Efforts and Lessons Learned in Making the Morehead State University's 21-m Ground Station Operational for NASA lunar missions support

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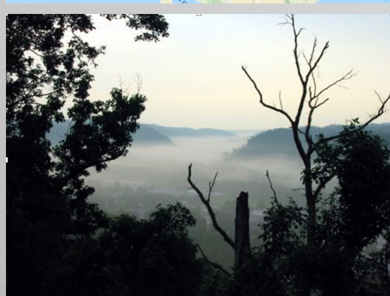
- Summary

Introduction to Morehead Station

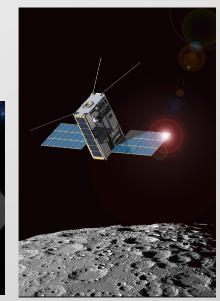
- Located at Morehead State University, Morehead, Kentucky, US
- Built in 2005 in support of LEO Cubesats and educational space research
- Upgraded for near Earth and deep space communications with Artemis 1 cubesats
  - Implementation started 2015; Operational in 2021
  - Full telemetry, tracking and command (TTC) capabilities
  - Primarily at X-band (8 GHz) as required for Artemis Cubesat support
    - S-band (2 GHz) capable, with feed switching



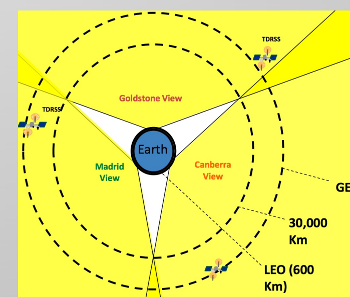
Morehead antenna (21-m)

Lunar H-map

CuSP



Lunar IceCube



DSN antennas (34-m/70-m)

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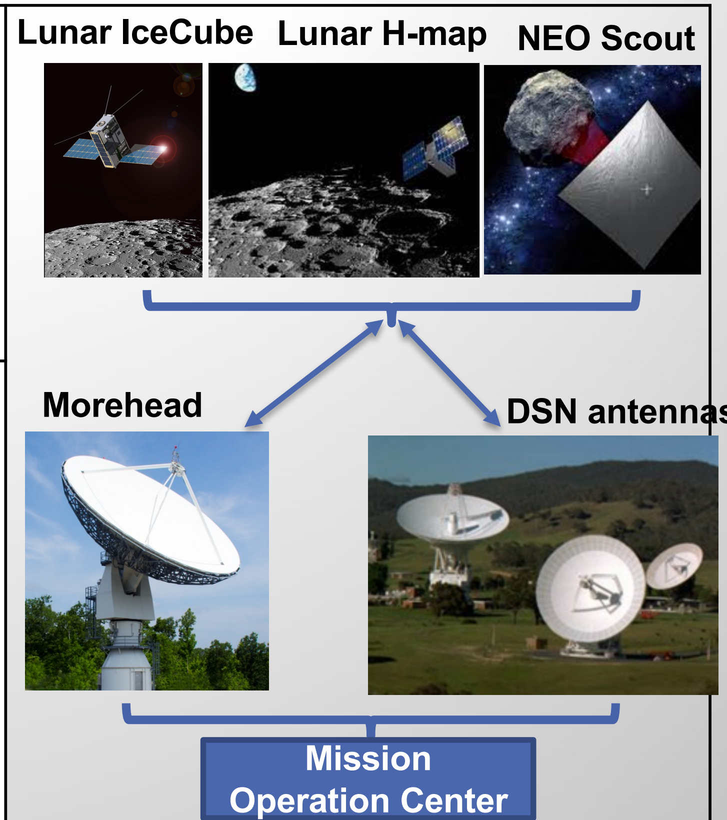
Mission Drivers

Project Description and Objectives

Demonstrate a cost-effective process for expanding DSN capabilities by utilizing non-NASA assets to provide communication and navigation services to Cubesat missions to the Moon and inner solar system, thereby enabling interplanetary research with small spacecraft platforms

DSS-17's operational philosophy: "A Class-D Ground Station Supporting Class D Interplanetary CubeSats"



Technical Approach

- Develop and implement a strategy to transfer Deep Space Network (DSN) equipment, processes and protocols to the MSU 21 m antenna system to enable integration into the DSN as an auxiliary station to support small spacecraft missions
- Implement deep space communications, tracking and navigation techniques as well as adoption of CCSDS standards
- Implement systems upgrades, conduct tests/demonstrations, and transition to an operational capability

Benefits

- Serves as a test-case for other non-NASA ground stations to provide auxiliary deep space navigation and tracking support for interplanetary small spacecraft missions
- Serves as an Experimental Station for Advanced DSN Communications Experiments
- Serves as a DSN node, transparent to missions being supported

Targets

Full DSN compatibility
Scheduled by DSN
Support CCSDS-SLE
DSN Tracking and Ranging
Support Lunar, NEA, Lagrange point missions

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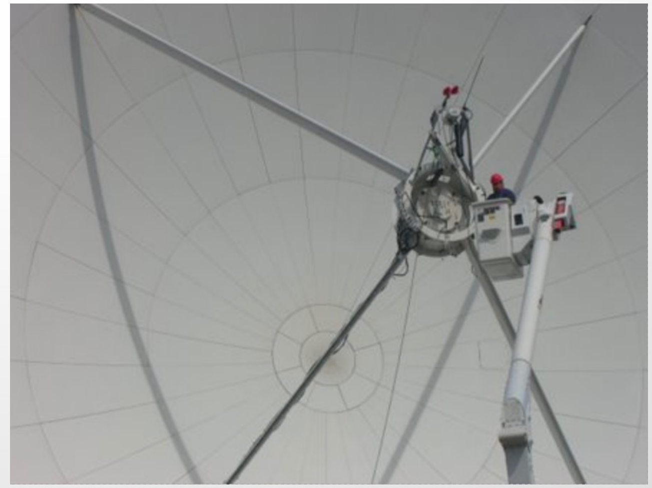
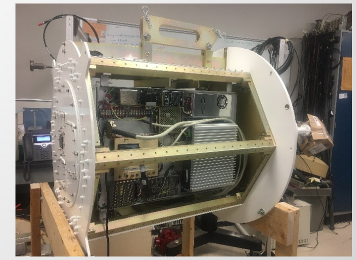
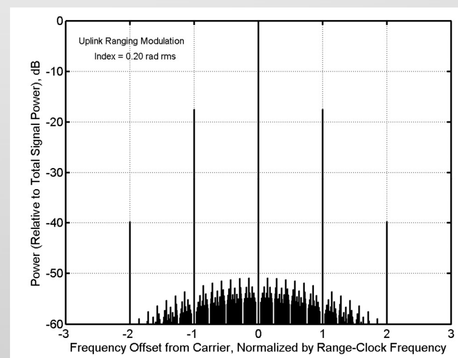
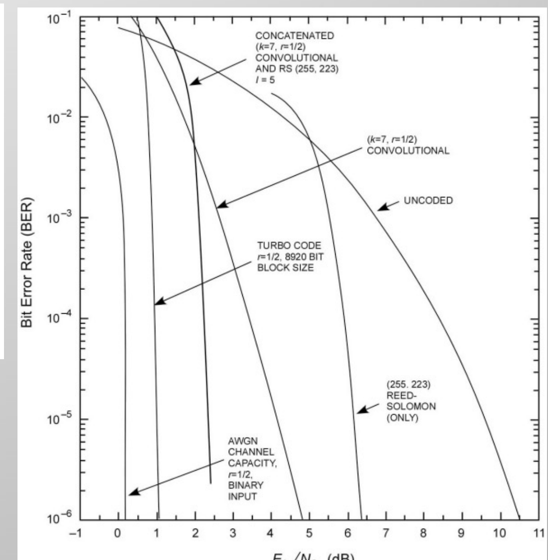
Implementation Objectives

- Upgrade MSU 21-m antenna to support Lunar IceCube and other EM-1 Cubesats
  - X-band operations
    - Deep space and near Earth
  - Full TTC functions
    - 3 kW power amplifier
  - Deep space specialization
    - Highly efficient FEC (e.g., turbo code, LDPC)
    - Pseudo-noise/sequential ranging
  - Interoperability with DSN and CCSDS compliant



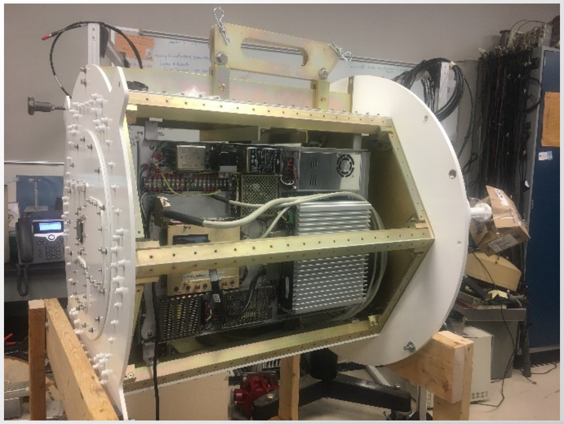


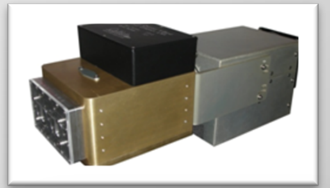




System Attributes

- Minimize implementation cost
  - Leverage on DSN-developed equipment
    - Specialized deep space signal processing for telemetry, ranging and commanding
    - Adapt the already-built equipment to only necessary functions
  - Implement rest of system with COTS equipment
    - With new and surplus components
- Adopt common user interfaces
  - Data delivery at JPL, as with other DSN antennas
- Create opportunity for student-developed projects
  - Station monitor & control
  - System integration and testing
  - Equipment operations





X-band Feed and LNA

DSN Equipment

Hydrogen MASER

System Architecture

Morehead State 21 m Antenna System

21 m Antenna Control System

"Lite" Version of DSN Exciter and Receiver developed for Morehead State

Deep Space Operation Center- JPL Mission Control

Updated Cryogenic X-Band Feed

- IF/RF – Intermediate Frequency/Radio Frequency Upconverter
- TXR – Transmitter
- ANT – Antenna
- LNA – Low Noise Amplifier
- RF/IF DC – Radio Frequency/Intermediate Frequency Downconverter
- NDA – Noise Diode Assembly
- M&C – Monitor & Control

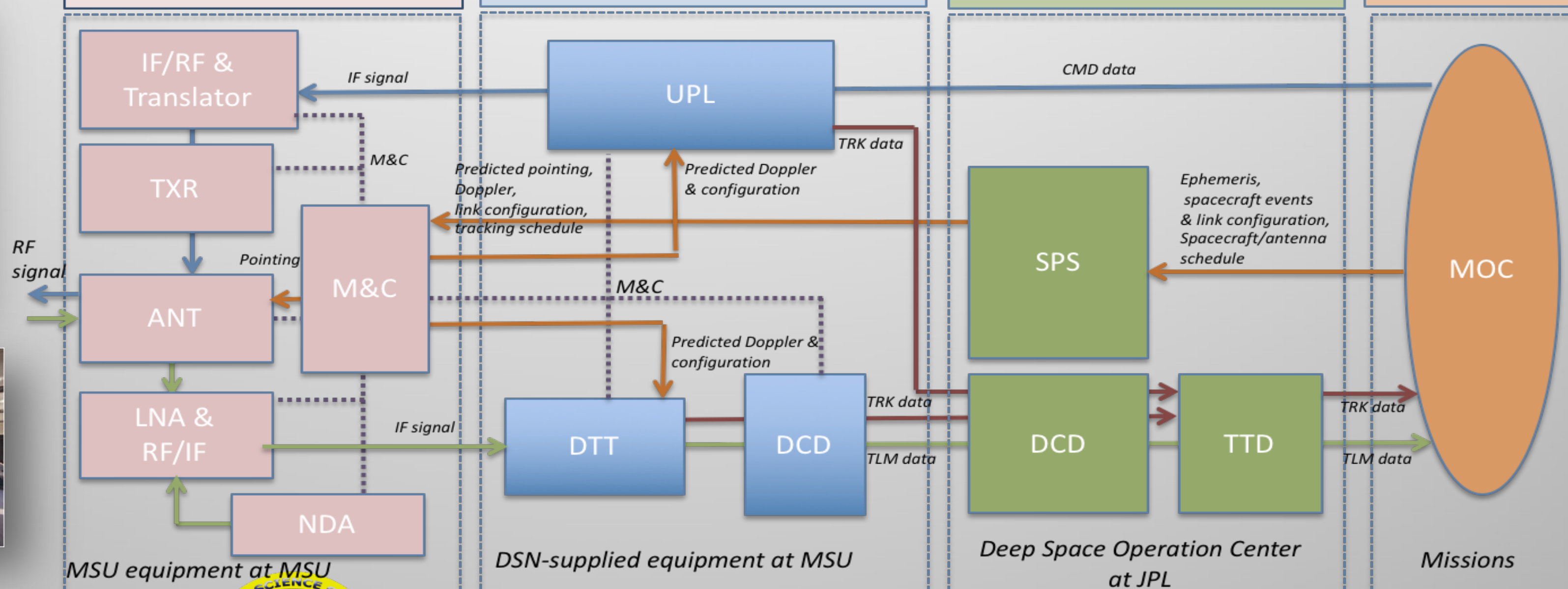
- UPL – Uplink
- DTT – Downlink Tracking & Telemetry
- DCD – Data Capture & Delivery

- SPS – Service Preparation Subsystem
- DCD – Data Capture & Delivery
- TTD – Tracking & Telemetry Delivery

- MOC – Mission Operation Center
- CMD – Command
- TRK – Tracking
- TLM - Telemetry

Hydrogen MASER

Morehead State University Mission Operations Center



System Performance

Performance Measure	Pre-Upgrade	Post-Upgrade
X-Band Frequency Range	7.0 – 7.8 GHz	7.0 – 8.5 GHz
LNA Temperature	70 K	< 20 K
System Noise Temperature	215 K	<100 K
Antenna Gain	62 dBi (@7.7 GHz)	62.7 dBi (@8.4 GHz)
System Noise Spectral Density	-175 dBm/Hz	<-178 dBm/Hz
G/T at 5° Elevation	37.5 dB/K	40.4 dB/K
Time Standard	GPS (40 ns)	Hydrogen maser (1 ns/day)
EIRP	N/A	93.7 dBW
HPBW	0.124 deg	0.115 deg
CCSDS Compliance	N/A	Yes
Forward Error Coding	Reed Solomon/Convolutional	Reed Solomon/Convolutional, Turbo, Low Density Parity Check
Radiometric	Angle, Doppler	Angle, Doppler, Ranging

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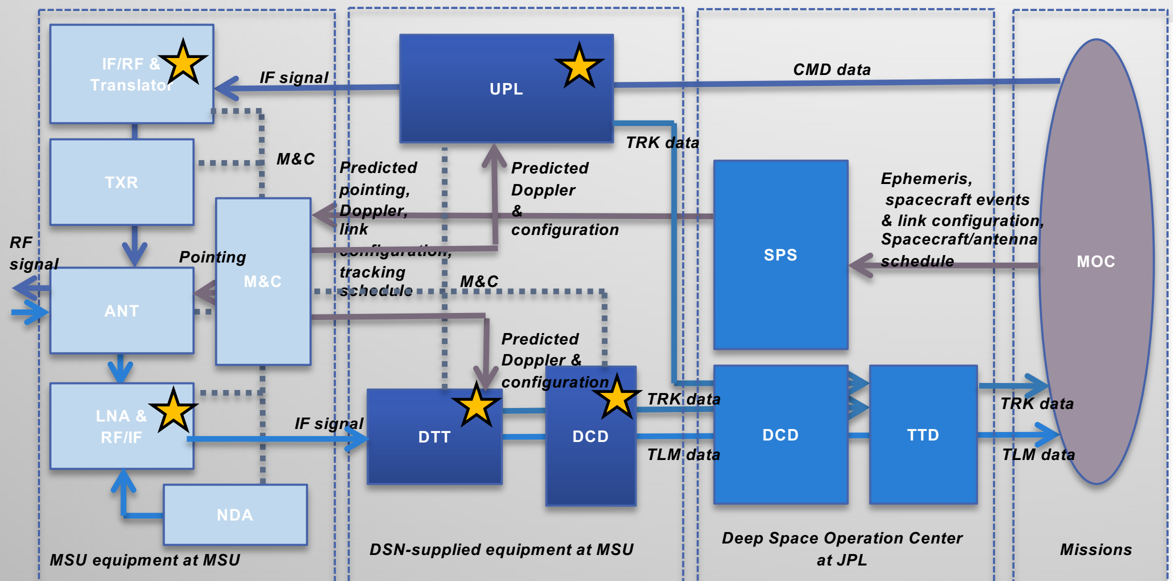
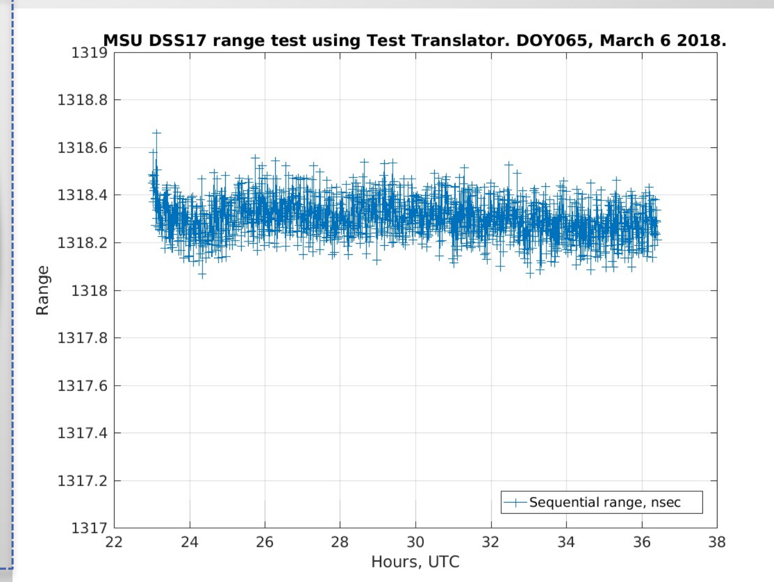
Incremental Test Approach

1. Station internal tests
2. Spacecraft shadow tracks
3. Simulated space link tests
4. Ground data system tests

Station Internal Tests

- Initial checkout, post installation of Exciter and Receiver, to validate signal processing
  - Exciter-to-Receiver loopback via 300 MHz IF
  - Exciter-to-Receiver loopback with built-in Test Translator (emulating spacecraft) at 8 GHz RF
    Validate integrity of ranging signal generation and reception (ranging calibration)
  - Validated integrity of command signal generation





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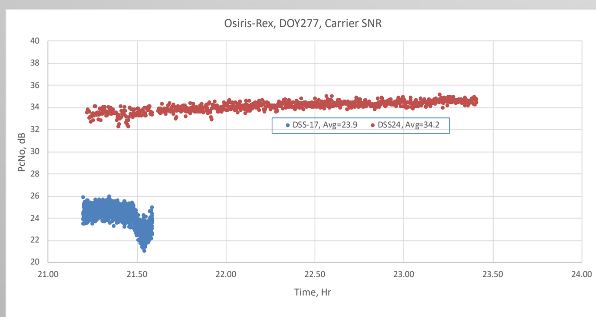
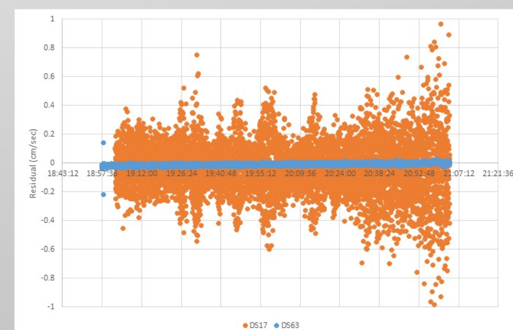
Spacecraft Shadow Tracks

- Riding on normal DSN passes without impacting missions
  - With various X-band deep space missions, e.g., STEREO-A, Osiris REX, Hayabusa 2, Lucy, DART
    - No near Earth X-band mission currently operational and tracked by the DSN
  - Telemetry validation
    - Validated key antenna Gain/Temp (G/T) performance
      - Comparison of telemetry and carrier SNRs received at DSN and MSU antennas
      - 10 dB in expected G/T difference between two antennas observed
  - Ranging validation
    - Validated ranging functions of MSU downlink via 3-way ranging with STEREO-A, DART
      - Uplink ranging signal transmitted by DSN antenna in 3-way mode
        - 2-way ranging at Morehead not done due to lack of mission support for Morehead uplink and spectrum license issue in deep space frequency band
  - Command validation
    - Not achieved because requiring missions willingness to support MSU uplink



10 dB difference in SNR observed between 21-m MSU (DSS-17) and 34-m DSN antenna (DSS-24), as expected



DSS-17 Ranging Results- precision within +/-1 range unit (0.94 ns). Implies 1 meter accuracy ranging at the Moon

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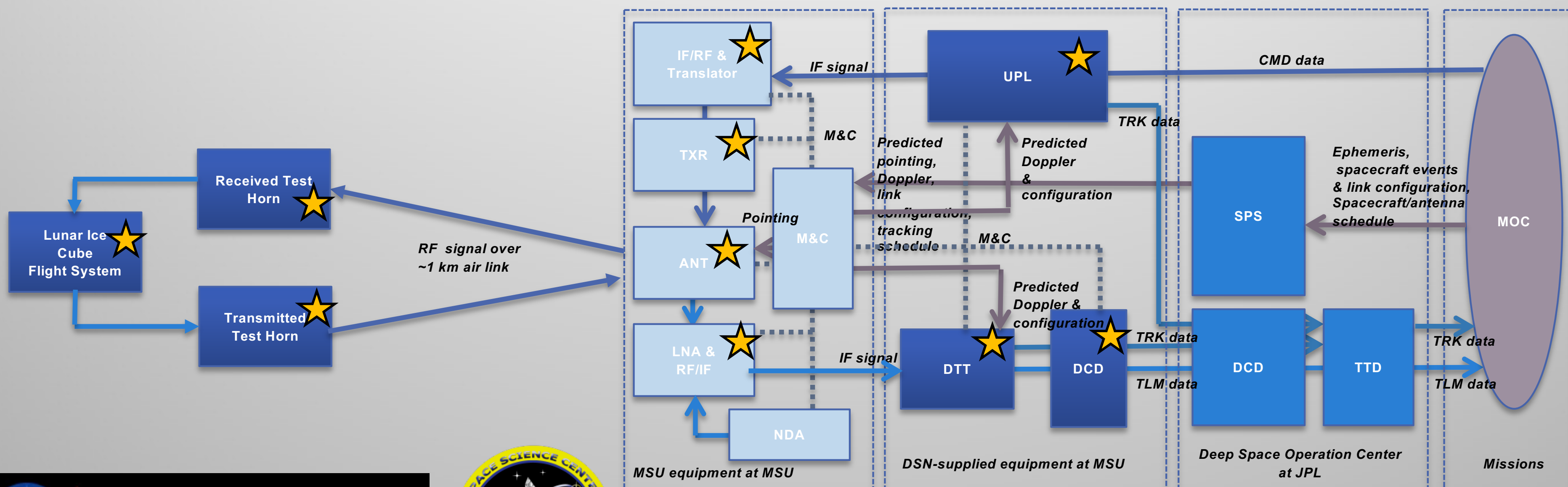
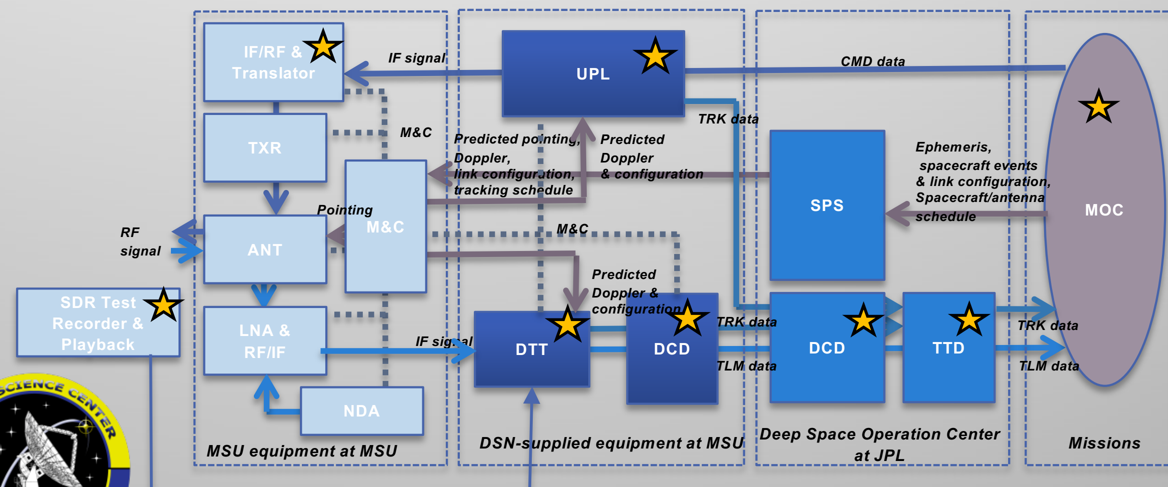
Simulated Space Link Tests

- Simulated space link condition via local air link between antenna and signal processing site
  - Use two additional test horn antennas, and other test equipment, to emulate spacecraft transmit/receive antenna
  - RF signal travels across 1 km air link between Exciter/Receiver and the antenna
  - Command data test
    - LIC MOC -> DSS-17 -> air link -> test feed -> LIC spacecraft
  - Telemetry data test
    - LIC spacecraft -> test feed -> air link -> DSS-17 -> receiver -> LIC MOC
  - Ranging (2-way) test
    - DSS-17 Exciter & Transmitter -> air link -> test feed -> DSS 17 Receiver



Ground Data System Tests

- GDS testing with Lunar IceCube, HMAP, CAPSTONE, CuSP, NEAScout
    - Verify data flow between Mission Operation Centers and MSU ground station
        - Telemetry & Command data - with standard CCSDS Space Link Extension (SLE) interfaces
        - Tracking data – with DSN specific interface
    - Workaround with generation of simulated spacecraft data
        - Lack of equipment to emulate spacecraft telemetry data is mitigated by use of SDR-based recorder/playback of pre-recorded IF samples of test signal waveform
        - Successful for most data rates but a few low data rate configurations had problem with data not being decoded
            - Saturation issue due to higher bit/symbol SNR?
- End-to-end test with spacecraft in development
    - Lunar IceCube done with actual LIC flight system since Morehead also responsible for LIC
        - Also done via local air link



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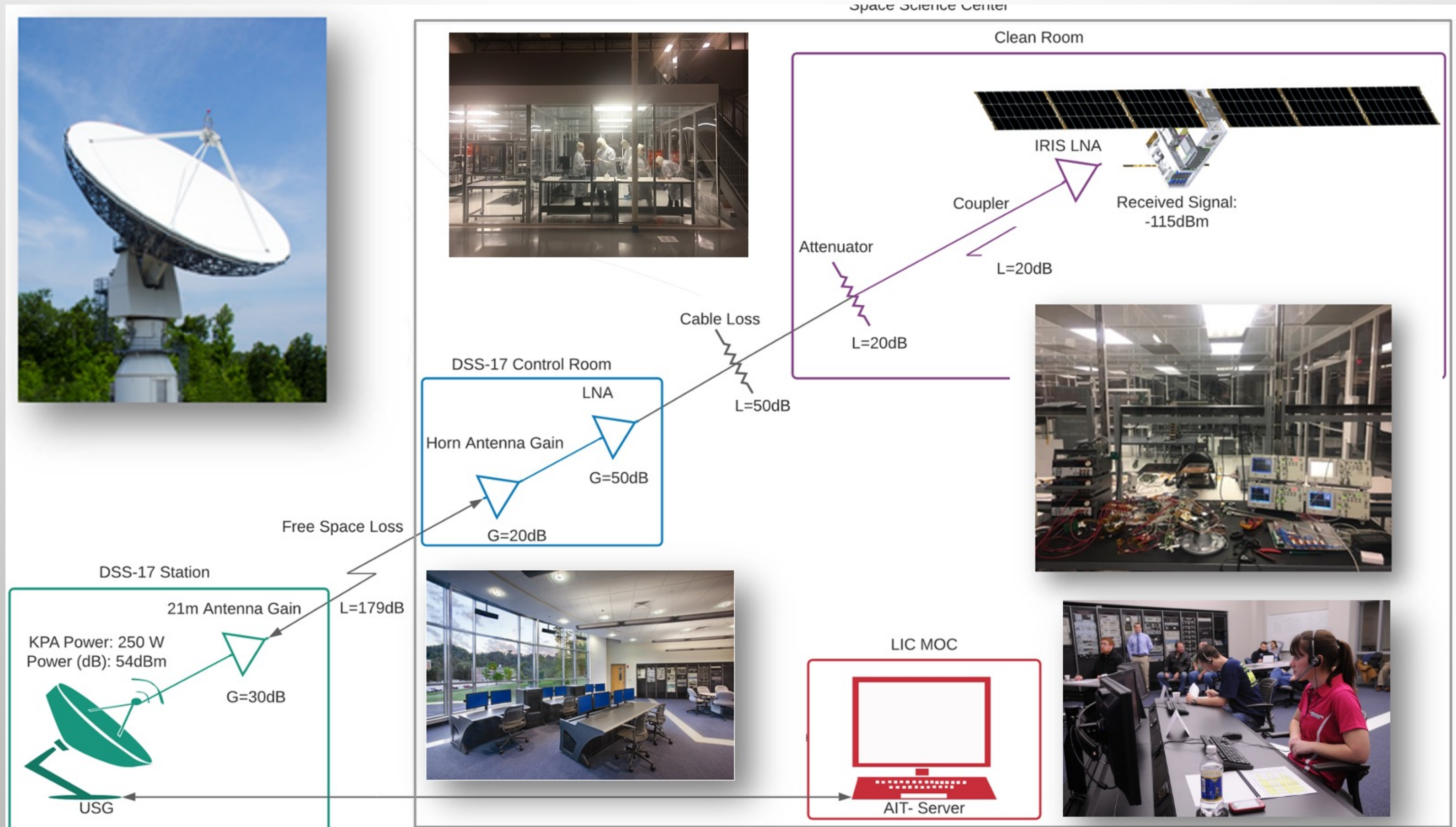
Flight & Ground Systems End-to-End Tests

- End-to-end test involved Lunar Ice Cube spacecraft, ground station and Mission Operation Control
  - Test done with actual LIC flight system since MSU is also responsible for LIC development



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Lessons Learned

- Incremental test approach, from a small portion to the entire system, helps:
  - Building confidence on system operation
  - Providing training opportunity to operation team
- Operational team was able to successfully transfer knowledge across multiple generations of students
  - Graduating students willing to share & teach. New students eager to learn
  - Converting key students to operation staff upon their graduation helps solidifying operational knowledge; thus, ensure mission success
- Making an operational ground station requires much dedication and resources
  - Strong project management and dedicated key technical staff
  - Funding resource to develop and maintain operational capabilities

Summary

- Implementation of ground station at Morehead State University
  - Supporting Artemis 1 Cubesat missions, at X-band
- A hybrid architecture
  - Combining DSN and COTS equipment
  - Common interfaces for missions that use both DSN and Morehead
- Incremental test approach builds up confidence of system operations from smaller segment to end-to-end system
- System is now ready to support Artemis 1 Cubesats, to be launched in 2022