OSIRIS-REx
ASTEROID SAMPLE RETURN MISSION

Architecture and Operations of the OSIRIS-REx Independent Navigation Team

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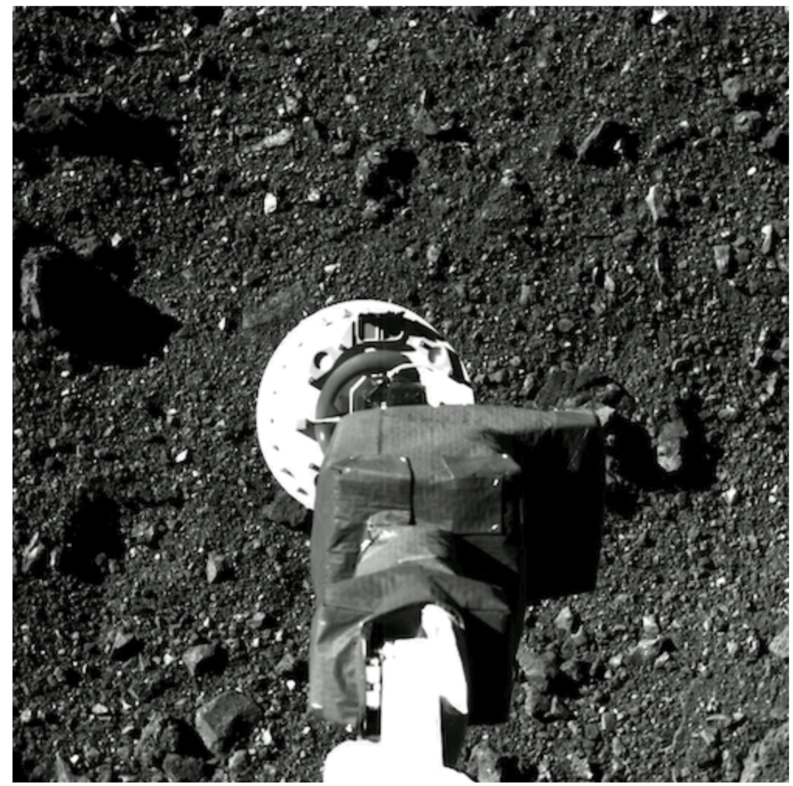

Fig. 1. OSIRIS-REx Touch and Go (TAG) sample collection [1].

OSIRIS-REx Mission Overview

- **O**rigins
  - Return and analyze a sample of pristine carbonaceous asteroid regolith
- **S**pectral **I**nterpretation
  - Provide ground truth for telescopic data of the entire asteroid population
- **R**esource **I**dentification
  - Map the chemistry and mineralogy of a primitive carbonaceous asteroid
- **S**ecurity
  - Measure the Yarkovsky effect on a potentially hazardous asteroid
- **R**egolith **Ex**plorer
  - Document the regolith at the sampling site at scales down to the sub-cm

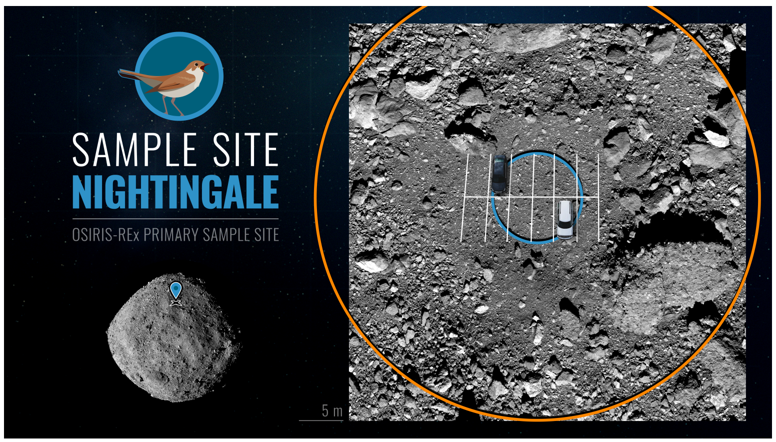

Fig. 2. Sample site Nightingale [2].

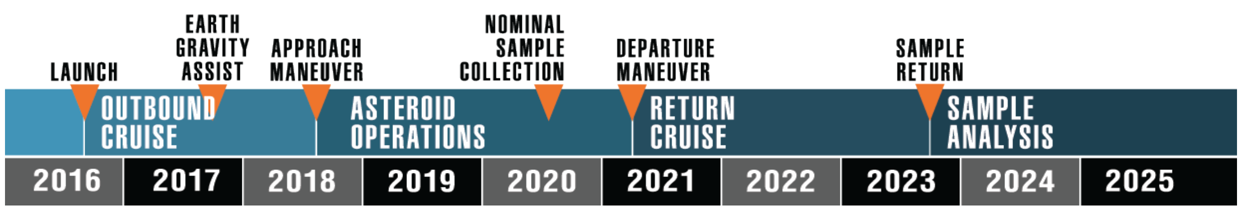

Fig. 3. OSIRIS-REx mission timeline [2].

Independent Navigation Team (INT)

- Primary Navigation Team (PNT):
  - KinetX Aerospace is the PNT responsible for official navigation product deliveries.
- Independent Navigation Team (INT):
  - The Goddard Space Flight Center (GSFC) Independent Navigation Team (INT) is composed of NASA civil servants and contractors from The Aerospace Corporation.
  - The INT provides an independent assessment of OpNav and OD in support of the PNT
  - The INT uses Goddard heritage tools for OpNav and OD.
- Both the PNT and INT perform OpNav and OD assessments in support of OSIRIS-REx operations.
- Both the PNT and INT make up the Flight Dynamics System (FDS) Team.

Fig. 4. Geographical distribution of FDS team.

SSMO vMMOC

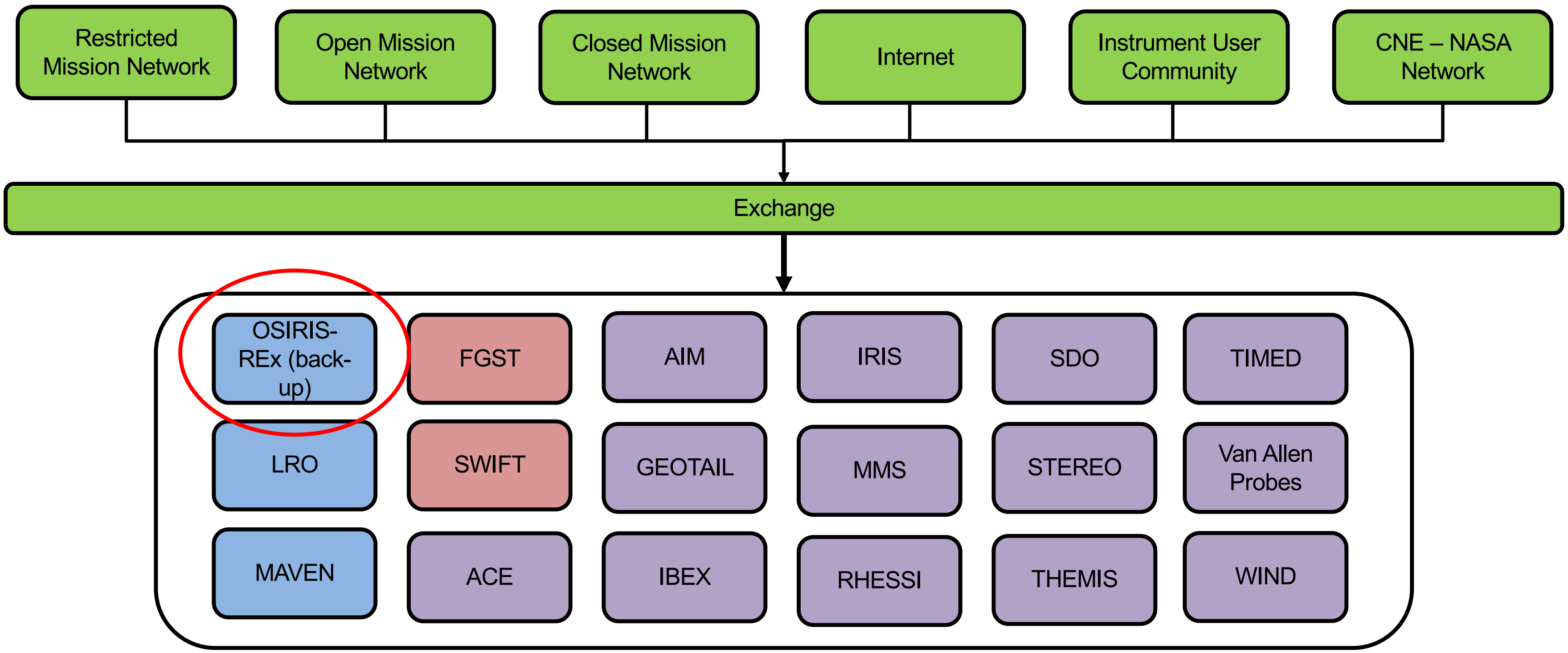

Fig. 5. SSMO vMMOC architecture adapted from Ref. [3] with updated mission information from Ref. [4]. Interplanetary, astrophysics, and heliophysics missions are represented in blue, red, and purple, respectively. Green denotes SSMO vMMOC network infrastructure.

SSMO virtual Multi-Mission Operations Center (vMMOC)

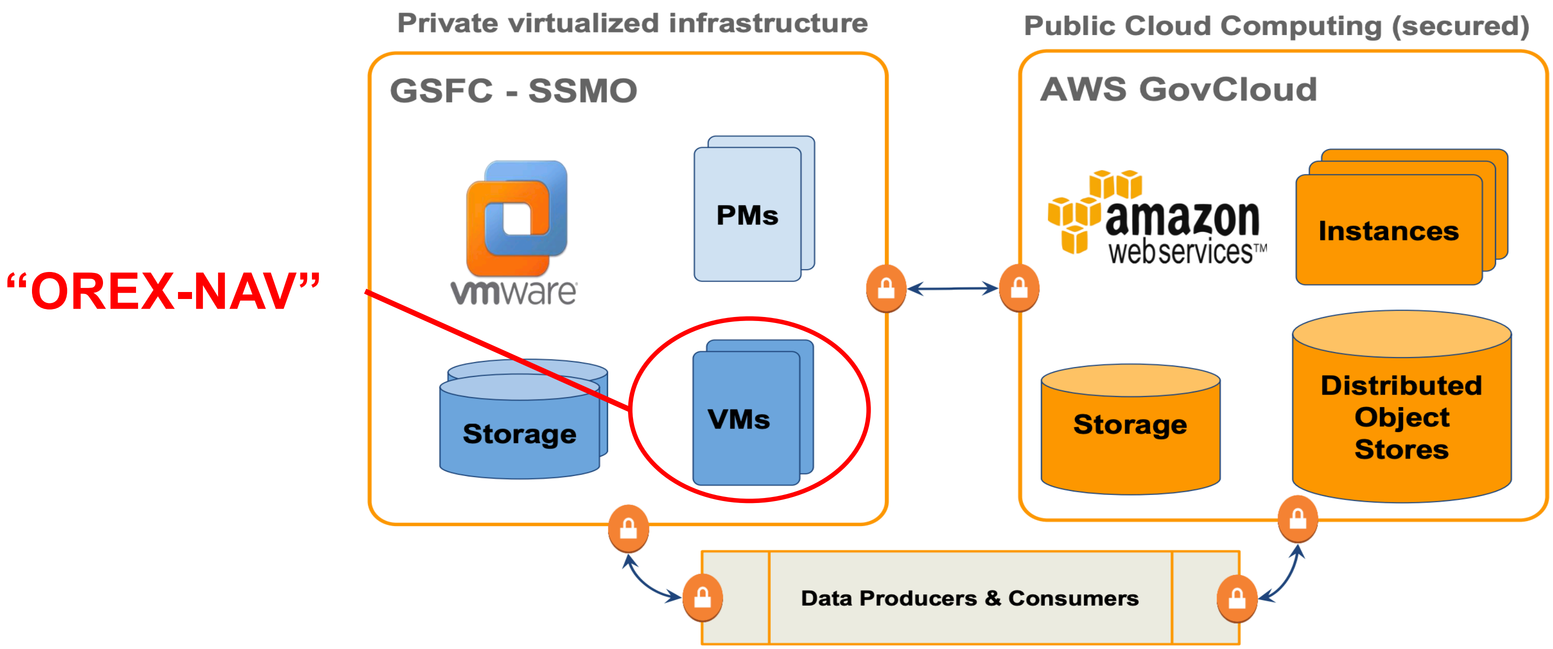

Fig. 6. SSMO cloud-computing services with Amazon Web Services (AWS).

Architecture of OREX-NAV: Overview

- OREX-NAV is a virtual operations environment on the SSMO vMMOC with capabilities to store, send, or retrieve information from secure external networks.
- Access:
  - Security classification: “moderate”, per NIST 800-60 Vol. 2
  - INT members are therefore able to remotely accessed operations environment over Secured Sockets Layer (SSL) Virtual Private Network (VPN) connection.
  - Allows for geographically (and organizationally) distributed teams from both within and outside the United States.
- Specs:
  - OREX-NAV is based on the Intel Xeon CPU E5-2699 v3 server class.
  - Utilizes 16 single-threaded, single socket x86_64 CPU cores, each operating at 2.30 GHz.
  - The L1, L2, and L3 CPU caches are 32 KB (D) and 32 KB (I), 256 KB, and 46080 KB, respectively.
  - CPUs 0-15 are continuously online.
  - 12 TB of allocated server memory capacity. An additional 1 TB of storage on mounting point.
- Tools:
  - The INT specifically uses the Goddard Image and Analysis Navigation Tool (GIANT) for OpNav image processing and computation of center-finding and landmark observables.
  - The INT uses two OD tools: GEODYN II and Mission Analysis, Operations, and Navigation Toolkit Environment (MONTE).

Optical Navigation and Orbit Determination

Orbit Determination (OD)

1. Perform observations (e.g., DSN radio links, images).
2. Estimate the spacecraft position and velocity (our “state”) at some epoch using these measurements and the current state estimate.
3. Propagate the spacecraft state forward in time using knowledge of dynamics and perturbing forces.

Observations

- Radio measurements via DSN
  - 2-way range and Doppler, Delta Differenced One-Way Range (DDOR) .
- Optical measurements via onboard cameras
  - Stellar OpNav, center-finding, surface feature navigation.

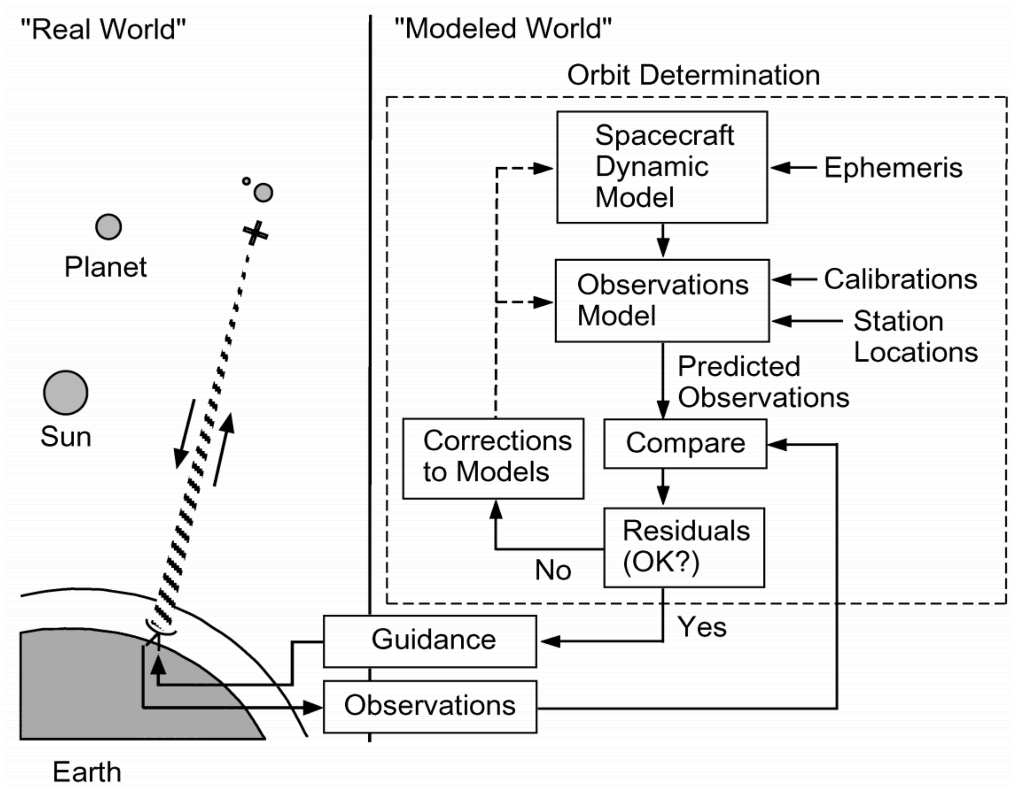

Fig. 7. The navigation process from [13]

Architecture of OREX-NAV: External Connections

- OREX-NAV sends and receives spacecraft data products from various external connections inside a secured network.
- Data flows from the Deep Space Network (DSN) to the Science Processing Operations Center (SPOC), JPL Flight Network, and to the Flight Operations Bucket (FOB) in the Lockheed-Martin OSIRIS-REx Mission Support Area (MSA).
- Data flows through a Restricted IONet to the NASCOM IONet Exchange.
- Data then flows to OREX-NAV on the SSMO vMMOC and to zion, the PNT's navigation server in the NavMSA.

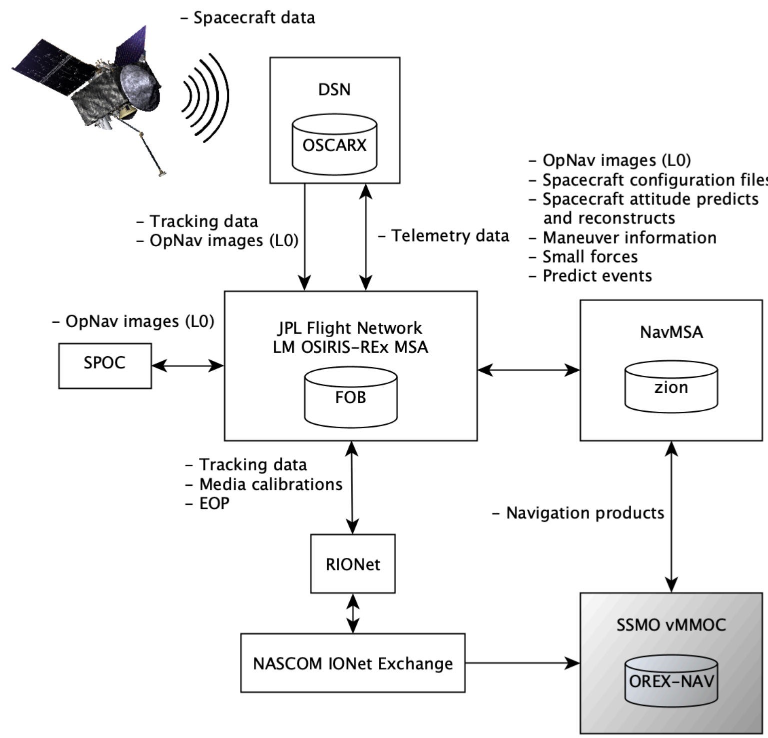

Fig. 8. Data flow from OSIRIS-REx spacecraft to SSMO vMMOC.

Navigation Operations on OREX-NAV: Scripts and Crons

- The INT developed a variety of bash and Python scripts to perform routine tasks including:
  - Automatically pulling mission data from the FOB and zion onto OREX-NAV.
  - Automatically running data preparation processes for maneuvers, radio tracking data and OpNav data.
  - Performing OD and OpNav analyses and plotting results.

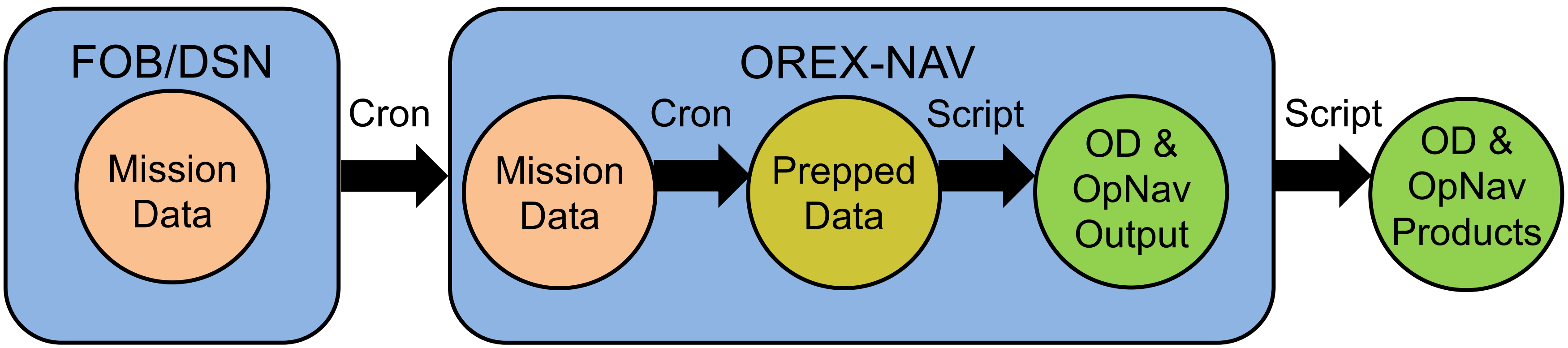

Fig. 9. Role of scripts and crons in navigation operations.

Architecture of OREX-NAV: Database

- A MySQL database is implemented on OREX-NAV, using open-source version of MariaDB Server for Linux distributions.
- In order to set up and interact with the tables, the Python API SQLAlchemy is utilized.
- The OREX-NAV database consists of 35 tables that store data products including
  - DSN data (range, Doppler, and Delta Differenced One-Way Range (DDOR) observables)
  - OpNav observables,
  - media calibration coefficients, maneuvers, momentum desaturations, and the mass history of the OSIRIS-REx spacecraft
- In total, the size of the database is 230 GB, a small fraction of the total available storage on OREX-NAV, and contains data spanning the duration of the mission.
- The database is primarily populated by a series of time-based automated processes (i.e., “crons”).

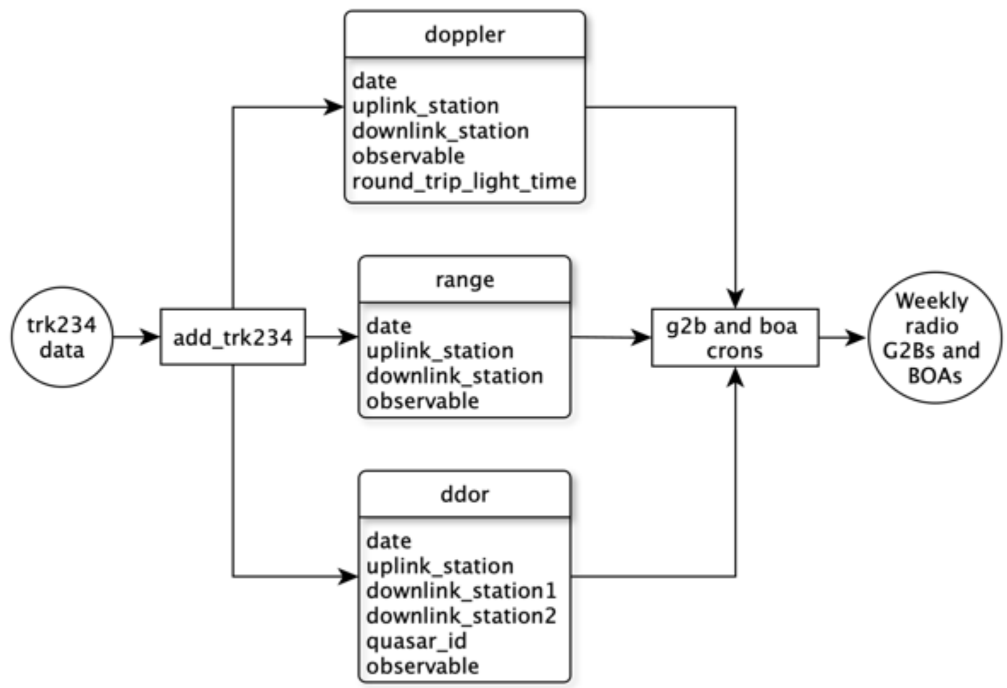

Fig. 10. Radio data flow on OREX-NAV database**.**

Navigation Operations on OREX-NAV: OpNav

- The INT uses GIANT to perform star-based (stellar) navigation and relative navigation (i.e., unresolved or resolved center-finding).
- GIANT is a Python API, developed by GSFC INT member Andrew Liounis.
- GIANT contains a module for feature-based navigation known as Surface Feature Navigation (SFN).
- The PNT uses Stereophotoclinometry (SPC) software developed by Dr. Robert Gaskell at the Planetary Science Institute (PSI) for feature-based navigation.

Fig. 12. GIANT.

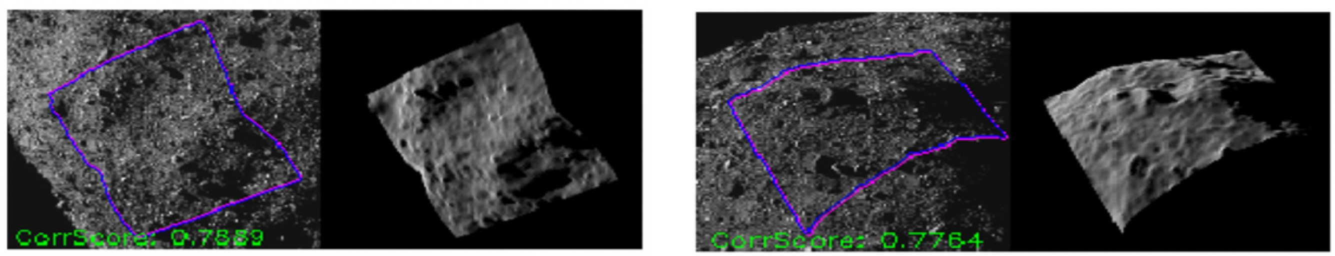

Fig. 13. Generated correlation surfaces using IV&V SFN capability.

INT SFN Workflow

- SFN processing uses inputs from the OREX-NAV SQL database and a SPICE meta-kernel
  - SPICE was created by JPL's NAIF to provide a framework for storing and retrieving spacecraft and celestial body information including ephemeris, attitude, time systems, and coordinate frame definitions
  - Camera models and image locations are retrieved from the database

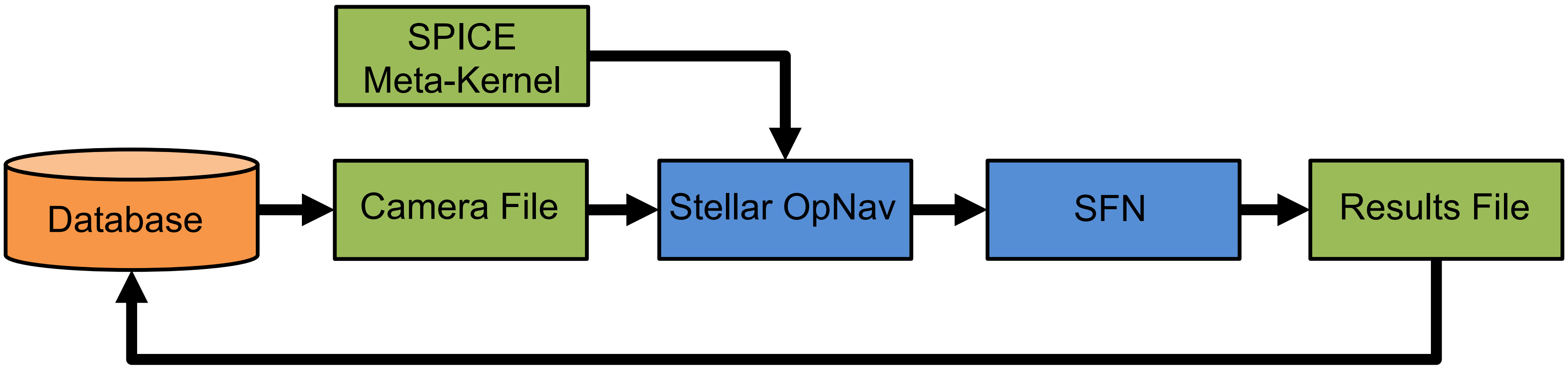

Fig. 14. OpNav SFN workflow.

INT Orbit Determination

- INT routinely delivered MONTE and GEODYN solutions to PNT for comparison.
- Trajectory predictions usually agreed to within 1-2σ of mapped uncertainties.

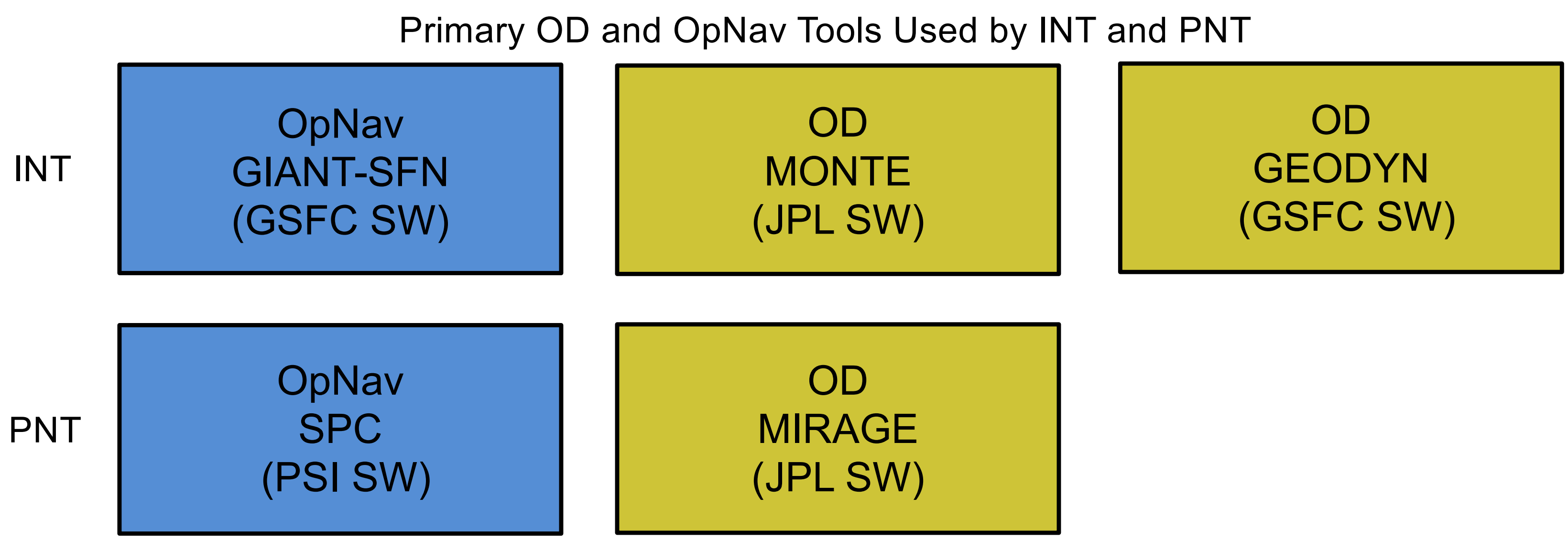

Fig. 11. INT and PNT OD and OpNav tools

Navigation Operations on OREX-NAV: OD

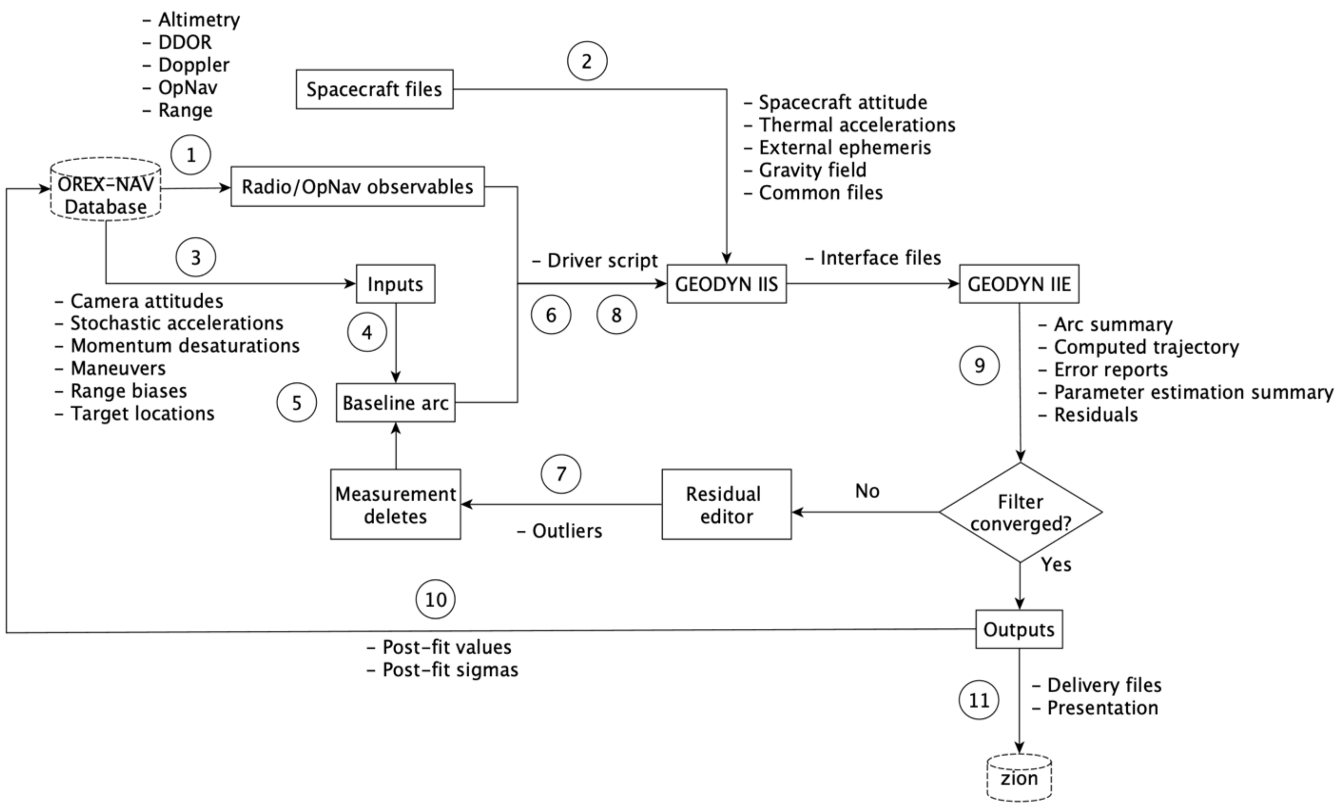

Fig. 15. GEODYN II OD process on OREX-NAV.

Conclusions/Lessons Learned

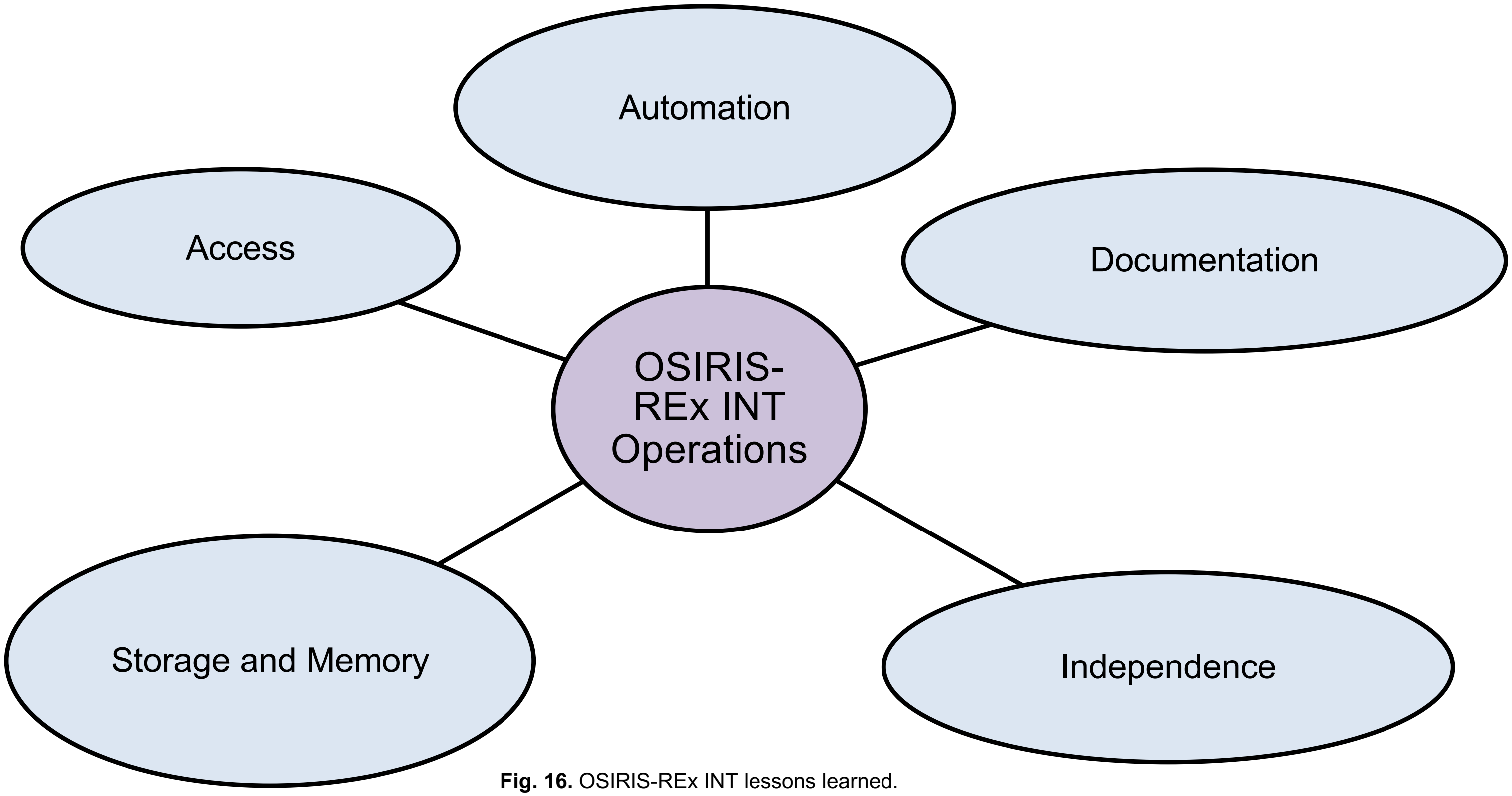

Fig. 16. OSIRIS-REx INT lessons learned.

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