National Aeronautics and
Space Administration

VIPER

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VIPER Technologies

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Rover Software

VIPER Rover Software

VIPER rover's software is split between on-board Rover Flight Software (RFSW) and off-board Rover Ground Software (RGSW).

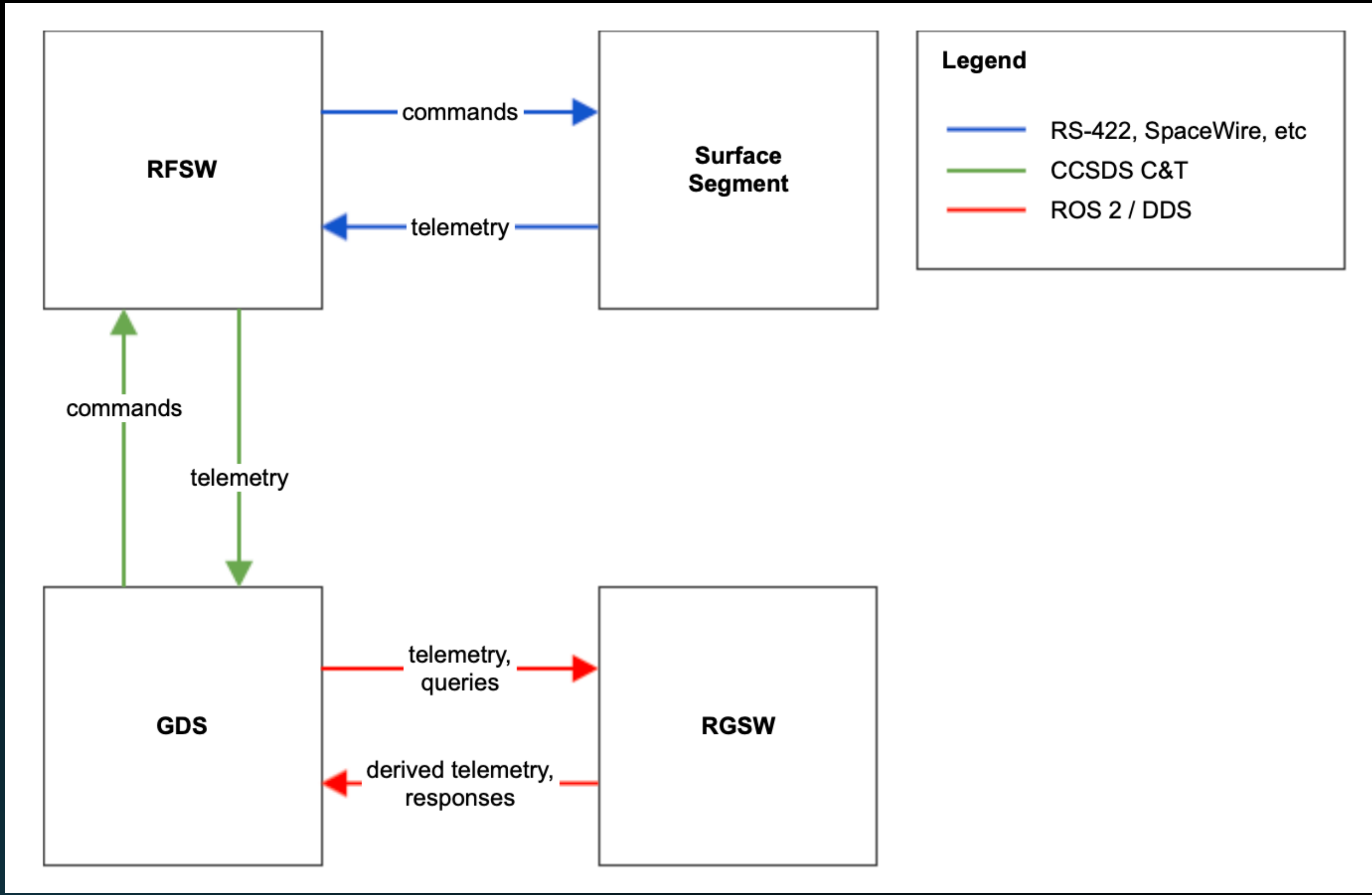
RFSW

- Runs on-board the rover on radiation hardened (RAD 750) and radiation tolerant (AiTech SP0-S)
- Utilizes NASA's Core Flight System (cFS)
- Provides low-level hardware interfaces, basic mobility control, waypoint driving, odometry, basic error checking, and device/payload services

RGSW

- Runs at mission control on Earth using commodity desktop computing
- Implemented as an ensemble of Robot Operating System 2 (ROS2) nodes
- Performs navigation, mapping, and generation of rover driver decision support data

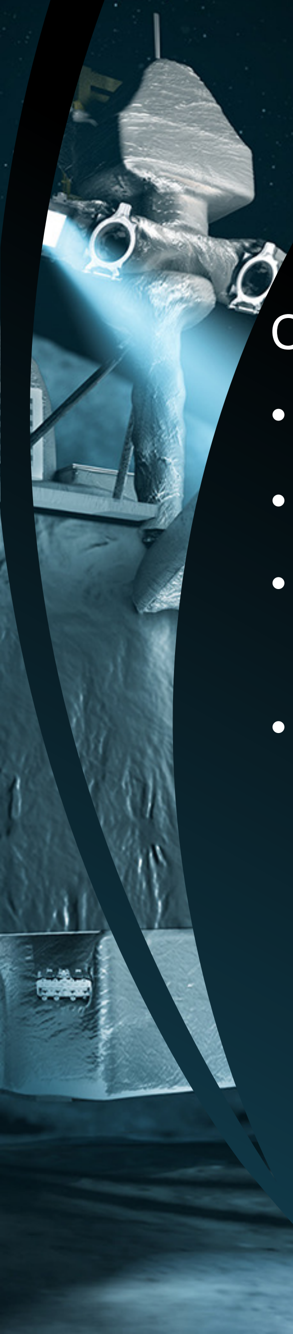
VIPER Software Architecture



Rover Flight Software (RFSW)

RFSW Architecture

- RFSW is the first NASA planetary rover flight software built on the Core Flight System / Core Flight Executive (cFS/cFE) framework and adds specific features needed for rover operations.
- Communication to ground (Mission Operations System) using CCSDS communication standards
- Connected to Rover Simulations by replacing IO-apps to rover avionics with simulator connections
- Functionality
  - Basic space-craft operations: Power, thermal, comm
  - Command and Data Handling (C&DH)
  - "GN&C": Surface mobility functionality up to the level of relative waypoint-driving w/ pose feedback
    - Relative pose estimation using wheel encoders, IMU & star tracker
    - Driving in straight lines (crabbing) between waypoints maintaining selected solar-panel and antennae pointing
    - Closing the control loop on pose to compensate for slip



RFSW Architecture

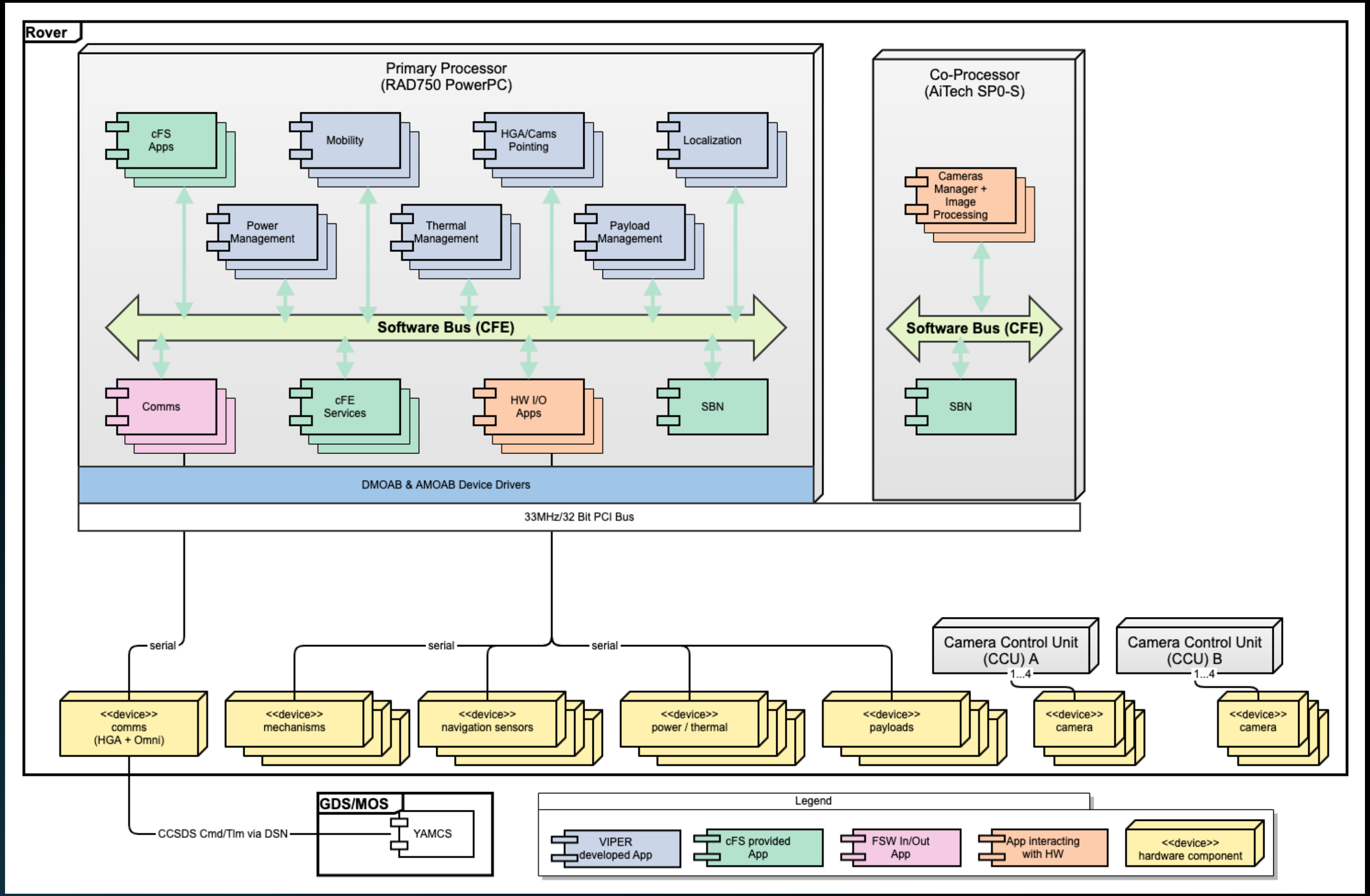
Core Flight Executive (cFE) Application Model

- The software is split into various apps
- Each app executes in a separate thread
- Interprocess data communication via message bus (software bus - SB)
- cFE SB on IAU & co-processor connected via cFS Software Bus Network (single logical SB)

RFSW Applications

- Apps are logically grouped into a set of components realizing the different function of RFSW
- Design is presented at the component level before branching into details of individual apps
- Different components combine apps from multiple sources (cFE, cFS, VIPER).

RFSW Deployment



RFSW Functions

System Services and Apps

Set of basic middleware services

Mode Management

Puts the vehicle into known states (modes) for operations, and for automatic fault responses

Comm Management

Commanding, configuration, monitoring and selection of the rover communication paths

Power Management

Manages the rover charge, power distribution and monitoring

Thermal Management

Maintains the correct temperature of the rover critical systems, and reports the thermal state of the rover to the ground

Mobility Management

Responsible for the motion of the rover chassis. Capable of managing both low-level motion primitives (like individual motor control) and high-level motion behaviors (like waypoint driving)

Navigation Management

Deals with Onboard Localization to support the antenna tracking and mobility functions, and Camera Management and Image Processing to support the ground localization function

Data Management

Handles up-link of commands and data, down-link of telemetry and files, and on-board data management

Payload Management

Fault Management

Contain, prevent, detect, isolate, diagnose, respond to and recover from conditions that may interfere with nominal mission operations

Egress Support

Release the lander-rover interface and the rover mechanisms locks during the Post-Landing Checkout Phase

Platform Management

Takes the Rover IAU from early hardware initialization (after reset/powerup) to a fully configured hardware system and booted operating system kernel capable of loading and running FSW

Gimbal Management (virtual)

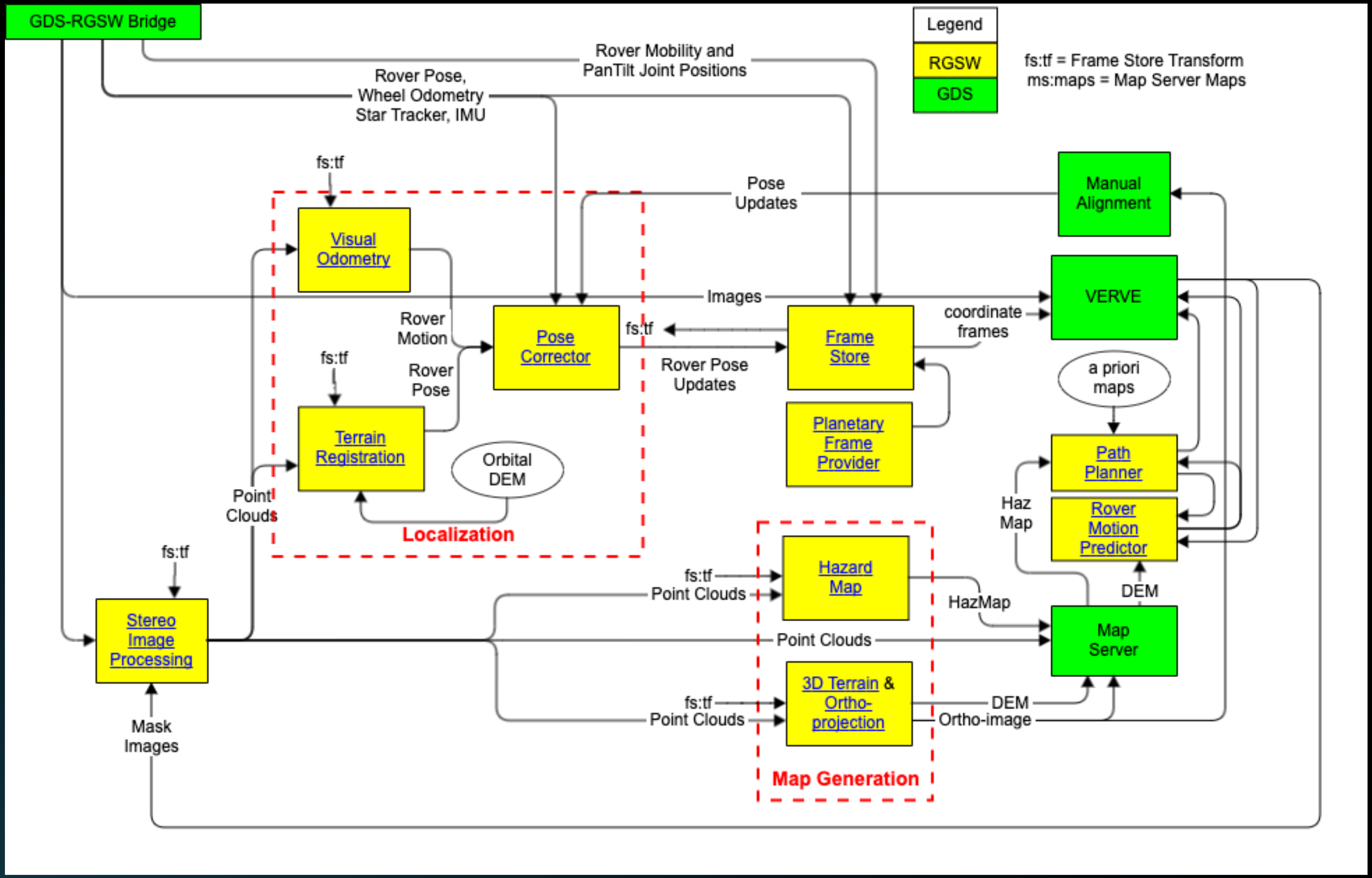
Manages the two gimbals located at the top of the rover mast

Rover Ground Software (RGSW)

RGSW Architecure

- Based on the ROS 2 open-source framework
  - Uses some ROS 2 features "as-is”
    - Predefined message types
    - Existing introspection, visualization, and control tools that are helpful for RGSW development and testing
- Each module runs as a ROS 2 node (or collection of nodes) that communicates with other nodes through the ROS 2 message API (ROS Middle-Ware, or RMW) using anonymous publish/subscribe or service calls.
- Some new and some heritage software is integrated by adding a ROS 2 interface
  - In many cases using existing ROS 2 message types
  - In a few cases defining a new message type or service interface

RGSW Architecture



RGSW Modules

3D Terrain Map

Generates a digital elevation model (DEM) of the local terrain from a given input point cloud

Frame Store

Provides a service to which allows clients to retrieve transformations between coordinate frames

Hazard Map

Produces a map indicating "traversability" of terrain

Orthoprojection

Produces orthographically projected surface maps from stereo camera point clouds

Path Planner

Finds a path from a starting location to a goal location chosen by operators

Planetary Frame Provider

Provides transformations between planetary body-centered frames, local-level surface frames, and map frames

Pose Corrector

Utilizes inputs from visual odometry and terrain registration to improve on the flight software rover localization output

Rover Motion Predictor

Predicts the expected trajectory and endpoint that the Rover will achieve given a waypoint command and a model of the terrain

Stereo Image Processing

Computes 3D point clouds from rover stereo images

Terrain Registration (TR)

Estimates the absolute position of the rover in the map coordinate frame by aligning rover stereo data to an orbital lunar DEM

Visual Odometry

Estimates the relative vehicle pose (position and orientation) between successive stereo image captures to improve the Pose Corrector's estimation of vehicle position and pose

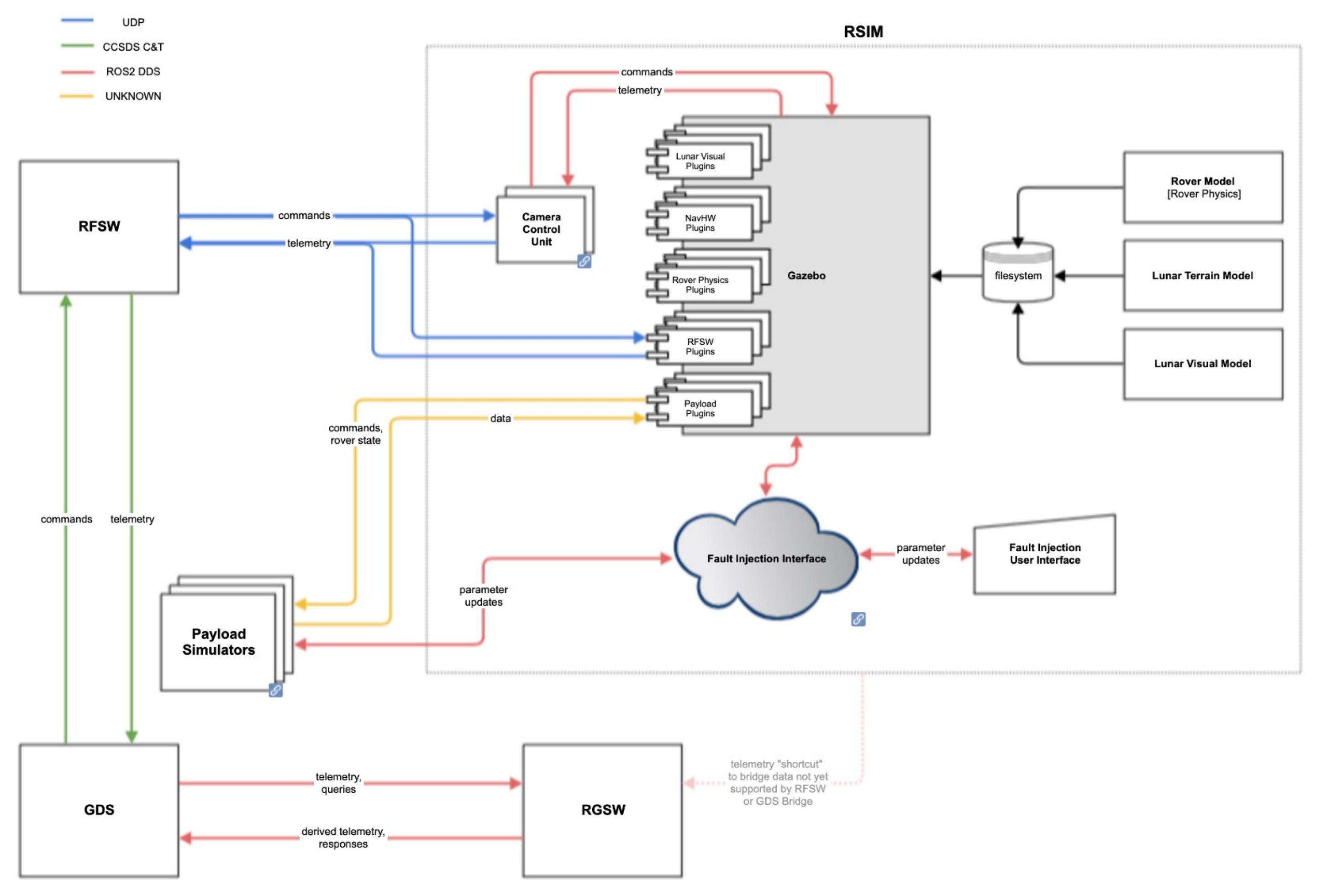
Rover Simulators (RSIM)

RSIM Uses

- Simulator integrated with research and mission software for rover driving, system monitoring, and science instrument simulation to constitute an end-to-end Lunar mission simulation capability
  - Supporting development of RFSW, RGSW, and GDS software
- Training simulations
- RGSW and RFSW Verification
  - Build spec
  - RFSW L4 requirements (when there is no other practical way to perform verification)
- Mission Operations System (MOS) support tool
- Built on modified ROS (Robot Operating System) Gazebo framework with Lunar plugins and communicates with modules developed for VIPER flight/ground software
- Plan to open-source portions of software after VIPER engineering concludes

Focus on Solar Lighting

RSIM Architecture



RSIM Modules

RSIM Lunar Terrain Modeling

- Synthesizes large scale, very high-resolution Digital Elevation Map (DEM) models of Lunar terrain with rover-scale hazards to be used for driving a simulated VIPER rover on candidate traverse plans. The synthesized terrains must be representative of the geomorphology expected at the Lunar poles.

RSIM Rover Models

- Converts the rover structure and mechanisms of the flight design (VIPER) and mobility test units (MGRU 2.5 and MGRU 3) to a model that can be simulated in RSIM

RSIM Rover Physics

- Models the multibody dynamics of the VIPER rover driving on simulated Lunar terrain

RSIM Visual Simulation

- Renders images of the lunar environment such that human operators are able to perceive hazards and maintain adequate situational awareness in order to safely drive a rover

RSIM NavHW Modeling

- Provides more realistic simulated NavHW components (cameras, IMU, star tracker, and lights) for development and testing of localization in RFSW and RGSW

RSIM RFSW Integration

- Provides interfaces that mimic the flight hardware communication protocols

RSIM Payload Simulators

- Provides communication protocol level simulation of instruments for development and test of RFSW Payload command and data handling

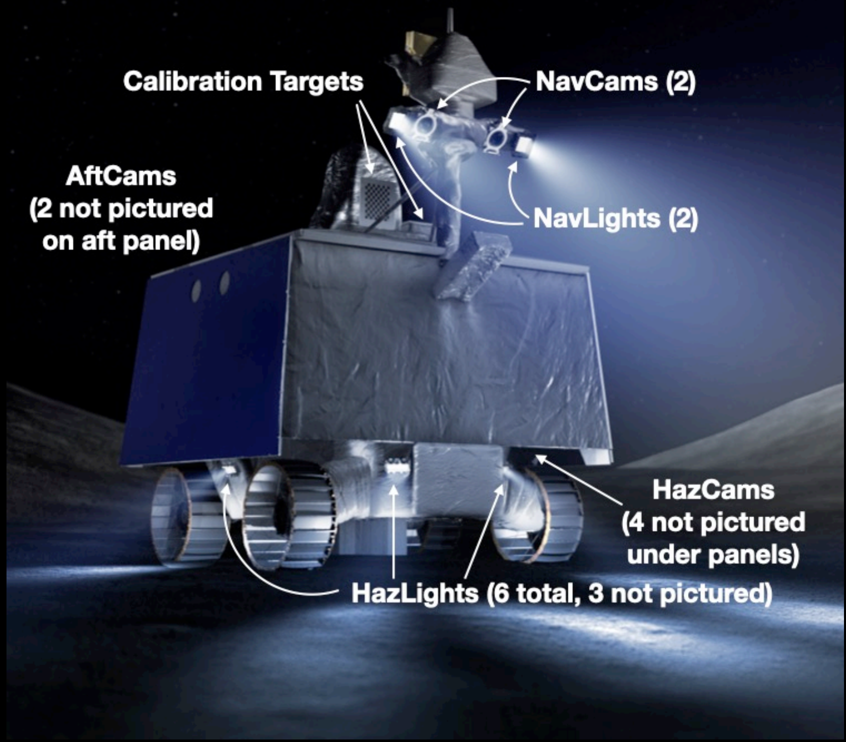
RSIM Fault Injection

- Provides an interface for users to trigger off-nominal events in the simulated environment

Navigation Hardware (NavHW)

Navigation Overview

- **VIPER Navigation Approach**
  - Primarily vision-based
    - Rover has 8 cameras and 8 luminaires (e.g. lights)
    - First rover using powerful "headlights" for terrain sensing
    - Optics are filtered and optimized for wavelength 460nm
  - Operate with short (~4.5m) waypoint drives
    - Drive is automated, but waypoint selected by human
  - Stereo vision provides 3D map of terrain
    - Identify hazards, driver visual aid, localization with terrain matching, visual odometry
  - Other sensors (e.g. IMU and Star Tracker) aid in orientation
- **Unique Navigation and Perception Challenges**
  - Polar lighting and terrain conditions push the envelope of existing planetary rover sensing
  - High-tempo operations required to follow traverse and meet hibernation/comm windows (Speed Made Good)



[Beyer, et al. 2022, LPSC]

Challenging Optical Phenomena

AS16-114-18415

Long Shadows, Opposition Effect, and High Dynamic Range

AS16-107-17482

Lens Flare, Veiling Glare, and Dust Accumulation

AS17-142-21745

Lack of Texture and Whiteout Condition

*photos from NASA Apollo Archives

Navigation Instruments

Navigation Cameras

- Product: High resolution images
- Purpose: Visual odometry, mapping, science needs and operating the rover

Aft Cameras

- Product: High resolution images
- Purpose: backing up the rover, complement to the Navcam images in the area obstructed by the rover body

Hazard Cameras

- Product: Medium/high resolution images
- Purpose: Science needs and operations situation awareness/safeguarding

Lights

- Product: High power illumination
- Purpose: Image clarity in shadowed regions and high contrast scenes

IMU

- Product: Navigation grade inertial dynamic measurement
- Purpose: attitude estimation, rover control and antenna pointing

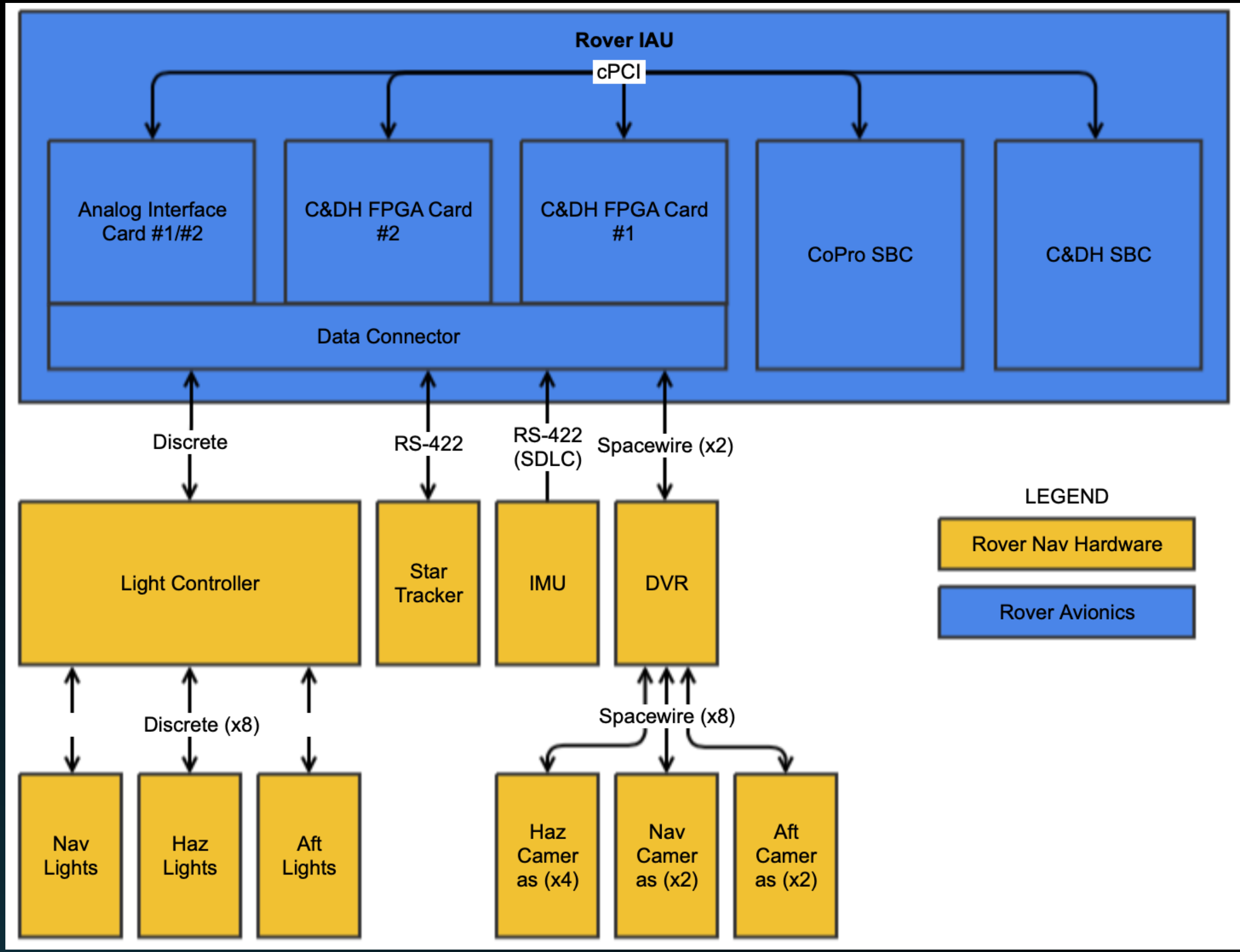
Star Tracker

- Product: Navigation grade orientation measurements
- Purpose: attitude estimation, rover control and antenna pointing, localization and mapping

Joint Resolvers (component owned by ROVER-MECH)

- Product: Wheel, steering and suspension odometry count
- Purpose: coordinated motion and dead reckoning

NavHW Interfaces

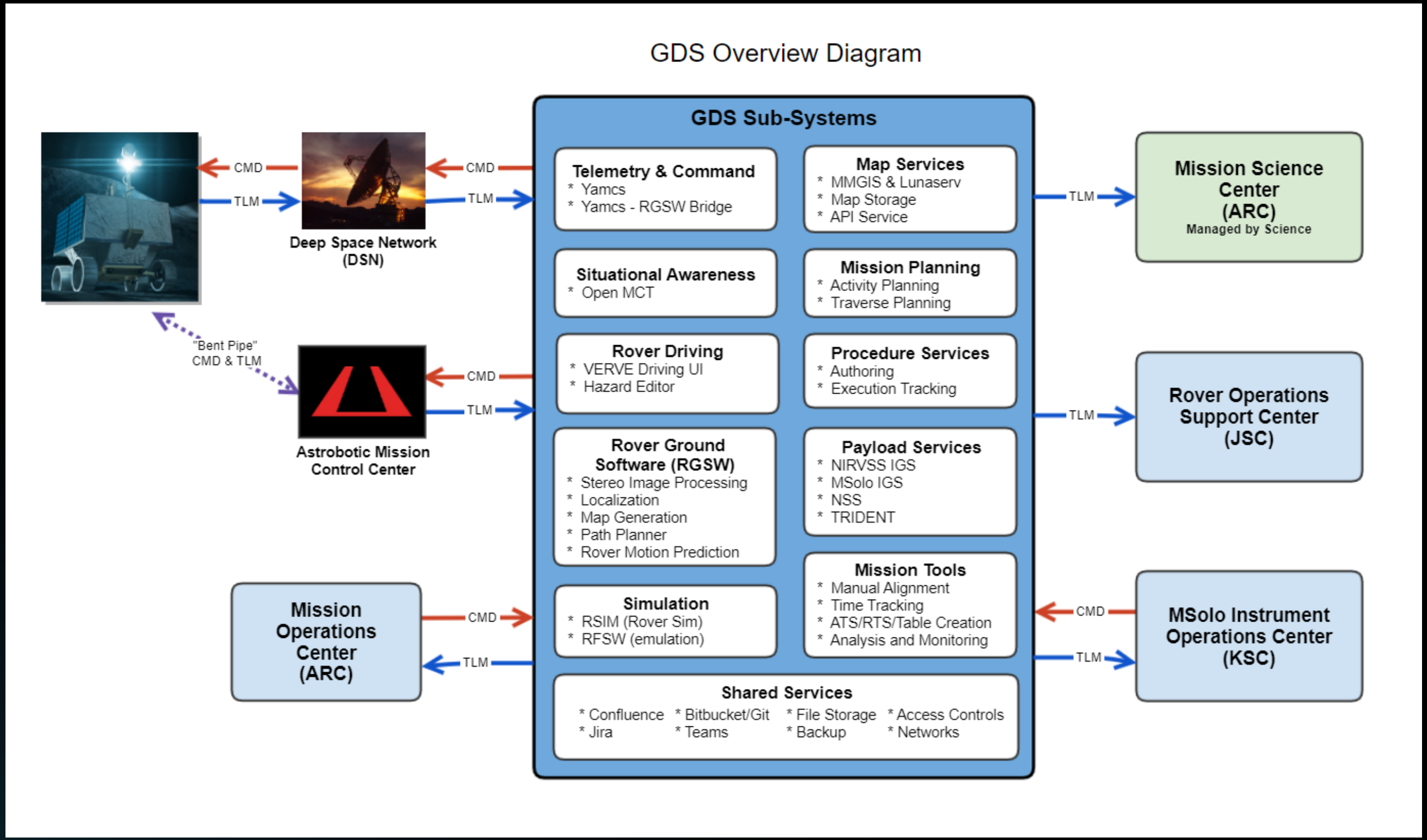


Ground Data System (GDS)

VIPER GDS Overview

The VIPER Ground Data System will support VIPER's lunar, real-time operations cadence:

- Integrates 10 primary mission applications, 2 instrument grounds data systems from 4 payloads, and 8 principal simulator components
- To support more than 30 real-time console operators 24x7 across 3 NASA Centers working in Integrated Simulations, ORTs, Mission Rehearsals, and throughout the mission
- To support additional access for science, operational and anomaly teams throughout testing and the mission



VIPER GDS Integrated Components

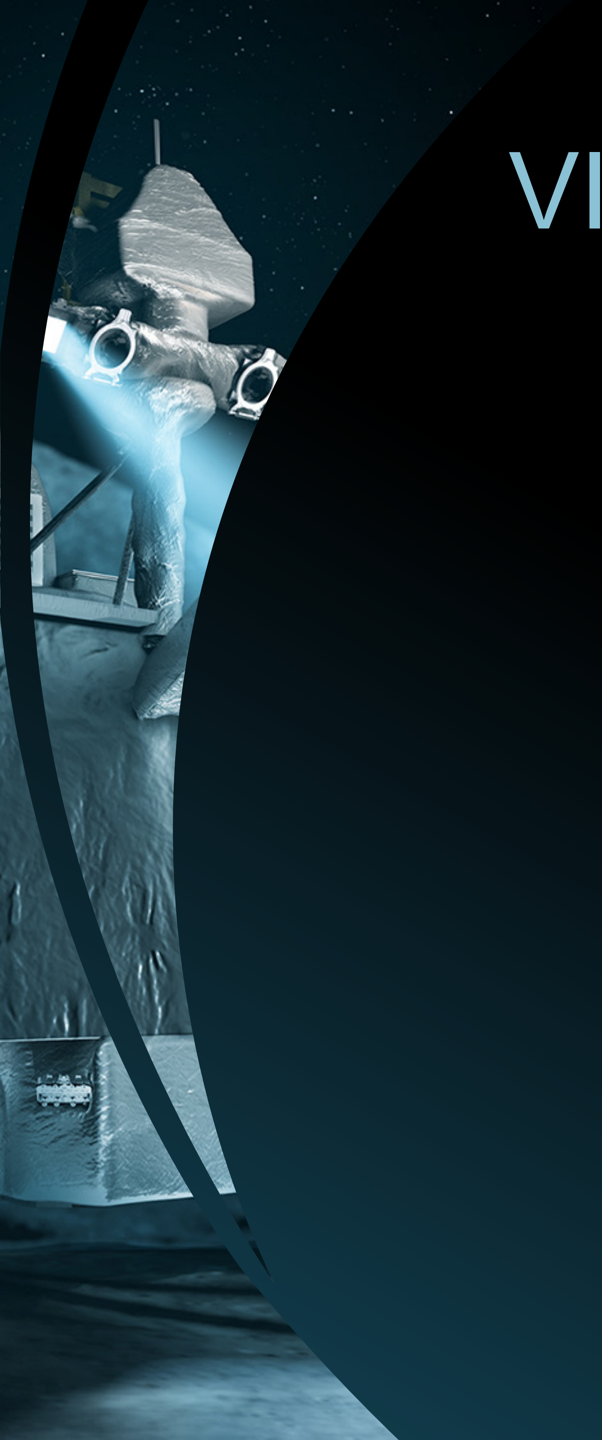
General Applications	Description	Source / Use
YAMCS	Yamcs is a central component for monitoring and controlling spacecraft. Yamcs stores and processes CCSDS packets and provides an interface for end-user applications to subscribe to real-time or archived data.	Open Source - COTS Developed by Space Application Systems. It supports European instrumentation on the ISS, various CubeSat missions, and other pending CLPS missions.
Open MCT *Open Mission Control Technologies*	Provides the primary situational awareness tool for mission operators. Open MCT is a web-based, open-source data visualization tool that allows custom generation of display layouts with time-based control over telemetry tables and plots, imagery, plans, and maps.	Open Source - GOTS Developed at NASA ARC within Code TI. Open MCT supports missions at JPL, GSFC, ARC, JSC and AFRL. Missions include JASON-3, NISAR, SWOT IceSat 2, MarCO, Landsat 9, DSA, GMSec, XCOM and XNAV, Asteria, BRUIE, Lunar Flashlight. It is part of JPL's AMMOS tool suite.
Map Server	Provides vector and raster mapping services for mission operations. Among other services it maintains the polar lunar base map, generates various heat map layers, and supports geospatial and time-based queries.	Adaptation of existing tools: • Lunaserv: Developed in support of LROC at Arizona State University • MMGIS: Part of JPL's AMMOS suite, currently in use for Curiosity and Perseverance.

VIPER GDS Integrated Components

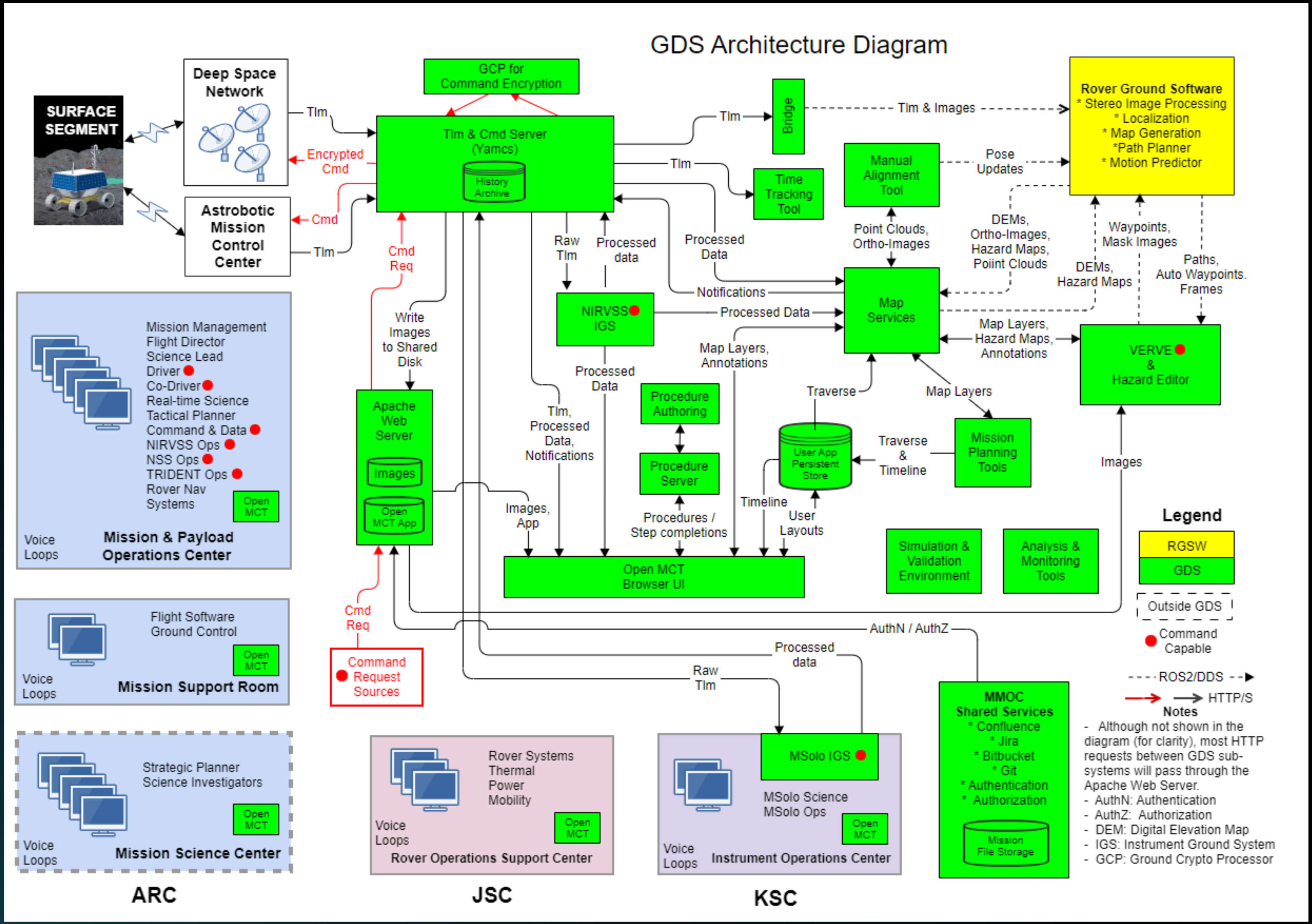
Position-Specific Applications	Description	Source / Use
VERVE *Visual Environment for Remote Virtual Exploration*	Allows the driver and co-driver to operate the rover. It generates a detailed 3D environment based on lunar base maps, stereographic imagery from the NAVCAMs, and traverse path projections that allow drivers to command the rover intelligently.	Open Source - GOTS Developed at NASA ARC within Code TI. VERVE has been adapted for use on a number of missions, including: Haughton Crater Site Survey, Surface Telerobotics (Commanding the K10 Rover from the ISS), Mohave Volatiles Project, Atacama Rover Astrobiology Drilling Studies, Seamless Autonomous Mobility (Nissan Research Center), Astrobee, and Desert Research and Technology Studies Field Test.
Planning Tool *Mission Tactical Planner*	Used to create mission timelines and generate traverse plans for the rover based on science prospecting goals and real-time lunar constraints.	VIPER-Specific, Real-Time Lunar Tool Developed at NASA ARC within Code TI.

VIPER GDS Integrated Components

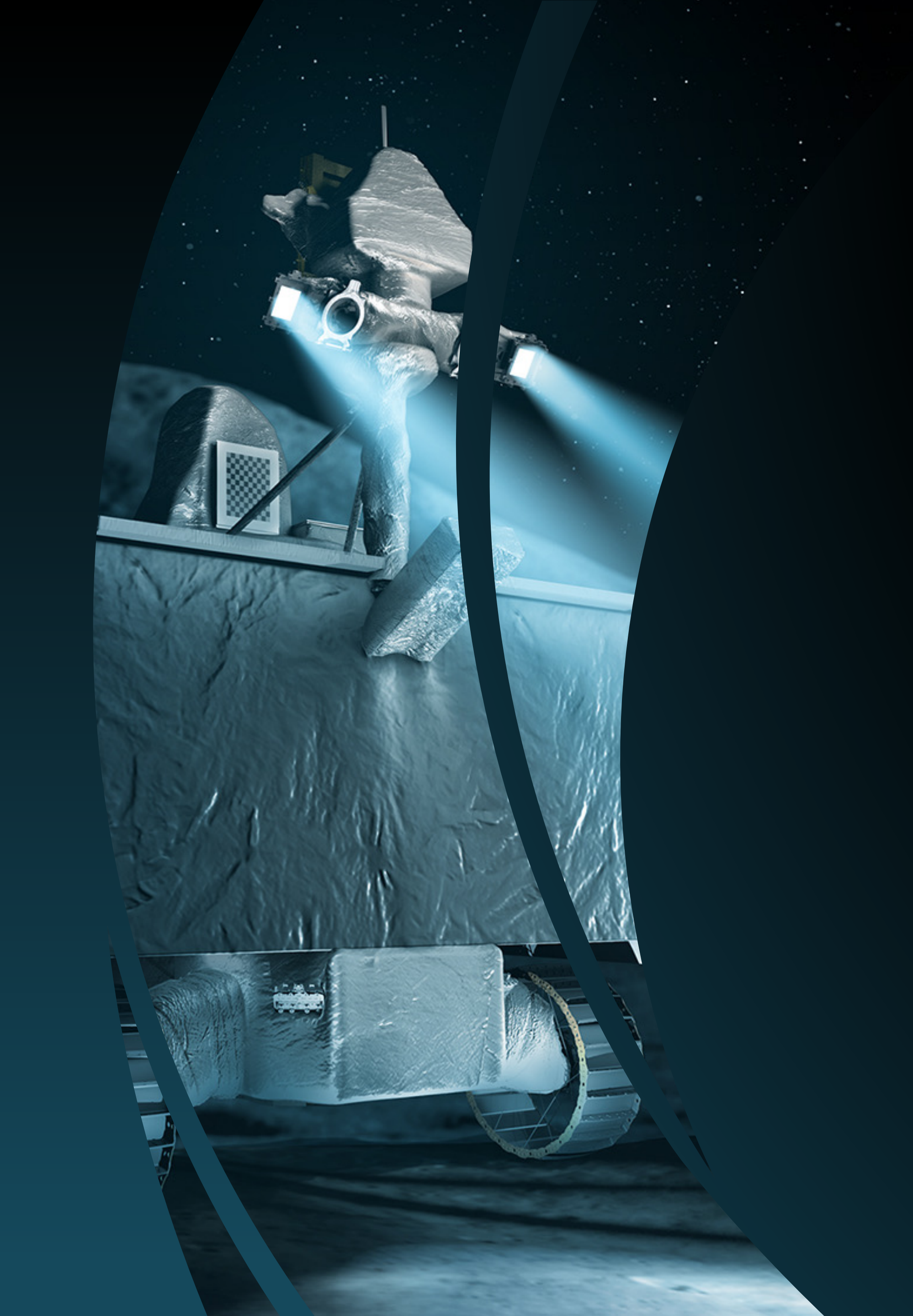
Position-Specific Applications	Description	Source / Use
Time Tracking Tool	Monitors the various clocks on the VIPER rover and allow mission operators to adjust them as required to keep them appropriately synchronized.	VIPER-Specific, Multi-Clock Monitoring Tool Developed at NASA ARC within Code TI.
Manual Alignment Tool	Allows mission operators to manually adjust map layers if an automated fit fails to meet required tolerances.	Adaptation of GOTS GeoCam Developed at NASA ARC within Code TI. Used as part of the Crew Earth Observation program.
PRIDE *Procedure Authoring and Execution Tool*	Allows for operator authoring, executing and monitoring of routine mission procedures.	COTS - SBIR Developed by TracLabs in cooperation with NASA ARC for ISS operations and Orion prototypes.
MSOLO Instrument Ground System	Allows for operation of MSOLO instrument on the VIPER rover.	Lunar Payload Developed by NASA KSC for use in various lunar missions.
NIRVSS Instrument Ground System	Allows for operation of NIRVSS instrument on the VIPER rover	Lunar Payload Developed at NASA ARC for use in various lunar missions.



VIPER GDS Architecture Overview

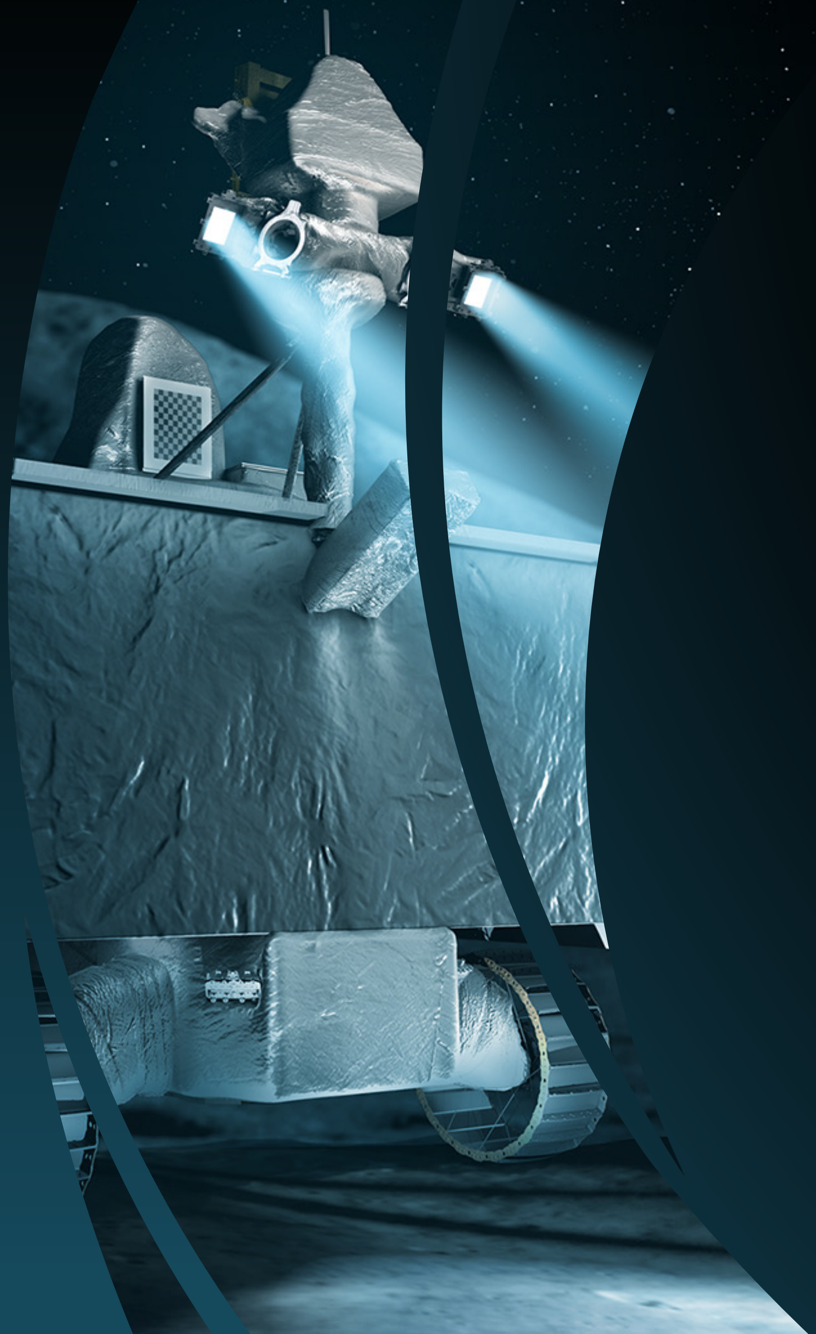


Data Sets



Lunar Lab Data Sets

The **Polar Optical Lunar Analog Reconstruction (POLAR)** dataset (https://ti.arc.nasa.gov/dataset/IRG_PolarDB/) seeks to recreate the imaging conditions at the poles of the Moon for stereo vision evaluation. The dominant factors of appearance at the Lunar poles are oblique sunlight, natural terrain, regolith reflectance, and the absence of atmospheric scattering. Lighting is therefore very harsh, resulting in long cast shadows and high dynamic range (HDR) conditions due to contrasting shadowed and illuminated regions. The surface appearance at the Lunar poles is part of a family of optical environments which are prevalent on airless bodies throughout the solar system, but rarely encountered here on Earth.



Lunar Lab Data Sets

The **Features Relevant to Ocean Worlds Surface Terrain (FROST)** dataset (https://ti.arc.nasa.gov/dataset/frost/) uses the same methodology used for VIPER. It was in fact funded by the OceanWATERs project in the Intelligent Systems Division at Ames Research Center.

FROST provides examples of possible terrain features, geometry, and appearance at the 1-10cm scale on ocean worlds/icy moons such as Europa, Enceladus, and Pluto. The motivation for collecting this dataset was a lack of available high-resolution digital models suitable for development of surface missions to these bodies (circa 2019), including use for simulation of mechanics, sampling, and imaging. We took advantage of NASA field opportunities to Death Valley, California and the Atacama Desert, Chile in order to observe and record analog sites.

Facilities

Lunar Lab

- Goal to develop high-fidelity physical test environment for use with optical hardware
  - Within the constraints of an agile mission like VIPER
- 2 Sandboxes
  - 4.5mx 15m x 0.1m filled with 12 tons of LHS-1 highlands simulant
  - 4m x 4m x 0.5m filled with 8 tons of JSC-1A mare simulant
- Due to local albedo variation, space weathering, and uncertainty, VIPER is using both materials to establish a performance bounds.

Roverscape with Sandbox

- 120m x 80m outdoor facility for rover testing
- Sandbox
  - Dimensions: 15 m x 30 m x 0.4 m
  - Fill: 450 tons of gray granite fines