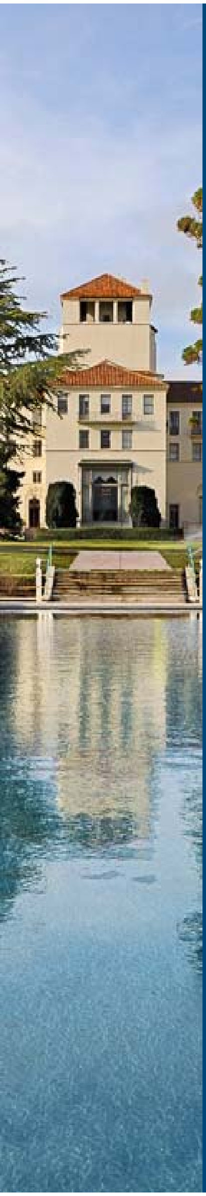


The Mobile CubeSat Command and Control (MC3) Ground Station Network

Giovanni Minelli, Lara Magallanes, Noah Weitz

David Rigmaiden, Ron Phelps, James Horning, James Newman

Space Systems Academic Group

Naval Postgraduate School

20 May 2020

MC3 Mission

Community-based US government ground infrastructure for SmallSats

MC3 Stations

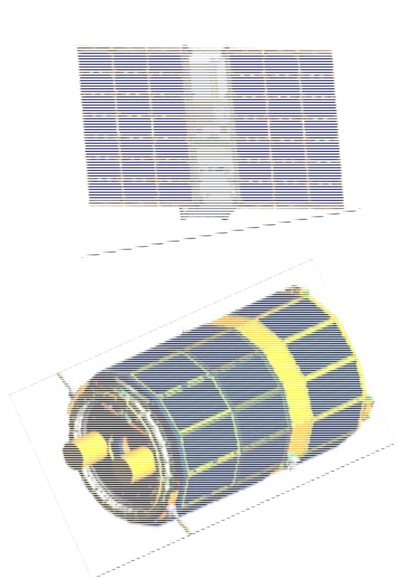
HSFL – Hawaii Spaceflight Lab
UAF – University of Alaska Fairbanks
NPS – Naval Postgraduate School
SDL – Space Dynamics Laboratory
UNM – University of New Mexico
AFIT – Air Force Institute of Technology
USCGA – US Coast Guard Academy
SMDC – Army Space & Missile Defense Command
MLB – Malabar Transmitter Annex

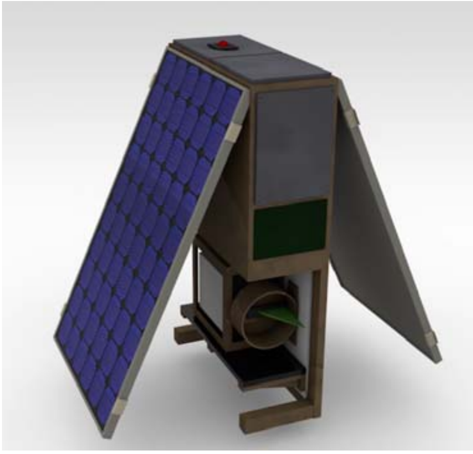
TAMU – Texas A&M University
USNA – US Naval Academy

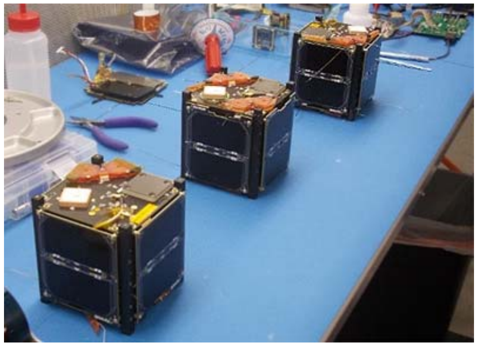
Supported Missions

Current/Past Missions:

- Colony II Program (2012-2015)
- PROPCUBE x 3 (2015/2017)
- Polar Scout x 2 (2018)
- RSAT (2018)
- DHFR x 2 (2017/2018)
- NPSAT1 (2019)
- FalconSat-7 (2019)







Upcoming Missions:

- CNCE Blk 1 (2020)
- CNCE Blk 2 (2020)
- CIRCE (2021)
- SMDC (Multiple)
- Square Dance (multiple)
- STPSat-4 (2020)
- MOLA & OTTER (2022)

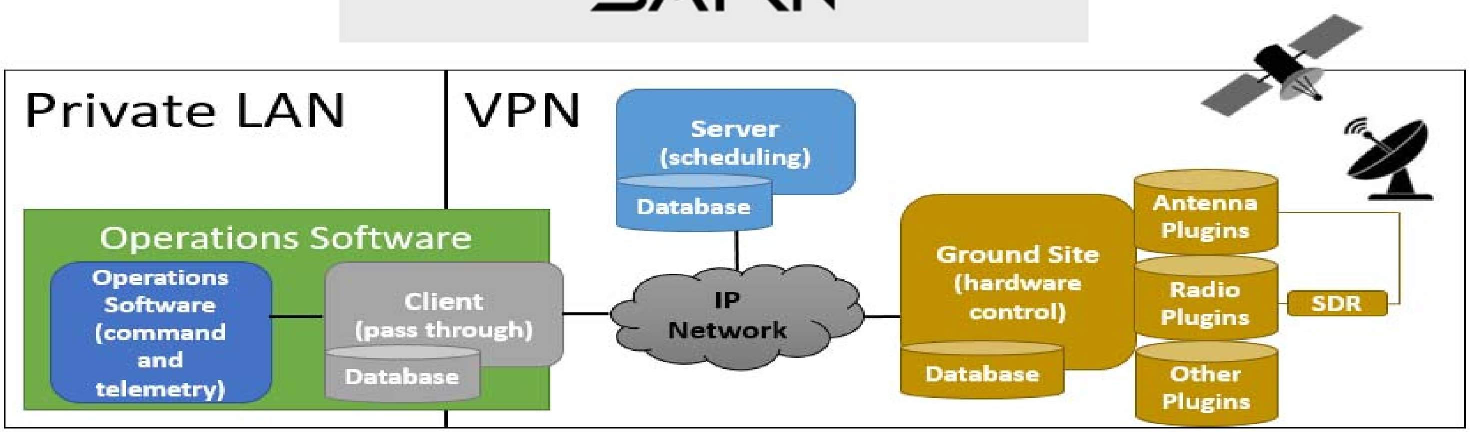
- And more…

MC3 Summary

Band	Frequencies	Designator
UHF uplink	449.75 – 450.25 MHz	12K5F1D 43K0F1D
UHF downlink	902 - 928 MHz	115KG1D
S-Band uplink	2025 - 2110 MHz	2M00G2D 2M45G1D
S-band downlink	2200 - 2290 MHz	1M60G1D 2M00G2D 2M45G1D
X-band uplink	7190-7250 MHz	TBD
X-band downlink	8025 – 8400 MHz	TBD

Bent-pipe communications from remote operations center

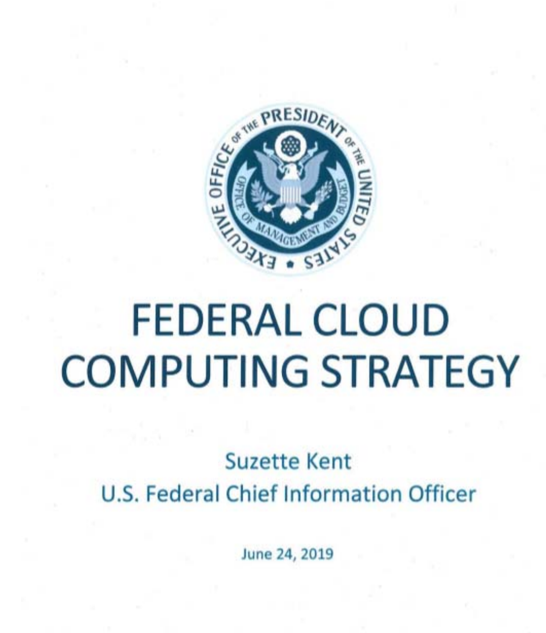
Satellite Agile Transmit Receive Network (SATRN)



AWS Integration

Amazon Web Services (AWS)

- Remote bent-pipe operations
- Conforms to DoD cybersecurity requirements
- Various levels of mission security
  - Industry and universities supported
- Scalable to many mission operations centers and remote ground terminals (RGTs)
- Interfaces to other ground networks

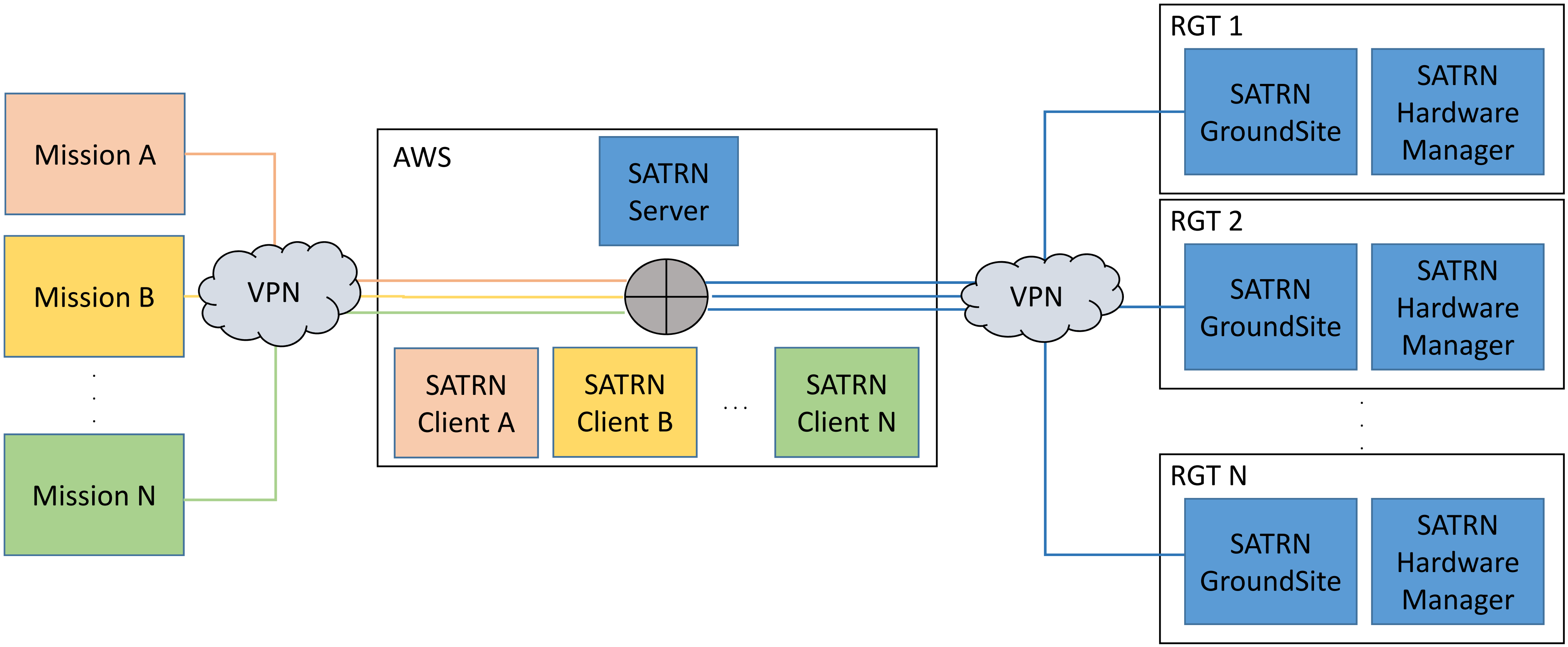

FEDERAL CLOUD COMPUTING STRATEGY

Suzette Kent
U.S. Federal Chief Information Officer

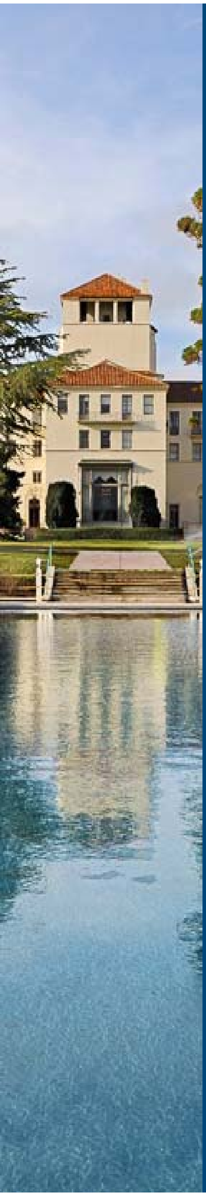
June 24, 2019

https://www.whitehouse.gov/wp-content/uploads/2019/06/Cloud-Strategy.pdf

AWS Integration

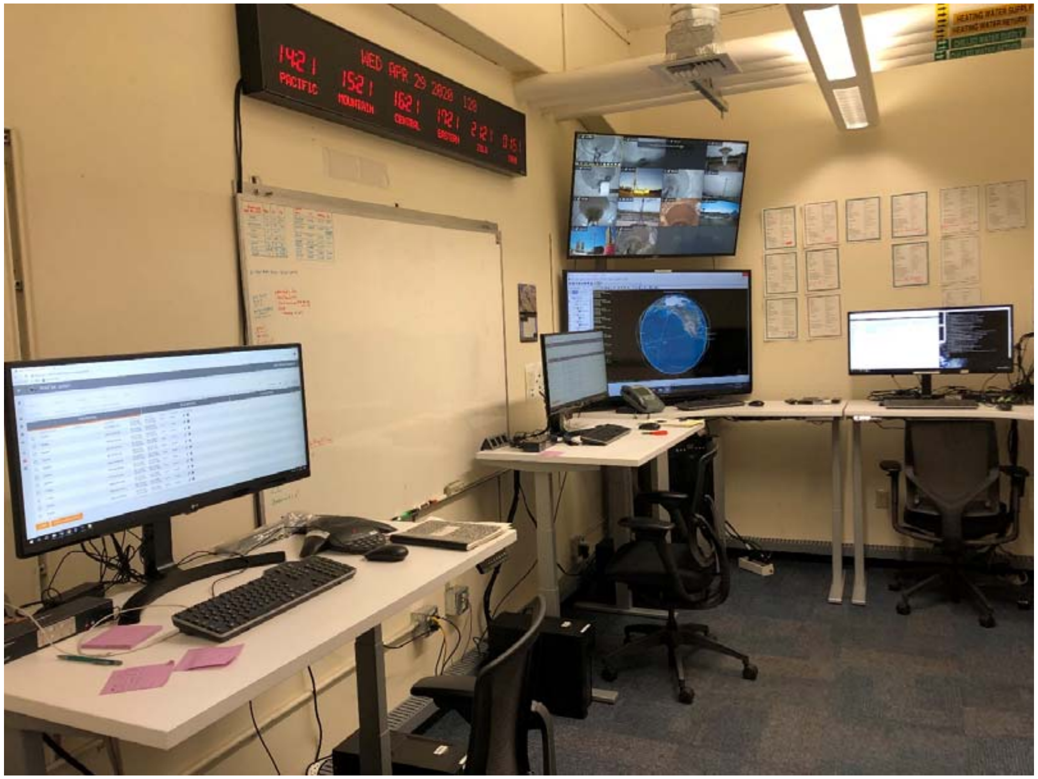


Sevillaparra, J., "Integration of Mobile CubeSat Mobile Command and Control (MC3) with Amazon Web Services", M.S. Thesis, Naval Postgraduate School, Monterey, CA, June 2020



Research Topics

Laboratory Facilities



- Satellite Operations Center
  - Consoles for operating satellites and managing MC3
  - Hands-on exposure to flight operations
- Radio Testing Laboratory
  - Prototyping ground station equipment for use on network
  - Testing with real satellites
- Small Satellite Laboratory
  - Vibration, TVAC, 3D Printing, Circuit design
  - Clean room, flight hardware handling
  - Interdisciplinary staff

Radio Laboratory

Radios Under Study (RUS)

RUS-1:
National Instruments USRP-2922

RUS-3:
Kratos SpectralNet Lite Digitizer & qRadio SDR

RUS-2:
Ettus Research USRP B205mini-i

RUS-4:
AMERGINT satTRAC Signal Converter & baseband modem

Wood, S., “Trade Study of Commercial Software-Defined Radio Technologies for Small-Satellite Ground Station Network Command and Control Applications”, M.S. Thesis, Naval Postgraduate School, Monterey, CA, June 2020

Objectives of Study

- Characterize performance/parameters of the four RUS
- Evaluate their suitability for utilization in small satellite ground stations like MC3
- Compare performance of high-end commercial systems against the baseline USRP systems
- Experiments conducted to evaluate radio parameters to include:
  - Receiver Noise Figure
  - Receiver Image Rejection
  - Receiver Sensitivity
  - System BER Performance
  - GUI Functionality

Noise Figure

- Independently verified the noise figure values for RUS-1:3
- Unable to conduct experiment on RUS-4 due to lack of access to baseband sample data

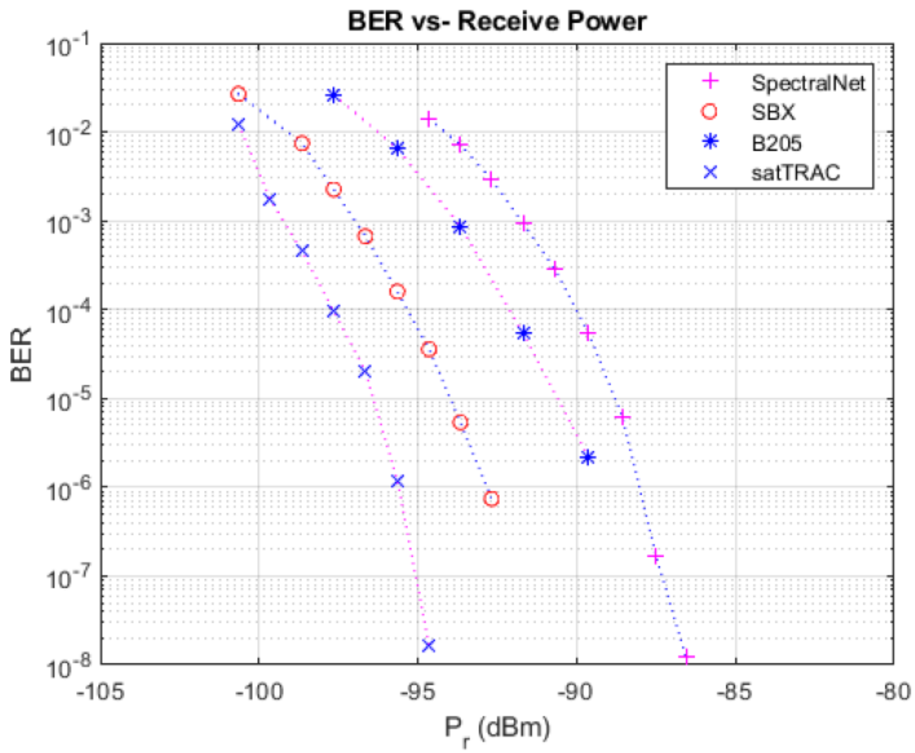
RUS	Manufacturer	Receiver Component	System Description	Specified Noise Figure (dB)	Measured Noise Figure (dB)
RUS-1	National Instruments	SBX-40 RF Daughterboard	Baseline USRP Standard	7	5.55
RUS-2	Ettus Research	B205mini (AD9364 Chip)	Common RF System-on-Chip (Soc)	8	6.32
RUS-3	Kratos	SpectralNet Lite Digitizer (AD9364 Chip)	High-End Commercial System	7	5.6
RUS-4	AMERGINT	satTRAC Signal Converter (super-heterodyne)	High-End Commercial System	8	*

Direct Conversion IQ Imbalance

	RUS-1 (USRP-2922)	RUS-2 (B205mini-i)	RUS-3 (Kratos)
Average IQ Imbalance Observed	-39.8 dBc	-61.5 dBc	IQ imbalance unmeasurable
Largest IQ Imbalance Observed	-37 dBc	-21.5 dBc	IQ imbalance unmeasurable
Smallest IQ Imbalance Observed	-40.9 dBc	-93.5 dBc	IQ imbalance unmeasurable

- The IQ imbalance contributions experienced by the three direct conversion receiver architectures evaluated through experimentation
  - RUS-1 exhibited consistent performance (~-40 dBc)
  - RUS-2 performed better but with large unexplained variance
  - RUS-3 seemingly mitigates IQ imbalance contribution completely!

Receiver Sensitivity

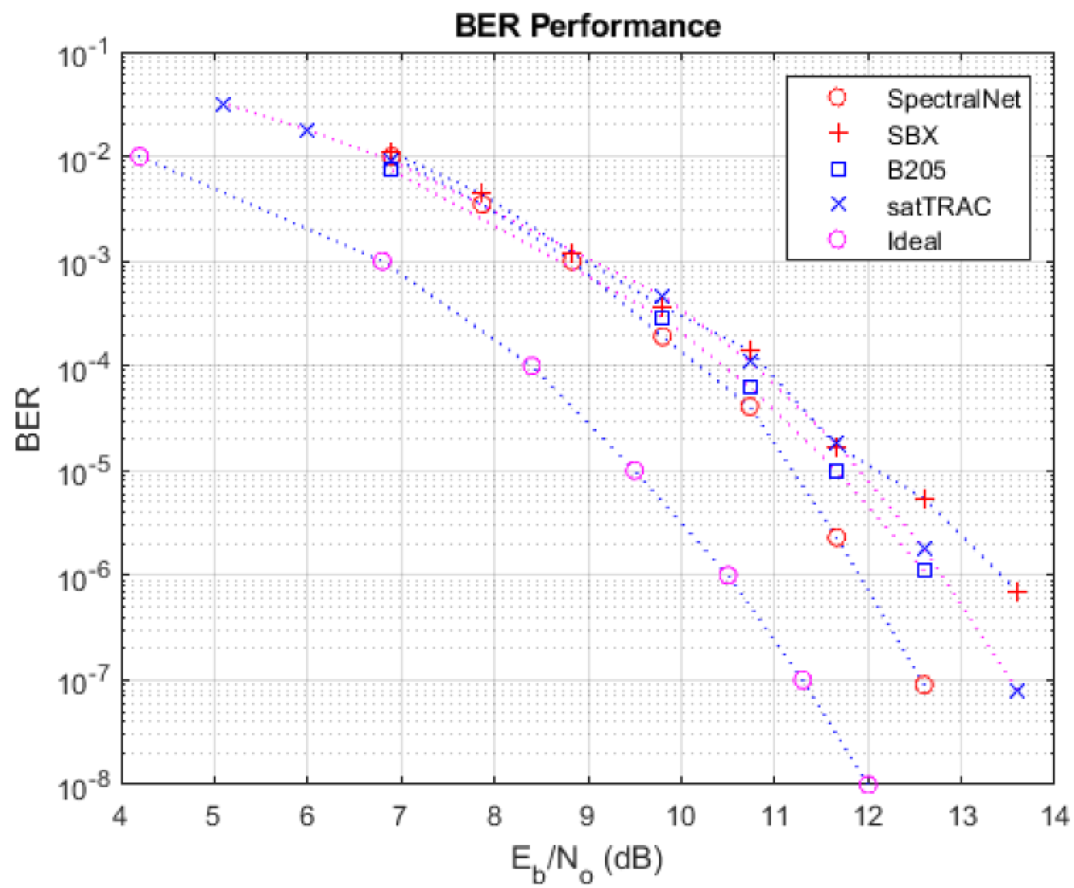


Target BER	RUS-1 P_r (dBm)	RUS-2 P_r (dBm)	RUS-3 P_r (dBm)	RUS-4 P_r (dBm)
10^{-5}	-94.5	-90.5	-89	-96

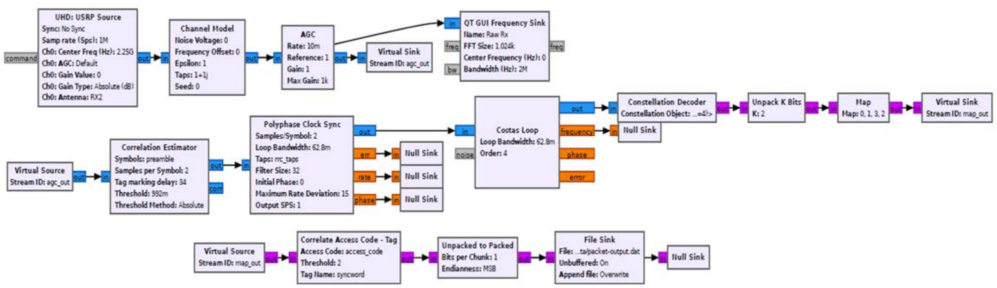
- Super-heterodyne receiver architecture inside AMERGINT satTRAC system (RUS-4) proved to be most sensitive
- Baseline USRP SDR RUS-1 (SBX) performed admirably during experimentation
- Similar results across all four RUS
    - Minimum power required to produce target BER ranged from -89 dBm (RUS-3) to -96 dBm (RUS-4)
- Baseline USRP systems performance comparable and sometimes better than high-end commercial systems

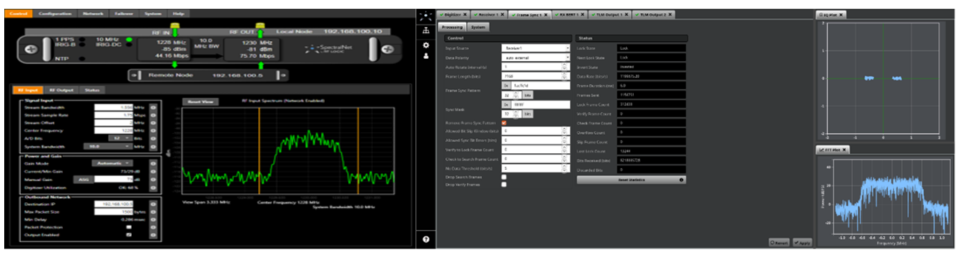
BER Performance

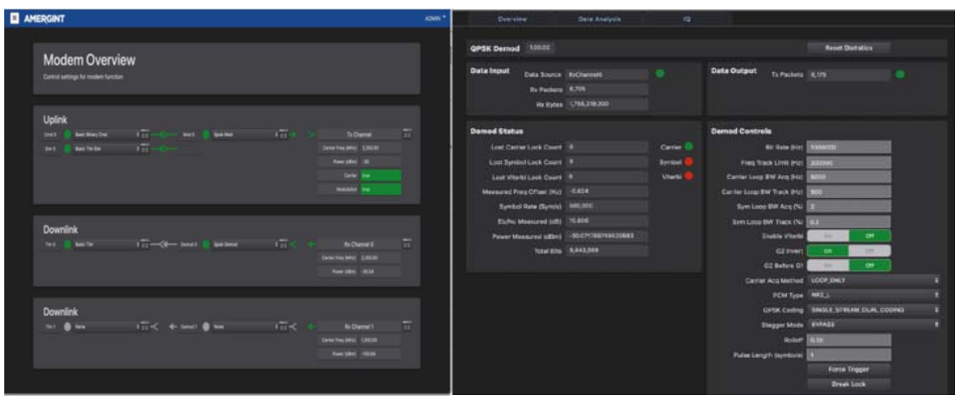
- No appreciable difference in BER performance between four RUS
- Measurement in low-SNR regimes challenging due to functionality SDR algorithms
- Software seemingly fails before hardware/theoretical limits with all four RUS



GUI Functionality



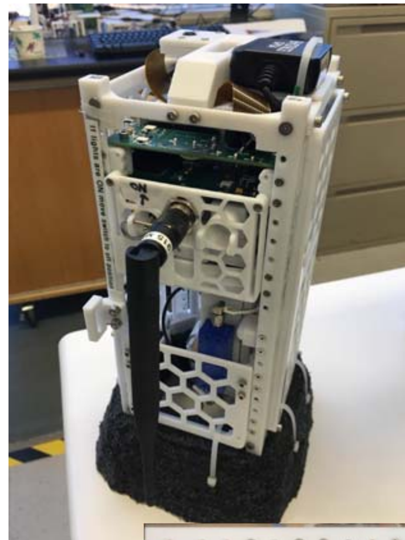
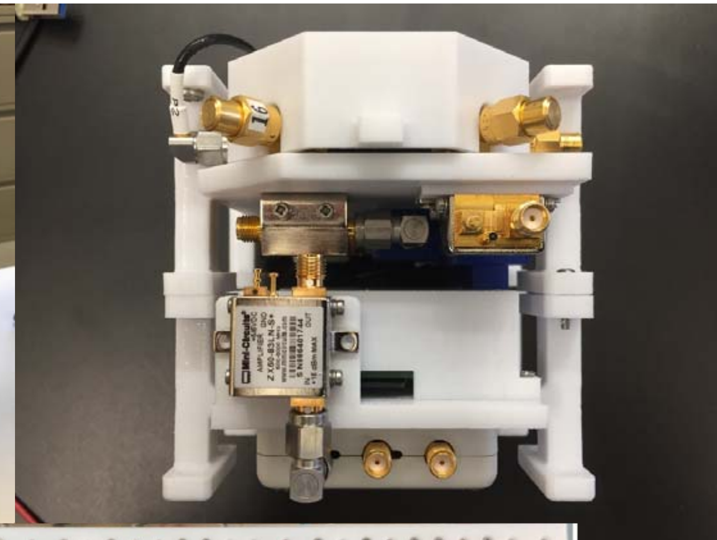
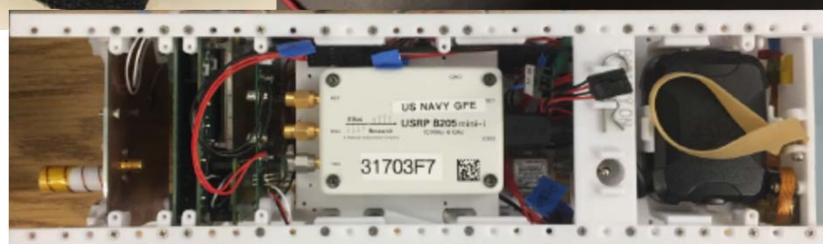


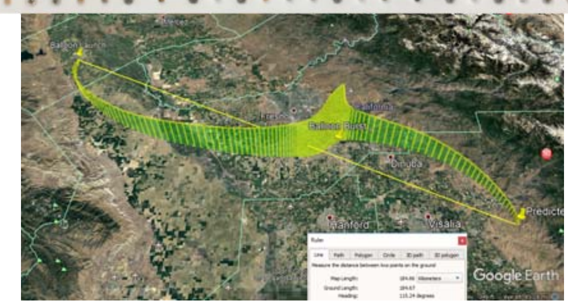


- RUS-1 and RUS-2 operated with GNU Radio software utilized by small-satellite community (top)
- RUS-3 operated with two separate proprietary applications (middle)
- RUS-4 operated with proprietary software applications (bottom)
- GNU Radio platform extremely flexible but largely unsupported
- Proprietary platforms offer more plug-and-play solutions but not without bugs, quirks, and rigidity requiring contractor support ($$$)

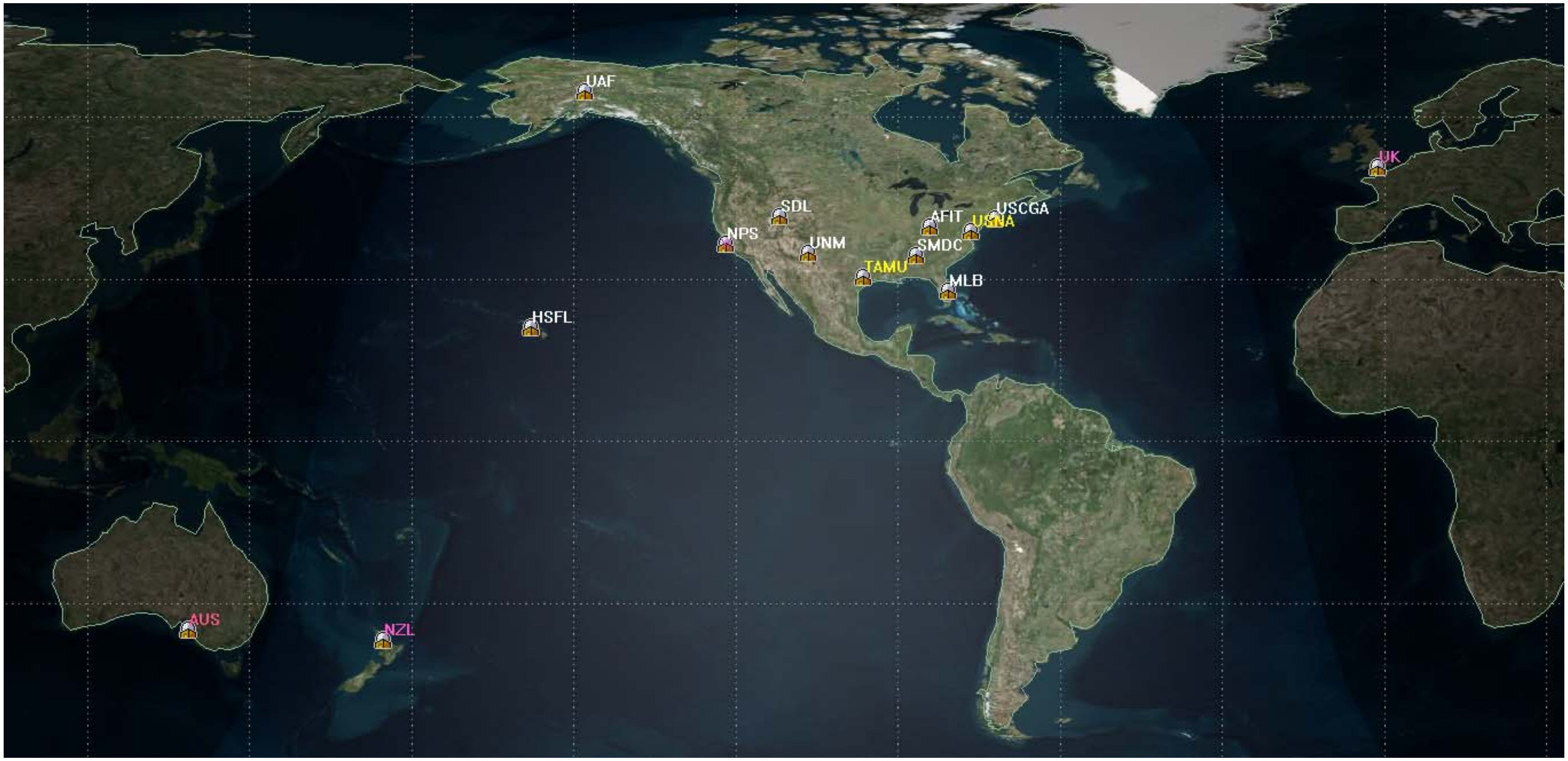
X-Band High Altitude Balloon

- Representative HAB flight
  - 100k ft burst altitude
  - 5 m/s assent
  - 5 m/s descent
- X-Band Transmitter
  - Antenna HPBW: 74 deg
  - Antenna gain: 6 dBi
  - Bandwidth 5 MHz
  - 8250 – 8400 MHz
- Radio cost ~$2,500
  - Raspberry Pi
  - USRP B205mini
  - GNURadio solution
  - RF upconversion components
  - 3D printed structure



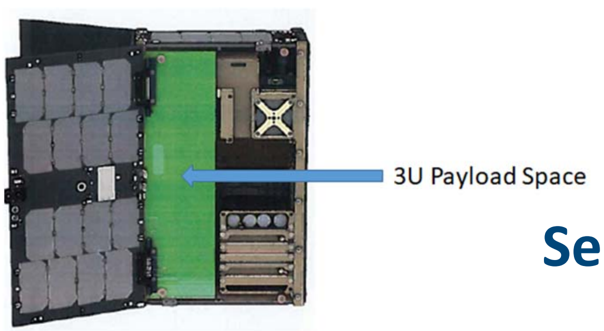
ISC2N



Member: International Small Satellite Command and Control Network (ISC2N)

MOLA & OTTER

2 x 6U CubeSats



THz Imaging

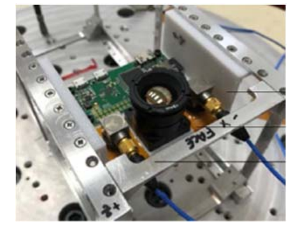
--Penetrates common materials--

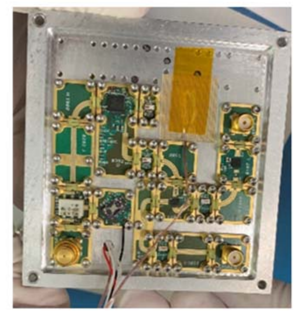
X-Band Test Radio

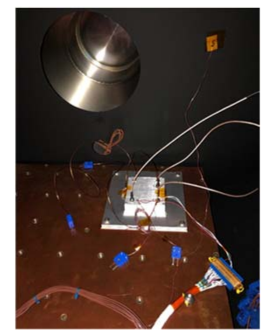
--Built by NPS students--

NZL Beacon Payload

--FlatSatNet--





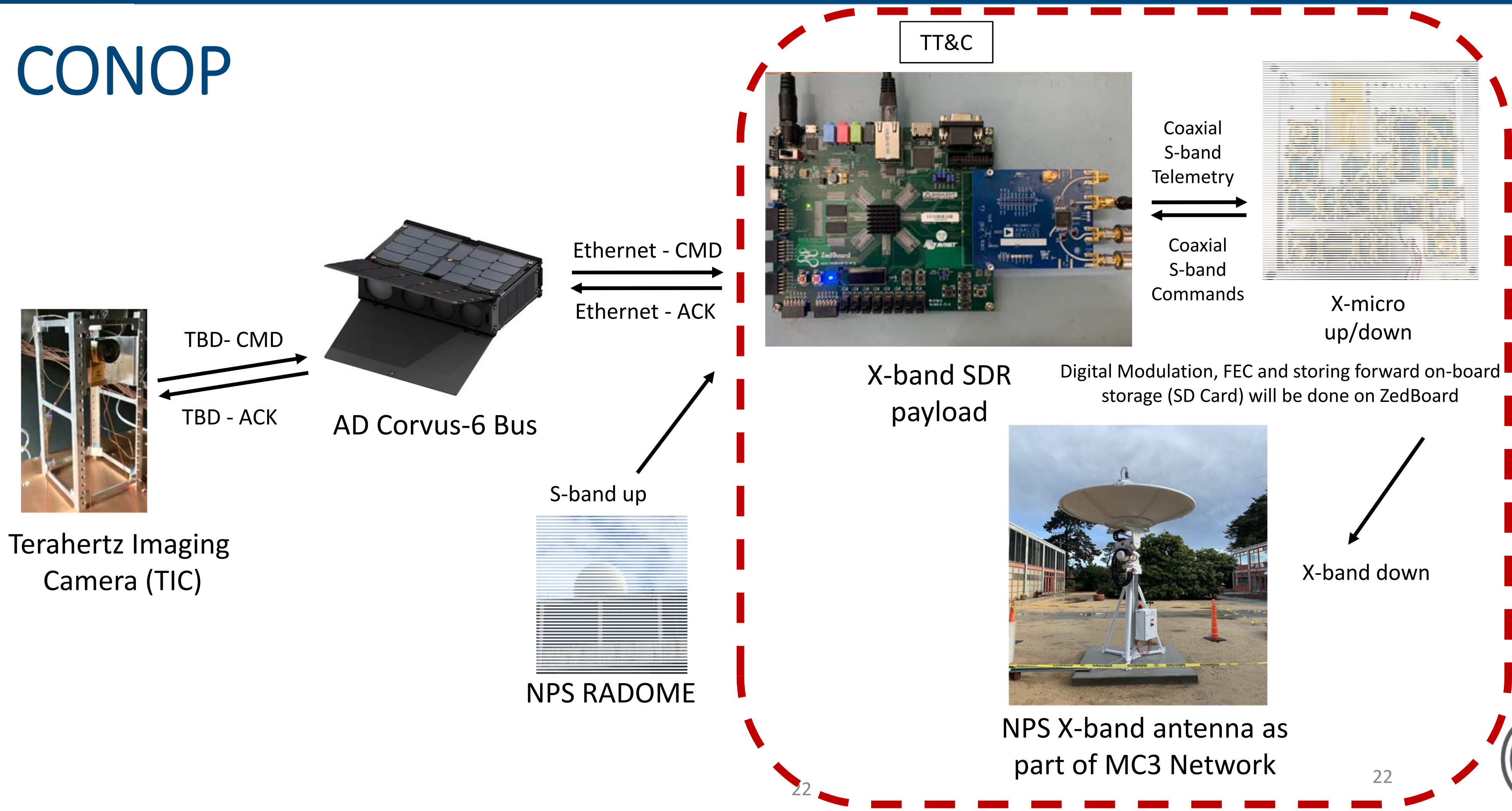


Seeking STEM Experiment(s)

English, H., “Concept of Operations, Software Development, and Flight Integration Testing for a THz Imaging Camera Payload”, M.S. Thesis, Naval Postgraduate School, Monterey, CA, June 2020

X-Band Radio Development

CONOP



Licensing

UNCLASSIFIED

(U) SmallSat Information Worksheet

(U) Date:

(U) Program Name:

(U) Point of Contact (Name/Phone):

Mission Information

a. Proposed launch date:
b. Dedicated launch or rideshare, and provider (if known):
c. Number of satellites:
d. Expected mission duration:
e. Mission Purpose (Space Research, etc.):
f. Mission Sponsor (Federal government (NTIA), FCC/Amateur):
g. Have any of the frequencies been registered or obtained frequency assignments already? If so, who was the approving agency and what is the approval document number (J/F 12, etc.)?

Orbit Data

a. Apogee and Perigee (kilometers):
b. Inclination (degrees):
c. Period of Orbit (minutes):

Ground Stations

a. List the ground station locations to be used for downlink/uplink (City & State):
b. If not an MC3 registered ground station, please provide the latitude, longitude, and elevation in meters above mean seal level of the antenna:

Satellite Transponders/ Radio

a. General
   i. Coherent uplink and downlink?
   ii. Ranging required?
   iii. Number of frequency pairs?
b. Receive – Uplink (include details for each signal)
   i. Frequencies:
   ii. Modulation type:
   iii. Bandwidth (or data rate) required:
   iv. Type of encoding (if any):
   v. Emission designator:
   vi. Transmitter power (watts):
   vii. Antenna gain (dBi):
   viii. Antenna beamwidth (degrees):

Van in Lot on Del Monte Ave between Municipal Beach and Monterey Bay Park

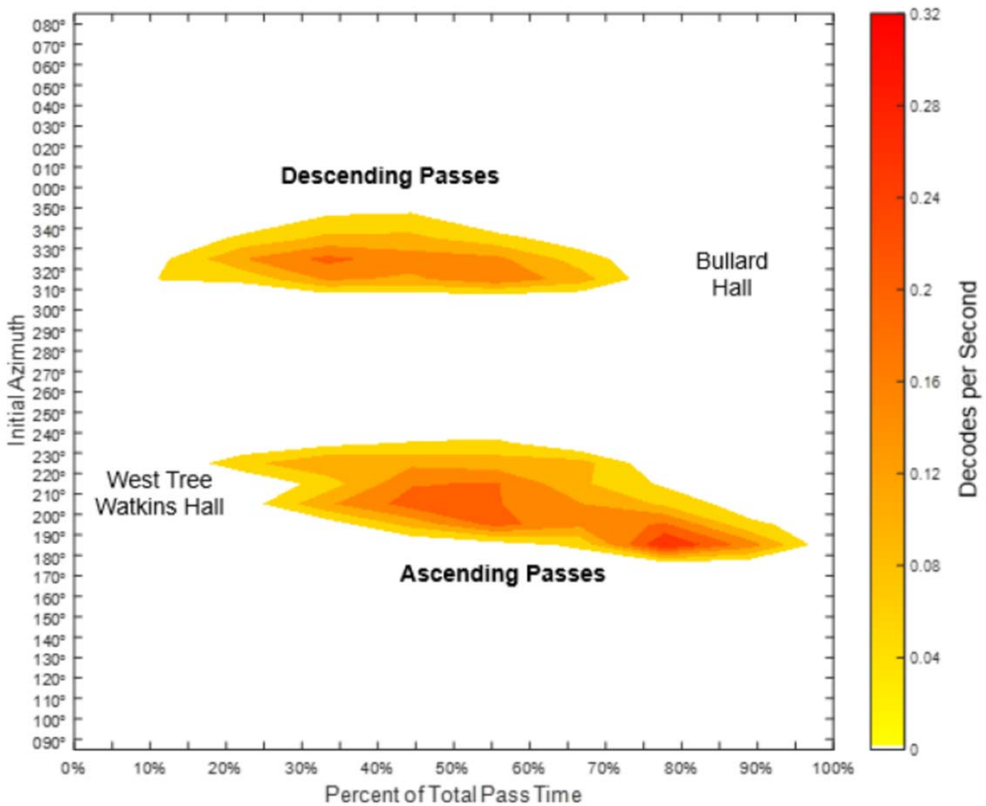
Fixed Transmit Antenna on Building Roof on Fisherman's Wharf

Forbes, A., "Sharing S-Band Communications to Conduct Small Satellite TT&C", M.S. Thesis, Naval Postgraduate School, Monterey, CA, March 2018

NASA/DoD/DoC (NDD) Coordination Process

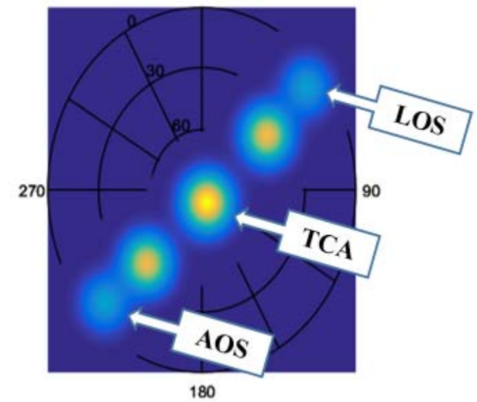
1. **Verify new Small Satellites fall within appropriate spectrum certification**
2. **Perform frequency selection and RFI analysis**
3. **Initiate and complete coordination**
    - **NASA, NOAA, ENG**
4. **Initiate RFA process referencing completed coordination**

- Applies only to LEO
- Mission duration < 5 years
- Specific frequencies for satellites must still be selected
- Earth stations given band assignments to support multiple missions
- Reduced processing time (~1 yr per program)
- Offers protection, streamlines process, efficient use of spectrum



Define: Objective, Dynamics, Constraints

$$
\begin{cases}
\text{Minimize} & J[x(\cdot),\mathrm{u}(\cdot),t_f] = E(x(t_f)) + \int F(x(t),u(t))dt \\
\text{subject to} & \dot{x}(t) = f(x(t),\mathrm{u(t)}) \\
 & x(t_o) = x^0 \\
 & t_o = t^0 \\
 & t_f = t^f \\
 & e(x(t_f)) = 0
\end{cases}
$$



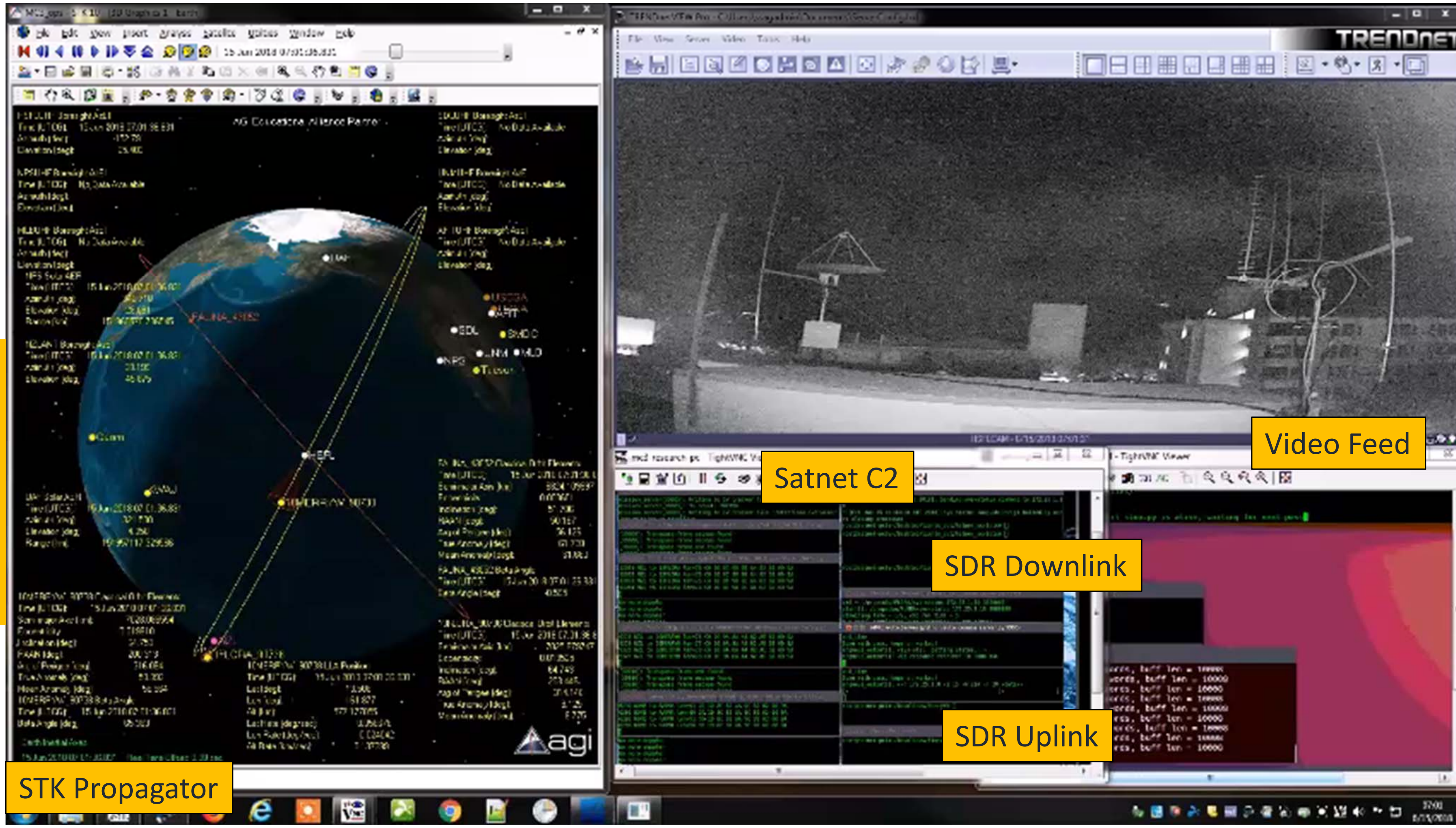
Leone, J., “CubeSat Pass Quality Analysis and Predictive Model”, M.S. Thesis, Naval Postgraduate School, Monterey, CA, June 2018

3SAT/1GS (2ANT) Demo

HSFL MC3

Merryweather
Fauna
Flora

~ 25 min

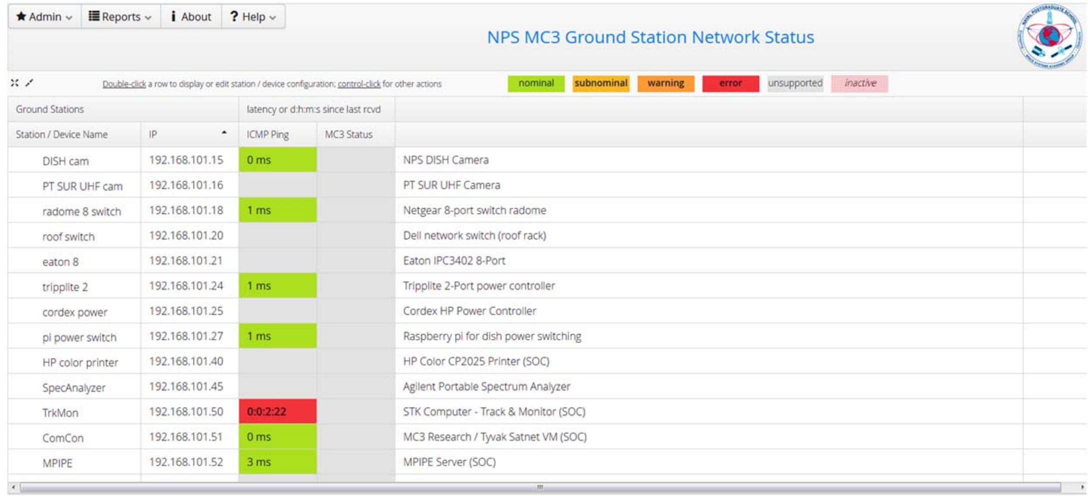


Environmental Monitoring

- Treat MC3 nodes as “satellites”
  - Collect health and environment telemetry
  - Introduce autonomous issue detection and classification
  - Remove operator involvement through autonomous issue resolution

- Health and Environmental Monitoring System (HEMS)
  - Voltage, current, temperature, humidity telemetry
  - Device-level power and network controllability
  - Inductive monitoring system (IMS)
    - Algorithm for real-time telemetry interpretation
    - Trains on healthy ground station data

- Automated G/T measurements in development
  - Trending for ground system performance



Admin | Reports | About | Help

NPS MC3 Ground Station Network Status

Double-click a row to display or edit station / device configuration; control-click for other actions

nominal | subnominal | warning | error | unsupported | inactive

Ground Stations		latency or d:h:m:s since last rcvd		
Station / Device Name	IP	ICMP Ping	MC3 Status	
DISH cam	192.168.101.15	0 ms		NPS DISH Camera
PT SUR UHF cam	192.168.101.16			PT SUR UHF Camera
radome 8 switch	192.168.101.18	1 ms		Netgear 8-port switch radome
roof switch	192.168.101.20			Dell network switch (roof rack)
eaton 8	192.168.101.21			Eaton IPC3402 8-Port
tripplite 2	192.168.101.24	1 ms		Tripplite 2-Port power controller
cordex power	192.168.101.25			Cordex HP Power Controller
pi power switch	192.168.101.27	1 ms		Raspberry pi for dish power switching
HP color printer	192.168.101.40			HP Color CP2025 Printer (SOC)
SpecAnalyzer	192.168.101.45			Agilent Portable Spectrum Analyzer
TrkMon	192.168.101.50	0:0:2:22		STK Computer - Track & Monitor (SOC)
ComCon	192.168.101.51	0 ms		MC3 Research / Tyvak Satnet VM (SOC)
MPIPE	192.168.101.52	3 ms		MPIPE Server (SOC)

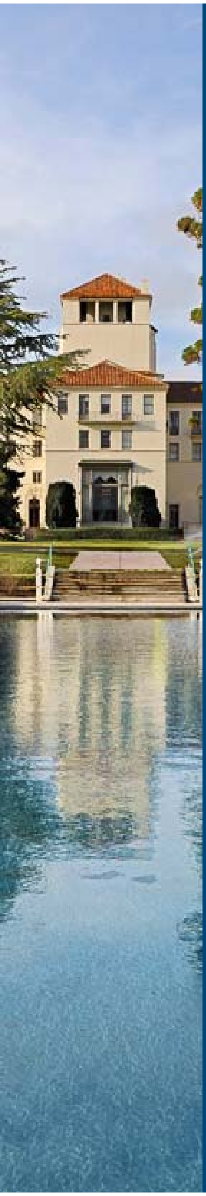
Future Work

We’re looking for partnerships!

- Ground network collaborations
  - Commercial and government networks
- Additional SDRs/ waveforms
  - Partner with ground and spacecraft radio providers
- X-band expansion
  - Licensing
  - Hardware
- Autonomous disaggregated constellation management
- Machine learning
  - Automated ground station anomaly resolution
- Laser Communications
- Electronics Steered Arrays
- Satellite transponders and passive tracking reflectors
- Optical tracking/ space situational awareness
- Additional resiliency
  - Software improvements
  - Cybersecurity – DoD accreditation

Contact Information

Mobile CubeSat Command and Control (MC3)
Space Systems Academic Group
Naval Postgraduate School
mc3@nps.edu

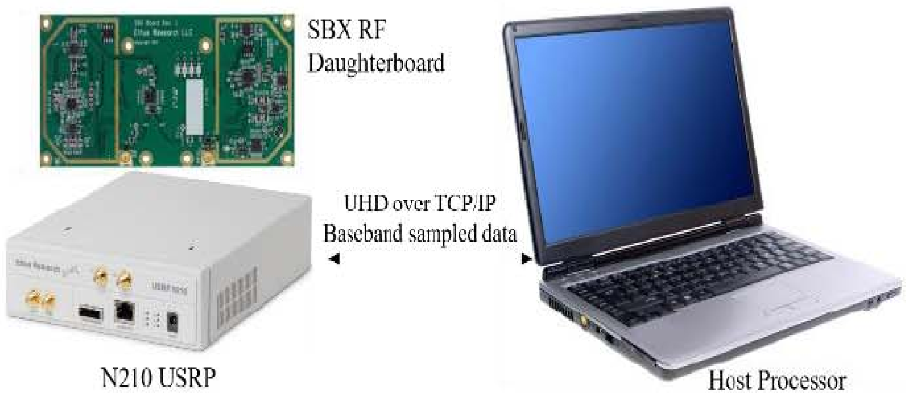


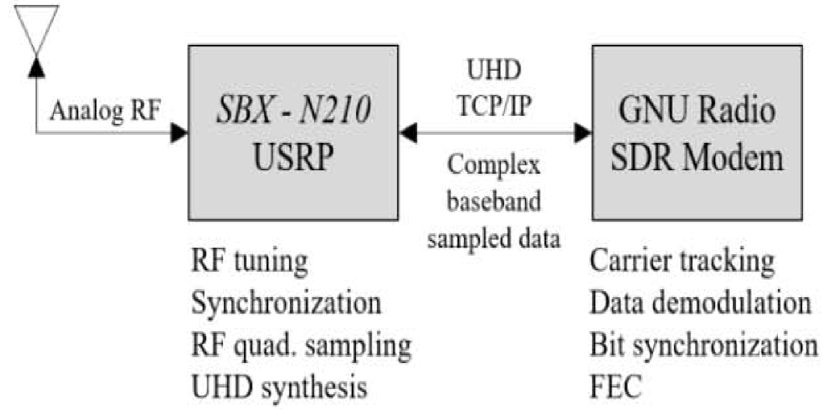
Backup

Naval Postgraduate School

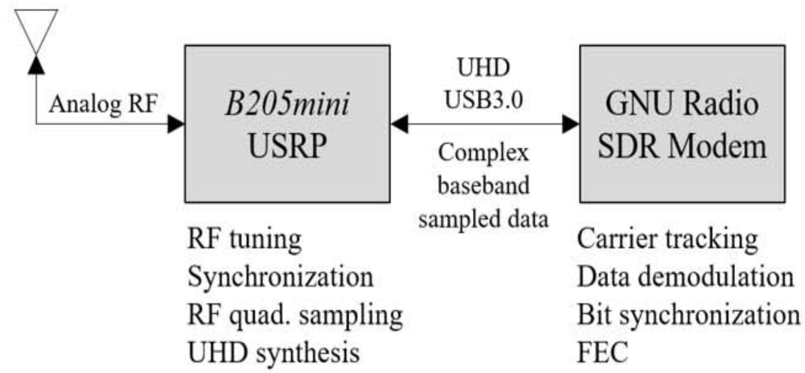
Radios Under Study (RUS)

RUS 1



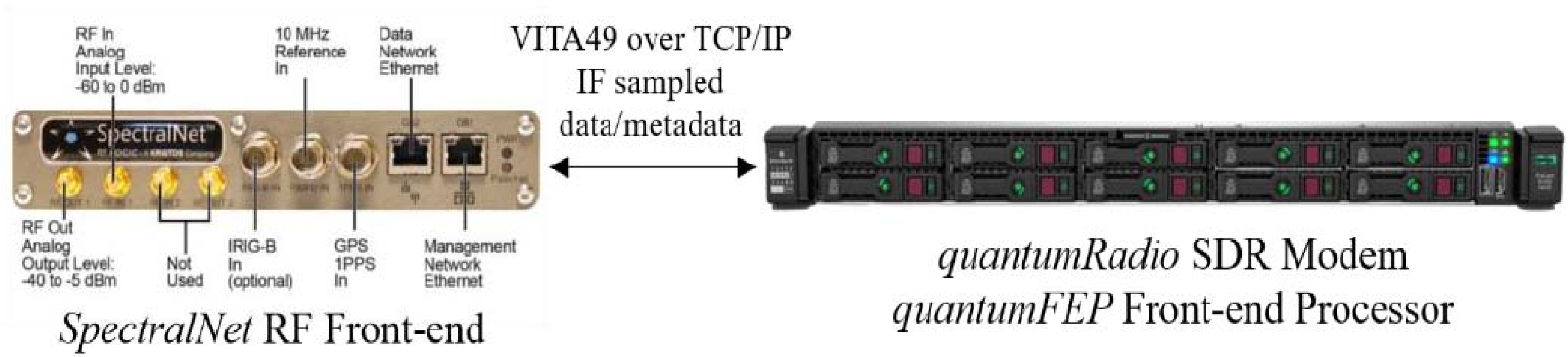


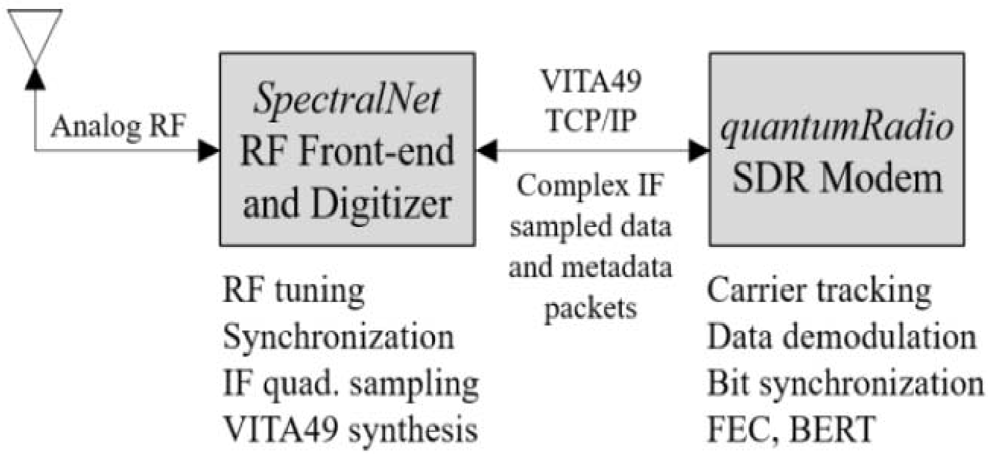
RUS 2



Radios Under Study (RUS)

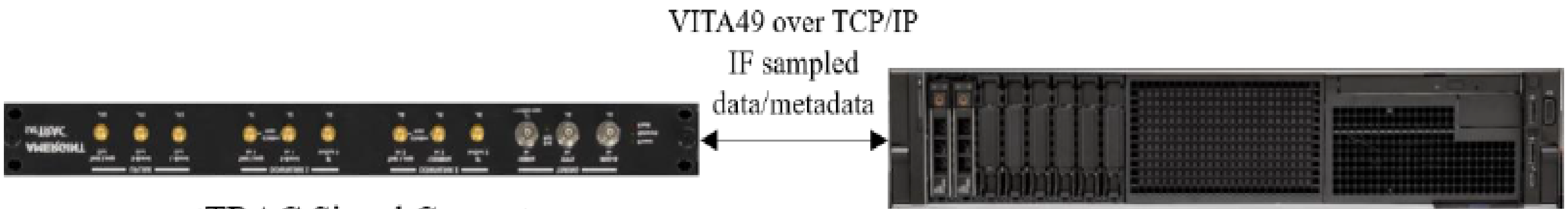
RUS 3





Radios Under Study (RUS)

RUS 4



satTRAC Signal Converter

satTRAC Modem