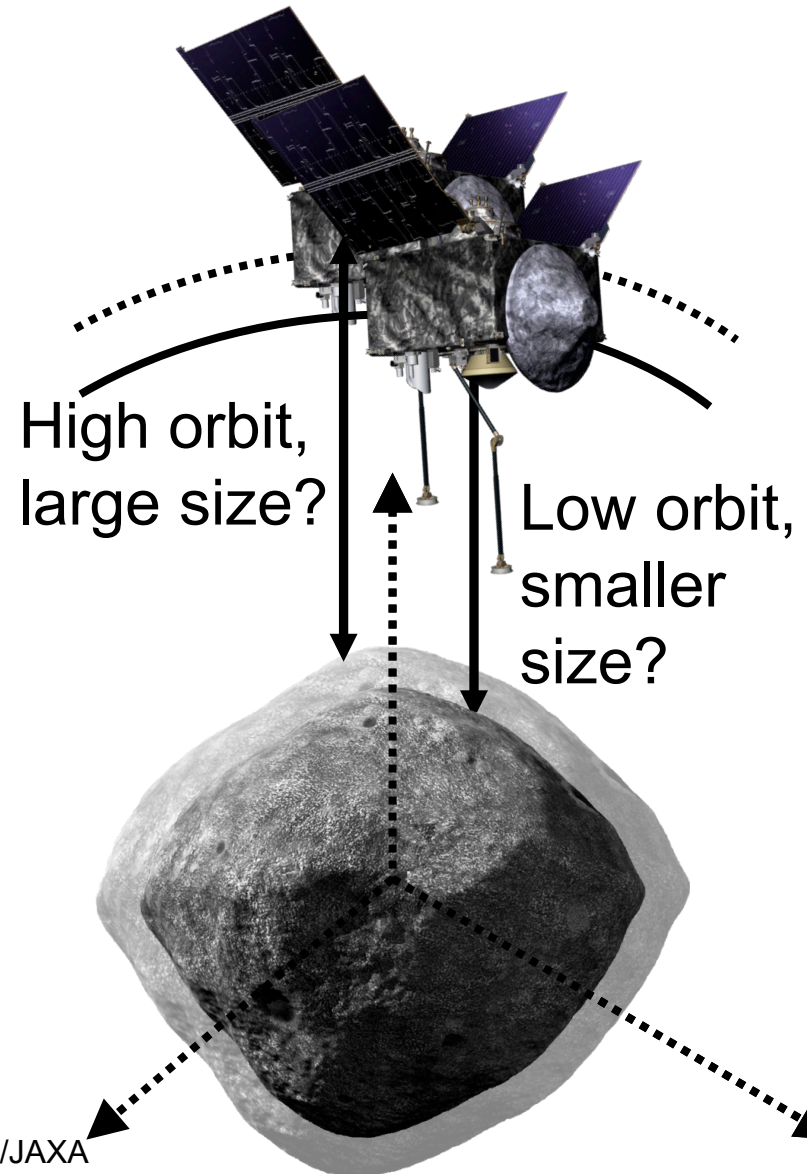
<https://doi.org/10.3847/PSJ/ac26c4>

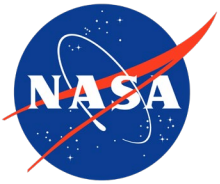


# Stating the problem

- Shape needs to be known with errors  $< \sim 15$  cm for TAG to ensure safe TAG in the designated target site.
- Shape models exist: based on camera data (stereophotoclinometry, SPC) or laser data (from OLA), but differ.
- Various parameters trade and need to be decorrelated: Digital Elevation Model (DEM) scale, orbit semi-major axis  $a$ , gravitational parameter  $GM$ , through Kepler's Third Law:

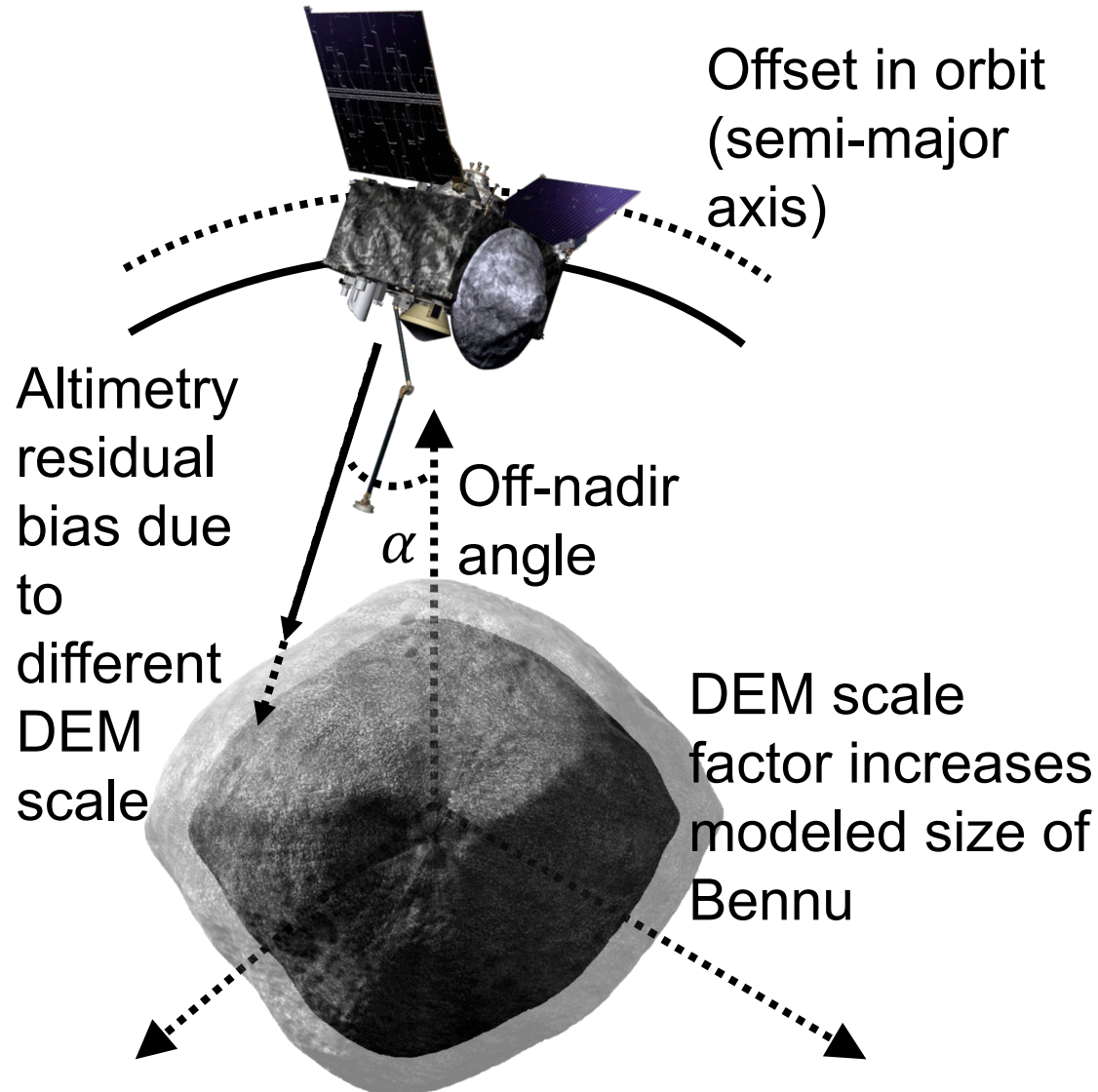
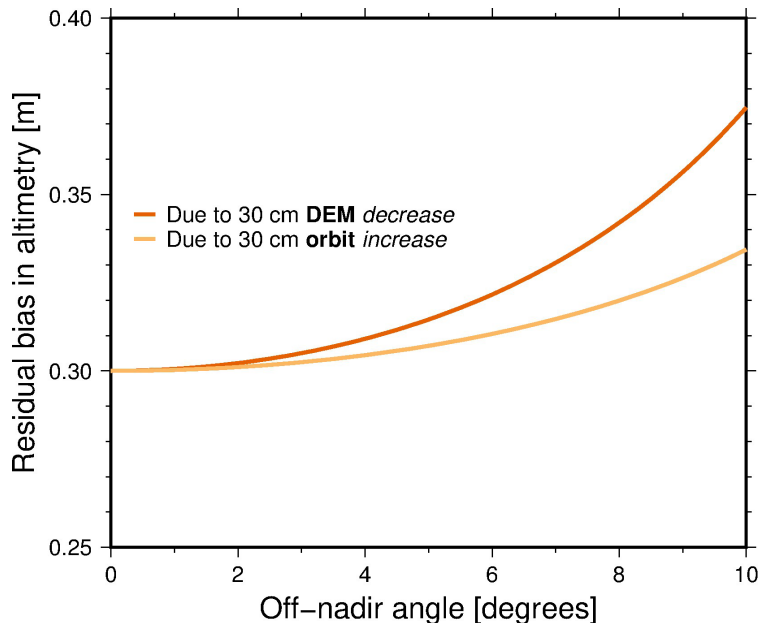
$$P^2 = 4\pi^2 \frac{a^3}{GM}$$

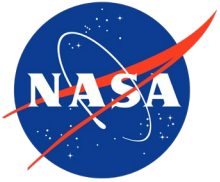




# Off-nadir altimetry

- Off-nadir altimetry measurements can help break the correlations between DEM scale and semi-major axis ( $GM$ ).
- The orbit effect is different from the DEM effect, especially at higher off-nadir angles.
- Extra off-nadir passes were requested during Recon





# OREx data analysis

- Use of a multi-arc analysis: processing OrbB and Recon simultaneously, with **image constraint data connecting the two periods.**
- Goal: simultaneously estimate parameters such as *GM*, DEM scale factor, OLA biases, from this multi-sat run.
- Evaluate contribution of inter-phase image constraints (*i.e.*, analysis with and without the inter-phase data).



# Parameter values

Results for the Geophysical Parameters of Interest

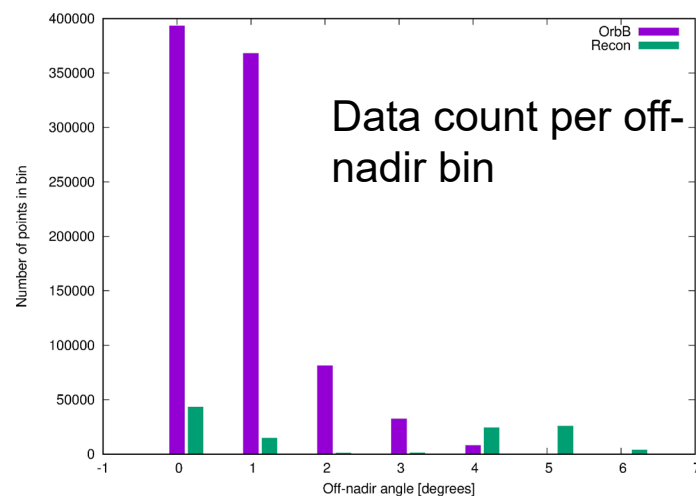
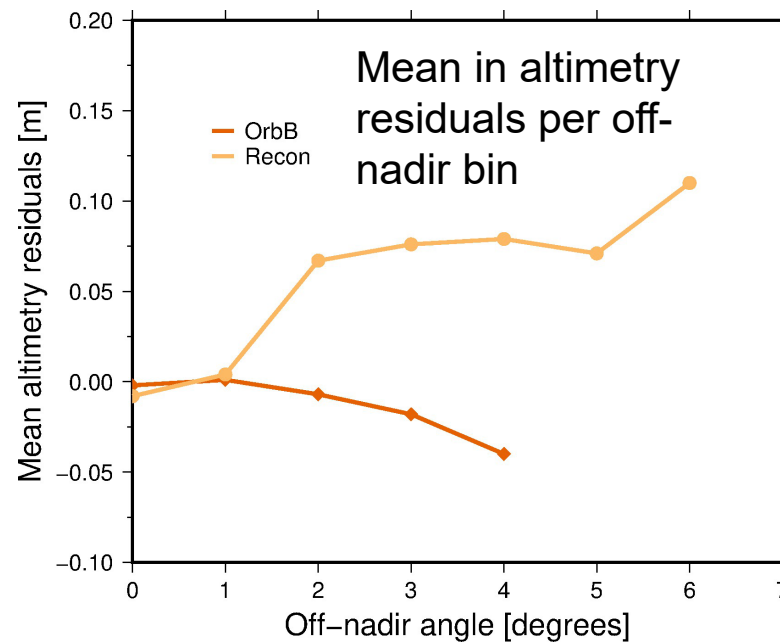
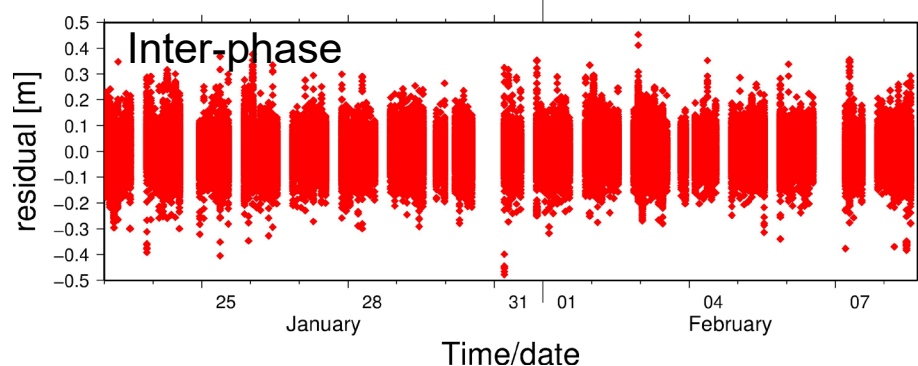
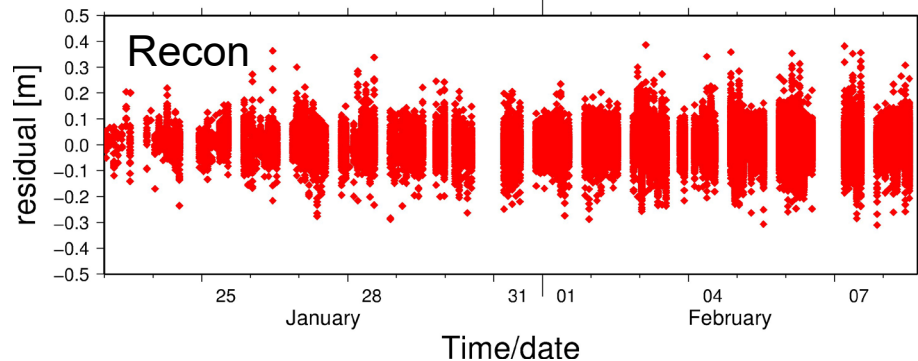
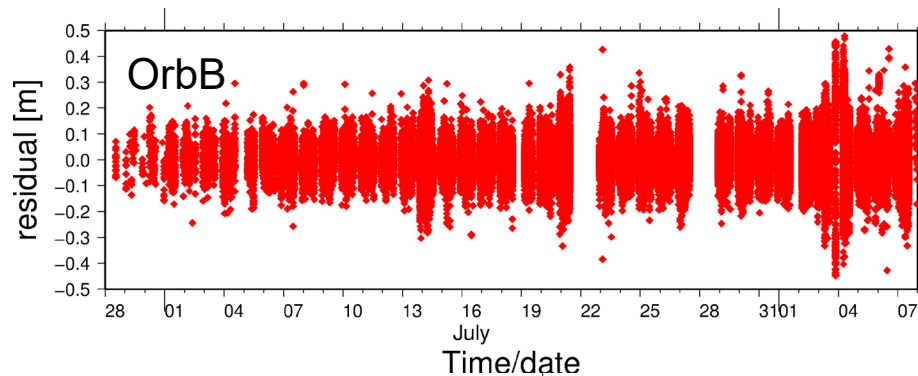
| Parameter                                               | Without Interphase<br>Image Constraints        | With Interphase<br>Image Constraints            |
|---------------------------------------------------------|------------------------------------------------|-------------------------------------------------|
| $GM$ ( $\text{m}^3 \text{s}^{-2}$ )                     | $4.89349 \pm 0.00052$                          | $4.89256 \pm 0.000035$                          |
| Scale factor                                            | $1.000963 \pm 0.000052$                        | $1.000896 \pm 0.000036$                         |
| GDTM angle $X$ (deg)                                    | $0.19428 \pm 0.00199$                          | $0.19878 \pm 0.00189$                           |
| GDTM angle $Y$ (deg)                                    | $0.010,09 \pm 0.00132$                         | $0.01066 \pm 0.001309$                          |
| GDTM angle $Z$ (deg)                                    | $-0.0001789 \pm 0.00133$                       | $-0.00001446 \pm 0.001319$                      |
| COF-COM $X$ (m)                                         | $0.0166 \pm 0.0049$                            | $0.0170 \pm 0.0049$                             |
| COF-COM $Y$ (m)                                         | $0.0175 \pm 0.0048$                            | $0.0178/ \pm 0.0048$                            |
| COF-COM $Z$ (m)                                         | $-0.0280 \pm 0.0098$                           | $-0.0368 \pm 0.0094$                            |
| Pole R.A. (deg)                                         | $85.442733544 \pm 0.0635$                      | $85.4500385719 \pm 0.0549$                      |
| Pole decl. (deg)                                        | $-60.371338829 \pm 0.0546$                     | $-60.367833873 \pm 0.00109$                     |
| Pole prime meridian (deg)                               | $139.144678916 \pm 5.730$                      | $139.136188582 \pm 0.000698$                    |
| Pole rotation rate ( $\text{deg day}^{-1}$ )            | $211.146232693 \pm 0.00177$                    | $211.14633738 \pm 0.00044$                      |
| Pole rotation<br>acceleration ( $\text{deg day}^{-2}$ ) | $1.774 \times 10^{-6} \pm 1.55 \times 10^{-7}$ | $1.7597 \times 10^{-6} \pm 6.13 \times 10^{-8}$ |
| Bias LEIT (m)                                           | $0.0743 \pm 0.0264$                            | $0.1169 \pm 0.010$                              |
| Bias HELT (m)                                           | $0.3234 \pm 0.035$                             | $0.3754 \pm 0.0225$                             |

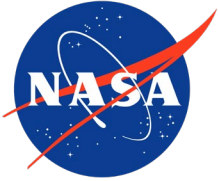
DEM angles (3 rotations) ensure that the DEM and pole are aligned.

LEIT biases OrbB and Recon are considered instrument biases and thus constrained to be the same.



# Data fit

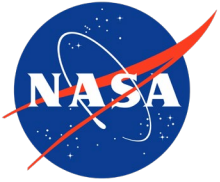




# Correlations

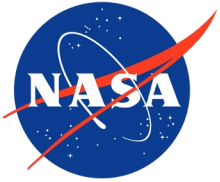
Correlations between Selected Parameters

|                                           | Without Interphase<br>Image Constraints | With Interphase<br>Image Constraints |
|-------------------------------------------|-----------------------------------------|--------------------------------------|
| Correlations with <i>GM</i>               |                                         |                                      |
| Scale factor                              | 0.705                                   | 0.059                                |
| GDTM angle <i>X</i>                       | −0.020                                  | −0.012                               |
| GDTM angle <i>Y</i>                       | −0.0063                                 | −0.0013                              |
| GDTM angle <i>Z</i>                       | 0.0054                                  | −0.0018                              |
| COF−COM <i>X</i>                          | 0.0131                                  | 0.0033                               |
| COF−COM <i>Y</i>                          | 0.0013                                  | −0.0043                              |
| COF−COM <i>Z</i>                          | −0.055                                  | 0.023                                |
| Bias LEIT                                 | −0.918                                  | −0.168                               |
| Bias HELT                                 | −0.766                                  | −0.085                               |
| Correlations with Prime Meridian          |                                         |                                      |
| Rotation rate                             | −0.90                                   | 0.015                                |
| Rotation acceleration                     | 0.716                                   | −0.016                               |
| Correlations with GDTM Scale Factor       |                                         |                                      |
| Bias LEIT                                 | −0.41                                   | 0.81                                 |
| Bias HELT                                 | −0.37                                   | 0.38                                 |
| Correlations between the Altimeter Biases |                                         |                                      |
|                                           | 0.79                                    | 0.35                                 |



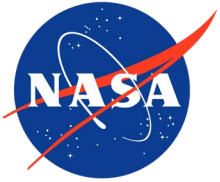
# Timeline for our MMX project

- **Project years 1 & 2** (October 2023 – March 2025):
  - Key activities: preparing processing tools; calibration.
  - Milestones: have an initial processing pipeline at the end of PY 1, with additional modifications for a final pipeline towards the end of PY 2.
- **Project year 3** (April 2025 – March 2026):
  - Key activities: Data analysis. Shape model verifications.
  - Milestones: Initial solutions for Phobos rotational state and gravity field.



# Timeline for our MMX project

- **Project year 4** (April 2026 – March 2027)
  - Key activities: Data analysis with a focus on providing precise geophysical parameters important for landing.
  - Milestones: Gravity, rotational state, and shape model verification for landing phase.
- **Project year 5** (April 2027 – March 2028)
  - Key activities: Contribute to landing phase; contribute to geodesy flagship paper; continued data analysis (e.g., interior modeling). Prepare for Deimos flyby.
  - Milestones: contribution to geodesy flagship paper; final rotational and gravity parameters for Phobos.



# Timeline for our MMX project

- **Project year 6** (April 2028 – March 2029)
  - Key activities: analysis of Deimos data; writing of publication(s); archiving updates to GIANT, and any supplementary materials for publications.
  - Milestones: Deimos parameters; publication summarizing our analysis and results.