OSIRIS-REx Science Data Management Plan (SP-OP-03)

OSIRIS-REx DOCUMENT

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RELEASED

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CM FORWARD

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DOCUMENT CHANGE LOG

Version	Description of Change/Remarks	Engineering Change #	DATE (MM/DD/YYYY)
0.1	Initial Draft	N/A	
1.3	Phase B first revisions. Changes to all sections to account for architecture and design changes from the CSR		6/30/2012
1.4	Phase B second revisions. Changes to all sections to account for revisions and refinements to the data processing architecture.		8/15/2012
1.5	Phase B third revisions. Updated all figures to use CORE generated diagrams. Updated all sections for Science Executive Council revisions		11/15/2012
1.6	Phase B revisions to Ground and SPOC Architecture Figures, and OLA and Altimetry Figures		01/06/2013
1.7	Phase B revisions to Section 3 OSIRIS-REx Archive to account for the change from PDS3 to PDS4 Added Regolith Development sub-section to Science Data Analysis Updated Appendix B – Data Products Review Schedule to reflect schedule negotiated between the project and the SBN. Replace '1999 RQ36' with 'Bennu'		5/31/2013
1.7.1	Incorporation of PDS comments to version 1.7		6/31/2013
1.7.2	CDR Refinements		11/30/2013
1.7.3	Updated Data Flow Diagrams and data flow descriptions		1/28/2014
2.0	MOR Updates, Data Flow Diagram updates		4/10/2015

3.0	ORR updates to all sections Update Document Template Update SPOC Architecture Update SPOC Instrument Data Processing Update SPOC Science Data Processing Architecture Update PDS Delivery Schedule to reflect ORR mission timeline Added Special Products Table 19	ECR-0017	4/15/2016
4.0	1. update signature page to include Allan Bacskay, Manager Planetary Mission Program Office. 2. Section 4.2.2 added "TAGCCMS are all spacecraft engineering components, calibrated data products are not necessary for their primary mission function, as such calibrated data products will not be produced." to TAGCAMS paragraph 3.Section 4.4.4 added " Table 19 - Remote Observations details the products to be cataloged or archived" . 4. Edited out a spurious line on page 76. 5. Added Preliminary coordinate system document delivery to Table 20. 6.Section 5.4.1 added the sentence "The OSIRIS-REx local data dictionaries will be delivered with the first official data delivery." 7. Fix numbering of a second Table 22 (last table in document) to be Table 23, and added PDS4 processing levels to table		5/26/2016

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ABBREVIATIONS AND ACRONYMS

Table 1-1: Abbreviations and Acronyms

Phrase/Acronym	Description
ADU	Analog to Digital Unit
ALTWG	Altimetry Working Group
APID	Application Process Identifier Definition
APL	Applied Physics Laboratory
APWG	Astrometry & Photometry Working Group
ASU	Arizona State University
CCD	Charge Coupled Device
CCSDS	Consultative Committee for Space Data Systems
CK	Camera-Matrix (Orientation of Vehicle) Kernel
Co-I	Co-Investigator
COF	Center of Figure
COM	Center of Mass
CSA	Canadian Space Agency
CSR	Concept Study Report
DEWG	Dynamical Evolution Working Group
DMP	Data Management Plan
DN	Digital Number
DPWG	Data Products Working Group
DRA	Design Reference Asteroid
DRM	Design Reference Mission
DSK	Digital Shape Kernel
DSN	Deep Space Network
EDR	Experiment Data Record
EK	Event Kernel
eV	Electron Volt

Phrase/Acronym	Description
FDS	Flight Dynamics
FEDS	Front End Data System
FEI	Front End Interface
FK	Frame Kernel
FSW	Flight Software
GDS	Ground Data System
GSFC	Goddard Space Flight Center
HLP	Higher-Level Product
IFL	Interactive File Load
IK	Instrument Kernel
IPWG	Image Processing Working Group
JPL	Jet Propulsion Laboratory
LIDAR	Light Detection and Ranging
LM	Lockheed Martin
LSK	Leap Second Kernel
MDA	McDonald Dettwiler and Associates Ltd.
MSA	Mission Support Area
NAIF	Navigation and Ancillary Information Facility
NASA	National Aeronautics and Space Administration
OCAMS	OSIRIS-REx Camera Suite
OLA	OSIRIS-REx Laser Altimeter
OpNav	Optical Navigation
OSIRIS REx	Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer
OTES	OSIRIS-REx Thermal Emission Spectrometer
OVIRS	OSIRIS-REx Visible and Infrared Spectrometer
PCK	Target Body Size, Shape and Orientation Kernel

Phrase/Acronym	Description
PDS	Planetary Data System
PDS/SBN	Planetary Data System Small Bodies Node
PI	Principal Investigator
RDR	Reduced Data Record
REXIS	Regolith X-Ray Imaging Spectrometer
RDWG	Regolith Development Working Group
ROE	Region of Exclusion
RSWG	Radio Science Working Group
S/C	Spacecraft
SAWG	Spectral Analysis Working Group
SBMT	Small Bodies Mapping Tool
SBN	Small Bodies Node
SCLK	Spacecraft Clock Kernel
SDA	Science Data Analysis
SDP	Science Data Processing
sftp	Secure File Transfer Protocol
SPC	Stereophotoclinometry
SPICE	Spacecraft, Planet, Instrument, C-Matrix, Event
SPK	Vehicle or Target Trajectory Kernel
SPOC	Science Processing and Operations Center
SRP	Solar Radiation Pressure
SXM	Solar X-ray Monitor
TAG	Touch-and-Go
TAGSAM	Touch-and-Go Sample Acquisition Mechanism
TAWG	Thermal Analysis Working Group
TCM	Trajectory Correction Maneuver
TDP	Telemetry Data Processor

Phrase/Acronym	Description
TES	Thermal Emission Spectrometer
UA	University of Arizona
USSTRATCOM	United States Strategic Command
UTTR	Utah Test and Training Range
VML	Virtual Machine Language

1 SCOPE

The OSIRIS-REx Data Management Plan encompasses all scientific data acquired by ground-based observations of Bennu not currently residing in a NASA approved data repository made by OSIRIS-REx science team members; by the instrument suite aboard the OSIRIS-REx spacecraft and the derived data products produced by the ground data processing system. Information concerning the OSIRIS-REx data rights and release policy is contained in the OSIRIS-REx Rules of the Road. Information pertaining to the recovery, storage and disbursement of the physical samples collected by OSIRIS-REx is contained in the Sample Curation Plan (OREx-DOCS-04.00-00096_Rev_1).

Specifically this plan addresses the:

- Generation of high-level mission, spacecraft and instrument documentation, instrument calibration reports, and documentation of algorithms and/or software used to produce derived data products;
- Generation and validation of OSIRIS-REx un-calibrated and calibrated data products as standard products, with associated documentation that determines when and where the data were acquired and for what purpose;
- Generation and validation of OSIRIS-REx derived data products, with associated documentation that determines the purpose of each data product;
- Validation and transfer of ground-based observational data of Bennu acquired by OSIRIS-REx science team members;
- Generation and validation of SPICE archives for use with software from the Jet Propulsion Laboratory's Navigation and Ancillary Information Facility (NAIF) and instrument team or facility team supplied algorithms and software;
- Generation and validation of logical and physical archive bundles containing un-calibrated through derived data products, documentation, and ancillary information;
- Delivery to the PDS of validated OSIRIS-REx archives;

1.1 Purpose

The OSIRIS-REx Data Management Plan describes the mission level plan for generation, validation and transfer of OSIRIS-REx archival data, documentation, algorithms, and software to the NASA Planetary Data System (PDS) Small Bodies Node (SBN) archives. This document will be used as a "living document", and will change and grow as the development and implementation phases of the mission progress.

1.2 Applicability

This plan begins with an overview of the OSIRIS-REx mission. The next portion of the plan includes a ground data system summary and an outline of the science data processing.

These sections are followed by a description of the archive bundles and collections. The archive description identifies the archive content, data volume, design, documentation, and data set collections. The final section of the document describes the archive generation, validation and transfer plans. This section also codifies the roles and responsibilities of all parties involved in the generation, validation and transfer of the archive.

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2 APPLICABLE DOCUMENTS

The following documents, of the exact revision and/or date shown, form a part of this specification to the extent specified herein. In the event of conflict between the documents referenced herein and the contents of this specification, the contents of this specification shall be considered a superseding requirement.

Table 2-1: Applicable Documents

Ref.	Document Number (include Revision and Date)	Title
AD-1	NNH09ZDA0070, April 20, 2009.	New Frontiers 2009 Announcement of Opportunity
AD-2	NWFR-PLAN-001, March 3, 2006	New Frontiers Program Plan
AD-3	NA	Data Management and Computation, Volume 1, Issues and Recommendations, 1982, National Academy Press, 167 p.
AD-4	NA	Issues and Recommendations Associated with Distributed Computation and Data Management Systems for the Space Sciences, 1986, National Academy Press, 111 p.
AD-5	Version 1.4.1, February 23, 2016	Planetary Data System Data Providers' Handbook Archiving Guide the PDS4 Data Standards
AD-6	Version 1.4.0, JPL D-7669, Part 2, September 22, 2015	Planetary Data System Data Standards Reference
AD-7	Version 3, August 5, 2013	OSIRIS-REx Asteroid Sample Return Mission Rules of the Road, Phase C-D
AD-8	NFP3-11-0010,	OSIRIS-REx Mission Operations Concept
AD-9	UA-PLN-9.4.1-007, Version 2.0, 2.4.2016	OSIRIS-REx Ground Systems Configuration Control Plan
AD-10	UA-ICD-9.4.4-101, Version 1.0, October 31,	SPOC–PDS ICD

	2013	
AD-11	(NFP-PN-12-OPS-6A) April 20, 2015	MSA-SPOC ICD
AD-12	UA-ICD-9.0.0-100, March 14, 2016	FDS-SPOC ICD
AD-13	UA-PLN-9.4.4-1005, Version 0.1, April 2016	Planetary Data System Archive Pipeline Configuration Management Plan

This plan is also meant to be consistent with:

1. The contracts negotiated between the OSIRIS-REx Project, Principal Investigator and Team Leaders in which Level 1 and Level 2 software, algorithms, and documentation (including calibration) are explicitly defined as deliverable products.
2. Agreements between the Project and PDS for delivery of data to the community served by the PDS.

3 OSIRIS-REx MISSION

3.1 Mission Overview

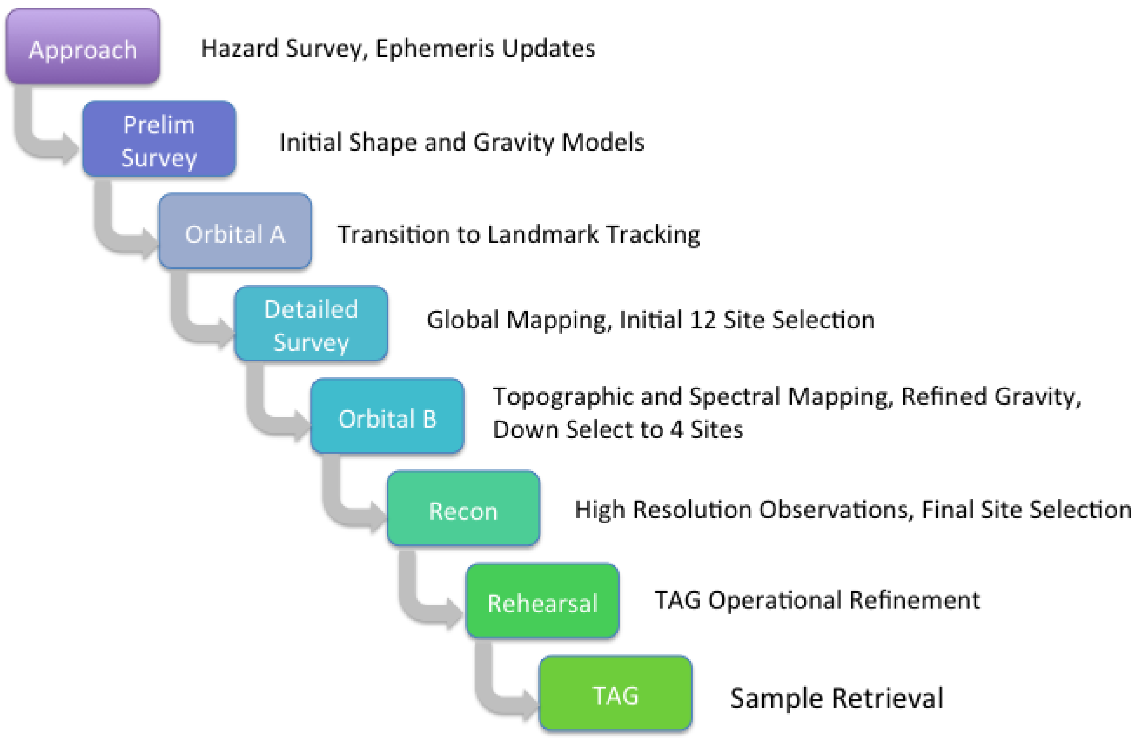
The primary objective of the Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) mission is to return pristine samples of carbonaceous material from the surface of a primitive asteroid. The target asteroid, near-Earth object Bennu, is the most exciting, accessible, volatile- and organic-rich remnant from the early Solar System. OSIRIS-REx returns a minimum of 60g of bulk regolith and a separate 26 cm^2 of fine- grained surface material from this body. Analyses of these samples provide unprecedented knowledge about pre-solar history through the initial stages of planet formation to the origin of life.

The five primary science goals of the OSIRIS-REx mission are:

1. Return and analyze a sample of pristine carbonaceous asteroid regolith in an amount sufficient to study the nature, history, and distribution of its constituent minerals and organic material.
2. Map the global properties, chemistry, and mineralogy of a primitive carbonaceous asteroid to characterize its geologic and dynamic history and provide context for the returned samples.
3. Document the texture, morphology, geochemistry, and spectral properties of the regolith at the sampling site in situ at scales down to the sub-centimeter.
4. Measure the Yarkovsky effect on a potentially hazardous asteroid and constrain the asteroid properties that contribute to this effect.
5. Characterize the integrated global properties of a primitive carbonaceous asteroid to allow for direct comparison with ground-based telescopic data of the entire asteroid population.

To meet the primary objective and science goals the OSIRIS-REx mission operates in a centralized fashion. Instruments that were chosen to meet the primary mission objectives are built by teams supervised by an Instrument Scientist. Once built, instruments are delivered to the project and instrument teams are integrated into either the Science Team or the Ground Team. The project, through the Design Reference Mission (Figure 1) controls all instrument-observation planning and command sequence generation. Observations are planned and executed primarily to inform sample-site selection and to meet the other scientific objectives of the mission. Data obtained from the instruments are centrally processed, and small subsets of the science team are responsible for individual higher-level data products. Data processing is prioritized such that data products necessary to proceed through the Sample Site Selection are processed first, whereas other science data collected during asteroid encounter are processed secondarily. Centralized data processing also allows for a single interface with the Planetary Data System.

Figure 1. OSIRIS-REx Design Reference Mission Phases



Operationally, the OSIRIS-REx mission begins with launch in September 2016, and a two-year cruise to Bennu that includes an Earth Flyby/Gravity Assist in September of 2017. OSIRIS-REx first detects Bennu 60 days in advance of rendezvous, using its slow approach to characterize the integrated properties of Bennu and survey its environment for natural satellites. OSIRIS-REx then spends the next 7 months characterizing the surface and orbital environment of Bennu, culminating with insertion into a 1km-radius "safe home" orbit from which all reconnaissance and sampling sorties are initiated. Four candidate sample sites are characterized with OSIRIS-REx's instrument suite, and each step in the Touch-And-Go (TAG) maneuver sequence is performed prior to attempting sample collection. In October 2019, OSIRIS-REx executes the TAG and collects both bulk and surface samples. After the first TAG attempt, the spacecraft is placed in "quiescent ops", or executes additional sampling attempts if needed. No earlier than March of 2021 OSIRIS-REx departs Bennu. After a 2.5-year ballistic return cruise, the Sample Return Capsule is released, re-entering Earth's atmosphere and landing at the Utah Test & Training Range in September, 2023. For a complete description of the OSIRIS-REx mission including a discussion of how the asteroid Bennu was chosen as the mission target see Lauretta, 2015.

3.2 Instrumentation

The OSIRIS-REx instrumentation was selected after thorough consideration of all mission science objectives. The OSIRIS-REx instruments meet all measurement requirements derived from the science objectives. This set of four primary science instruments, one student experiment and three spacecraft instruments operate in concert with ground-based modeling efforts to refine the knowledge of Bennu at each phase of the mission, culminating in the detailed documentation of the sample site. All instruments have direct heritage to flown planetary missions. All measurement requirements are well within existing capabilities, with no new technology needed. The sample-acquisition mechanism has been designed and tested to ensure collection of at least 60g of regolith sample. The bulk sample mass acquired is verified by measurement of the change in spacecraft moment of inertia after sampling. The total surface-sample area acquired is confirmed by direct imaging.

The OSIRIS-REx instruments are:

OSIRIS-REx Camera Suite (OCAMS) provides long-range acquisition of Bennu and imaging of its surface down to sub-cm, along with global mapping, sample-site characterization, and sample acquisition documentation.

OSIRIS-REx Laser Altimeter (OLA) provides ranging data in support of radio science; global topographic mapping; and local topographic maps of candidate sample sites.

OSIRIS-REx Visible and IR Spectrometer (OVIRS) provides mineral and organic spectral maps, albedo information and local spectral information of candidate sample sites from 0.4 - 4.3 µm.

OSIRIS-REx Thermal Emission Spectrometer (OTES) provides mineral and thermal emission spectral maps and local spectral information of candidate sample sites from 5.5 - 50 µm.

Regolith X-ray Imaging Spectrometer (REXIS) is a student experiment directed by a team from Harvard and MIT and provides an X-ray map of Bennu, complementing core OSIRIS-REx mission science.

Touch-and-Go Camera Suite (TAGCAMS) provides one camera that produces wide field-of-view images for optical navigation **(NAVCAM),** one camera that provides wide field of view images for natural feature tracking (**NFTCAM**) and one camera for images of sample stowage (**STOWCAM**)

Touch-and-Go Sample Acquisition Mechanism (TAGSAM) provides sample acquisition, verification, and safe storage of the pristine sample in the SRC.

Guidance Navigation and Control LIDAR (GNC LIDAR) provides range information during the TAG operation.

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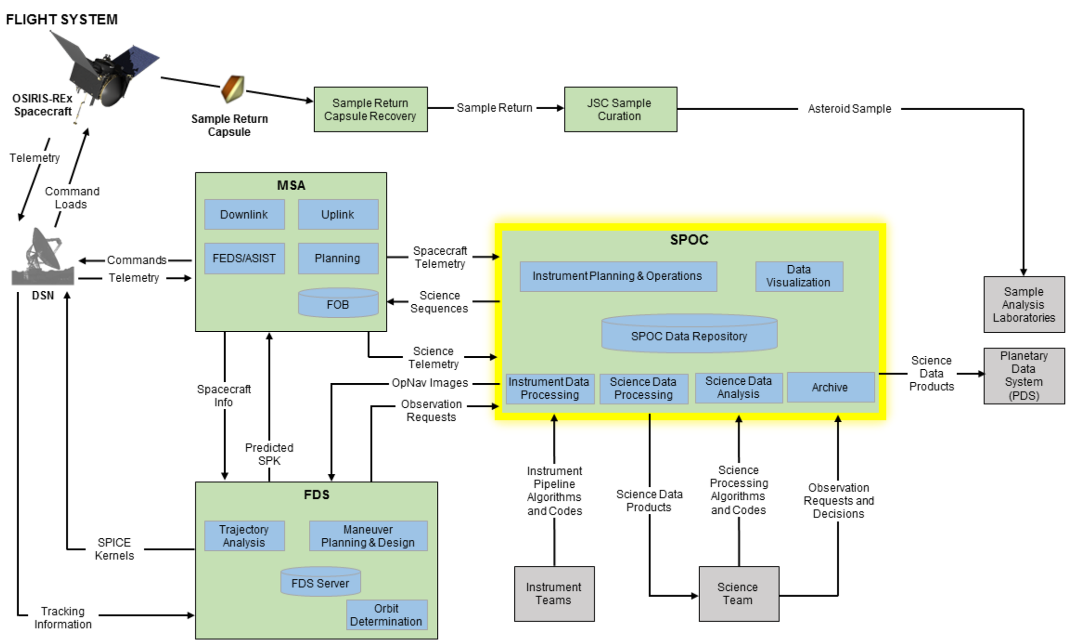
3.3 Ground Data System

The ground data system is comprised of three elements: the Mission Support Area (MSA), the Flight Dynamics System (FDS), and the Science Processing and Operations Center (SPOC). The OSIRIS-REx Ground Architecture Diagram (Figure 2) is a graphical illustration of the relationship between and among these parts. The OSIRIS-REx spacecraft is commanded by and returned telemetry is processed at the MSA. The data are parsed, and passed to other ground elements via the Front-End Data System (FEDS). FDS uses spacecraft and instrument data to produce mission design and navigation products. Science data are processed from instrument telemetry to high-level derived data sets at the SPOC. Overviews of each of the ground system elements are given in the following sections.

Figure 2. OSIRIS-REx Ground Data System Architecture



3.3.1 Mission Support Area

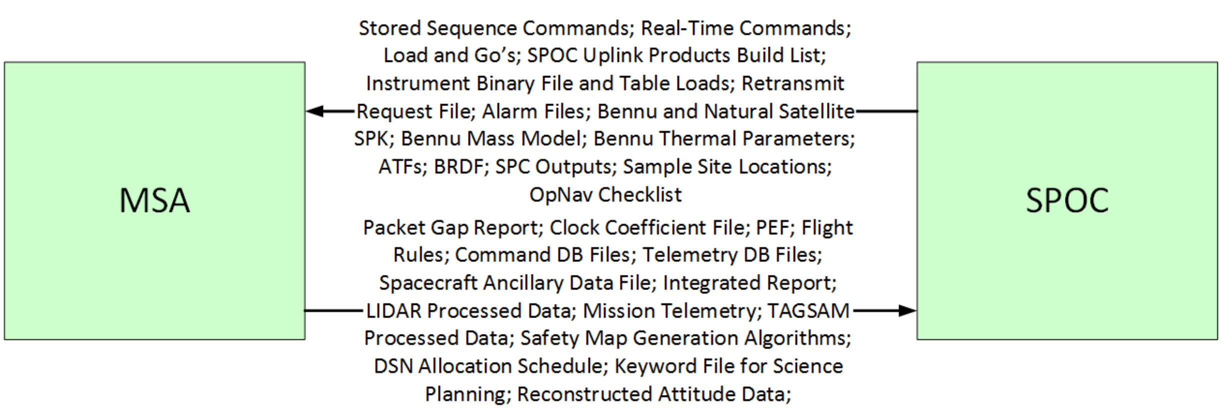
OSIRIS-REx mission operations are conducted at the Lockheed Martin Mission Support Area (MSA), in Littleton, Colorado. The MSA is the system of software, hardware and people that enables engineers to command the OSIRIS-REx spacecraft and analyze its telemetry.

The MSA radiates commands and command sequences through the Deep Space Network (DSN) to the spacecraft. The SPOC passes instrument planning and command sequences to the MSA for incorporation into the spacecraft command and sequence development process. Command and sequence generation development is performed on MSA development workstations, reviewed and tested in the Spacecraft Simulation Laboratory, placed on the project flight operations file system, and passed thru the Front End Data System (FEDS) for uplink at the DSN. The OSIRIS-REx command and sequence generation process has over twenty years of operational heritage.

All spacecraft data, engineering telemetry, and science data complies with the CCSDS (Consultative Committee for Space Data Systems) format for data packets. Spacecraft data are first received on the ground at the DSN and is then transmitted to Building 230 at the Jet Propulsion Laboratory (JPL). Building 230 performs two functions: the first is to forward the data to the MSA, and the second is to retain a short-term backup copy.

Upon receipt at the MSA, data are processed by the FEDS, identified as either engineering or science data based on its Application Process Identifier Definition (APID) number. Each producer of data packets on the spacecraft has one or more APIDs to identify the type of data it is creating. All engineering and science data are assigned an appropriate APID relative to their data type. The FEDS reads the data packets, determines the APID number, and distributes the packet to the appropriate end user (i.e., MSA, FDS, SPOC). Additionally all data are stored onto a project server at the MSA where it is available to the various mission teams for the duration of the Project. Data packets containing engineering telemetry are further processed into channelized data that are displayed for real-time monitoring. Additionally, the MSA performs telemetry trending and analysis that is used for future spacecraft performance predictions. All science data and instrument engineering data are distributed to the SPOC for further processing. A complete description of the roles and responsibilities of the MSA, as well as a detailed explanation of the mission operations concept, can be found in the OSIRIS-REx Mission Operations Concept Document (NFP3-PN-11-OPS-8). The interfaces between the MSA and the SPOC are identified in Figure 3 and are fully described in the MSA-SPOC ICD (NFP-PN-12-OPS-6A).

Figure 3. SPOC - MSA Interface



3.3.2 Flight Dynamics System

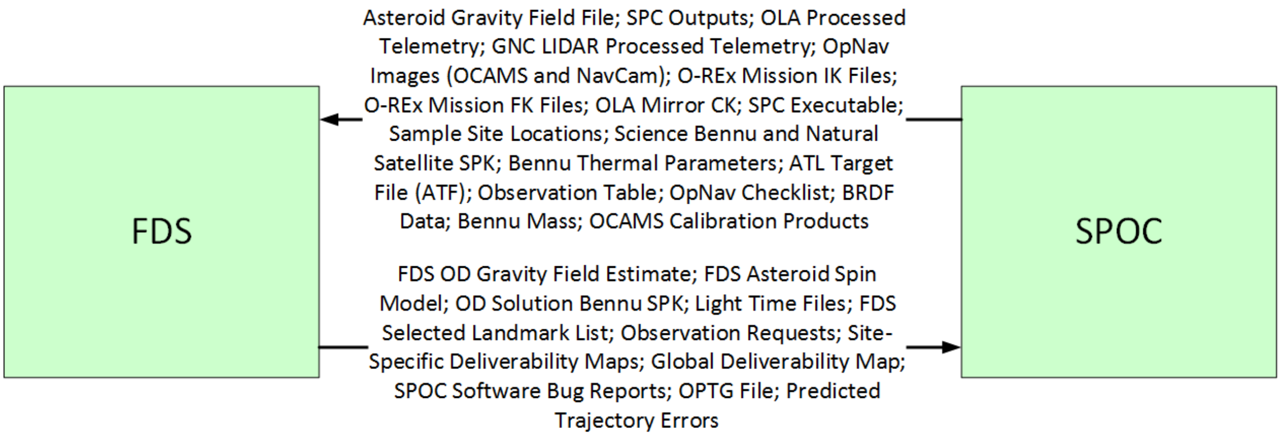
The OSIRIS-REx Flight Dynamics System (FDS) consists of mission design and navigation elements, encompassing trajectory analysis, mission design and orbit determination (OD) functional areas. Mission design is concerned with the spacecraft–launch vehicle interface, trajectory design and optimization, preliminary maneuver planning, maneuver design, and mission event planning. Navigation uses DSN tracking, LIDAR, optical and other data for orbit determination, Bennu spin, shape and gravity modeling, real-time maneuver monitoring, maneuver design and reconstruction, and high-fidelity trajectory propagation.

FDS receives DSN tracking and calibration data directly from the DSN. FDS provides trajectory predictions directly back to the DSN. FDS also provides information to other OSIRIS-REx mission elements (MSA, SPOC) via the Flight Operations Bucket (FOB), sftp, static data reports, standard file formats, and through web-based information.

FDS receives a variety of information from the MSA, including spacecraft properties, such as initial mass, cross-sectional areas affected by solar radiation pressure (SRP), RF antenna locations and science or engineering LIDAR properties. Other data provided by the MSA include small forces files, spacecraft attitude history and predictions, and associated clock kernels defining expected on-board clock drift. There are also files which describe the effects of propulsive maneuvers, including launch injection co-variances, maneuver execution errors, maneuver implementation and configuration files containing implementation details for a particular maneuver, and maneuver performance data files specifying changes to mass, center of mass, moments of inertia and thruster locations and directions. FDS uses these files to perform or verify a maneuver design and support trajectory analysis and orbit determination for trajectory prediction. FDS also passes maneuver profile files, maneuver reconstruction reports, ranging profiles during asteroid proximity operations, light times, orbit propagation timing and geometry, and predicted spacecraft, asteroid and any nearby natural satellite ephemerides back to the MSA for incorporation into sequence planning and generation. Light times and ephemerides are also provided to the SPOC to support science planning and reconstruction. Spacecraft ephemerides and accompanying Earth entry states and data are also provided to the MSA, Utah Test and Training Range (UTTR) and US Strategic Command (USSTRATCOM) near the end of mission to support Earth return and sample recovery operations.

FDS makes optical navigation (OpNav) image requests to the SPOC, which are then incorporated into instrument planning and command files passed to the MSA and sent to the DSN for subsequent radiation to the spacecraft. FDS receives OpNav images from the SPOC via the FOB and processes these images using image-processing software that is configuration controlled by the SPOC. The critical OpNav images are reconstructed by the SPOC as soon as they are received from the instrument telemetry stream, and processed to add geometric information. LIDAR data are also received from the FOB in the case of the GNC lidar or the SPOC in the case of OLA and can be used in association with OpNav images and DSN tracking data for orbit determination during asteroid proximity operations. Models of Bennu spin, shape, gravity and landmarks are updated via interaction and iteration with the SPOC over the entire period of asteroid proximity operations, from approach through TAG and departure. Asteroid models can also be made available to the MSA as needed to support possible on-board autonomy for asteroid TAG operations. The FDS-SPOC interface is illustrated in Figure 4.

Figure 4. SPOC- FDS Interface



3.3.3 Science Processing and Operations Center

The Science Processing and Operations Center (Figure 5) at the University of Arizona has primary responsibility for science data processing and analysis, archive, and science planning and operations for the OSIRIS-REx asteroid sample return mission. An overview of the SPOC is presented below.

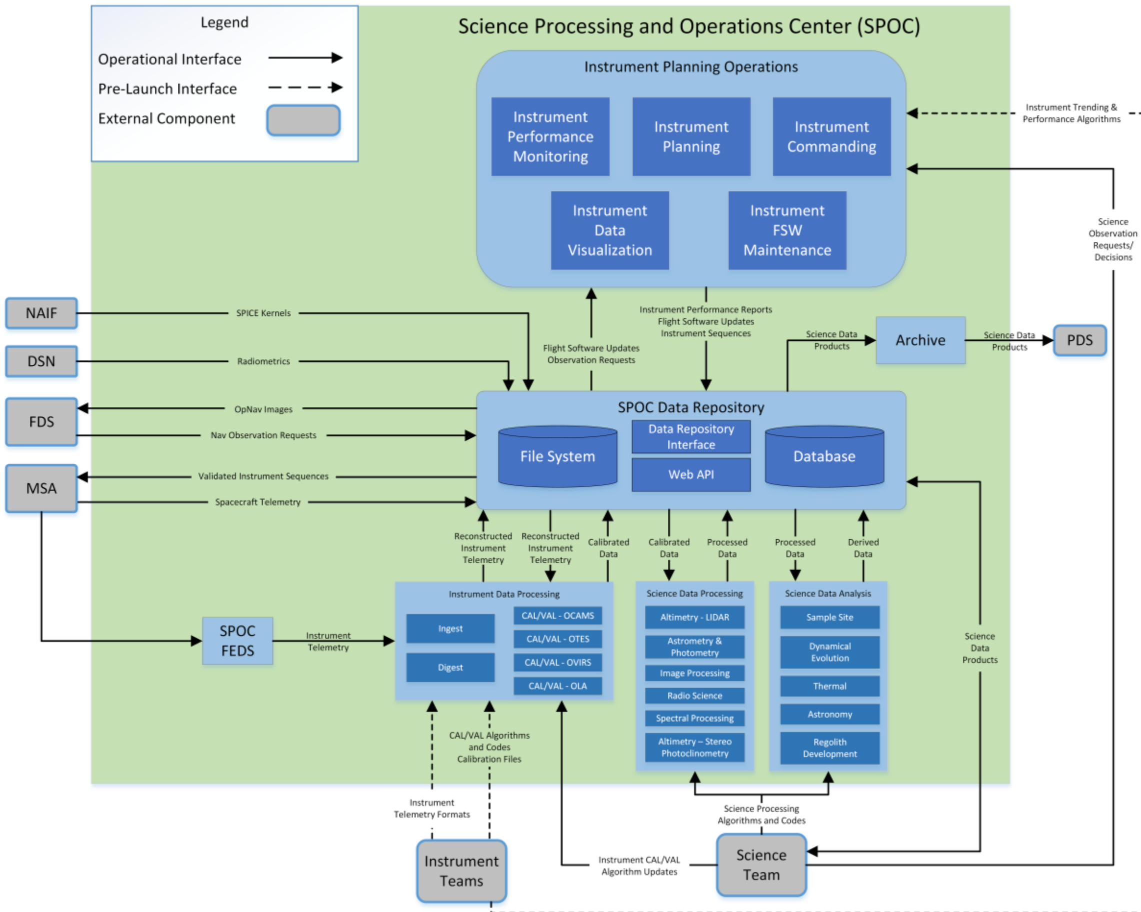
The SPOC receives spacecraft telemetry, science instrument data, and NAIF SPICE information from the MSA, and observation requests, FDS derived asteroid properties, and deliverability maps from FDS. Data received by the SPOC are sorted, validated and packaged for insertion into the SPOC data repository for storage and/or further processing. The data repository consists of a relational database, a file system and a collection of algorithms that ingest science, spacecraft and ancillary data into the repository. Once data are available in the SPOC database further processing is initiated.

There are three major sub-systems in the science data processing and analysis portion of the SPOC; data repository, calibration/validation (cal/val) pipeline, and science data processing. The cal/val pipeline sub-system of the SPOC is a fully automated package of algorithms that produce un-calibrated and calibrated instrument-specific data products for delivery to the OSIRIS-REx science and operations teams via the SPOC data repository and the PDS through mutually acceptable transfer mechanisms. The Instrument Teams develop the instrument specific pipeline algorithms. The SPOC implements, validates, and packages the cal/val algorithms that produce standard products. Individual cal/val data product algorithms and the cal/val package are configuration-controlled and comply with all PDS standards and formats. The science data processing element of the SPOC is a partially automated collection of algorithms that use calibrated instrument data and ancillary information to produce higher-level data products such as a map of a single spectral band depth, or topographic maps. Science data processing is partially automated in that many of the algorithms require expert user interactions in order to create valid scientific results. Science data processing algorithms are developed by the appropriate Science Team Working Group, and are hosted at the SPOC. Science data analysis is a sub-set of science data processing and is a collection of algorithms and procedures that allow for the combination of both low-level and high-level data products as well as ancillary information to produce data products used for analysis in the sample-site selection and scientific publication processes. All science data analysis algorithms require expert user interactions in order to create scientifically valid results. Science Team Working Groups are responsible for the development of the algorithms, which are then delivered to and hosted at the SPOC.

The SPOC is the centralized location for all OSIRIS-REx science data processing. The decision to centralize science data processing was made to facilitate the sample site selection process. Consequently, many science team members will be co-located at the SPOC during the asteroid encounter to support the site selection process. The components of the data processing sub-systems of the SPOC are aligned with instrument and science team working groups to ensure that software developed by those teams and implemented at the SPOC has been validated and has the appropriate oversight for data product production.

The SPOC also contains the Archive sub-system, which is the data processing environment that packages data sets and documentation for delivery to the PDS. OSIRIS-REx Instrument Scientists, Science Working Group Leads, PDS Lead, and representatives of the PDS Small Bodies Node work together through the OSIRIS-REx Data Products Working Group (DPWG) to manage and oversee the PDS archive process. The OSIRIS-REx PDS Lead oversees the day-to-day PDS development, review process, submission and validation of archive bundles.

Figure 5. Science Processing and Operations Center Architecture



The SPOC also supports the OSIRIS-REx Science Planning and Operations activities in which science instrument command sequences are planned, generated, validated and passed to the MSA. The science planning process for instrument observations begins before asteroid encounter with initial sequence planning based on mission phases, objectives, and timing set out in the OSIRIS-REx Design Reference Mission. Strategic planning and preliminary command sequences are developed in the mission phase prior to use. These sequences are developed, built, fully tested and put on the shelf until needed. On a daily basis, the tactical planning process allows for review of acquired data and for updates and small changes to stored command sequences. The complete discussion of Science Planning and Operations and the instrument commanding process is contained the OSIRIS-REX Mission Operations Concept Document (NFP3-PN-11-OPS-8), as this plan is primarily concerned with the data processing portion of the SPOC.

3.4 Science Processing and Analysis

The SPOC is tasked with all OSIRIS-REx science data processing during the operational phases of the mission. Data processing at the SPOC falls into two major categories, Instrument Data Processing (IDP) and Science Data Processing (SDP). IDP processing is focused on automated processing of instrument telemetry and ancillary information to produce calibrated instrument data that can be used for subsequent scientific processing and analysis. Ingest/Digest ingests and stores telemetry into the SPOC environment, assembles complete instrument observations from telemetry, maps digital numbers to physical units for housekeeping data and calculates observational geometry for spectral and lidar data. Calibration/Validation (Cal/Val) removes instrument artifacts, external noise, and applies radiometric correction to map digital number telemetry values to physically meaningful values. The results of the Cal/Val pipeline are used to produce the OSIRIS-REx standard data products for delivery to the PDS. SDP uses the Cal/Val produced calibrated data products to produce derived data products that can either be used to answer a specific simple scientific question (e.g. what does the surface of Bennu look like?), or can be combined with other derived products for advanced analysis.

SDP data products are used individually or combined with other products in the sample site selection process. The products integrated for scientific analysis (e.g. what is the geologic history of Bennu?) are the most highly processed OSIRIS-REx data products. The mission produces four Sample Site Selection Maps; Sampleability, Safety, Science Value, and Deliverability by integrating several derived data products. Members of Science Team Working Groups produce the first three maps, Sampleability, Safety and Science Value. The fourth map, Deliverability, is produced by FDS. SDP data products are the higher-level and special data products to be delivered to the PDS.

The OSIRIS-REx mission is broken down into a number of mission phases with very specific data collection criteria for providing the optimal data set for sample site selection. The sample site selection process and the mission phase exit criteria define data processing priorities. Data products that directly inform the sample site selection decision have the highest priority through the complete data processing flow. Those data products necessary to close out Level-2 science requirements, but not immediately necessary for sample site selection, are second priority. Those data products necessary for ancillary science investigations have third priority.

3.4.1 Instrument Data Processing

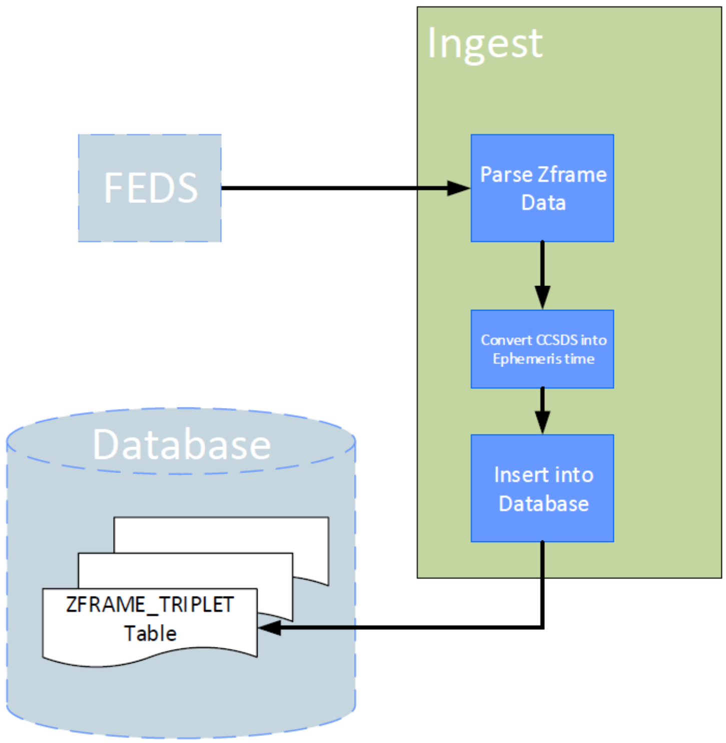
3.4.1.1 Global Specification

The SPOC uses a single, human-readable, parse-able JavaScript Object Notation (JSON) file called the “Global Specification” that describes the format of incoming telemetry packets and SPOC data products. This file both describes and relates the information for each piece of telemetry or data to be ingested or stored in the SPOC data repository. The Global Specification lists all of the fields that are contained within the instrument payload packets and the header placed on the files sent by the spacecraft. The file contains mapping information describing where to store data in the database, conversion function names and arguments, and validation and alarm values. The Global Specification is referenced by both the Ingest and Digest modules, which are described in subsequent sections of this document, as needed in order for the modules to complete the processing of the data. Since the modules reference one definitive specification, there is functional consistency between all modules.

3.4.1.2 Ingest

The SPOC ingest software component (Figure 6) is the process by which spacecraft telemetry and science instrument data (science observations and housekeeping) are fed into the SPOC Data Repository. The SPOC Ingest component connects with the FEDS via a network socket. Once the connection is established spacecraft telemetry packet data can be transferred. Ingest uses a parsing algorithm along with information from the Global Specification to parse the telemetry header and store the data in a holding table. The holding table contains the parsed FEDS annotation data, time data, raw instrument data, and several data processing tracking fields. All data are retained in the holding table for long term project storage, and in the case re-processing is necessary. Further processing of the raw instrument data are done by the Digest component.

Figure 6. Ingest Data Flow

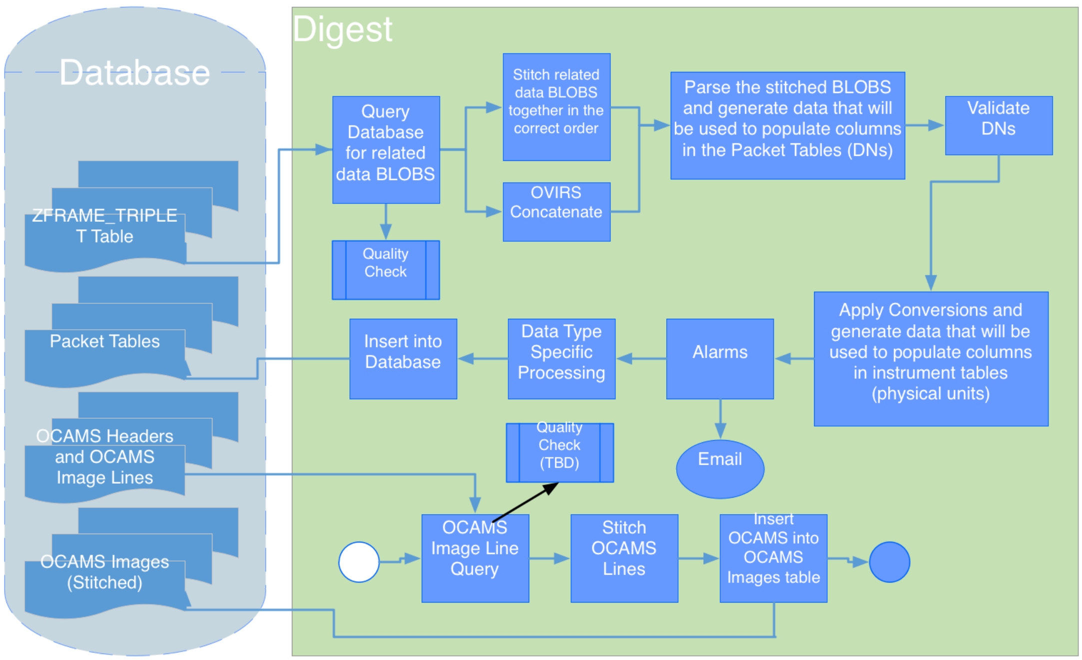


3.4.1.3 Digest

The Digest component (Figure 7) has the following main functions:

1. Composes complete observations from telemetry packets.
2. Processes L0 science data products.
3. Generates L0 and L1 engineering data products of all science instruments.
4. Creates the FDS OpNav deliverables.

Figure 7. Digest Data Flow



To compose the complete science observations from telemetry packets Digest queries the holding table for all rows that contain the same APID and time. Digest then stiches the returned rows together to create a single parse-able unit similar to how the observation data was originally sent from the instrument to the spacecraft computer. The complete observation telemetry product is then parsed according to the payload section of the Global Specification. The payload section includes all information about the payload packet type including bit-fields. All parsed fields are validated against the Global specification and stored in instrument and data type specific tables in the SPOC data repository. These are the L0 science data products.

All instruments produce housekeeping data that are transmitted from the spacecraft in formatted binary telemetry packets. As transmitted from the spacecraft, housekeeping data are in digital numbers (DN). These unconverted products are the raw L0 (level-0) products. To be useful for instrument monitoring DNs, must be converted to physical units (i.e. voltage, temperature, amperes). Once data has been parsed, Digest calls parameter specific functions to convert housekeeping DNs to physical units. Converted housekeeping data products are the L1 (level-1) data products. Converted housekeeping values are compared to instrument alarm limits. Digest can spawn an alarm if a limit is triggered. Converted housekeeping values are stored in the SPOC data repository.

3.4.1.3.1 NAVCAM/OCAMS OpNav Processing

The final major piece of Digest is the assembly of the FDS Optical Navigation (OpNav) data products. L0 NavCam or OCAMS image metadata identified by APID are queried from the SPOC data repository. Based on the time tag of the image, appropriate SPICE kernels are queried from the SPOC data repository to build a meta-kernel covering the time range of the images. Image metadata and SPICE information are combined using SPICE data processing routines to calculate additional timing information, image spatial and geometric information for each image. The values are then stored in the SPOC data repository for each image of interest. Once a complete set of metadata are calculated for an OpNav image, Digest calls a process to write a FITS (Flexible Image Transfer System) file that contains the OpNav image and relevant metadata, and deliver this file to a designated file interchange location.

3.4.1.3.2 REXIS Processing

As a Student Collaboration Experiment (SCE), REXIS will be incorporated into the OSIRIS-REx spacecraft on a non-impact basis and will remain clearly separable from the rest of the OSIRIS-REx investigation. Data analysis will be handled as a student project, available to both Harvard and MIT students, for credit or non-credit within the MIT curriculum, and within the MIT Undergraduate Research Opportunities Program (UROP). As the data analysis is a student project, the SPOC will only process REXIS observations into raw L0 products, which will be delivered to the REXIS team for further processing and analysis.

3.4.1.4 Ancillary Data

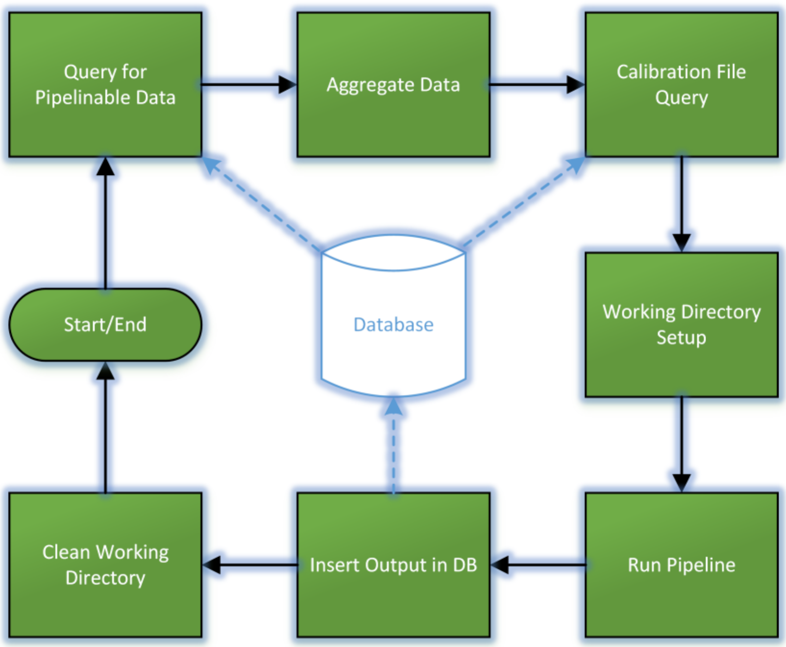
There are several other types of ancillary data required by the SPOC that are stored to the SPOC Data Repository. SPICE Kernels produced by the Navigation and Ancillary Information Facility (NAIF) and radiometric tracking data and ancillary files from the Deep Space Network (DSN) are retrieved from the MSA Flight Operations Bucket (FOB) and are moved directly into the SPOC data repository. Flight System instrument processed data (TAGSAM, GNC LIDAR, NFTCAM, STOWCAM) are also received in this way by the SPOC. FDS OpNav observation requests are sent directly to the SPOC data repository.

3.4.1.5 Calibration/Validation Pipeline

The Calibration/Validation (Cal/Val) pipelines are a collection of automated instrument data processing algorithms that on an instrument-by-instrument basis remove instrument and environmental artifacts from the downlinked data, and convert that data into physically meaningful values. The end result of Cal/Val is the calibrated data products necessary to produce scientifically meaningful derived data products used for sample-site selection.

Once instrument and ancillary data are stored in the data repository, Cal/Val pulls instrument and necessary ancillary data from the repository for processing. As each instrument has specific processing requirements, there are separate processing streams for OCAMS, OTES, OVIRS, and OLA data. REXIS and NavCam data are not processed via a Cal/Val pipeline, as the SPOC is only responsible for the level-0 raw science observations produced by Ingest/Digest. An end-to-end validation and PDS peer review of the Cal/Val pipelines followed by review lien resolution will be completed prior to the start of regular PDS deliveries (See Table 22 for the complete review schedule). Individual Cal/Val data product algorithms and the Cal/Val initialization package are configuration-controlled and comply with all PDS standards and formats. The generalized Cal/Val data flow for all instrument data is illustrated in Figure 8.

Figure 8. Generalized Cal/Val Pipeline Data Flow



In contrast to other missions, there is not a direct link between the PDS and the instrument providers. During development, the SPOC, PDS Lead, Payload Office, Mission Instrument Scientist and Instrument Scientists work closely to coordinate Cal/Val software development, delivery, implementation, and test. After instrument delivery, Instrument Scientists and their teams are pulled into the larger science team. For each instrument several members of the instrument build team will be reassigned to the SPOC. Thus, instrument specific expertise will reside at the SPOC. It is through this structure that the PDS Lead, the software developers at the SPOC, and the Instrument Scientists can ensure the timely and cost-effective response to any liens levied on un-calibrated, calibrated, and derived data products. See Table 22 for a comprehensive data products review schedule.

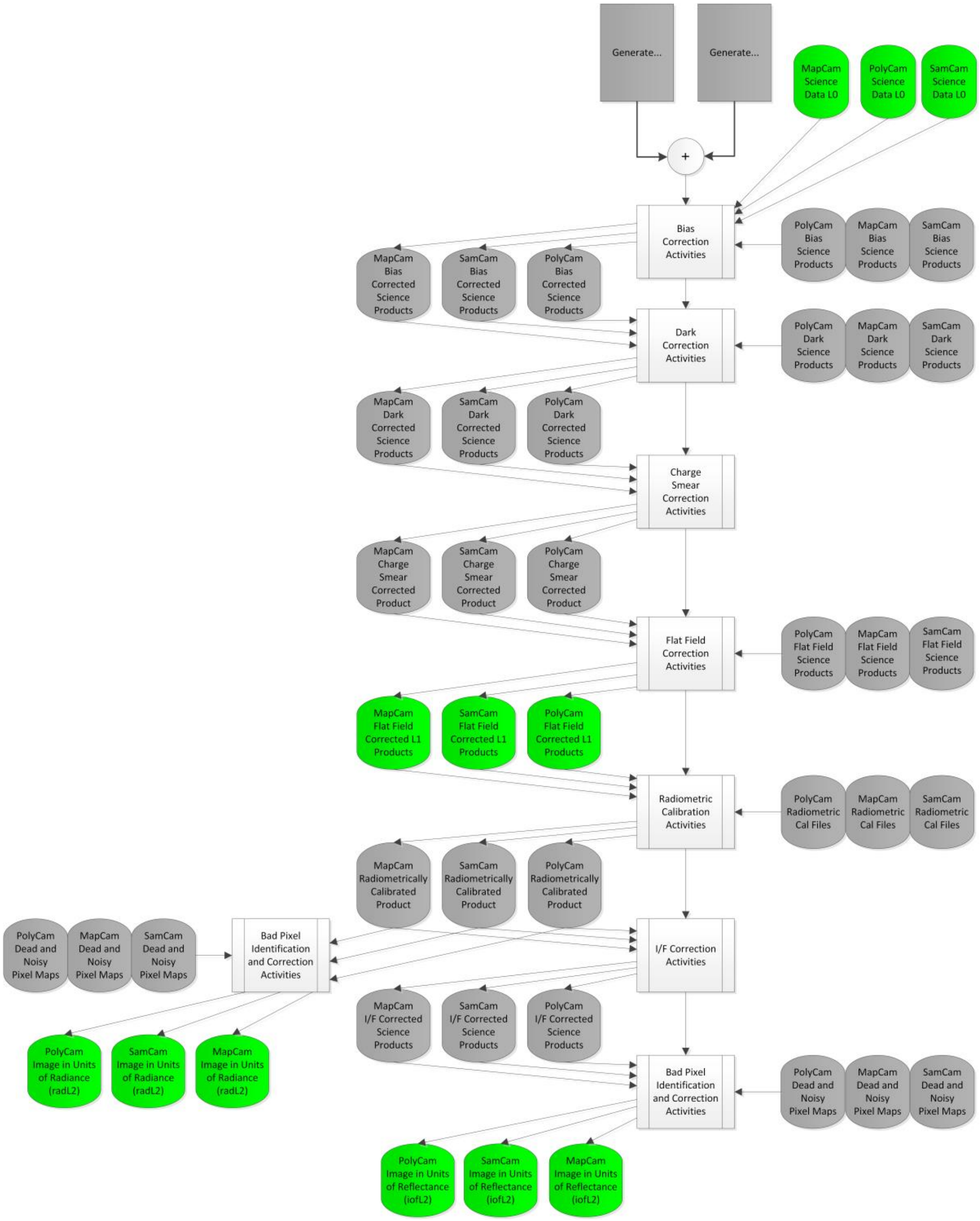
In addition to formal PDS peer-reviews, periodic internal OSIRIS-REx software reviews are held throughout the software development lifecycle that include both science team members and instrument providers. This participation ensures that all software implemented, developed or hosted at the SPOC has been fully vetted by the science and instrument teams. If, after final software delivery, changes are required to any instrument's software based on updated knowledge of the instrument, the SPOC Change Control Board consisting of members of the Cal/Val software team, the archive team, the instrument team and the science team will be convened to discuss the merits of the proposed change. The specific configuration management process for all software at the SPOC is addressed in the SPOC Configuration Management Plan (UA-9.4.3-007). Additionally, it should be noted that all instrument data used by the science team to perform their work on OSIRIS-REx is the same data that is delivered to the PDS, and is therefore vetted not only by the instrument teams, but also by the entire OSIRIS-REx science team. The instrument specific standard OSIRIS-REx data products are listed in Table 17.

3.4.1.5.1 OCAMS Pipeline

The OSIRIS-REx Camera Suite (**OCAMS**) consists of PolyCam an 8" Richey-Chretien telescope capable of detecting up to 12th magnitude objects; MapCam, a four-color mapping camera; and SamCam a wide-angle camera used to document sample context. Together they image asteroid Bennu and provide global mapping, sample site reconnaissance and characterization, high-resolution imaging, and record the sample acquisition with sub-centimeter resolution imaging. All cameras use identical detector arrays but are characterized by focal lengths separated by a factor of 5 [Smith et al. 2013]. The data processing flow is nearly identical for each of the three cameras.

The OCAMS data processing flow Figure 9 takes OCAMS instrument housekeeping and image data from the SPOC Data Repository and bias, dark subtracts, charge smear corrects, and flat-fields the images. These flat field images are stored in the SPOC data repository as the initial un-calibrated OCAMS data product. The un-calibrated images are radiometrically and spectrally calibrated resulting in the OCAMS radiometrically calibrated data product in units of radiance. The radiance product is then corrected for solar flux, resulting in a reflectance data product. The final step of processing is to mask and filter both the radiance and reflectance products to remove the effects of cosmic-rays and dead/noisy pixels. Both products are stored in the SPOC data repository for later delivery to the PDS.

Figure 9. OCAMS Cal/Val Data Processing Flow

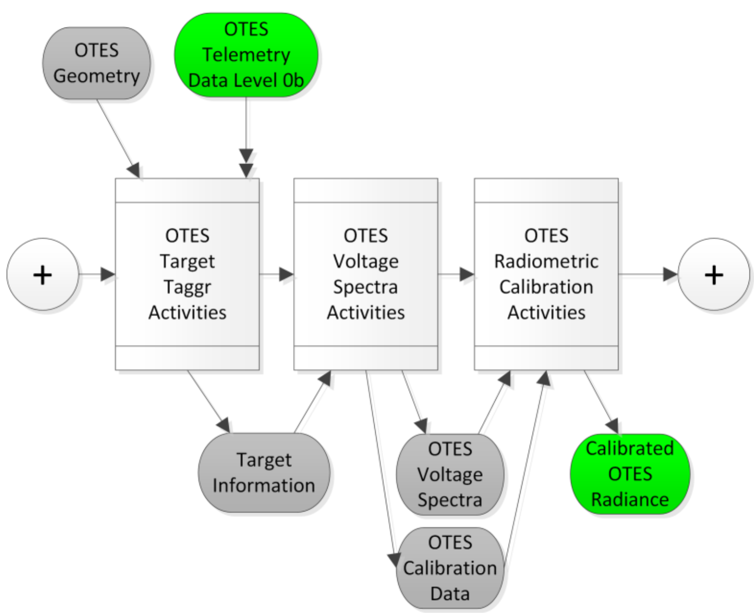


3.4.1.5.2 OTES

The OSIRIS-REX Thermal Emission Spectrometer (**OTES**) is a small, simple, infrared (5.5 - 50 µm) point spectrometer that is a derivative of the Mars Exploration Rover Mini-TES and the Mars Global Surveyor TES instruments. OTES acquires one interferogram every 2 seconds and uses space and internal calibration flag views for calibration. OTES maps Bennu from a distance of 7 to 0.5 km with 55 to 4 m spatial resolution using spacecraft and asteroid motion. Data processing is based on heritage processing algorithms from both TES and Mini-TES.

The OTES pipeline data processing flow Figure 10 takes raw OTES interferograms and processes these to radiometrically calibrated radiance spectra. This flow uses spectra acquired of the internal OTES calibration target and of space to perform a two-point calibration to radiance. The internal calibration target and space observations are time-tagged in the observing sequence, and the appropriate target temperatures are extracted from the OTES internal telemetry data. These calibration observations are used to compute the instrument response function (gain) and the instrument radiance (offset) parameters. These parameters are linearly interpolated between calibration observations and applied to each asteroid spectrum to convert the instrument voltage spectra to the calibrated radiance.

Figure 10. OTES Cal/Val Data Processing Flow



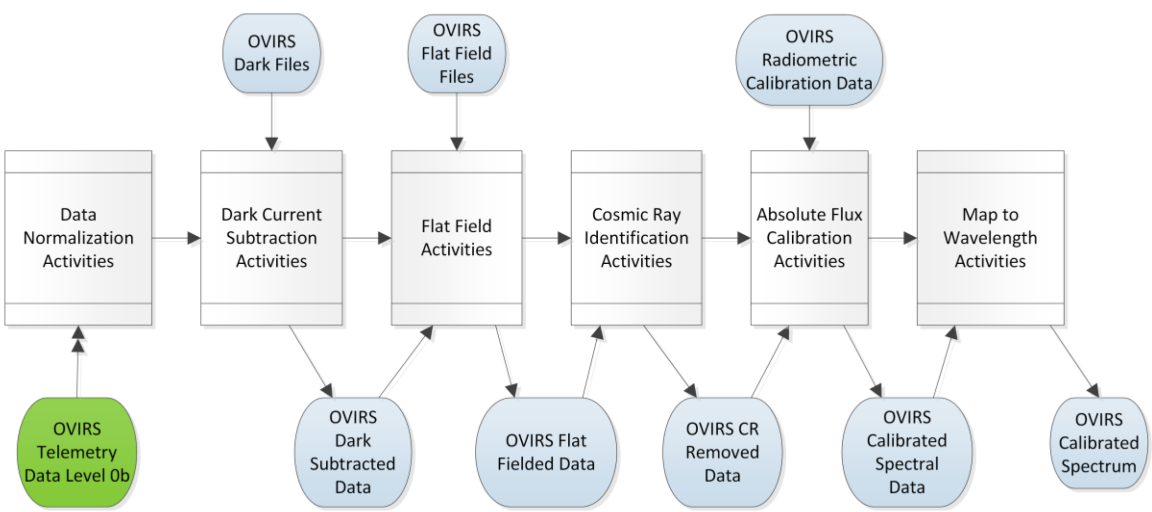
CHECK THE OSIRIS-REX DOCUMENT SERVERS AT https://soedms.as.arizona.edu/ TO VERIFY THAT THIS IS THE CORRECT VERSION PRIOR TO USE.

3.4.1.5.3 OVIRS

The OSIRIS-REx Visible and Infra-Red Spectrometer (**OVIRS**) is a simple, passively cooled, point spectrometer with a wavelength range of 0.4 to 4.3-microns. The optical design draws from New Horizons Ralph (LEISA). OVIRS has a 4-millirad FOV resulting in a 20-meter surface resolution at 5-km altitude with. Data processing is based on heritage processing method developed for New Horizons Ralph (LEISA).

The OVIRS data processing flow Figure 11 takes the raw OVIRS spectral data and converts the digital number spectra to spectra in physical units. The OVIRS raw spectral data are dark current subtracted and flat fielded. The resulting spectra are examined for cosmic-ray hits. Any data with cosmic-ray influence is flagged and removed from further processing. An absolute flux calibration is applied to the dark, flat, cosmic-ray corrected data resulting in a set of calibrated spectral data. The final step in the processing is the mapping of super-pixels (the summed result of several pixels of the same wavelength) to wavelength, the result of which is a set of radiance spectra (W/cm^2/µm/sr) that correspond to a single OVIRS observation. The number of spectra included for a single observation depends on detector settings that specify regions of interest in the OVIRS detector. Each region of interest is represented by a single spectrum that covers a portion of the wavelength range between 0.4 and 4.3-microns. The pointing of the instrument bore-sight as well as other standard geometric properties of the observation are included with the spectral product. Processing algorithms are based on heritage software developed for processing data from the New Horizons LEISA instrument and will be modified for the spectral range and pixel summing planned for OVIRS.

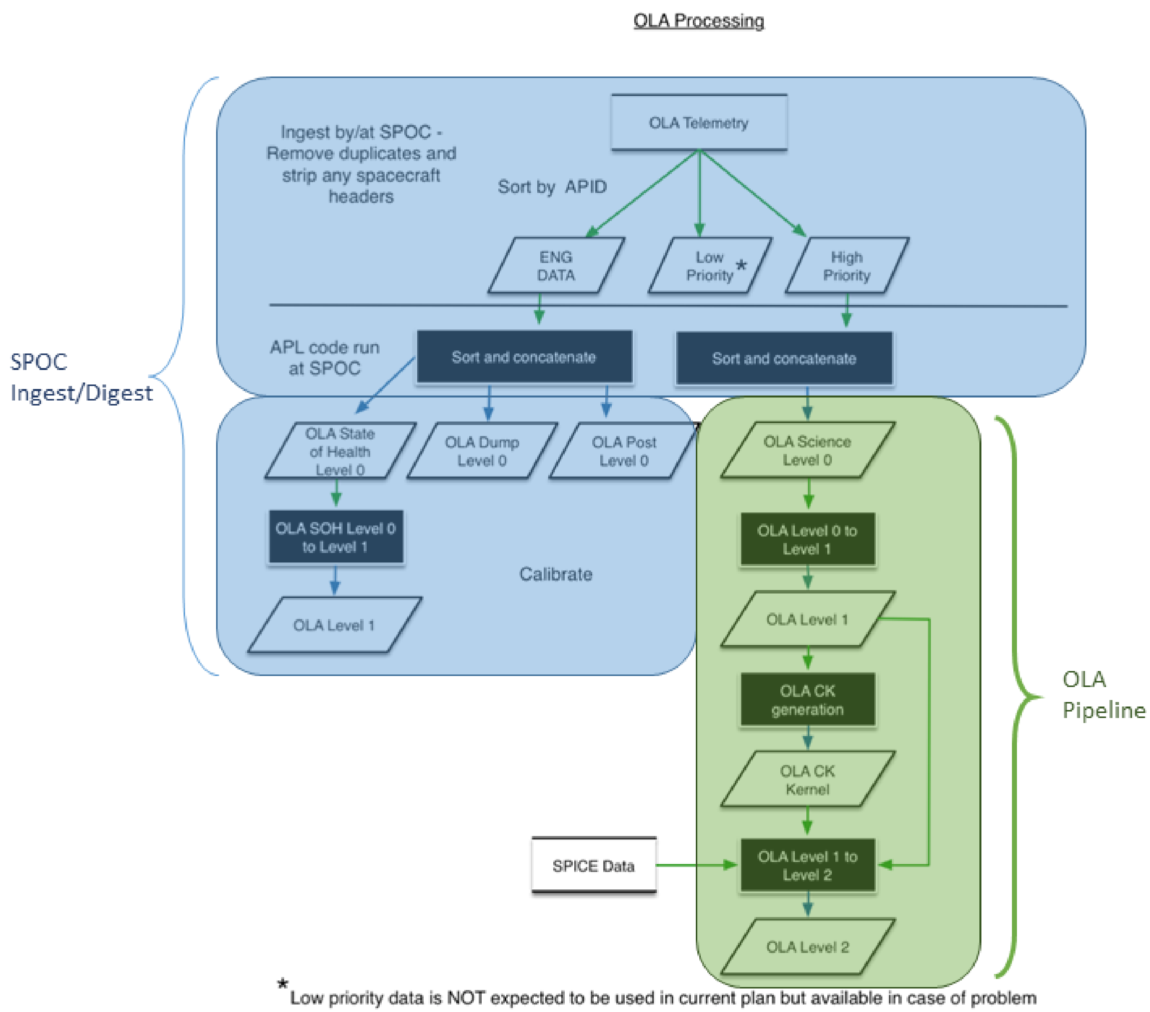
Figure 11. OVIRS Cal/Val Processing Flow



3.4.1.5.4 OLA

The OSIRIS-REx Laser Altimeter (**OLA**) has the primary task of mapping the topography of the surface of Bennu. OLA is a monostatic lidar design with two selectable Nd:YAG laser transmitters that operate at a wavelength of 1064 nm. The system's design is a hybrid of the flight-proven scanning lidar instruments on the XSS-11 and Phoenix Mars Lander missions. OLA's high-energy laser transmitter is used for ranging from 1–7.5 km. The low-energy transmitter is used for rapid ranging and imaging from 1 km to 500 m. The OLA data processing flow (Figure 12) possesses heritage from the NEAR, Hayabusa and MESSENGER missions. The processing flow for OLA is derived from the one used to deliver the LIDAR data of the Hayabusa Mission to the Small Body Node of the Planetary Data System by Co-I Barnouin. Details on the processing are explained in Barnouin-Jha et al. 2008.

Figure 12. OLA Ingest through Cal/Val Pipeline Processing



CHECK THE OSIRIS-REX DOCUMENT SERVERS AT https://soedms.as.arizona.edu/ TO VERIFY THAT THIS IS THE CORRECT VERSION PRIOR TO USE.

OLA single observation data are taken form the SPOC Data Repository and sorted and concatenated to produce a package of OLA observations (OLA L0). This package is saved to the OLA database. The OLA L0 State of Health (SoH) and OLA L0 science data are processed to OLA L1 data products. The OLA L1 science un-calibrated data product contains the most basic OLA measurement data in a binary table format separated by day. OLA L1 data has no corrections applied. Here data are stored in physical units (i.e. ranges in meters and scan angles in degrees or radians as opposed to voltages and digital numbers). One data record is available for each OLA shot fired. The OLA pipeline then calculates two SPICE kernels necessary for the creation of OLA Level 2 calibrated gridded data products. OLA SPK generation pinpoints information from the OSIRIS-REx's spacecraft and Bennu's ephemera and computes the location of each object relative to each other every time one of the OLA lasers fire. This information is captured in a standard SPICE SPK file called the OLA SPK. OLA CK generation calculates a standard SPICE C kernel relative to the OLA mirror position. This is necessary as the standard spacecraft C kernel is calculated at the center of the spacecraft, roughly a meter different than the position of the OLA mirror. The difference in position has an effect on the pointing accuracy of the calibrated OLA data.

OLA L1 science data products are converted to OLA L2 science data products using the OLA specific SPIC information. Ranges and scan angles (OLA L1) are converted to body fixed coordinates (OLA L2) using the appropriate SPICE data. In other words a point cloud is created from OLA measurements. OLA L2 data products are then used to create shape models. The fidelity of the shape model depends on the fidelity of the SPICE kernels used.

3.4.2 Science Data Processing

The Science Data Processing subsystem of the SPOC uses instrument raw, un-calibrated, and calibrated data products stored in the SPOC data repository to produce science data products used to quantify specific physical properties of Bennu. SDP data products are stand alone data products and do not include the added value of scientific interpretation.

SDP is broken down into six components that correspond to five Science Team Working Groups listed in Table 3. The SPOC components and the Science Team Working Groups are aligned by discipline and are closely tied throughout the mission lifecycle. The Science Working Groups are responsible for defining algorithms and developing software to produce the SDP data products (see tables in the following sections). The SPOC is responsible for implementing the software and integrating it with the SPOC data repository subsystem. The SPOC is responsible for testing the software and verifying that the integrated software produces the expected output.

Table 3. Science Data Processing Working Groups

Science Working Group	Data Processing Component	Group Lead

Science Working Group	Data Processing Component	Group Lead
Image Processing	Image Processing	Della-Giustina
Radio Science	Radio Science	Scheeres
Astrometry/Photometry	Astrometry/Photometry	Hergenrother
Altimetry	Altimetry-OLA, Altimetry-Stereophotoclinometry	Barnouin
Spectral Analysis	Spectral Processing	Hamilton

3.4.2.1 Image Processing

The Image Processing Working Group (IPWG) is responsible for verifying and analyzing data returned from OCAMS. The IPWG specifies requirements, defines software algorithms and develops or implements software for the data processing necessary to build data products derived from calibrated OCAMS data. Image processing software is implemented and used at the SPOC. There is a close collaboration between the IPWG and the SPOC software engineers throughout the mission to ensure that image processing data products are produced and analyzed in a timely manner. Image Processing is responsible for the data products listed in Table 4. Not all of the products produced by the IPWG are required to be delivered to the PDS. Several products (videos or sequences of images) are developed for public engagement activities using base data products delivered to the PDS as individual images or mosaics. One product is used for a specific operational purpose, and is derived from images delivered to the PDS. Finally, on analysis product will be produced as a peer reviewed publication based on images delivered to the PDS.

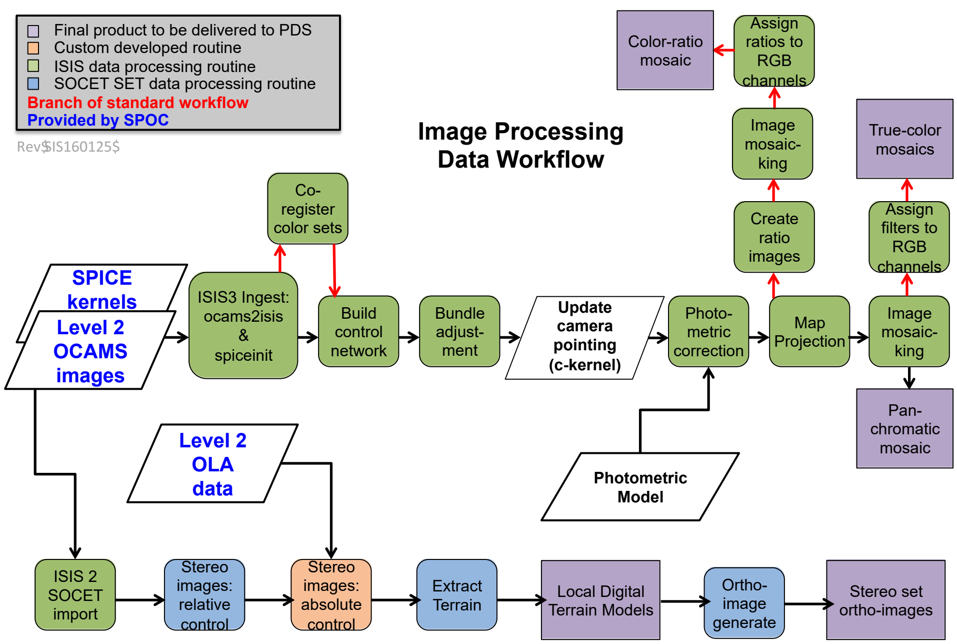
Table 4. IPWG Data Products

Product Type (if PDS, then archive bundle specified)	MRD Numbers	Data Product
Image Processing PDS Bundle	121,119, 576, 183a, 116	Global and Site-specific Panchromatic Mosaics
Sample Site PDS Bundle	121, 183a, 116	Global Hazard Map and Site-specific Particle Map
Image Processing PDS Bundle	141, 119	Global and Site-specific Color Mosaics
Image Processing PDS Bundle	n/a	Site-specific Stereo Products
Public Engagement	121	Image Sequences of Asteroid Surface
Image Processing PDS Bundle	149	Global Photometric Model
Operational Product	183a	Global 1064nm Map

Product Type (if PDS, then archive bundle specified)	MRD Numbers	Data Product
Public Engagement	380	Video of TAG
OCAMS PDS Bundle	586	In-focus images of TAGSAM Contact Surface
Operational product, Peer Reviewed Publication	190a	Estimate of collected surface sample area

The image processing data flow illustrated in Figure 13 shows the flow of data from data stored in the SPOC Data Repository into the Image Processing SPOC component, through Image Processing sub-components that produce higher-level data products.

Figure 13. Image Processing Data Flow



All algorithms used to create single-band (i.e. panchromatic) mosaics are implemented in the ISIS3 software developed by the USGS. All OCAMS images brought into ISIS3 use the OCAMS image import function and camera model which translates important keywords in the image FITS header with ISIS3 variables and associates the image with the OSIRIS-REx SPICE kernels, geometric distortion correction, and converts the files into an ISIS3 image cube. Geometry from the SPICE kernels and Bennu shape model are then calculated across the entire image with a user specified shape model. Images can be map projected and mosaicked according to their initial SPICE kernel geometry to create an uncontrolled mosaic. Controlled mosaics can be generated using the bundle adjustment routines within ISIS3. Bundle adjustment is the photogrammetric technique used to control images relative to one another and a shape model before mosaicking. Prior to bundle adjustment, initial ground coordinates of tie points are generated by intersection with an available shape model. During bundle adjustment estimates of the extrinsic camera parameters and the 3D position of common points of features are refined, updated, and exported as smithed SPICE kernels. The elements of the cost function optimized during this process are derived from the corresponding tie-points in the set of images. After frames have updated geometry, a photometric correction can be applied using the photometric angles determined by the geometry refinement. The final step in the mosaicking process consists of stacking the individual image frames according to pixel priority. The "priority" parameter will determine how input pixels are combined with the output mosaic. The selection of input pixels can be based on resolution, photometric angles, averaging schemes, etc. The final mosaic will be generated in a standard cartographic projection, such as equirectangular or polar stereographic. Color (multi-band) mosaics are developed along a similar data processing flow, however co-registered image color-cubes are created and used in the mosaicking process.

The Hazard Maps consist of a PostGIS spatial database with a corresponding color-coded global mosaic that can be thresholded and translated into hazards-only binary mask. This three-part data product satisfies MRD-121 and 138 and will use the panchromatic base map generated by the IPWG during Detailed Survey as its input. The main hazards to be identified include boulders and other large objects (>21 cm), craters, linear features and other areas of exclusion. Areas of exclusion are defined as areas which are unfit for sample acquisition including, rocky terrain, overhangs, or areas in close proximity to multiple large objects. Areas will be classified as regions of interest if they satisfy the requirements that they are relatively smooth, accessible, and a safe distance from any large hazards. Hazards and regions of interest will be identified using both manual and automated methods.

Stereo image data processing will be done using the commercial BAE Systems SOCET SET with mission specific scripts. DTMs are derived from a set of stereo-images that have comparable resolution and illumination, using ISIS and SOCET SET stereo-photogrammetry software. Values of elevation are extracted every ~ 4 pixels, depending on the stereo strength of the image set, and are controlled to OLA Level 2 altimetry data. Elevation is reported in units of meters from either the body center, or relative to a predefined planetary geoid. DTMs are generated from both MapCam and PolyCam for up to 2 candidate sample sites from Reconnaissance imagery.

An orthoimage (or orthophoto) is an image that has been geometrically corrected ("orthorectified") such that scale is as uniform as possible. Orthographic rectification uses topography measurements (e.g. DTMs) to reproject images as though they were taken at nadir, thereby removing any distortion due to topography, oblique camera angles, or artifacts of lens distortion. The uniform scale allows orthoimages to be used as map products when latitude/longitude information has been associated with each pixel. Orthoimages are generated from each stereo-image in a set according to the DTM (e.g. the highest-resolution terrain model available). Orthoimages are produced from MapCam and PolyCam stereo-images for up to 2 candidate sample sites from Reconnaissance imagery and are paired with a DTM.

3.4.2.2 Radio Science

The Radio Science Working Group (RSWG) is responsible for the characterization of the gravity field of asteroid Bennu using Radio Science and analytical modeling. The RSWG defines all algorithms and develops software needed to produce the radio science data products listed in Table 5. Algorithms, software, and associated documentation are delivered to the SPOC for integration, implementation and verification and validation. The RSWG supports the SPOC through verification and validation, and also provides software maintenance throughout operations.

Table 5. Radio Science Data Products

Product Type **(if PDS, then archive bundle specified)**	**MRD Number**	**Data Product**
Radio Science PDS Bundle	126	Global slope map
Radio Science PDS Bundle	130	Global gravity field map
Radio Science PDS Bundle	131	Roche lobe
Radio Science PDS Bundle	133	Asteroid mass model
Radio Science PDS Bundle	134	Spherical harmonic coefficients
Radio Science PDS Bundle	135	Center of mass
Radio Science PDS Bundle	194	Density model for internal structure
Radio Science PDS Bundle	196	Orbital stability analysis
Radio Science PDS Bundle	196	Satellite ephemerides
Radio Science PDS Bundle	150	Bennu ephemeris
Intermediate Product	602	Bennu pseudo-ranging

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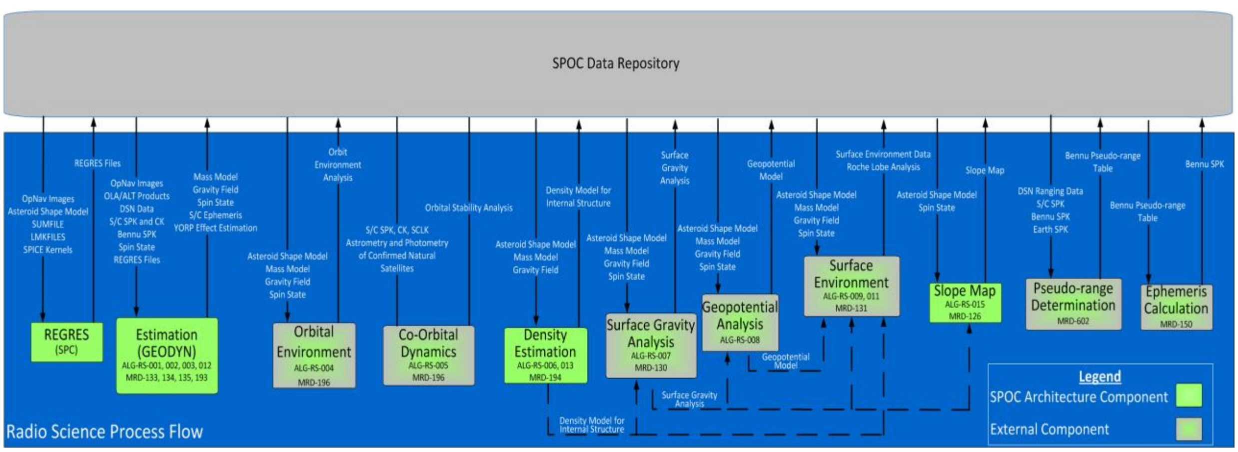
Product Type (if PDS, then archive bundle specified)	MRD Number	Data Product
Radio Science PDS Bundle	193	YORP effect

Radio Science data processing (Figure 14) uses DSN tracking information, optical navigation images, spin state, spacecraft events, spacecraft attitude and previous navigation solutions. These data products are combined within a least-squares orbit determination filter to precisely estimate the asteroid mass, gravity field, spin state and ephemeris. The estimation process is done using the GEODYN II software, which was created at NASA Goddard Spaceflight Center. The estimated products are updated in the SPOC repository for distribution to the Science Team for a variety of purposes. Radio science data products are also used in conjunction with the estimated asteroid shape for analysis of the orbital environment, the internal density distribution of the asteroid, the surface gravity, the geopotential analysis, and for development of a precise surface environment.

Radio Science will calculate and deliver the final Bennu ephemeris as well as any ephemerides of natural satellites found in orbit of Bennu.

The YORP effect algorithm (Estimation) will consist of the estimated migration of the asteroid spin rate over the mission duration and its comparison with the predicted degree of migration based on the existing asteroid shape model and photometric properties. The output will be the estimated change in spin rate, along with the errors in the estimate, and the predicted change in spin rate parameterized as a function of the asteroid's surface photometric properties.

Figure 14. Radio Science Data Flow



3.4.2.3 Astrometry and Photometry

The Astrometry & Photometry Working Group (APWG) is responsible for quantifying the astrometric and photometric properties of asteroid Bennu observed as a point source by the spacecraft instruments during the Approach Phase of the mission. They are also responsible for searching for satellites in orbit around Bennu and characterizing their orbital elements and photometric properties. The APWG defines all algorithms and develops the software needed to produce the astrometry and photometry data products listed in Table 6. Algorithms, software, and associated documentation are delivered to the SPOC for integration, implementation and verification and validation. The APWG supports the SPOC through verification and validation, and also provides software maintenance throughout operations.

Table 6. Astrometry and Photometry Data Products

Product Type (if PDS, then archive bundle specified)	**MRD Number**	**Data Product**
Astrometry & Photometry PDS Bundle	144	Satellite images & proof of existence
Astrometry & Photometry PDS Bundle	142	Approach dust plume survey
Astrometry & Photometry PDS Bundle	146	Satellite light curves
Astrometry & Photometry PDS Bundle	148	b-v index, v-x index, and 0.7-µm color ratios of satellites
Astrometry & Photometry PDS Bundle	157	Asteroid light curves
Astrometry & Photometry PDS Bundle	158	Asteroid phase functions

Astrometry & Photometry data processing uses OCAMS images and ancillary data to search for natural satellites in the vicinity of the asteroid. If any natural satellites are detected, information will be passed to Radio Science for ephemeris determination. Also if any natural satellites are detected, the APWG will obtain additional OCAMS images of the satellites in order to produce follow-up astrometry, which will be passed to Radio Science. Approach phase images and ancillary data including SPICE kernels are examined to determine the presence of any dust plumes emanating from the surface of Bennu. The plume data products will contain both images where plumes were identified and measurement of unresolved dust in the close vicinity of Bennu. Images, ancillary data and stellar photometric catalogs are used to produce a temporal and phased rotational light curve and rotation period for the asteroid and detected natural satellites. Astrometry & Photometry produces phase function photometry and phase function models as well as color index astrometry for the asteroid and satellites if data are of sufficient quality.

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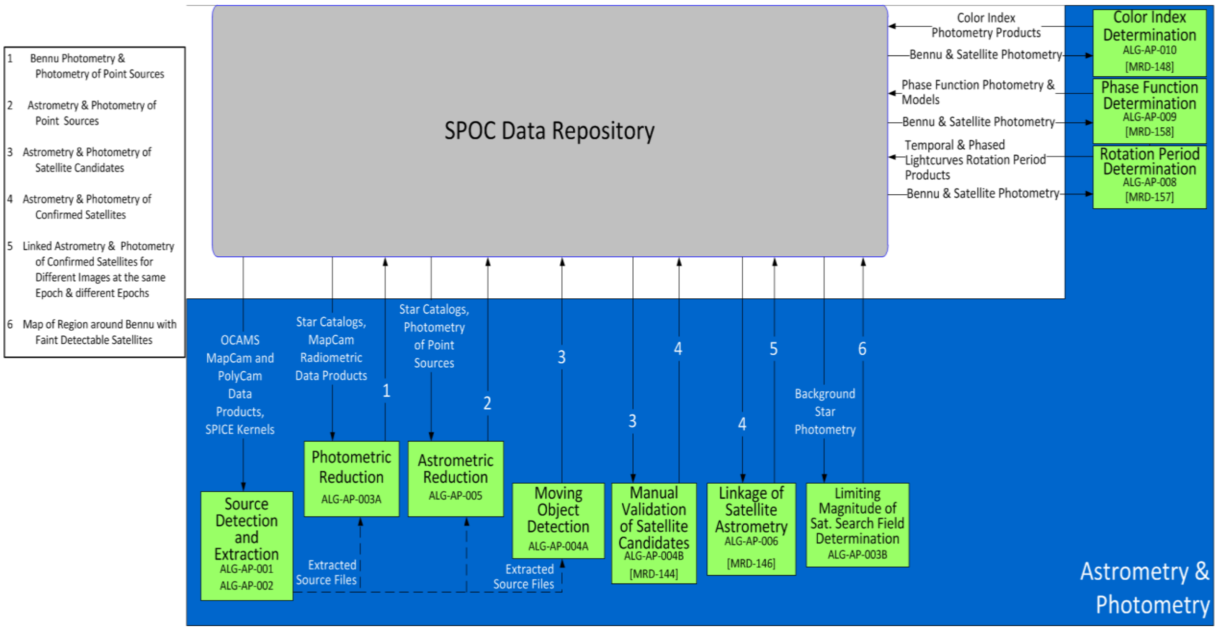
Figure 15. Astrometry and Photometry Data Flow



3.4.2.4 Altimetry

The Altimetry Working Group (ALTWG) is responsible for characterizing the shape, rotation state, and topography of the asteroid in support of sample-site selection and asteroid science objectives. The ALTWG has three separate data processing paths to meet these objectives.

Altimetry is focused on the higher-level altimetry data products derived from OLA and image data. The OLA processing path is concerned with derivation of topographic properties of the asteroid using OLA data. Stereophotoclinometry (SPC) is focused on providing shape and rotation state higher-level products derived from image data. The combined OLA-Stereophotoclinometry processing path combines OLA and image data to create the highest quality data products from Altimetry data processing.

The ALTWG defines algorithms and develops software needed to produce the Altimetry data products in Table 7. Algorithms, software, and associated documentation are delivered to the SPOC for integration, implementation and verification and validation. The ALTWG supports the SPOC through verification and validation, and also provides software maintenance throughout operations.

Table 7. Altimetry Data Products

Product Type **(if PDS, then archive bundle specified)**	**MRD Number**	**Data Product**

Product Type (if PDS, then archive bundle specified)	MRD Number	Data Product
Altimetry PDS Bundle	MRD-115	Site-specific topographic maps
Altimetry PDS Bundle	MRD-122	Global topographic maps
Altimetry PDS Bundle	MRD-123	Asteroid shape model
Altimetry PDS Bundle	MRD-124	Asteroid center of figure
Altimetry PDS Bundle	MRD-125	Asteroid coordinate system
Altimetry PDS Bundle	MRD-127	Pole location
Altimetry PDS Bundle	MRD-128	Pole wobble
Altimetry PDS Bundle	MRD-129	Rotation period
Altimetry PDS Bundle	MRD-132	Asteroid volume
Altimetry PDS Bundle	MRD-608	Site-specific tilt maps

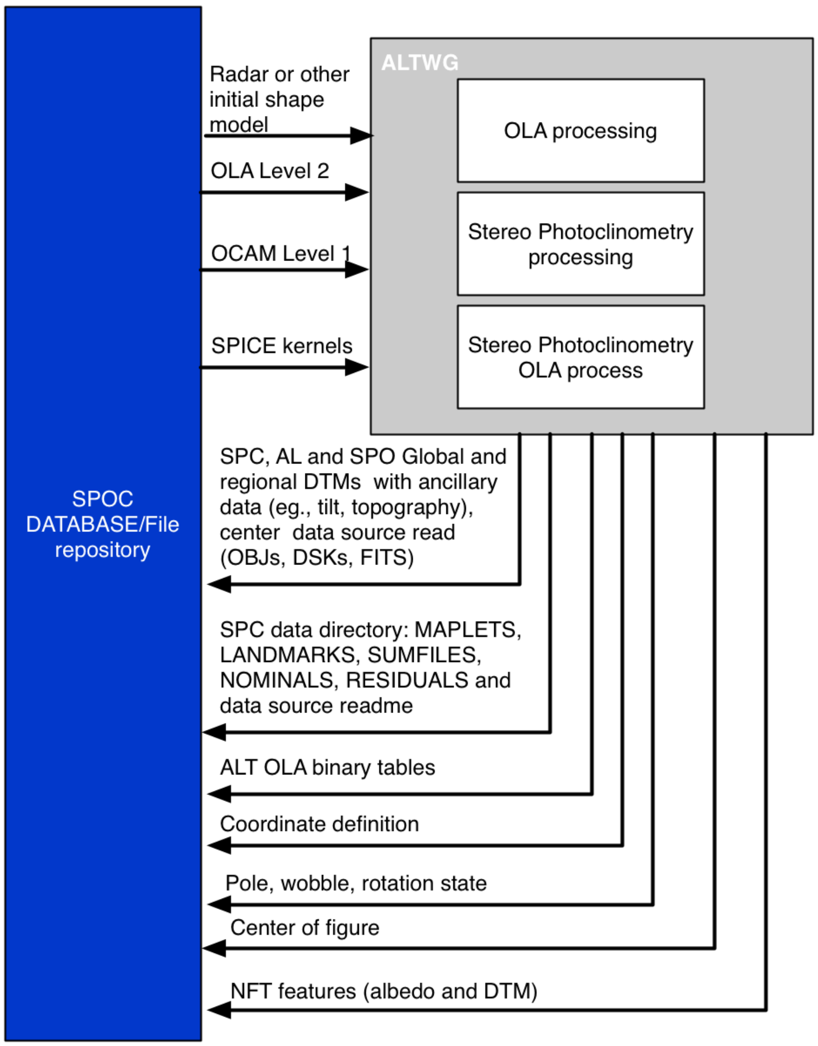
Altimetry OLA data processing uses the OLA shape model to perform crossover analysis to determine the accuracy of the SPK SPICE kernels and to place OLA data spots accurately on geodetic grids. As soon as OLA is in range of Bennu, the Altimetry Group will employ the initial trajectory provided by the navigation team, pointing data from the spacecraft, and measurements from OLA's scanner to determine surface transects. The trajectories are fit using least squares between thrusts. These trajectories provide a reasonable first estimate of the LIDAR footprints on the surface of Bennu. Additional optical navigation data from the onboard imaging system (OCAMS) providing the location of the spacecraft are also employed as additional heavily weighted tie points for these fits. Obvious landmarks on the surface, such as large boulders, provide additional constraints on the S/C trajectory. As additional tracks are processed, significant overlaps between tracks will be obtained. Overlapping tracks will be fit relative to each other using least squares techniques to minimize differences in the measured x, y, and z of each altimetric footprint while maintaining the geometry of the spacecraft trajectory arcs. The resulting map is relative to the center of figure (COF) of the asteroid.

Iteratively, and with use of more sophisticated trajectory models, the altimetric (or geodetic) model of the surface is built up, now relative to the center of mass (COM). Trajectory models require evaluation of the gravitational field and small forces (solar pressure acting on the spacecraft). The Altimetry team will generate high fidelity topographic maps of the figure of Bennu, making extensive use of many planned crossovers.

Stereophotoclinometry (SPC) data processing (Figure 16) uses several procedures to contribute to the determination of shape from LIDAR and imaging data. LITHOS uses imaging data with a priori navigation and shape information to construct a set of "maplets," digital topography, and albedo maps of small regions of the body's surface. The central point of each maplet represents a control point, a fixed reference point on the body's surface. LITHOS determines the image space locations of a control point under a wide range of resolutions, illuminations and viewing geometries by correlating the imaging data with the illuminated maplet topography. It also determines the control point location in images in which a portion of the maplet is seen on the limb. Finally, because neighboring maplets may share common topography, the relative surface positions of their associated control points provide an additional constraint. The central point of each maplet and the control points are carried into GEOMETRY, along with their formal uncertainties, where a linear estimation procedure is used to update the camera pointing and spacecraft position at each image time, and the body-fixed location of each control point. In order to construct a maplet, LITHOS extracts imaging data and projects it onto the nominal maplet. The slopes and albedos of the maplet are adjusted to minimize the residuals between the image and illuminated maplet brightness in the least square sense. The slopes are then integrated to produce the maplet topography. If the camera pointing or spacecraft position are incorrect, the data will be misaligned, and if the height distribution within the maplet is incorrect, the projected image will be distorted. For this reason, the procedure is an iterative one, with GEOMETRY providing improved estimates of the spacecraft state and maplet position, and LITHOS providing improved topography and control point location. The principal product of LITHOS is the ensemble of thousands of overlapping maplets (MAPFILES) at varying resolution. These maplets are passed to DENSIFY to construct a global topography (shape) model as well as larger high-resolution "bigmaps" of regions of the surface. The shape model and maplets are passed to the SHIFTER0 procedure to produce the asteroid volume, area, and center of mass. Summary files and landmark files (SUMFILES, LMKFILES), are image information and landmark information files updated by LITHOS and GEOMETRY are passed along with several other pieces of information to the POLE procedure to produce asteroid pole data including the right ascension, declination and obliquity.

Combination of the OLA derived shape and topographic products and the SPC derived shape and topographic products yields the highest fidelity products.

Figure 16. Altimetry Data Processing Flow



3.4.2.5 Spectral Processing

The Spectral Analysis Working Group (SAWG) is responsible for verifying and analyzing all data related to the measurement of the intensity of reflected and emitted electromagnetic radiation from the surface of Bennu using OVIRS and OTES. The SAWG defines algorithms and develops software needed to produce spectral data products listed in Table 8. All algorithms, software, and associated documentation will be delivered to the SPOC for integration, implementation and verification and validation. The SAWG supports the SPOC through verification and validation, and also provides software maintenance throughout operations.

Spectral Processing uses OTES and OVIRS data combined with ancillary data as needed to produce higher-level products on a spectrum-by-spectrum (single point on the surface of the asteroid) basis, as well as mapping these data to produce mineral and chemical abundance, Bond albedo, and dust cover index maps (Figure 17).

For OVIRS, calibrated spectra and solar distance are fed into an algorithm that resamples the OVIRS data to a common wavelength scale. Next, the contribution from thermal emission at long wavelengths is removed from the near-infrared portion of the spectrum by subtracting a modeled thermal tail. The thermal-excess removed OVIRS spectra are then corrected for the solar spectral contribution by dividing the observed target spectra by a solar model. The I/F spectra are used to create a photometric model, which is then applied to all OVIRS I/F spectra. The photometric model uses the OVIRS spectral data (spectral measurements at a wide range of observing viewing angles (incidence, emission, and phase)) to predict the radiance from the surface at un-measured viewing and illumination geometries. The model is relevant to the spatial scale represented by the input data. For OVIRS, this means 6-19 meter diameter round spots over 80% of the surface of Bennu. The "best fit" model, based on visual inspection as a function of incidence, emission, and phase angle, will be selected from among three possible functional forms (Modified Lommel-Seeliger, ROLO and Modified Minnaert) and applied to the OVIRS spectra on a wavelength-by-wavelength basis. Photometric correction constants will be delivered to the calibration collection within the Spectral Analysis PDS bundle. The photometrically corrected OVIRS spectra (spectral reflectance factors, REFF) are then used to calculate the bolometric Bond albedo. The photometrically corrected OVIRS data also are run through an algorithm that calculates band strengths at specific wavelengths to enable the rapid identification of signatures of minerals or organics of interest. The spot parameter strength information from these OVIRS analyses is sent to the spectral mapping algorithm for mapping to the surface of the asteroid.

Table 8. Spectral Processing Data Products

Product Type (if PDS, then archive bundle specified)	**MRD Number**	**Data Product**
Spectral Analysis PDS Bundle	140	Resampled Calibrated Radiance (OVIRS)
Intermediate product	140	Thermal-excess removed radiance spectra (OVIRS)
Spectral Analysis PDS Bundle	140	Spot emissivity spectra (OTES)
Spectral Analysis PDS Bundle	155	Spot brightness temperature (OTES)
Spectral Analysis PDS Bundle	140	I/F spectra (OVIRS)
Spectral Analysis PDS Bundle	118	Site-Specific mineral and chemical maps

Product Type (if PDS, then archive bundle specified)	MRD Number	Data Product
Spectral Analysis PDS Bundle	118	Global mineral and chemical maps
Contingency product	143	Plume spectral characteristics*
Contingency product	147	Satellite mineralogy and chemistry*
Spectral Analysis PDS Bundle	149	Global photometric model
Peer reviewed paper	149	Global photometric correction
Spectral Analysis PDS Bundle	154, 156	Spot bond albedos
Spectral Analysis PDS Bundle	156	Site-specific bond albedo map
Spectral Analysis PDS Bundle	118, 154	Spot OVIRS Reflectance Factor
Spectral Analysis PDS Bundle	118	Site-specific reflectance factor maps
Spectral Analysis PDS Bundle	154	Global bond albedo map
Spectral Analysis PDS Bundle	154	Global reflectance factor maps
Spectral Analysis PDS Bundle	159	Rotationally resolved spectral characteristics
Spectral Analysis PDS Bundle	183c	Spot dust cover index
Spectral Analysis PDS Bundle	183c	Global dust cover index map
Spectral Analysis PDS Bundle		Site-specific dust cover index map

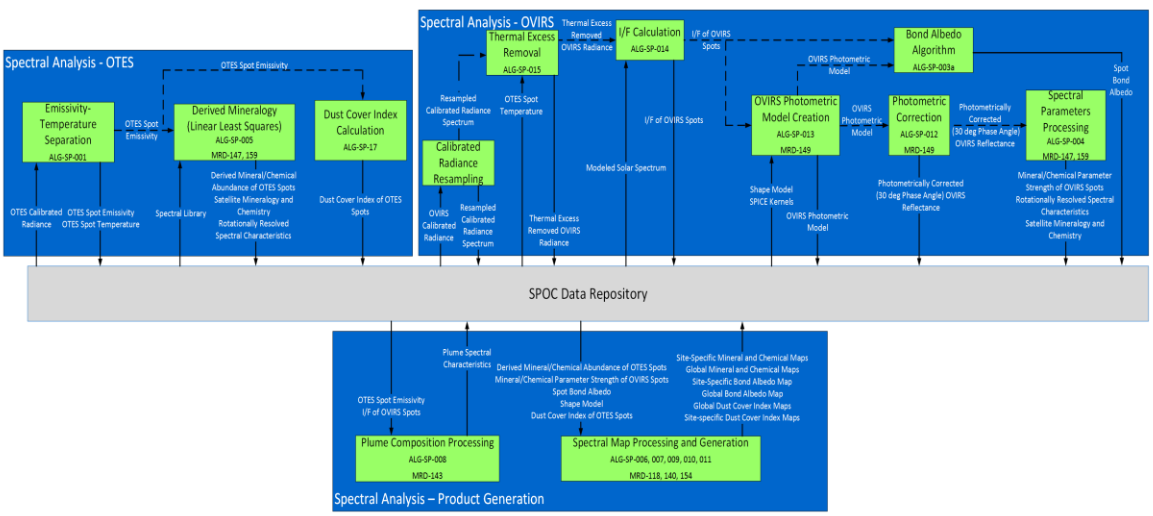
*Contingency product produced if satellites or plumes are present

Calibrated OTES spectra are first processed to separate the contributions of temperature and emissivity from the calibrated radiance spectra. The temperature derived from each spectrum will be fed into a thermal model, see section 3.4.3.4 Thermal Analysis for a full discussion of the analysis of temperature data. Emissivity spectra are analyzed by a linear least squares mixing model that uses the OSIRIS-REx spectral library to determine the quantitative mineralogy represented by each spectrum. The spot mineralogy information from these OTES analyses is sent to the spectral mapping algorithm for mapping to the surface of the asteroid. Emissivity spectra are also used to calculate a parameter, the average emissivity over a specified wavelength range, representing the relative abundance of dust on the uppermost surface of the asteroid (dust cover index); this parameter is also sent to the mapping algorithm for characterization of the asteroid's surface.

The OSIRIS-REx spectral library is a set of laboratory spectral observations of geologic phases or samples (e.g., meteorites). The library spectra are used for comparison with and to model/reproduce spectra taken of the surface of Bennu to determine chemical and/or mineral composition of the asteroid surface. The spectral library observations together with documentation and correlative data that provide additional information are stored in the SPOC data repository and are available to the science team.

Data values for individual measurements (spots) for both OVIRS and OTES derived quantities can be mapped to the surface of Bennu using custom build methods for combining data point values and projecting them on to the appropriate Bennu shape model. Spectral or compositional maps can be displayed using data visualization tools that will be made available to the end-users. Spot data products are released to the PDS during regular PDS deliveries (every 3 months). All map products are delivered with the higher-level products.

Figure 17. Spectral Processing Data Flow



3.4.3 Science Data Analysis

The Science Data Analysis (SDA) subsystem of the SPOC uses processed and derived data products produced in the SDP subsystem as well as ancillary information stored in the SPOC data repository to produce science data products that interpret the physical properties and formational history of Bennu. SDA data products include the added value of scientific interpretation.

SDA is divided into five components that correspond to five Science Team Working Groups and one Systems Engineering Working Group listed in Table 9. SPOC components and the Science Team Working Groups are aligned by discipline and are closely tied throughout the

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mission lifecycle. The Science Working Groups are responsible for specifying data product production algorithms, scientific input during data product production, and assessing the quality and scientific value of the products produced. The SPOC is responsible for developing sample-site selection data processing software based on algorithms defined by the Science Working Groups, providing access to all necessary input data products and for ingesting final SDA data products back into the SPOC data repository subsystem.

Table 9. Science Data Analysis Working Groups

Working Groups	Data Processing Component	Group Lead
Sample Site Science	Sample Site	Nakamura-Messenger
Safety Map	Sample Site	Lorenz
Dynamical Evolution	Dynamical Evolution	Bottke
Regolith Development	Regolith Development, Sample Site	Walsh
Thermal Analysis	Thermal	Emery
Asteroid Astronomy	Astronomy	Hergenrother

3.4.3.1 Sample Site

The Sample Site component of the SPOC is responsible for the production of the Safety and Science Value Maps. Table 10 is a list of the Sample Site Data Products.

The Safety Working Group, a mission systems engineering lead team, is responsible fro developing the algorithms for the safety map production. The SPOC is responsible for implementation and verification and validation of the safety map production software.

The Safety Map (Figure 18) is a quantitative measure of the flight system safety during TAG operations. The Safety Maps are a quantitative integration of all factors that determine the safety of a region:

1. Tilts – a product of the shape of the asteroid, surface slopes, approach vector and landing ellipse.
2. Temperature – the predicted surface temperature at the time of TAG
3. Reflectance – albedo of the surface of the asteroid
4. Gravity Uncertainty – surface gravity of the asteroid, spherical harmonic coefficients of Bennu's gravity field to fourth degree and order.

The global safety map, created from data collected during the orbital and detailed-survey phases of the mission, allows the definition of the initial (up to) 12 candidate sample sites and assess the safety of those sites against the performance constraints of the flight system. The site-specific maps provide higher-resolution coverage of the final candidate sites, improving our fidelity of the safety assessment. This assessment, when combined with the

Deliverability Maps, ensures the selected primary site satisfies a greater than 99% probability of ensuring the safety of the flight system during sampling. The Flight System Safety Map will display regions of the surface of Bennu that (green) satisfy all FS safety limits with positive margin, (yellow) satisfy all Flight System safety limits within 95% of limits, and (red) do not satisfy one or more safety limits.

The Science Value Map (Figure 18) is a qualitative to semi-quantitative ranking of the characteristics of the asteroid surface that feed directly into the scientific desirability of a specific location to be ranked as candidate site for sample collection. The Sample Site Science Working group is responsible for developing the algorithm for the science value map. The current mission plan calls for three resolutions of the Science Value Map: Global 21cm imaging resolution, Orbital Phase B candidate sample site 5cm imaging resolution (up to 12), and Reconnaissance candidate sample site <1cm imaging resolution (up to 4). A number of input data products are combined with a specific weighting to produce a chemical composition score, mineralogy score, geologic feature score and temperature score. These scores are combined to give an integrated science value map. The map will be used to determine areas of high science value with no regard for flight system safety, deliverability or sample-ability. Science value of the sample-site is lowest priority in determining where to sample compared to flight system safety, deliverability, and sample-ability.

Table 10. Sample Site Data Products

Product Type **(if PDS, then archive bundle specified)**	**MRD Number**	**Data Product**
PDS Sample Site Bundle	570a	Global safety map
PDS Sample Site Bundle	570a	Sample-site safety map
PDS Sample Site Bundle	114	Global science value map
PDS Sample Site Bundle	114	Sample-site science value map

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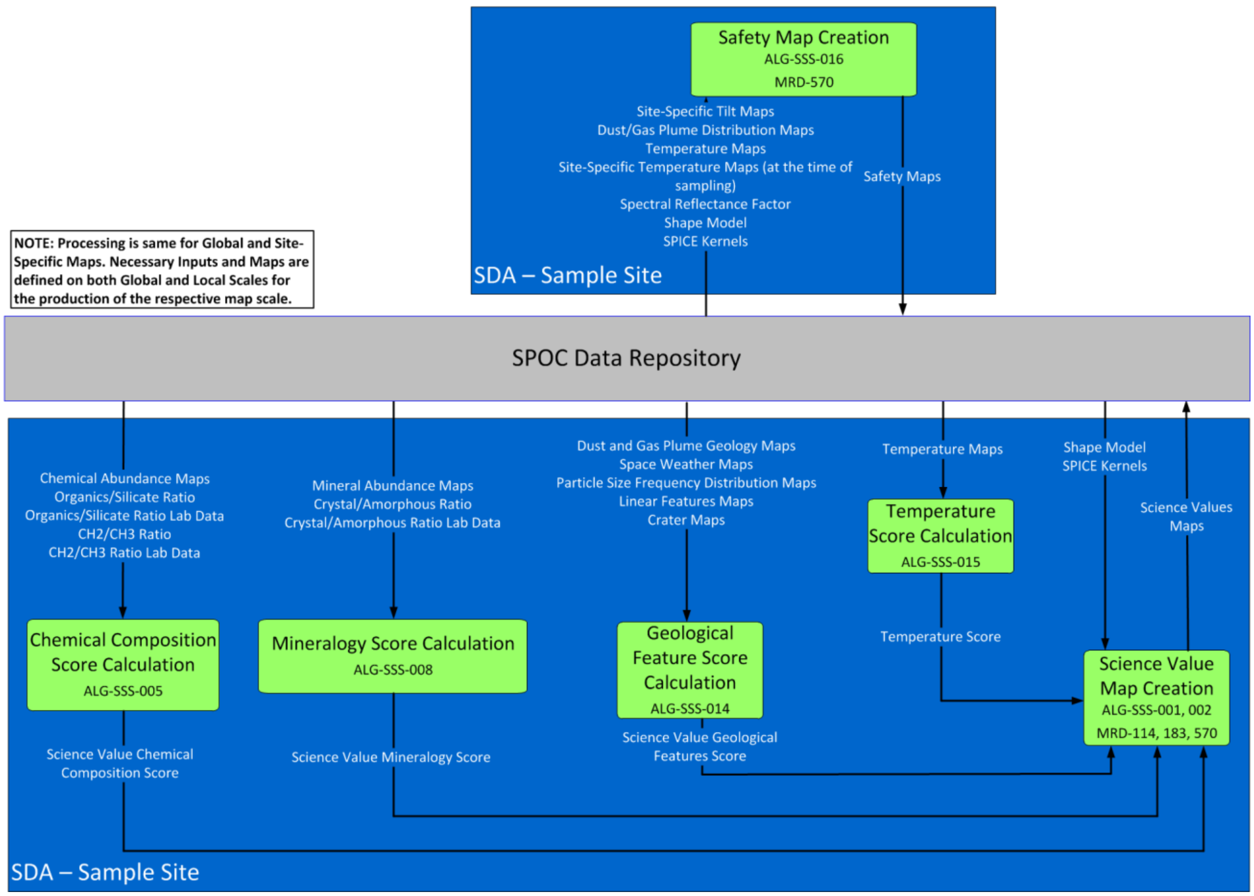
Figure 18. Sample Site Data Flow



3.4.3.2 Dynamical Evolution

The Dynamical Evolution component of the SPOC is responsible for creating data products that describe the dynamical history of Bennu. These data products (Table 11) are produced using several different software algorithms developed by the Dynamical Evolution Working Group (DEWG) or through proprietary software at the home initiations of DEWG members. DEWG members have indicated that access to the full SPOC Data Repository will allow all needed analysis for the publications that DEWG expects to produce. DEWG members will use the standard Data Repository access methods provided to all OSIRIS-REx team members. No data flow diagram is presented for the DEWG, as their work only requires Data Repository access.

Table 11. Dynamical Evolution Data Products

Product Type (if PDS, then archive bundle specified)	**MRD Number**	**Data Product**
Peer Reviewed Publication	150	Yarkovsky acceleration
Peer Reviewed Publication	195b	Planetary Encounters & Impact hazard
Peer Reviewed Publication	195b	Dynamical evolution

3.4.3.3 Regolith Development

The Regolith Development component of the SPOC (Figure 19) is responsible for developing data products (Table 12) that describe the surface properties and geological context and history of the surface of Bennu.

Table 12. Regolith Development Data Products

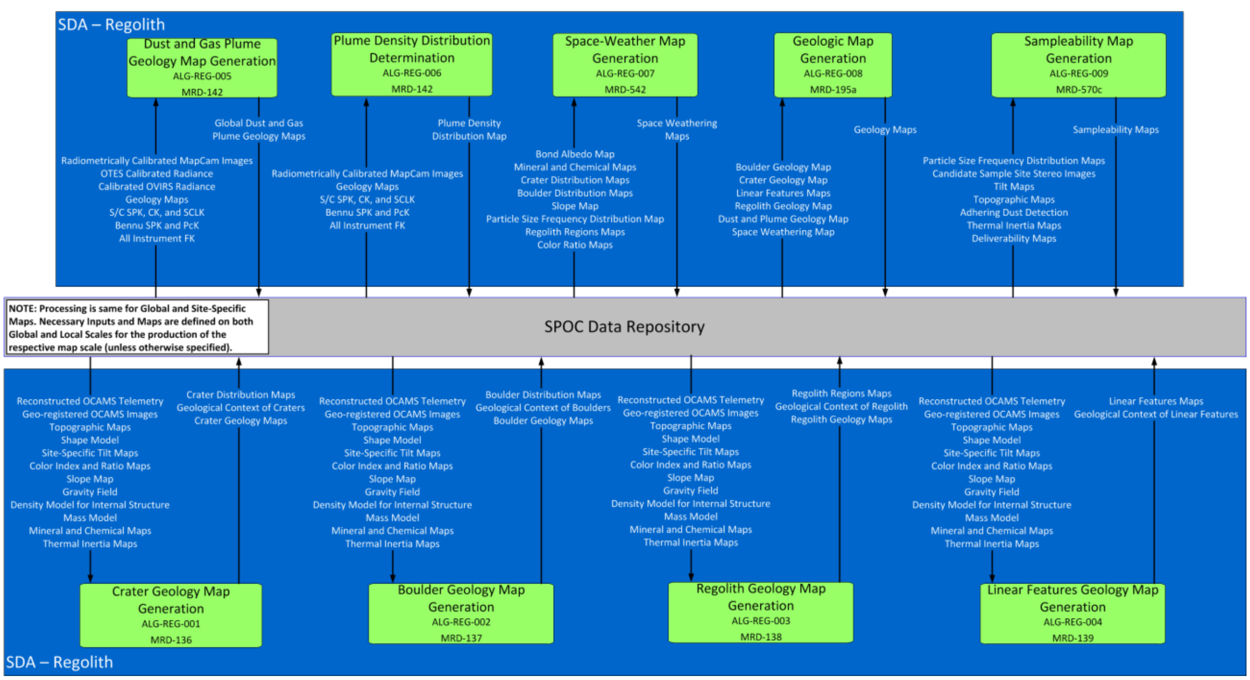
Product Type (if PDS, then archive bundle specified)	**MRD Number**	**Data Product**
Intermediate Product	136	Global crater map
Intermediate Product	137	Global boulder map
Intermediate Product	138	Global regolith map
Intermediate Product	139	Global linear features map
Contingency/Intermediate Product	142	Global dust and gas plume geology map
Intermediate Product	142	Plume density distribution in asteroid environment
Intermediate Product	542	Global space weathering map
Regolith Development PDS Bundle	195a	Global geologic map
Regolith Development PDS Bundle	195a	Site-specific geologic map
Sample Site Selection PDS Bundle	183c	Global sampleability map
Sample Site Selection PDS Bundle	183c	Site-specific sampleability map
Sample Site Selection PDS Bundle	16	TAG reconstruction

The primary operational data products the Regolith Development Working Group (RDWG) is responsible for are the global and site-specific Sampleability Maps. These maps are used during the sample site selection process to assess the ingestability of regolith material into the TAGSAM head. The Sampleability Map is based on average grain size, tilt, and thermal inertia of the surface of Bennu mapped against regions of exclusions (ROE) identified by the Image Processing Working Group thematic Hazard Map. Results are correlated with the global slope map and dust cover index map to add confidence to the sampleability results.

The geologic features (craters, boulders, regolith, linear features, space weathering), context and history data products are produced in the OSIRIS-Rex Data Visualization Tool using algorithms developed by the RDWG. Geologic features are mapped individually, and are used to create a single comprehensive geologic map of Bennu.

Dust and gas plume data products are contingency products developed in the case that dust or gas plumes are identified. The dust and gas plume algorithm will use a forward modeling technique to match predicted dust and gas plume shapes and brightness against observed plume morphologies and brightness. Inputs to this process are images of the plumes as well as asteroid and image positional information. Outputs are simulated images, image projections onto maps, and plume density distributions.

Figure 19. Regolith Development Data Flow



3.4.3.4 Thermal Analysis

The Thermal component of the SPOC is responsible for the data products Table 13 that describe the thermal properties of Bennu. The thermal data products include temperature maps, a thermal model, and thermal inertia of Bennu. These products are used in both sample site selection and flight systems safety analysis.

Table 13. Thermal Analysis Data Products

Product Type (if PDS, then archive bundle specified)	**MRD Number**	**Data Product**
Thermal PDS Bundle	544	Rotationally resolved thermal inertia
Operational Product	411	Sample site predicted temperature maps
Thermal PDS Bundle	540	Sample site thermal inertia maps
Thermal PDS Bundle	155	Global temperature maps (7)
Thermal PDS Bundle	155	Global thermal Inertia map
Thermal PDS Bundle	411	Sample -site observed temperature maps
Peer Reviewed Publication	156	Asteroid thermal model

Temperature maps will be constructed from individual OTES spot brightness temperature data. These maps will be used as inputs to the thermal inertia data products and as the initial indicator of the temperature environment of the asteroid that the spacecraft will experience. This data product is needed because temperature is an indicator of surface physical properties and these maps provide the initial, model-independent evidence for spatial variation in physical properties across the surface of Bennu. These maps will also be used as one of the inputs to the thermal inertia data products.

The OTES spot brightness temperature data from the Detailed Survey phase will be used to produce global temperature maps. These data will be collected from a fixed observing point as Bennu rotates beneath the spacecraft. As a result the local time will be constant for the entire map and the time-of-day effects on surface temperature will be minimized. There will, however, be latitude-dependent effects on temperature due to the variation in solar illumination and the resultant surface heating with latitude. In addition to the temperature maps, two ancillary maps will be produced that give: 1) the number of OTES spectra included in each element of the map; and 2) the average local time of the OTES data used in each map element.

The OTES spot brightness temperature data from individual Reconnaissance Phase overflights of each candidate sample site will be mapped using the mission standard map format to produce temperature maps of each site. The local time will vary across each sample site (~30 minutes for a 50-m diameter equatorial site). This time-of-day effect will not be removed from the temperature data product. In addition to the temperature maps from the Reconnaissance Phase data, maps can be made of each site using data acquired during other mission phases for comparison with other instrument data and derived data products. Two ancillary maps will also be produced that give: 1) the number of OTES spectra included in each element of the map; and 2) the average local time of the OTES data used in each map element.

Thermal inertia estimates will contribute to interpretation of the physical properties (including mean particle size) of the surface. A thermal model is required to calculate thermal inertia from measured temperatures, albedos, and surface slopes. Thermal inertia will be derived at three spatial scales that are linked to different mission phases. These will assist interpretation of the physical properties (including mean particle size) of the surface and will be used for the investigation of the Yarkovsky force.

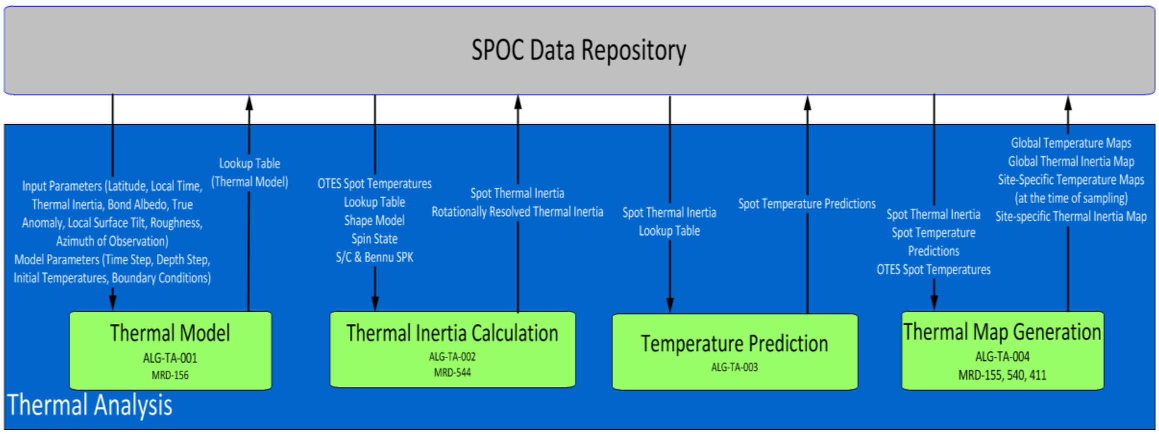
The rotationally resolved thermal inertia will be derived from full disk observations during approach phase. Disk-integrated thermal inertias will enable a reassessment of prediction of surface temperatures for the survey phases and will be directly comparable to the Spitzer Space telescope observations, providing a nice bridge to ground-truthing telescopic data of Bennu. The results will be reported as a single value (with appropriate uncertainty) for each rotational phase observed.

Global thermal inertia maps will be derived from data from the Detailed Survey phase. Global thermal inertia maps will enable refined prediction of surface temperatures for later mission phases. Global thermal inertia maps will be used to assist interpretation of the physical properties of the surface (including mean particle size) and to study anisotropies in thermal emission for the investigation of the Yarkovsky force. The results will be reported as a map of single values (with appropriate uncertainty) for each shape model facet.

Site-specific thermal inertia maps will be derived from data from the Reconnaissance phase. Thermal inertia will be derived for each OTES spot measurement. These will assist interpretation of the physical properties (including mean particle size) of the surface of Bennu, and in particular, for each potential sampling ellipse. The results will be reported as a single value (with appropriate uncertainty) for each OTES spot.

An asteroid thermal model will be developed to enable the team to ingest measurements of the surface and calculate thermal inertia and temperature imbalance (for Yarkovsky experiment) and to predict temperatures for future mission phases. Temperature prediction is important for planning subsequent mission phases, in order to determine optimum altitude for spectral mapping as well as inform flight system safety during rehearsal and sampling. Temperature measurements from early mission phases will be used to "tune" the thermal model (i.e., determine unknown surface properties, such as thermal inertia), which will in turn be used to predict the temperatures that the spacecraft will see in subsequent phases.

Figure 20. Thermal Analysis Data Flow



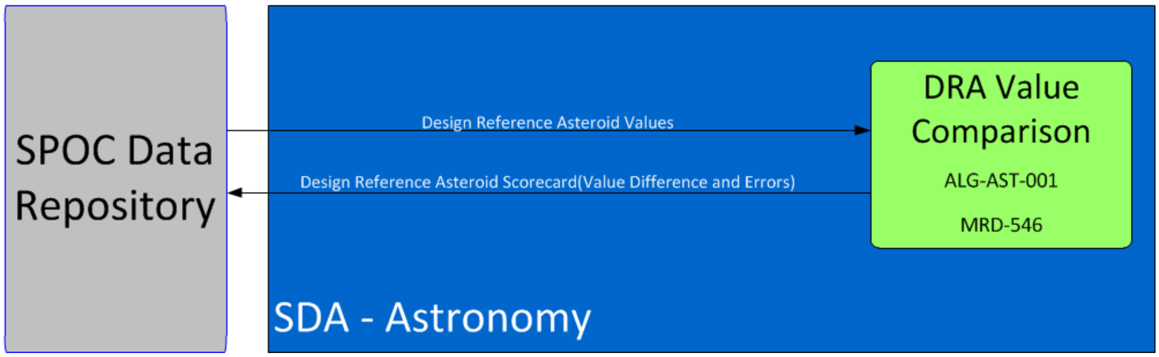
3.4.3.5 Astronomy

The Astronomy component of the SPOC Figure 21 is responsible for a single data product (Table 14) the evaluation of properties of Bennu measured during encounter with respect to the astronomical observations of the asteroid prior to encounter. This evaluation will be a direct comparison of the OSIRIS-REx Design Reference Asteroid as compiled before asteroid encounter with the same asteroid properties calculated through the mission resulting in a scorecard for each parameter. This comparison will give astronomers a "ground truth" data set to reduce errors in observations of other objects.

Table 14. Astronomy Data Product

Product Type (if PDS, then archive bundle specified)	**MRD Number**	**Data Product**
Peer Reviewed Publication	546	Design reference asteroid scorecard

Figure 21. Astronomy Data Flow



3.4.4 SDP/SDA Inputs to Other Mission Elements

The SDA and SDP SPOC subsystems produce data products that are passed via ICD interfaces to FDS in order create map products used for sample site selection.

The deliverability map is a numerical measure of TAG accuracy capability based on site-specific Monte Carlo analysis. The product is used to quantify the ability of FDS to deliver to spacecraft to the surface within a predetermined accuracy. The deliverability product is produced by FDS and includes 12 measurements of TAG accuracy, one for each of the proposed site selection sites. This product will be updated with improved knowledge of the asteroid prior to sample site down selection to 4 candidate sample sites, and again for final sample site selection. The SPOC is responsible for visualization of this product. Science Inputs to this product are listed in Table 15.

Table 15. Inputs to other mission elements

Input	From	To
Coordinates of 12 potential TAG sites	Sample Site Selection Board	FDS
Bennu Gravity Model	Altimetry	FDS
Bennu Shape Model	Altimetry	FDS
Bennu Spin Axis	Altimetry	FDS

3.4.5 SPOC Data Repository

The SPOC Data Repository is the primary warehouse of all data collected by or produced at the SPOC. Access to data stored in the database system is through a database interface layer. The database interface layer is accessed either by a Web based query tool or through automated data processing algorithms. The database interface manages classes of users to maintain appropriate security on all stored data. Data other than telemetry data (e.g. ancillary data) is stored in the repository using either a Web based data ingestion too or an automated process that connects to the database interface layer that in turn connects directly to the database. The SPOC supplied data repository query and insert protocols will be used for all data acess and insertion to enforce data product configuration control.

3.5 Science Planning and Operations

The SPOC supports the Science Planning and Operations activities in which all instrument command sequences are planned, generated, validated and passed to the MSA. The science planning process for instrument observations begins before asteroid encounter with initial sequence planning based on mission phases, objectives and timing set out in the Design Reference Mission. Strategic planning and preliminary command sequences are developed in the mission phase prior to use. These sequences are developed, built, fully tested and put on the shelf until needed. On a daily basis, the tactical planning process allows for review of acquired data and for updates and small changes to stored command sequences.

The complete discussion of Science Planning and Operations and the instrument commanding process is contained the OSIRIS-REX Mission Operations Concept Document (NFP3-PN-11-OPS-8).

4 THE OSIRIS-REX ARCHIVE

4.1 Archive Content

The OSIRIS-REx archive is designed to the PDS4 standard. The PDS4 standard uses modern information technology concepts to build an archival system around a 'data model' that defines each of its components and the relationships among them. PDS4 is implemented using the eXtensible Markup Language (XML) and a set of "open source" rules for encoding documents and data structures. For additional information regarding the PDS4 standards see the PDS4 website (https://pds.nasa.gov/pds4/about/).

PDS4 archives are structured as data bundles that contain collections that in turn contain data products. The OSIRIS-REx archive is organized into bundles for each detector (OCAMS, OTES, OVIRS, OLA, REXIS, TAGCAM,), DSN data, SPICE, higher-order data products bundled by scientific discipline (Altimetry, Astrometry and Photometry, Image Processing, Radio Science, Spectral Processing, Regolith Development, Thermal Analysis), and finally two special products bundles, a Sample Site selection bundle that contains the data products used to make the sample site selection and a Remote Observations bundle that contains data and pointers to Bennu observational data collected by OSIRIS-REx team members from Earth or space-based telescopes. Each bundle contains data collections grouped by data processing level and by time interval. Each PDS bundle also contains a document collection, a context collection, and a schema collection to provide the appropriate ancillary information to properly interpret and use the data. The collections that may be included in OSIRIS-REx bundles are shown in Table 16. Not all bundles will contain all the collections. Optional collections are indicated with an asterisk.

Table 16. PDS Bundle Collections

Collections	Contents
*Browse**	'Quick-look' products designed to facilitate use of the archive
*Calibration**	Contains data and files necessary for calibration of basic products.
Context	List of products comprising various objects, identified within the PDS4 registry, that are specific to the science bundle. These include physical objects such as instruments, spacecraft, and planets and conceptual objects such as missions and PDS nodes.
Data	One or more data collections containing observational data products, separated according to processing level, mission phase etc.
Document	The document collections included with a bundle are those deemed useful for understanding, interpreting, and using other collections in the bundle. Documents may include software interface specifications (SISs), calibration reports etc.

Collections	Contents
*Geometry**	Non-SPICE geometry products — for example, Supplementary Experiment Data Record (SEDR) data, gazetteers, tables of anaglyph pairs, or footprint files. Detailed information about particular cartographic projections used in the archive may also be included.
XML Schema	All XML schema files included in or referenced by XML labels in the bundle along with any Schematron files created for validation purposes. There can be no more than one XML schema collection per bundle.
SPICE Kernels	Individual SPICE files and their XML labels, organized by kernel type.

OSIRIS-REx data products broken down into three broad classes with two delivery methods. The classes of data products are instrument specific science products, which are the basic raw to calibrated instrument products, the derived science products, which are the higher-level products that may combine measurements from more than one instrument, and special science products, which are special collections of products. Any of these products can be delivered to the PDS in either a configuration-controlled pipeline fashion or in a single delivery. Table 17 gives the list of instrument specific products broken down by PDS bundle and data processing level.

Table 17. Instrument specific science bundles

Bundle	***Responsible Co-I***	***Raw Data Products***	***Raw Data Volume (MB)***	***Un-calibrated Data Products***	***Un-calibrated Data Volume (MB)***	***Calibrated Data Products***	***Calibrated Data Volume***	**PDS Delivery Method**
OCAMS	Rizk	1. MapCam, PolyCam or SamCam image data that has been reconstructed from raw telemetry packets. Data in units of DN 2. Housekeeping and Engineering data in units of DN	113253	1. MapCam, PolyCam or SamCam bias, dark and flat fielded images. Data in units of DN. 2. Housekeeping and Engineering data in physical units	106876	MapCam, PolyCam or SamCam radiometrically calibrated and cosmetically corrected images. Data in units of radiance.	188510	Pipeline

Bundle	***Responsible Co-I***	***Raw Data Products***	***Raw Data Volume (MB)***	***Un-calibrated Data Products***	***Un-calibrated Data Volume (MB)***	***Calibrated Data Products***	***Calibrated Data Volume***	**PDS Delivery Method**
OLA	Daly, Barnouin	1. Uncalibrated Spot Data in units of DN 2.State of Health in units of DN	206885	1. Processed Spot Data in physical units 2.Processed State of Health in physical units	253405	Calibrated spot data with associated timing and spatial information,	113847	Pipeline
REXIS	Binzel	Raw Images, Ancillary Data	1460	n/a	n/a	n/a	n/a	Single Delivery
OTES	Christensen, Hamilton	1. Raw Interferograms 2. Raw housekeeping data	2284	n/a	n/a	Calibrated Radiance Spectra	2171	Pipeline
OVIRS	Reuter, Simon	1. Raw Science Data 2. Raw housekeeping units of DN	171804	Housekeeping in physical Units	90	Calibrated science data	274824	Pipeline
TAGCAMS	MSA	Raw NavCam, NFTCam or StowCam images with associated metadata	87034	n/a	n/a	n/a	n/a	Pipeline
DSN Data	FDS	DSN Tracking Data and ancillary files	30000	n/a	n/a	n/a	n/a	Pipeline
SPICE	Acton	n/a	n/a	n/a	n/a	SPICE Archives including kernels and ancillary information (data volume based on STARDUST)	2048	Pipeline
Total Data Volumes			**612720**		**360371**		**581400**	

Higher-level derived data products are divided into bundles based on subject matter. The archive includes bundles for Altimetry, Astrometry & Photometry, Image Processing, Spectral Processing, Radio Science, Regolith, Thermal, and Astronomy. Specific data products for each of these bundles are listed in Table 18. Descriptions of these products can be found in Sections 3.4.2 and 3.4.3, and in the bundle specific data product SISs.

Table 18. Derived data products

Bundle	***Responsible Co-I***	***Derived Data Product***	***Derived Data Volume (MB)***	***PDS Delivery Method***
Altimetry	Barnouin			
		Sample Site Topographic Maps	8200	Single Delivery
		Topographic Map of Asteroid	1500	Single Delivery
		Asteroid Shape Model	2200	Single Delivery
		Asteroid Properties (Pole, Coordinate System, Wobble etc.)	7	Single Delivery
Astrometry & Photometry	Hergenrother			
		Dust Plume Search	300	Single Delivery
		Color Index Photometry	22000	Single Delivery
		Phase Function Photometry	7500	Single Delivery
		Satellite Orbits & Ephemeris*	2000	Single Delivery
		Temporal & Phased Light curves	22000	Single Delivery
Image Processing	Della Giustina			
		I/F Images	186000	Pipeline
		Pan Mosaics Maps, Projections	200000	Single Delivery
		Color Maps, Projections	200000	Single Delivery
		Color Ratios, Maps, Projections	200000	Single Delivery
		Stereo Products	100000	Single Delivery
Radio Science	Scheeres			
		Co-Orbital Dynamics*	10	Single Delivery
		Gravity Field Model	50	Single Delivery
		Spin State	10	Single Delivery
		Spherical Harmonic Coefficients	50	Single Delivery
		Slope Map	8200	Single Delivery
		Asteroid Ephemerides (Final)	50	Single Delivery
Spectral Processing	Hamilton			
		Spot Emissivity spectra and Temperatures	5000	Pipeline

Bundle	*Responsible Co-I*	*Derived Data Product*	*Derived Data Volume (MB)*	*PDS Delivery Method*
		Spot re-sampled OVIRS Spectra	300000	Pipeline
		Spot OVIRS I/F Spectra	300000	Pipeline
		Spot OVIRS REFF Spectra	300000	Single Delivery
		Spot Mineral and Chemical Abundances	300000	Pipeline
		Spot Dust Cover Index	2500	Pipeline
		Spot Bond Albedo	300000	Pipeline
		Sample Site Mineral and Chemical Abundance Maps	450000	Single Delivery
		Global Mineral and Chemical Abundance Maps	850000	Single Delivery
		Global Dust Cover Index Map	8500	Single Delivery
		Global Bond Albedo Map	4500	Single Delivery
		Site-Specific Dust Cover Index Map	8500	Single Delivery
		Site-Specific Bond Albedo Map	4500	Single Delivery
		Rotationally Resolved Mineralogy and Chemistry	8500	Single Delivery
		Plume Spectral Characteristics*	8500	Single Delivery
		Satellite Spectral Characteristics*	8500	Single Delivery
Regolith	Walsh			
		Global Geologic Maps	8500	Single Delivery
		Site-Specific Geologic Maps	4500	Single Delivery
Thermal	Emery			
		Site -Specific Thermal Inertia Maps	4500	Single Delivery
		Global Thermal Inertia Maps	8500	Single Delivery
		Global Temperature Maps	8500	Single Delivery
		Sample-Site Temperature Maps	4500	Single Delivery

*Contingency Products

OSIRIS-REx also produces two special product bundles, Sample-Site Selection and Remote Observations. Products contained in each bundle are listed in Table 19. The final contents of the special product bundles are subject to change due to operational conditions. In the end there may be additional products identified for inclusion in the special products, or products listed here may be removed.

Table 19. Special Science Products

Bundle	*Responsible Co-I*	*Derived Data Product*	*Derived Data Volume (MB)*	*PDS Delivery Method*
Remote Observations	Crombie			
		Spitzer Data Pointer	<1	Single Delivery
		HST Data Pointer	<1	Single Delivery
		ECAS/R-band lightcurve, color and phase angle photometry images (Hergenrother)	TBD	Single Delivery
		SOAR BVRI lightcurve photometry images (Hergenrother)	TBD	Single Delivery
		WHT BVRI lightcurve images (Licandro)	TBD	Single Delivery
		McDonald Obs visible spectra (Howell)	TBD	Single Delivery
		IRTF SpeX NIR spectra (Clark)	TBD	Single Delivery
		Magellan FIRE NIR spectra (Binzel)	TBD	Single Delivery
Sample Site Selection	Beshore			
		Safety Maps	TBD	Single Delivery
		Deliverability Maps	TBD	Single Delivery
		Sampleability Maps	TBD	Single Delivery
		Science Value Maps	TBD	Single Delivery
		Science Value Chemical Composition Score Map	TBD	Single Delivery
		Science Value Mineralogy Score Map	TBD	Single Delivery
		Science Value Geological Feature Score Map	TBD	Single Delivery
		Science Value Temperature Score Map	TBD	Single Delivery
		Image Processing Hazard Map	TBD	Single Delivery
		Sample Site Predicted Temperature Maps	TBD	Single Delivery
		TAG Reconstruction	TBD	Single Delivery
		GNC LIDAR	TBD	Single Delivery
		TAGSAM Engineering Data	TBD	Single Delivery

4.2 Archive Data Volume

Table 17 lists the expected data volume from the instrument specific data products derived from each instrument and data processing component. The data volumes given in the table are derived from Design Reference Mission Rev. C., that accounts for all science data acquired during the course of the mission. All data volume estimates are based on estimated volumes of test data products. These data volumes will be updated over the course of development as exact data formats are refined.

Instrument specific data product data volumes are relatively small compared to other missions. Data volumes transferred according to the release schedule outlined in section 4.4.1 Delivery Schedule will be relatively small, so transfer using existing methods will not be an issue. The nominal delivery plan is via sftp.

Data Volumes for higher-level derived data products are listed in Table 18. Data volumes for these products are estimates based on test data products. Updates to the data volumes are expected as refinements are made to the products. Special Product data volumes are as yet to be determined.

4.3 Bundle Documentation Files

PDS requires a number of volume documentation files for each archive bundle, including a readme.txt describing the contents of the bundle. The bundle as a whole has an inventory of the collections it contains, and each of the collections has an inventory of the files it contains. The details of these files are specified in the PDS Standards Reference.

In addition to the bundle documentation files, each bundle contains context information to relate items in one bundle to another. These files will follow the PDS4 Standard for context information.

4.4 Archive Bundles

4.4.1 Science Data Packets

Science and instrument packet data as well as relevant spacecraft channelized data are passed from the DSN, and are stored at the MSA and at the SPOC. The data stream is stored to be used in a disaster recovery scenario and the unlikely event that either the MSA engineering database or the SPOC science data databases need to be recreated. These "safed" data streams will not be archived with the PDS, but will be held indefinitely by the Project.

4.4.2 Instrument Specific Science Bundles

The instrument specific science bundles (Table 17) are comprised of the OSIRIS-REx un-calibrated data products derived from science telemetry and ancillary data and the calibrated data products derived from un-calibrated data products. Un-calibrated and calibrated data products are produced by the SPOC using a validated, configuration-controlled data processing pipeline built from validated algorithms passed to the SPOC from the instrument providers. The data processing pipeline is validated both by the OSIRIS-REx Team and further by a PDS led peer review, followed by a review lien resolution period.

Instrument specific data bundles are comprised of data and documentation collections that include science goals for specific measurement sequences, instrument description files, calibration reports, data processing methodology, and data anomaly reports. The following paragraphs are short descriptions of each of the instruments standard data products. Full definitions of these data products can be found in the specific instrument pipeline data product SISs.

OCAMS: OCAMS data consists of images and auxiliary data of temperatures and voltages recorded during remote operation. Image and auxiliary data are reduced using software developed or implemented by the OCAMS and Image Processing Working Groups. Test and calibration data are also included in the dataset to allow a recalibration of all three cameras. Image and auxiliary data are formatted in PDS compliant image and table formats. Un-calibrated data are raw images with associated auxiliary data. Calibrated data are geometrically, radiometrically and spectrally corrected images with associated auxiliary data.

OLA: The data from OLA consists of scanning lidar data with instrument derived timing, pointing, and mechanical status. OLA data are reduced using software developed at APL and CSA/MDA. The data reduction methodology is similar to that used by Co-I Barnouin on NEAR and Hayabusa [Barnouin-Jha et al. 2008], as well as the Mercury Laser Rangefinder [Barnouin-Jha et al. 2009]. Un-calibrated data are lidar footprints with associated instrument timing, spatial and temperature information. Calibrated data are lidar footprint data that are geometrically calibrated to yield asteroid shape information.

OVIRS: The data from OVIRS consists of visible and near infrared point spectra and ancillary instrument data. OVIRS follows a performance verification and calibration plan similar to that used by Co-I Reuter for the New Horizons Ralph/LEISA [Reuter et al. 2008], but using Earth and internal calibration lamps in place of solar calibrations. Data reduction is straightforward and includes bias and background removal, as well as spectral calibration. Un-calibrated data are raw OVIRS spectral data. Calibrated data are radiometrically calibrated spectral data and instrument temperature trend data.

OTES: OTES data consists of thermal infrared interferograms and ancillary instrument data. Radiometric calibration is provided by periodic views of space and an internal calibration flag. Reduction of interferograms to calibrated radiance follows a methodology similar to that used by Co-I Christensen for the MER Mini-TES instruments [Christensen et al., 2003]. Un-calibrated OTES data are raw voltage spectra with ancillary instrument data. Raw interferograms will not be archived. Calibrated OTES data are radiometrically-calibrated spectra with associated instrument data.

REXIS: As a Student Collaboration Experiment (SCE), REXIS will be incorporated into the OSIRIS-REx spacecraft on a non-impact basis and will remain clearly separable from the rest of the OSIRIS-REx investigation. Data analysis will be handled as a student project, available to both Harvard and MIT students, for credit or non-credit within the MIT curriculum, and within the MIT Undergraduate Research Opportunities Program (UROP). Over 15 semesters, more than 100 undergraduate, and more than 10 graduate students from MIT and Harvard are expected to participate in the REXIS project. Only raw REXIS telemetry sorted into science observations and housekeeping data will be archived to the PDS.

TAGCAMS: TAGCAMS is a camera suite that consists of the navigation camera (NavCam), the natural feature tracking camera (NFTCam) and the stowage camera (StowCam). NavCam data consists of images and auxiliary data of temperatures and voltages recorded during remote operation. Images are not calibrated, they are simply observations reconstructed from raw telemetry and appended with appropriate timing and spatial metadata. Housekeeping observations are converted from DN values to physical units and packaged by time. As TAGCCMS are all spacecraft engineering components, calibrated data products are not necessary for their primary mission function, as such calibrated data products will not be produce.

DSN Radiometric Data: This data set is comprised of DSN tracking data as well as the ancillary files necessary to interpret and analyze the tracking data. Data products to be archived are Orbit Data Files (TR-2-34), DSN light time files, DSN media calibration files, DSN weather data,

SPICE: The Navigation and Ancillary Information PDS Node will archive all SPICE kernels used by the OSIRIS-REx Mission. Archived kernels will include leap second kernels (LSK), spacecraft clock kernels (SCLK), planetary constants kernels (PCK), ephemeris and trajectory kernels (SPK), orientation kernels (CK), frame kernels (FK), instrument kernels (IK), digital shape kernels (DSK), and event kernels (EK). Other kernels may be added as mission progresses. SPICE kernels used to process instrument data will also be cross-listed in instrument-specific bundles.

4.4.3 Derived Bundles

Higher-Level products are bundled by disciple area as listed in Table 18. The bundles contain collections of derived data products. Higher-Level OSIRIS-REx derived data products are produced at the SPOC using algorithms developed by subject matter specific Working Groups consisting of subsets of the Science Team. Science team members are

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assigned to the working groups based on area of expertise and interest. See 3.4.2 and 3.4.3 for a complete discussion of higher-level data processing and the Science Working Groups.

4.4.4 Special Derived Science Data Bundles

The OSIRIS-REx team has identified two types of special derived science bundles, remote asteroid observations and sample site selection data. During proposal development and in the years leading to asteroid encounter a number of OSIRIS-REx science team members have made ground and space-based observations of Bennu. These observations include visible CCD images, visible spectra, near-Infrared spectra, radar data, Spitzer data, astrometry data, and orbital elements and ephemerides. Data that are not routinely ingested into other public data archives will be ingested into the PDS/SBN using standard, well-defined procedures on a predefined schedule. Data that are available in other archives will be cataloged, so that users can see the complete set of OSIRIS-REx Science team ground-based observations. Table 19 – Remote Observations details the products to be cataloged or archived.

The second bundle of special derived science data products identified is the group of derived data products from which the sample site selection is made. These data products may not be the ultimate data set for science purposes, but they are the operational data set from which the site selection was made. The sets of Science Value, Sampleability, Deliverability and Safety Maps will be archived, along with an explanation of how these data products were produced. The data products that are inputs to the Sampleability, Deliverability and Safety are also expected to be included in the sample site decision special product. Additionally, the TAG reconstruction data product that describes what happened during the TAG event will also be included. Other products may be added to the special product as needed to document the sample site selection and sampling event.

5 ARCHIVE GENERATION, VALIDATION, AND TRANSFER

5.1 Roles and Responsibilities

5.1.1 OSIRIS-REx

The OSIRIS-REx Project and the OSIRIS-REx Principal Investigator have the overall responsibility for generation and validation of PDS-compliant archives for release to the PDS. To accomplish these tasks the Project has appointed an Archiving Lead (Archive Scientist) to oversee the archiving process and has consolidated archiving activities at the SPOC. The Project will ensure archive transfers to the PDS according to the plans specified in this document and in detail in relevant Interface Control Documents. In preparation for

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the delivery of archive products, the Project will conduct an end-to-end validation of the SPOC led archive process.

Coordination and oversight of the implementation of this Archive Plan and relevant Interface Control Documents is accomplished by the formation of the OSIRIS-REx Data Products Working Group (DPWG). The DPWG will consist of members of the science team who are cognizant of, and involved in archive preparation, together with relevant Project and PDS personnel.

5.1.1.1 Science Processing and Operations Center

The SPOC implements, validates, and packages data reduction algorithms into an automated routine (pipeline) that prepares data for delivery to the PDS. Instrument Providers deliver to the SPOC data processing algorithms and documentation for each instrument. Individual data product algorithms and the pipeline package are configuration-controlled and comply with all PDS standards and formats. An end-to-end validation and PDS peer review of the pipeline followed by review lien resolution will be completed prior to the start of regular PDS deliveries (See the OSIRIS-REx Archive Pipeline Configuration Control Plan (AD-13) for a discussion of the archive CM process). See Section 3.4 for a complete discussion of pipeline data processing at the SPOC.

The SPOC contains all the necessary resources for the relevant Science Working Groups to produce specific derived data products based on the OSIRIS-REx Level-2 science requirements. See Table 18 for a list of these data products and the responsible working group. OSIRIS-REx derived data products are subject to validation, PDS peer review and review lien resolution prior to delivery to the PDS. See Sections 3.4.2 and 3.4.3 for a complete discussion of higher-level data product processing.

5.1.2 PDS Small Bodies Node

The PDS Small Bodies Node (PDS/SBN) will be the lead PDS discipline node for the OSIRIS-REx mission and will serve as the interface between the Project and the PDS.

The PDS/SBN will work with Project Personnel, through the DAWG and through bilateral discussions to ensure that the OSIRIS-REx archives are compatible with PDS standards and formats. These deliberations will be formalized through generation and approval of Interface Control Documents that specify procedures and institutional arrangements for transfer of validated archives to the PDS.

The PDS/SBN is responsible for accepting validated, PDS-compliant archives from the OSIRIS-REx Project and making the archives available to the research and other communities, according to the plans specified in this document.

5.1.3 National Space Science Data Center

The NSSDC will maintain a deep archive of OSIRIS-REx data for long-term preservation and for filling large delivery orders to the science community and other customers. PDS/SBN will submit all OSIRIS-REx PDS-archived data products to NSSDC for deep archive.

5.2 Archive Generation

An archive is a logical construct that is independent of the medium on which it is stored. OSIRIS-REx personnel generate science data products at the SPOC located at the University of Arizona. The SPOC assembles data products, ancillary data, calibration data, documentation and context files to produce complete PDS archive bundles.

An automated configuration-controlled pipeline process is used to generate un-calibrated and calibrated science data products in PDS compliant formats. Irreversibly processed and derived data products are produced at the SPOC in the science data processing environments. Each data file (data table or image file) is in a format approved by PDS and will be accompanied by a PDS "label," which describes the content and structure of the accompanying data file. Navigation and geometry data necessary to interpret the data (e.g., spacecraft ephemeris and attitude records, command histories, and spacecraft housekeeping files) are provided as ancillary archive components. Calibration data are provided where necessary for instrument data. In addition, files documenting the archive components will be prepared by the SPOC. In general, all information necessary to interpret and use the data is to be included in the archive.

The PDS context objects, contained in the context collections of each bundle, refer to context documentation files describing the mission, spacecraft, instruments, and data products. These documentation files are maintained in a PDS context repository and are available to provide context information enabling future scientists to make correct use of the data when mission personnel are no longer available to support them.

The Navigational and Ancillary Information Facility (NAIF) will generate an archive bundle of all OSIRIS-REx SPICE data using well-established processes and procedures.

5.3 Archive Validation and Peer Review

Data validation falls into three categories, validation of data packets, validation of the compliance of the data archive with PDS archiving standards, and validation of usefulness of data for scientific purposes. The SPOC is responsible for validation of data packets as they are received from the spacecraft telemetry data stream. Comparing checksums as data are ingested into the OSIRIS-REx database validates data packets. The OSIRIS-REx science team is responsible for validating that the data are of the appropriate coverage areas and of sufficient quality to produce the required data products.

The PDS, in conjunction with the OSIRIS-REx archive team, is responsible for validating that data archives are in compliance with PDS archiving standards. This validation is performed throughout the design lifecycle of each data product. Sample data products are produced by the OSIRIS-REx team, and are presented to the PDS for comment. An iterative process is used to ensure that data products conform to PDS standards. As data product formats stabilized, data format peer reviews were held. Table 22 contains a list of the data format peer reviews held and their completion dates.These reviews looked at early iterations of the planned instrument data products to ensure that the planned products met PDS4 standards and were the appropriate products for the scientific community.

The PDS/SBN conducts pipeline, in-flight and single delivery peer reviews that evaluate the archive bundles for data content, adequacy of documentation, and most importantly, usefulness of the data for scientific purposes. The peer review process is coordinated by the PDS/SBN, using reviewers who are unfamiliar with the data archive, but who are experts in the type of data presented in the archive. The peer review process typically results in "liens" against the archive. The OSIRIS-REx team is responsible for resolving the liens before regular delivery of data begins. The OSIRIS-REx team has planned time within the PDS development schedule for peer reviews and end-to-end delivery validation tests on un-calibrated and calibrated data products, the data processing pipeline, and higher-level derived data products produced by the SPOC science data processing elements. Once peer reviews and lien resolutions are complete, the PDS conducts a final validation and check before data are released. See Section 7 for a complete schedule of data product reviews.

5.4 Transfer

Transfer of the raw observations, un-calibrated, calibrated and derived data to the OSIRIS-REx Science Team is the responsibility of the SPOC. All data transfer is likely to be electronic, and most data processing will be housed at the SPOC. Transfer of data from science team members to the SPOC and the SPOC data repository will for the most part be electronic, however it is possible some transfers could occur on such media as optical and magnetic disks. Transfer of archive products to the PDS during the mission shall be by electronic means. The specifics of this transfer will be detailed closer to the time of data transfer, with the nominal transfer method being sftp.

5.4.1 Delivery Schedule

The delivery schedule for un-calibrated and calibrated data products as well as all other data products is presented in Table 20. The delivery schedule is compliant with the New Frontiers Program Plan, and is the preferred PDS/SBN delivery schedule. Further refinement of the delivery schedule may take place as the program progresses. Generally, the delivery schedule is a first delivery of data delivered 9 months after the start of encounter, with regular deliveries every 3 months of data 6 to 9 months old. The OSIRIS-REx local data dictionaries will be delivered with the first official data delivery.

Table 20. OSIRIS-REx Nominal Delivery Schedule

PDS Delivery	Data Collected From	Data Collected To	Delivery To SBN
EGA Cal + 1st Half cruise	Launch	EGA	2018-05-22
2nd Half Cruise	2017-10-22	2018-08-16	2018-11-16
Prelim Coordinate System	N/A	N/A	2019-02-01
Pipeline Products 1	2018-08-17	2018-11-17	2019-05-17
Pipeline Products 2	2018-11-17	2019-02-17	2019-08-17
Pipeline Products 3	2019-02-17	2019-05-17	2019-11-17
Pipeline Products 4	2019-05-17	2019-08-17	2020-02-17
Pipeline Products 5	2019-08-17	2019-11-17	2020-05-17
Pipeline Products 6*	2019-11-17	2020-02-17	2020-08-17
Pipeline Products 7*	2020-02-17	2020-05-17	2020-11-17
Pipeline Products 8*	2020-05-17	2020-08-17	2021-02-17
Final Coordinate System	Encounter		Stow + 3 Months
Special Product 1	Remote Observations		2017-09-01
Special Product 2	Sample Site Products		Stow + 1 year
Higher-Level Products	Encounter		Departure +1 year

* Pipeline Product Deliveries 6, 7, and 8 are not needed with the current DRM schedule, however we expect to produce them as schedule margin is applied to mission events. Should TAG be delayed after July 2020, additional pipeline deliveries will be scheduled.

Table 21 presents a list of mission phases for reference.

Table 21. Mission Events

Mission Phase Start	***Date***
Launch	2016-09-08
Cruise 1	2016-10-05
Earth Flyby	2017-06-24
Earth Gravity Assist	2017-09-22
Cruise 2	2017-10-22
Approach	2018-08-17

Mission Phase Start	*Date*
Preliminary Survey	2018-11-19
Orbital A	2018-12-09
Detailed Survey	2019-01-09
Orbital B	2019-03-13
Recon Phase	2019-05-12
TAG Rehearsal	2019-08-18
TAG 1	2019-09-29*
Sample Stow	TAG + 1 Month
TAG 2	If Needed
TAG 3	If Needed
Quiescent Orbit	2019-10-22
Departure	2021-03-03
Earth Return	2023-09-24

* with application of schedule reserves, this date likely pushes back to July 2020.

The PDS peer review schedule can be found in Appendix B - PDS Peer Review Schedule

5.5 Distribution

Once released to the PDS, the OSIRIS-REx archives will be available on-line through a set of PDS search and retrieval tools. The SBN plans to incorporate OSIRIS-REx archive bundles into the Small Bodies Image Browser, which will allow a user to search for images based on a number of search criteria.

6 APPENDIX A – OSIRIS-REX DATA LEVELS

Table 22. OSIRIS-REx Data Levels

Level		
PDS4 Level	OSIRIS – REx Level	Defintion
Raw	OREx Level 0	*Telemetry*. Raw instrument data reconstructed from telemetry with header and ancillary information appended. Appended header and ancillary data are data necessary for further processing.
Partially Processed	OREx Level 1	*Uncalibrated.* Data in one of the fundamental structures. This data will be archived to the PDS.
Calibrated	OREx Level 2	*Calibrated*. Data in units proportional to physical units. Because PDS allows offsets and scaling factors in its array and table structures, this would be the minimum level capable of satisfying the "in physical units" requirement. These data will be archived to the PDS
Derived	OREx Level 3	*Irreversibly processed*. Higher-level products from a single source that cannot be losslessly converted back to the lower-level products from which they were derived. These might also satisfy the "in physical units" requirement.
Derived	OREx Level 4	*Derived data*. Products created by combining data from more than one source (instrument, observer, etc.).

7 APPENDIX B - PDS PEER REVIEW SCHEDULE

The review schedule presented below is the currently proposed OSIRIS-REx schedule. This schedule has been negotiated between the UA SPOC and the PDS SBN, and reflects the maturity of the software development process at various stages throughout the mission.

Table 22. PDS Peer Review Schedule

Review Type	Review Name	Review Start
Data Product Format Review		
	OCAMS Raw and Calibrated	*2014-11-21
	OLA, Raw and Calibrated	*2015-01-12
	OTES Raw and Calibrated	*2015-04-28
	Derived Higher-Level Data Products	2017-06-01
Pipeline Peer Reviews		
	NavCam/OCAMS Raw and Calibrated	2016-08-15
	OLA Raw and Calibrated	2016-08-15
	OTES and OVIRS Raw and Calibrated	2016-08-15
	Image Processing I/F Images	2017-05-15
	SAWG Spot Products	2017-05-15
	Radio Science (DSN data)	2017-09-15
In-Flight Reviews		
	OCAMS Pipeline Products	2018-06-01
	NavCam Pipeline Products	2018-06-01
	OLA Pipeline Products	2019-06-01
	OTES and OVIRS Pipeline Products	2018-06-01
	Radio Science (DSN data) Pipeline Products	2019-06-01
Other Reviews		
	Special Product 1 Delivery Review	2017-09-01
	SPICE	2018-03-15
	Coordinate System Review	2019-02-15
	Special Product 2 Delivery Review	Stow +1 year
	Derived Higher-Level Data Products Delivery Review	2022-06-15

*Actual start dates

8 APPENDIX C – REFERENCES

Barnouin-Jha, O.S. , A. F. Cheng, T. Mukai, S. Abe, N. Hirata, R. Nakamura, R. W. Gaskell, J. Saito, and B. E. Clark. Small-scale topography of 25143 Itokawa from the Hayabusa laser altimeter. Icarus, 198(1):108–124, 2008.

D.S. Lauretta. OSIRIS-REx Asteroid Sample-Return Mission. J.N. Pelton, F. Allahdadi (eds.), Handbook of Cosmic Hazards and Planetary Defense, DOI 10.1007/978-3-319-03952-7_44, 2015.