Orion Optical Navigation

2021 Flight Software Workshop

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OpNav Contacts

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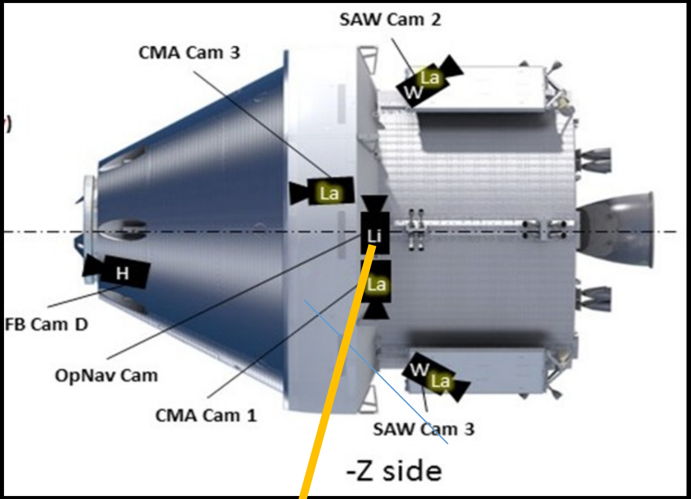
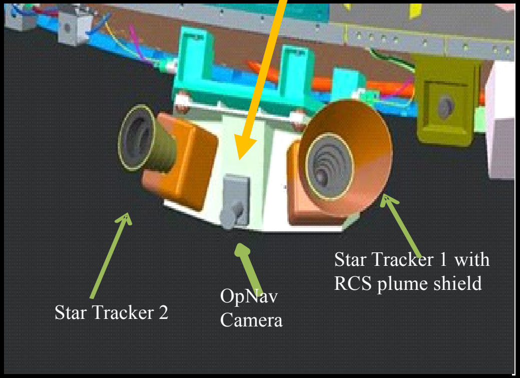
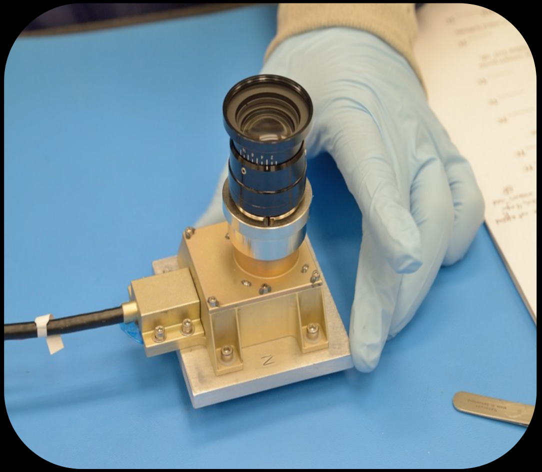
Orion Optical Navigation (OpNav) Software



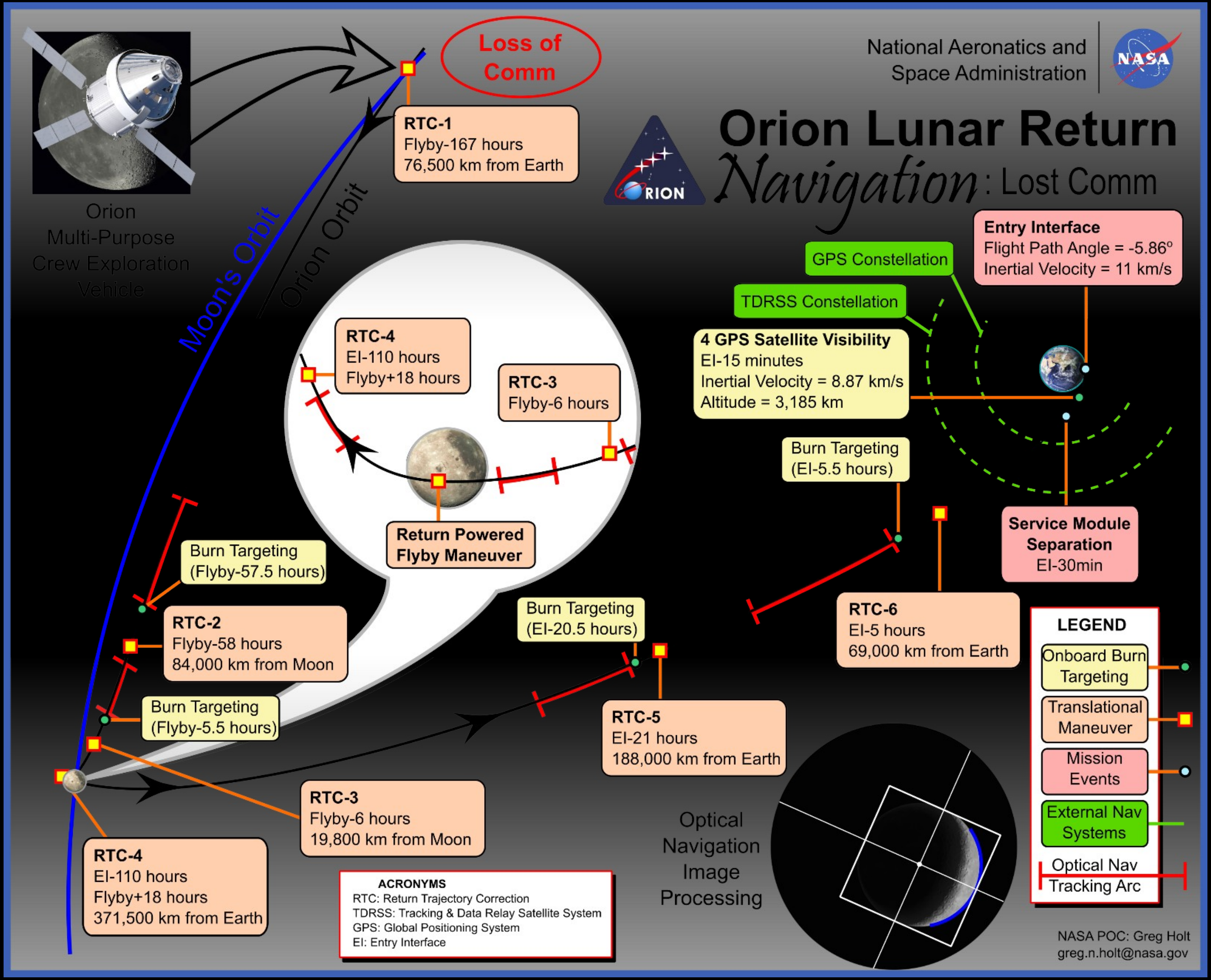
- Optical still images are processed for autonomous spacecraft navigation
  - Completes the mission if Earth communication is lost
  - Onboard computed navigation data substitutes for nominally provided ground trajectory course maneuver updates





- Fixed mounted commercial optical camera

Loss of Comm Navigation



Loss of Comm

National Aeronautics and Space Administration

Orion Lunar Return Navigation: Lost Comm

Orion Multi-Purpose Crew Exploration Vehicle

Moon's Orbit

Orion Orbit

RTC-1
Flyby-167 hours
76,500 km from Earth

Entry Interface
Flight Path Angle = -5.86°
Inertial Velocity = 11 km/s

GPS Constellation

TDRSS Constellation

4 GPS Satellite Visibility
EI-15 minutes
Inertial Velocity = 8.87 km/s
Altitude = 3,185 km

RTC-4
EI-110 hours
Flyby+18 hours

RTC-3
Flyby-6 hours

Return Powered Flyby Maneuver

Burn Targeting
(EI-5.5 hours)

Service Module Separation
EI-30min

Burn Targeting
(Flyby-57.5 hours)

RTC-2
Flyby-58 hours
84,000 km from Moon

Burn Targeting
(EI-20.5 hours)

RTC-6
EI-5 hours
69,000 km from Earth

Burn Targeting
(Flyby-5.5 hours)

RTC-5
EI-21 hours
188,000 km from Earth

RTC-3
Flyby-6 hours
19,800 km from Moon

RTC-4
EI-110 hours
Flyby+18 hours
371,500 km from Earth

Optical Navigation Image Processing

LEGEND

- Onboard Burn Targeting
- Translational Maneuver
- Mission Events
- External Nav Systems
- Optical Nav Tracking Arc

ACRONYMS
RTC: Return Trajectory Correction
TDRSS: Tracking & Data Relay Satellite System
GPS: Global Positioning System
EI: Entry Interface

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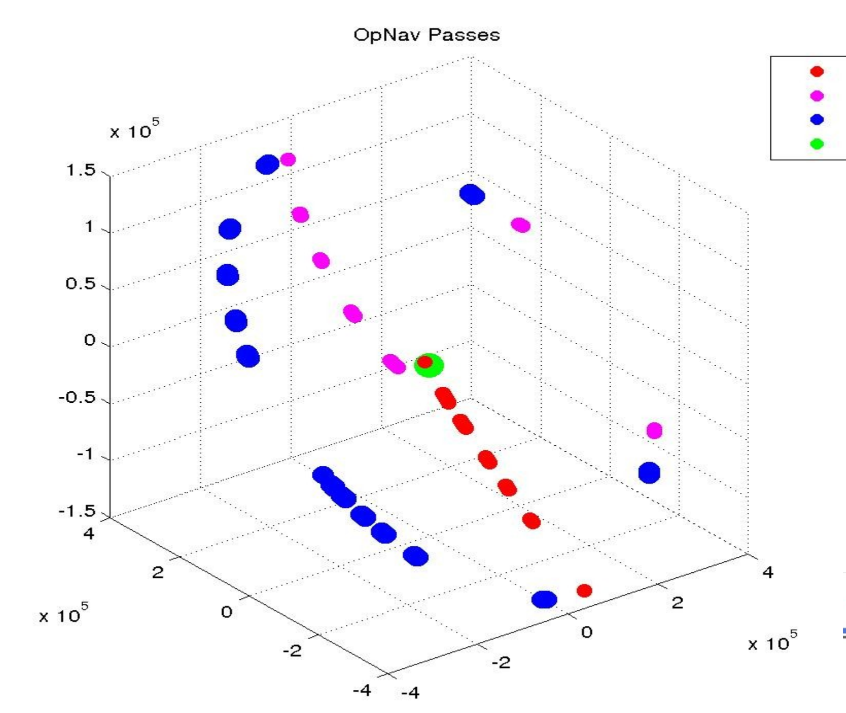
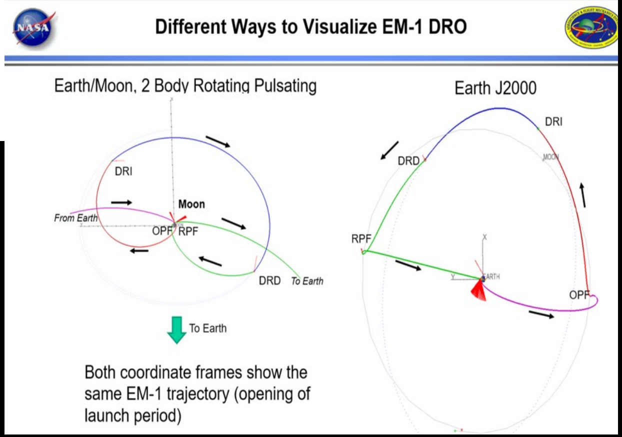
Orion EM-1 OpNav Pass Visualization



- Images taken every 30 seconds during dedicated "OpNav Passes"
  - Vehicle slewed to take measurements



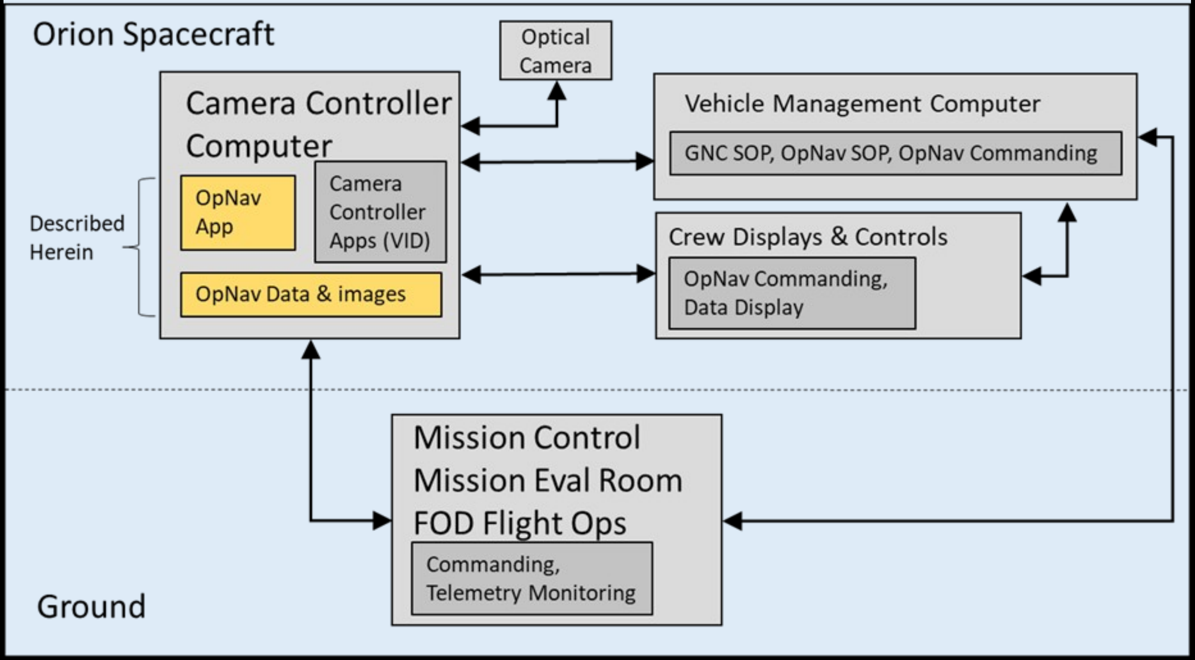
Different Ways to Visualize EM-1 DRO

Earth/Moon, 2 Body Rotating Pulsating

Earth J2000

Both coordinate frames show the same EM-1 trajectory (opening of launch period)

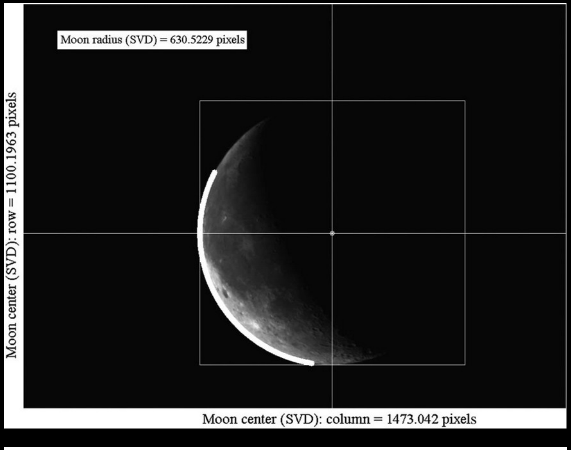
Orion Optical Navigation (OpNav) System Architecture

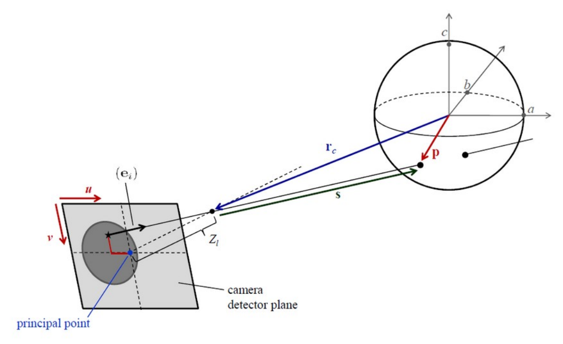

Orion Spacecraft
Optical Camera
Camera Controller Computer
OpNav App
Camera Controller Apps (VID)
OpNav Data & images
Described Herein
Vehicle Management Computer
GNC SOP, OpNav SOP, OpNav Commanding
Crew Displays & Controls
OpNav Commanding, Data Display
Mission Control
Mission Eval Room
FOD Flight Ops
Commanding, Telemetry Monitoring
Ground

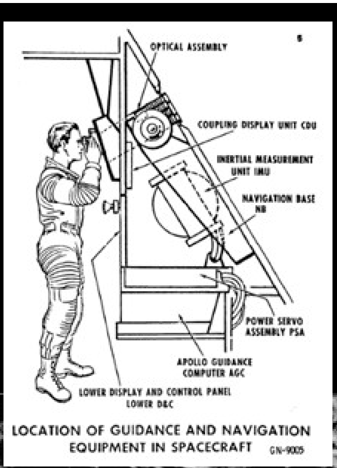
- OpNav Software Runs on a Camera Control Computer, external from the primary flight computers
    - 64-bit Linux running Core Flight System (CFS)
    - Images taken when commanded by GNC
- Bi-directional communication with GNC software in primary flight computers
    - Star tracker data, closed loop exposure adjustments
    - Range, bearing, attitude provided in real time

OpNav Software Basics

- Still images of Moon or Earth are processed to find apparent angular diameter and centroid in camera focal plane
  - This raw data is transformed into range and bearing angle measurements using planetary data and precise star tracker inertial attitude
- Artemis Mission Progression
  - Artemis 1 – range/bearing with star tracker attitude
  - Artemis 2 – self attitude determination from star centroiding
  - Artemis 3 – rendezvous targeting for Gateway
- The measurements are sent to the main flight computer’s Kalman filter to update the onboard state vector.
- Calibrates and undistorts images in real-time based on star centroids
- Class A Safety-Critical Software, developed according to the following process standards:
  - NPR 7150.2B
  - CMMI Level 3
- 18 month development time for Artemis I

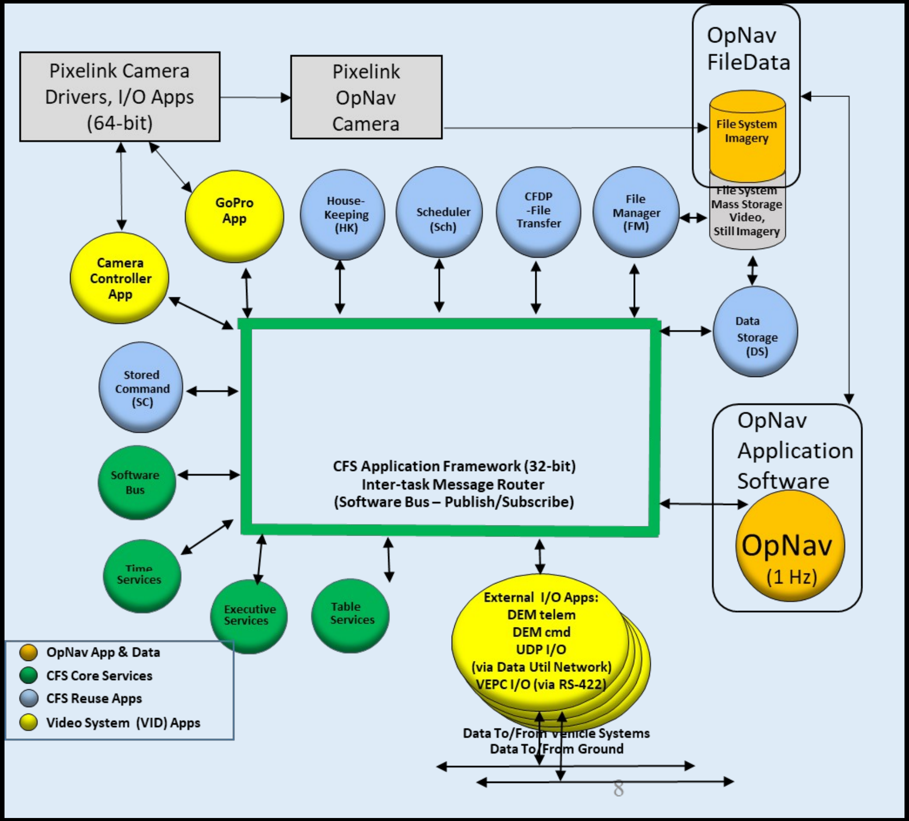





OPTICAL ASSEMBLY
6
COUPLING DISPLAY UNIT CDU
INERTIAL MEASUREMENT UNIT IMU
NAVIGATION BASE NB
POWER SERVO ASSEMBLY PSA
APOLLO GUIDANCE COMPUTER AGC
LOWER DISPLAY AND CONTROL PANEL LOWER D&C
GN-9005

LOCATION OF GUIDANCE AND NAVIGATION EQUIPMENT IN SPACECRAFT

Orion Optical Navigation (OpNav) Software Architecture



Pixelink Camera Drivers, I/O Apps (64-bit)

Pixelink OpNav Camera

OpNav FileData

File System Imagery

File System Mass Storage Video, Still Imagery

GoPro App

Camera Controller App

House-Keeping (HK)

Scheduler (Sch)

CFDP -File Transfer

File Manager (FM)

Data Storage (DS)

Stored Command (SC)

Software Bus

Time Services

Executive Services

Table Services

CFS Application Framework (32-bit)
Inter-task Message Router
(Software Bus – Publish/Subscribe)

OpNav Application Software

OpNav (1 Hz)

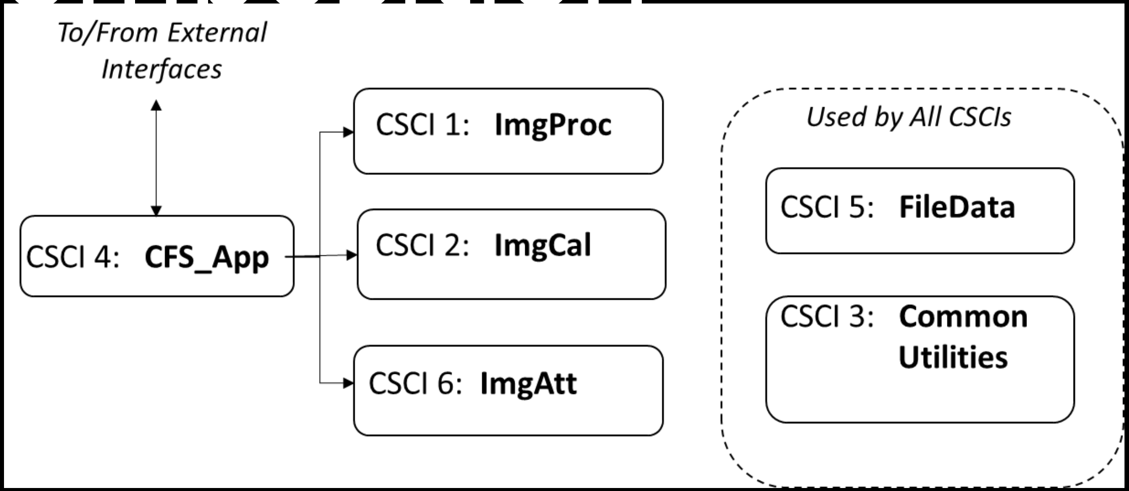
External I/O Apps:
DEM telem
DEM cmd
UDP I/O
(via Data Util Network)
VEPC I/O (via RS-422)

Data To/From Vehicle Systems
Data To/From Ground

- 🟧 OpNav App & Data
- 🟩 CFS Core Services
- 🟦 CFS Reuse Apps
- 🟨 Video System (VID) Apps

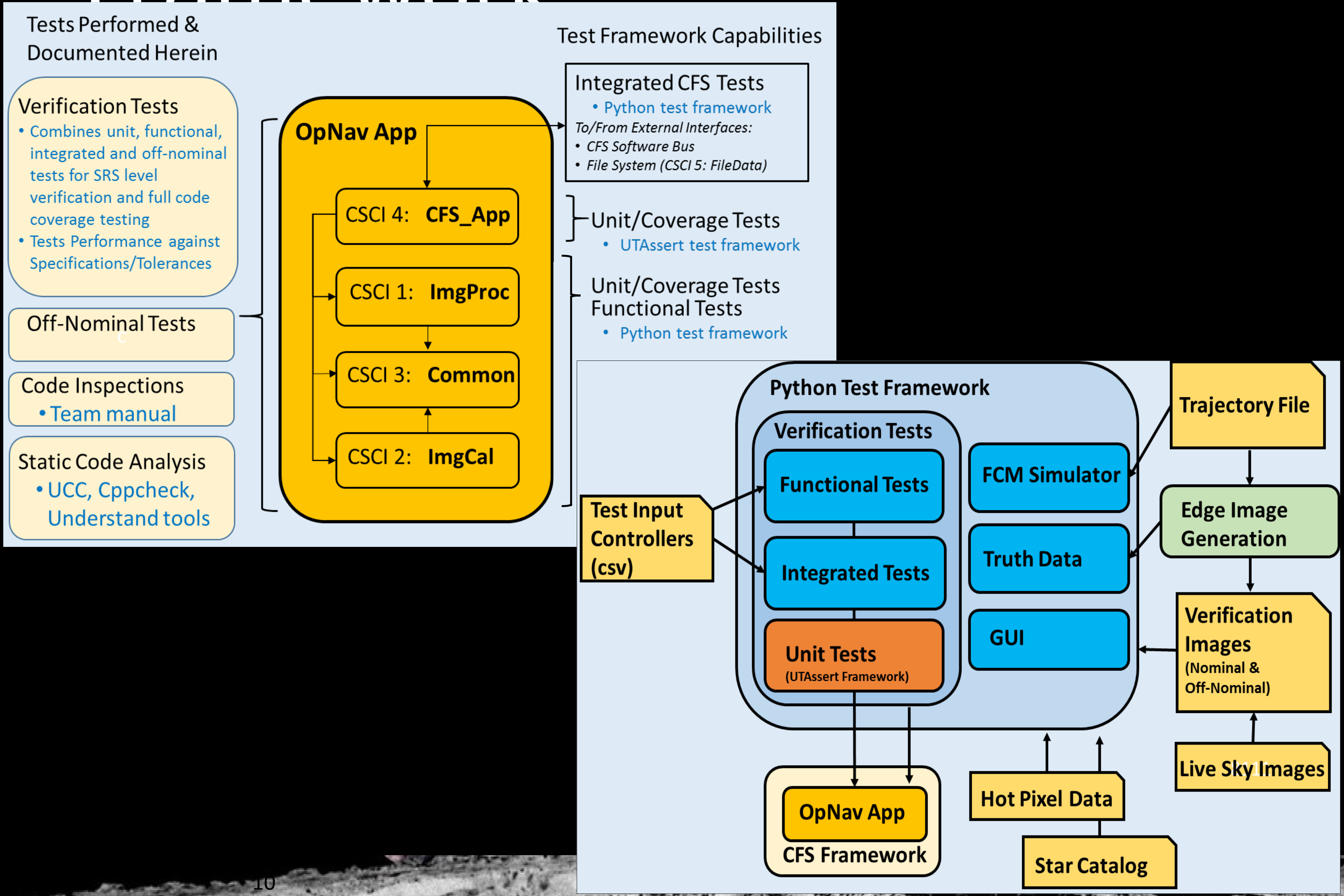
- OpNav is Single CFS App at 1 Hz
    - Reads images from file system
- Camera Drivers running in “non CFS” environment communicate with CFS Camera Controller Apps to take and store images as instructed by GNC
- Data Sent to/from Orion onboard network with Custom Orion CI/TO functioning Applications

Opnav Software Decomposition



CSCI Number	CSCI Name	Description
1	OpNav_ImgProc	ImgProc Performs calculations necessary to produce range and bearing information to a target planetary body from optical image data.
2	OpNav_ImgCal	ImgCal analyzes star field image data to produce data that characterizes image distortions and camera alignment adjustments. It also includes object centroiding.
3	OpNav_Common	Common provides utility functions and math libraries needed as service routines to the other CSCI's. It also provides image processing utilities, interpolation functions, sorting, and ephemeris calculations.
4	OpNav_CFS_App	CFS_App is the outermost application running part of the CFS framework, serves as the overall driver for optical navigation and calibration functionality, implements external interfaces, manages global data, and provides real-time control.
5	OpNav_FileData	FileData consists of files and/or tables of data both needed as well as produced by CSCIs which are delivered along with the flight software. This CSCI excludes files and data used for verification. Data used for verification will be outlined in the OpNav software Verification Plan, Procedures, and Report document.
6	OpNav_ImgAtt	ImgAtt performs on-demand attitude determination and star identification based on images exposed to show stars. The images may contain extended objects in the field of view such as the Earth or Moon, or other non-stellar objects.

OpNav Test Types & Framework



Tests Performed & Documented Herein

Verification Tests
- Combines unit, functional, integrated and off-nominal tests for SRS level verification and full code coverage testing
- Tests Performance against Specifications/Tolerances

Off-Nominal Tests

Code Inspections
- Team manual

Static Code Analysis
- UCC, Cppcheck, Understand tools

Test Framework Capabilities

Integrated CFS Tests
- Python test framework

To/From External Interfaces:
- *CFS Software Bus*
- *File System (CSCI 5: FileData)*

Unit/Coverage Tests
- UTAssert test framework

Unit/Coverage Tests
Functional Tests
- Python test framework

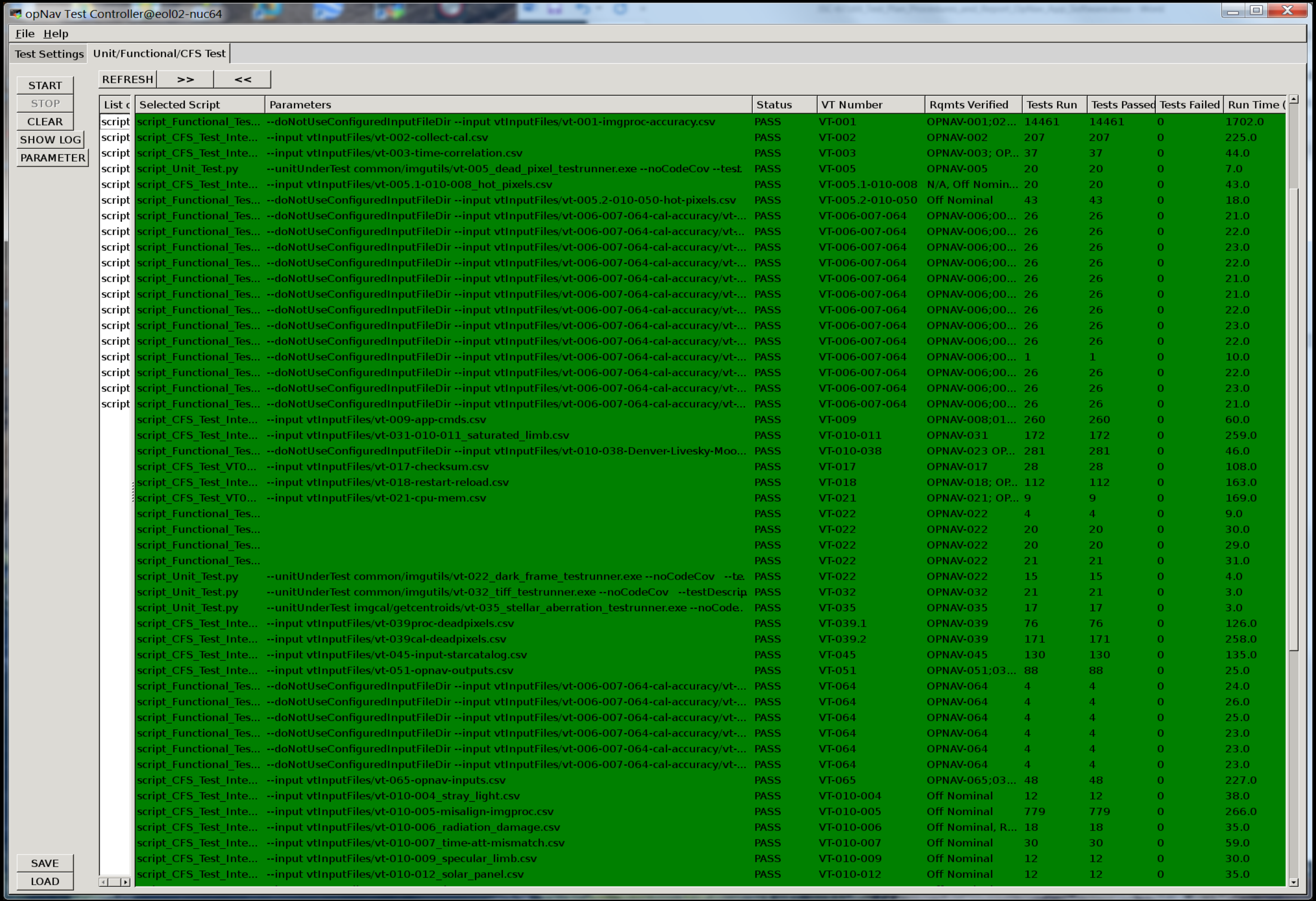
OpNav Software Test Campaign

- Key performance requirements on accuracy of calibration, undistortion, range/bearing, and attitude drove test success criteria
  - No output data allowed out of spec
  - Better to NOT provide output, than provide output out of tolerance
- Test campaign consisted of the following
  - Lifecycle reviews (SDP, SRS, PDR/CDR, VTR, TRR)
  - Unit testing
    - 100% Multiple Condition Coverage – Utassert / gcov
  - Code inspections & static code analysis
  - Verification testing – synthetic imagery
    - Generated with EDGE tool
    - Verification test peer reviews
    - Extensive nominal and off nominal test cases
  - Robustness testing
  - Continuous integration & regression
  - Integration testing – higher fidelity labs
  - Validation – final validation with actual imagery in-flight during outbound leg of Artemis I

Item	Quantification
Flight Software Size (SLOC)	8,800
Test Software Size (SLOC)	35,400
Individual Pass/Fail Test Cases (Total)	21,322
Unit Test Cases	2,769
Verification Test Cases (Nominal)	16,618
Verification Test Cases (Off Nominal)	1,935
Nominal Synthetic Test Images	3,382
Off Nominal Test Images	2,299

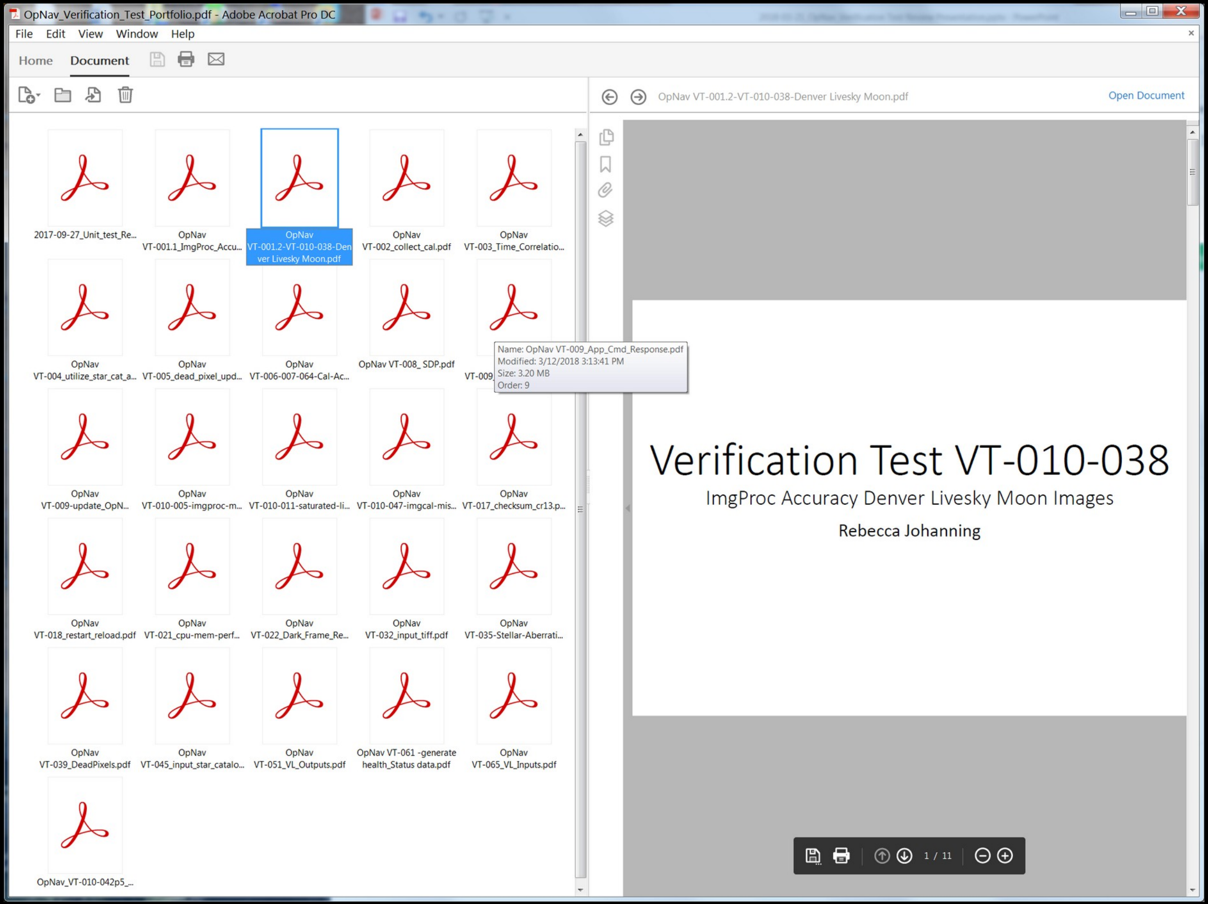
Review Type / Product	Major Issues	Minor Issues
Software Development Plan (SDP)	1	6
Software Requirements Specification (SRS)	4	21
Critical Design Review (CDR)	7	11
Verification Test Review (VTR)	0	7
Test Readiness Review (TRR)	0	0
Code Inspections	49	305

Expected Test Results (Run from opnav_gui)



List c	Selected Script	Parameters	Status	VT Number	Rqmts Verified	Tests Run	Tests Passed	Tests Failed	Run Time (
script	script_Functional_Tes...	--doNotUseConfiguredInputFileDir --input vtInputFiles/vt-001-imgproc-accuracy.csv	PASS	VT-001	OPNAV-001;02...	14461	14461	0	1702.0
script	script_CFS_Test_Inte...	--input vtInputFiles/vt-002-collect-cal.csv	PASS	VT-002	OPNAV-002	207	207	0	225.0
script	script_CFS_Test_Inte...	--input vtInputFiles/vt-003-time-correlation.csv	PASS	VT-003	OPNAV-003; OP...	37	37	0	44.0
script	script_Unit_Test.py	--unitUnderTest common/imgutils/vt-005_dead_pixel_testrunner.exe --noCodeCov --test	PASS	VT-005	OPNAV-005	20	20	0	7.0
script	script_CFS_Test_Inte...	--input vtInputFiles/vt-005.1-010-008_hot_pixels.csv	PASS	VT-005.1-010-008	N/A, Off Nomin...	20	20	0	43.0
script	script_Functional_Tes...	--doNotUseConfiguredInputFileDir --input vtInputFiles/vt-005.2-010-050-hot-pixels.csv	PASS	VT-005.2-010-050	Off Nominal	43	43	0	18.0
script	script_Functional_Tes...	--doNotUseConfiguredInputFileDir --input vtInputFiles/vt-006-007-064-cal-accuracy/vt-...	PASS	VT-006-007-064	OPNAV-006;00...	26	26	0	21.0
script	script_Functional_Tes...	--doNotUseConfiguredInputFileDir --input vtInputFiles/vt-006-007-064-cal-accuracy/vt-...	PASS	VT-006-007-064	OPNAV-006;00...	26	26	0	22.0
script	script_Functional_Tes...	--doNotUseConfiguredInputFileDir --input vtInputFiles/vt-006-007-064-cal-accuracy/vt-...	PASS	VT-006-007-064	OPNAV-006;00...	26	26	0	23.0
script	script_Functional_Tes...	--doNotUseConfiguredInputFileDir --input vtInputFiles/vt-006-007-064-cal-accuracy/vt-...	PASS	VT-006-007-064	OPNAV-006;00...	26	26	0	22.0
script	script_Functional_Tes...	--doNotUseConfiguredInputFileDir --input vtInputFiles/vt-006-007-064-cal-accuracy/vt-...	PASS	VT-006-007-064	OPNAV-006;00...	26	26	0	21.0
script	script_Functional_Tes...	--doNotUseConfiguredInputFileDir --input vtInputFiles/vt-006-007-064-cal-accuracy/vt-...	PASS	VT-006-007-064	OPNAV-006;00...	26	26	0	21.0
script	script_Functional_Tes...	--doNotUseConfiguredInputFileDir --input vtInputFiles/vt-006-007-064-cal-accuracy/vt-...	PASS	VT-006-007-064	OPNAV-006;00...	26	26	0	22.0
script	script_Functional_Tes...	--doNotUseConfiguredInputFileDir --input vtInputFiles/vt-006-007-064-cal-accuracy/vt-...	PASS	VT-006-007-064	OPNAV-006;00...	26	26	0	23.0
script	script_Functional_Tes...	--doNotUseConfiguredInputFileDir --input vtInputFiles/vt-006-007-064-cal-accuracy/vt-...	PASS	VT-006-007-064	OPNAV-006;00...	26	26	0	22.0
script	script_Functional_Tes...	--doNotUseConfiguredInputFileDir --input vtInputFiles/vt-006-007-064-cal-accuracy/vt-...	PASS	VT-006-007-064	OPNAV-006;00...	1	1	0	10.0
script	script_Functional_Tes...	--doNotUseConfiguredInputFileDir --input vtInputFiles/vt-006-007-064-cal-accuracy/vt-...	PASS	VT-006-007-064	OPNAV-006;00...	26	26	0	22.0
script	script_Functional_Tes...	--doNotUseConfiguredInputFileDir --input vtInputFiles/vt-006-007-064-cal-accuracy/vt-...	PASS	VT-006-007-064	OPNAV-006;00...	26	26	0	23.0
script	script_Functional_Tes...	--doNotUseConfiguredInputFileDir --input vtInputFiles/vt-006-007-064-cal-accuracy/vt-...	PASS	VT-006-007-064	OPNAV-006;00...	26	26	0	21.0
	script_CFS_Test_Inte...	--input vtInputFiles/vt-009-app-cmds.csv	PASS	VT-009	OPNAV-008;01...	260	260	0	60.0
	script_CFS_Test_Inte...	--input vtInputFiles/vt-031-010-011_saturated_limb.csv	PASS	VT-010-011	OPNAV-031	172	172	0	259.0
	script_Functional_Tes...	--doNotUseConfiguredInputFileDir --input vtInputFiles/vt-010-038-Denver-Livesky-Moo...	PASS	VT-010-038	OPNAV-023 OP...	281	281	0	46.0
	script_CFS_Test_VT0...	--input vtInputFiles/vt-017-checksum.csv	PASS	VT-017	OPNAV-017	28	28	0	108.0
	script_CFS_Test_Inte...	--input vtInputFiles/vt-018-restart-reload.csv	PASS	VT-018	OPNAV-018; OP...	112	112	0	163.0
	script_CFS_Test_VT0...	--input vtInputFiles/vt-021-cpu-mem.csv	PASS	VT-021	OPNAV-021; OP...	9	9	0	169.0
	script_Functional_Tes...		PASS	VT-022	OPNAV-022	4	4	0	9.0
	script_Functional_Tes...		PASS	VT-022	OPNAV-022	20	20	0	30.0
	script_Functional_Tes...		PASS	VT-022	OPNAV-022	20	20	0	29.0
	script_Functional_Tes...		PASS	VT-022	OPNAV-022	21	21	0	31.0
	script_Unit_Test.py	--unitUnderTest common/imgutils/vt-022_dark_frame_testrunner.exe --noCodeCov --te.	PASS	VT-022	OPNAV-022	15	15	0	4.0
	script_Unit_Test.py	--unitUnderTest common/imgutils/vt-032_tiff_testrunner.exe --noCodeCov --testDescrip	PASS	VT-032	OPNAV-032	21	21	0	3.0
	script_Unit_Test.py	--unitUnderTest imgcal/getcentroids/vt-035_stellar_aberration_testrunner.exe --noCode.	PASS	VT-035	OPNAV-035	17	17	0	3.0
	script_CFS_Test_Inte...	--input vtInputFiles/vt-039proc-deadpixels.csv	PASS	VT-039.1	OPNAV-039	76	76	0	126.0
	script_CFS_Test_Inte...	--input vtInputFiles/vt-039cal-deadpixels.csv	PASS	VT-039.2	OPNAV-039	171	171	0	258.0
	script_CFS_Test_Inte...	--input vtInputFiles/vt-045-input-starcatalog.csv	PASS	VT-045	OPNAV-045	130	130	0	135.0
	script_CFS_Test_Inte...	--input vtInputFiles/vt-051-opnav-outputs.csv	PASS	VT-051	OPNAV-051;03...	88	88	0	25.0
	script_Functional_Tes...	--doNotUseConfiguredInputFileDir --input vtInputFiles/vt-006-007-064-cal-accuracy/vt-...	PASS	VT-064	OPNAV-064	4	4	0	24.0
	script_Functional_Tes...	--doNotUseConfiguredInputFileDir --input vtInputFiles/vt-006-007-064-cal-accuracy/vt-...	PASS	VT-064	OPNAV-064	4	4	0	26.0
	script_Functional_Tes...	--doNotUseConfiguredInputFileDir --input vtInputFiles/vt-006-007-064-cal-accuracy/vt-...	PASS	VT-064	OPNAV-064	4	4	0	25.0
	script_Functional_Tes...	--doNotUseConfiguredInputFileDir --input vtInputFiles/vt-006-007-064-cal-accuracy/vt-...	PASS	VT-064	OPNAV-064	4	4	0	23.0
	script_Functional_Tes...	--doNotUseConfiguredInputFileDir --input vtInputFiles/vt-006-007-064-cal-accuracy/vt-...	PASS	VT-064	OPNAV-064	4	4	0	23.0
	script_Functional_Tes...	--doNotUseConfiguredInputFileDir --input vtInputFiles/vt-006-007-064-cal-accuracy/vt-...	PASS	VT-064	OPNAV-064	4	4	0	23.0
	script_CFS_Test_Inte...	--input vtInputFiles/vt-065-opnav-inputs.csv	PASS	VT-065	OPNAV-065;03...	48	48	0	227.0
	script_CFS_Test_Inte...	--input vtInputFiles/vt-010-004_stray_light.csv	PASS	VT-010-004	Off Nominal	12	12	0	38.0
	script_CFS_Test_Inte...	--input vtInputFiles/vt-010-005-misalign-imgproc.csv	PASS	VT-010-005	Off Nominal	779	779	0	266.0
	script_CFS_Test_Inte...	--input vtInputFiles/vt-010-006_radiation_damage.csv	PASS	VT-010-006	Off Nominal, R...	18	18	0	35.0
	script_CFS_Test_Inte...	--input vtInputFiles/vt-010-007_time-att-mismatch.csv	PASS	VT-010-007	Off Nominal	30	30	0	59.0
	script_CFS_Test_Inte...	--input vtInputFiles/vt-010-009_specular_limb.csv	PASS	VT-010-009	Off Nominal	12	12	0	30.0
	script_CFS_Test_Inte...	--input vtInputFiles/vt-010-012_solar_panel.csv	PASS	VT-010-012	Off Nominal	12	12	0	35.0

Verification Test Review Portfolio



OpNav_Verification_Test_Portfolio.pdf - Adobe Acrobat Pro DC
File
Edit
View
Window
Help
Home
Document
Open Document
1 / 11

OpNav VT-001.2-VT-010-038-Denver Livesky Moon.pdf

2017-09-27_Unit_test_Re...
OpNav VT-001.1_ImgProc_Accu...
OpNav VT-001.2-VT-010-038-Denver Livesky Moon.pdf
OpNav VT-002_collect_cal.pdf
OpNav VT-003_Time_Correlatio...
OpNav VT-004_utilize_star_cat_a...
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OpNav VT-008_ SDP.pdf
VT-009
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OpNav VT-010-011-saturated-li...
OpNav VT-010-047-imgcal-mis...
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OpNav VT-035-Stellar-Aberrati...
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OpNav VT-045_input_star_catalo...
OpNav VT-051_VL_Outputs.pdf
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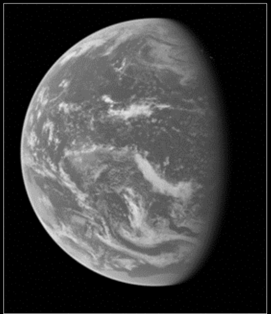
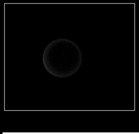
Verification Test VT-010-038

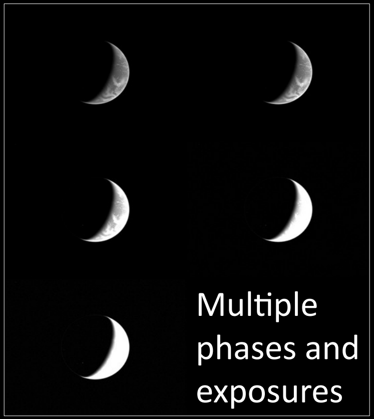
ImgProc Accuracy Denver Livesky Moon Images

Rebecca Johanning

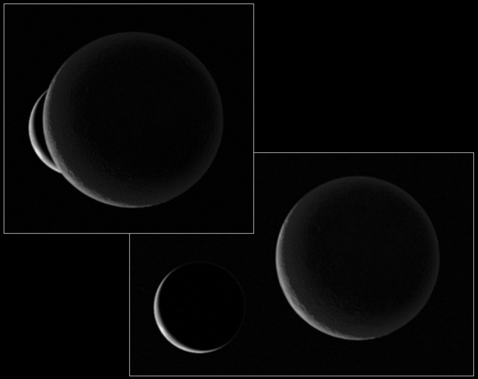
Sample OpNav Synthetic Test Imagery

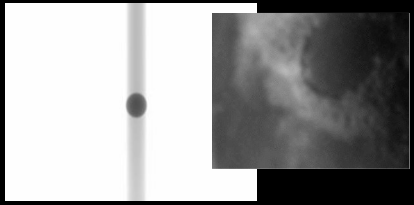



Nominal Images expected during mission timeline

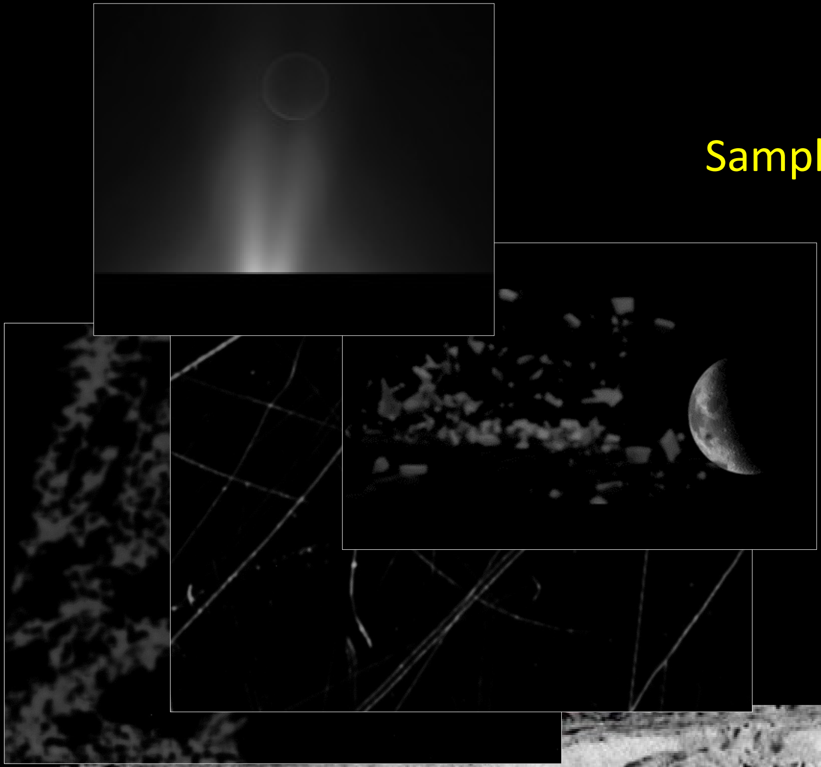
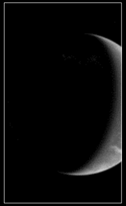
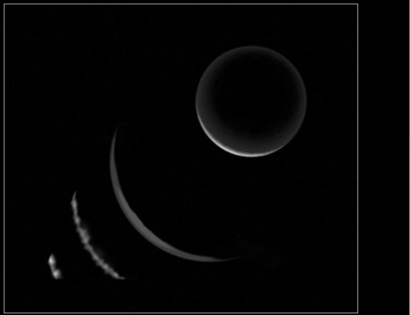
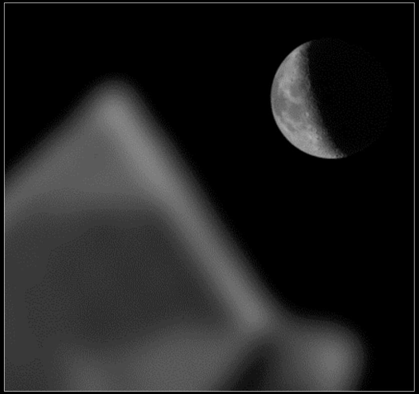


Multiple phases and exposures





Sample Off Nominal Images

Lessons Learned - Observations

- Team started with Matlab/Simulink Autocode and quickly chose to hand code for tighter control, optimization, readability / maintainability, and better control of testing for off-nominal conditions
  - Learning to code in “C” with engineers experienced only on Matlab was *not* a big schedule or learning curve hit, team adapted quickly and easily
- Should have initially used Doxygen to link code to SDD, and generate certain SDD sections – corrected in next release
- Should have used CCDD tool so Requirements & Test Matrix for Commands/Telemetry maintained synchronization with code rather than maintaining by hand – initially thought project “too small”
- Began notion of “Incremental Verification Test Reviews (VTR)” - was a very valuable process addition, peer reviewed each individual verification test with entire group/stakeholders as each test was completed -- spanned over 8 months of time
  - Added an additional useful formal review prior to TRR called “VTR”, Verification Test Review at end to recap all prior “Incremental Verification Test Reviews”
- Code inspections were very value added on this project - if *right people* involved with devoted time
  - Static analysis tools unable to find what was *missing* from code
- Schedule should allow for slack/risk introduced with Class A flight certifying first-time/new technology (crossed many TRL levels rapidly on this project 3 ⎵ 8)
- Testing, yet again, was underscoped. This time took 4x SLOC that of flight code, planned for 2x
  - Should have standard CFS test framework rather than re-invent every time (believe in work at JSC)

Conclusions

- OpNav will be the first autonomous safety-critical onboard navigation system
- OpNav was developed for the Orion Artemis Missions
  - Artemis I – Range/bearing
  - Artemins II - self attitude determination added
  - Artemis III – automated rendezvous targeting for Gateway
- OpNav was developed as Government Furnished Equipment (GFE), and is available US Release
  - https://software.nasa.gov/software/MSC-26456-1

Thank you for your attention