Relative Navigation, Timing & Data Communications for CubeSat Clusters

Tethers Unlimited
Advanced Propulsion, Power, & Comm. for Space, Sea, & Air

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Motivation

- **Tethered CubeSats**
  - Relative distance and position important for tether dynamics knowledge and control
- **Fractionated Spacecraft (e.g. DARPA F6 clusters)**
  - Collision avoidance
  - Relative position knowledge for orbit maintenance
  - Aid in pointing higher gain apertures
- **Distributed Sensing systems**
  - Relative position knowledge for orbit maintenance
  - Timing for synchronized sampling
  - Knowledge of sensor baselines and orientations

RelNav Enables Cluster Operations

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- **Spacecraft subsystem that will enable a 'flock' of satellites to operate as a coordinated cluster**
  - Relative Position and Orientation for Formation Flight
    - Provide reference data for cluster-based sensors
  - Cluster Synchronization and Timing
    - Essential for coordinated operations and coherent measurements
  - Inter-satellite communication
    - Data exchange for cluster-based sensors

	Kinematic GPS w/ UHF link	TUI's "Raw" RelNav
Relative Ranging Precision (1-σ)	0.1 m	**<0.1 m**
Relative Velocity Precision (1-σ)	10 mm/sec	**5 mm/sec**
Relative Attitude Precision (1-σ)	N/A	**1˚**
Relative Timing Precision (1-σ)	1 nsec	**0.3 nsec**
Comm Data Rate(BER≤10^{-6})	0.0192 Mbps	**>10 Mbps**
Range of Operations	< 10km	**<10 km**

RelNav provides improved relative navigation, timing, and inter-sat communications over GPS-based methods to enable precision cluster flight and coherent sensing.

RelNav Core Technologies

- **Attitude Measurement Algorithms**
  - Processing of pseudo-Doppler signals to measure relative phase of signals between antennas
  - Processing of relative phase signals to estimate signal angle of arrival within 1˚ (1-σ) from a small array
- **Ranging Measurement Algorithms**
  - Pseudo-random noise (PRN) ranging measurements
  - Two-way ranging signaling to minimize errors due to clock offsets and drift
- **High-reliability, space-qualifiable SDR platform**
  - Current brassboard prototype constructed of COTS equivalent military-grade high-rel components

RelNav Configurations

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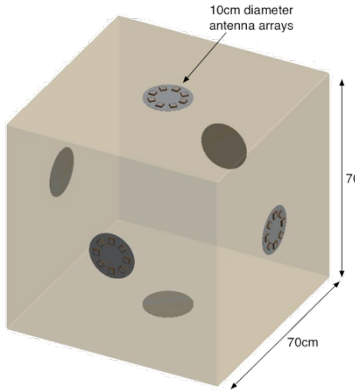
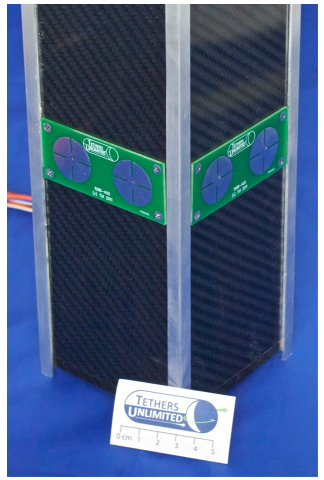
- **Microsat-scaled RelNav System**
  - Radiation-hardened subsystem for LEO microsatellite (≈100kg)
    - Includes multiple antenna arrays (nominally 6) to ensure full sphere field of view
- **CubeSat RelNav System**
  - Simplified antenna array configuration to minimize footprint on 3U CubeSat
  - Include single antenna array to measure relative attitude in one dimension
    - Measures azimuth in what is nominally local horizontal FOV
      - Assumes long axis is nadir pointed
    - Use of highly integrated COTS parts reduces avionics SWaP
      - Does not affect ranging, timing, or communications performance



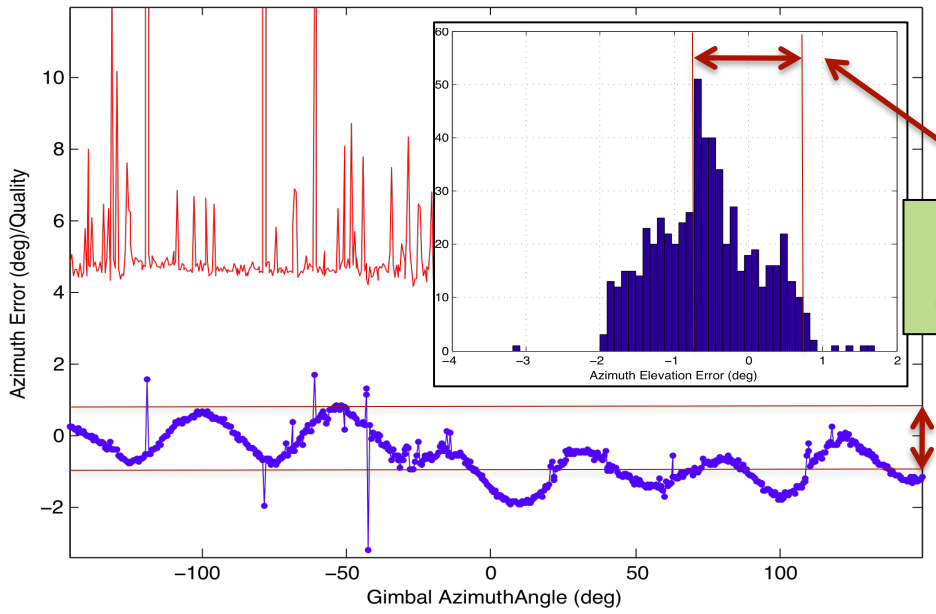


	MicroSat RelNav	CubeSat RelNav
Size	15x15x7.5	10x10x3.5
Mass	2.1 kg	0.38 kg
Power	2.4W avg.* 7.5W peak	1.4 W avg.* 5.0W peak

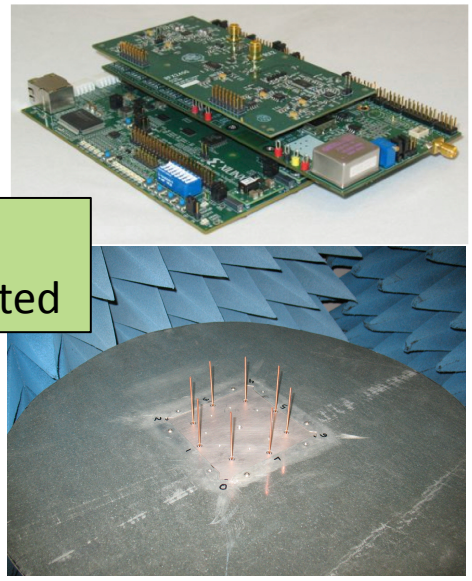
** 3 satellites in cluster, 1 Hz update rage, 3Mbps communications (25% of time after nav)*

Demonstrated Attitude Performance

- **Relative Attitude Measurement**
  - Single antenna array performance with brassboard prototype
    - Azimuth precision: $\sigma_A = 0.69^\circ < 1^\circ$ requirement
    - Coarse estimate of elevation $\sigma_A = 5.4^\circ$ (auxiliary estimate)
  - Error analysis indicates that calibration can increase precision



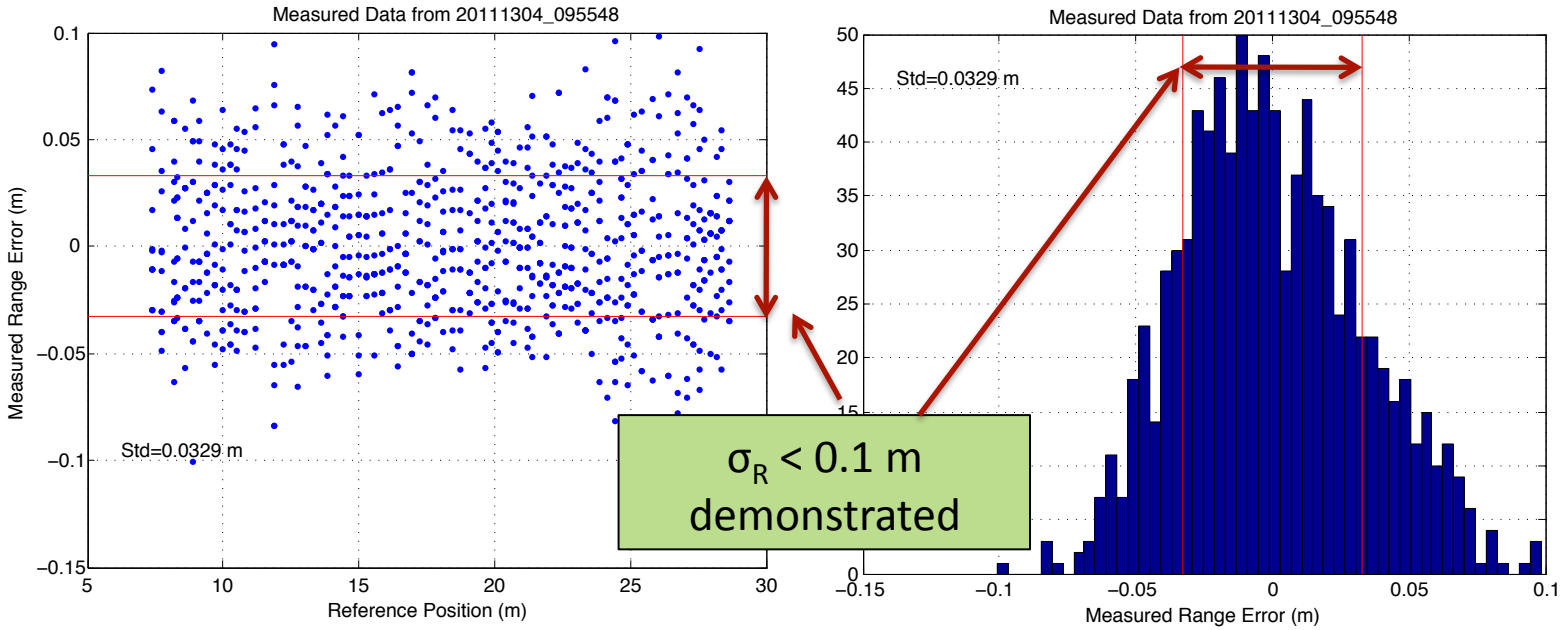
$\sigma_A < 1^\circ$ demonstrated



Test Configuration

Demonstrated Ranging Performance

- **Relative Range (Timing) Measurements**
  - Two-way ranging performance with brassboard prototype
    - Typical single-bit measurement precision: σ_R= 0.02-0.09 < 0.1 meters
      - Outdoor measurements (not on RF range)
    - Time synchronization derived from ranging 0.1 meters ≈ 0.3 nsec
  - Improved clocking and averaging will increase precision
    - <1 cm resolution feasible with further improvements



Demonstrated Ranging Performance

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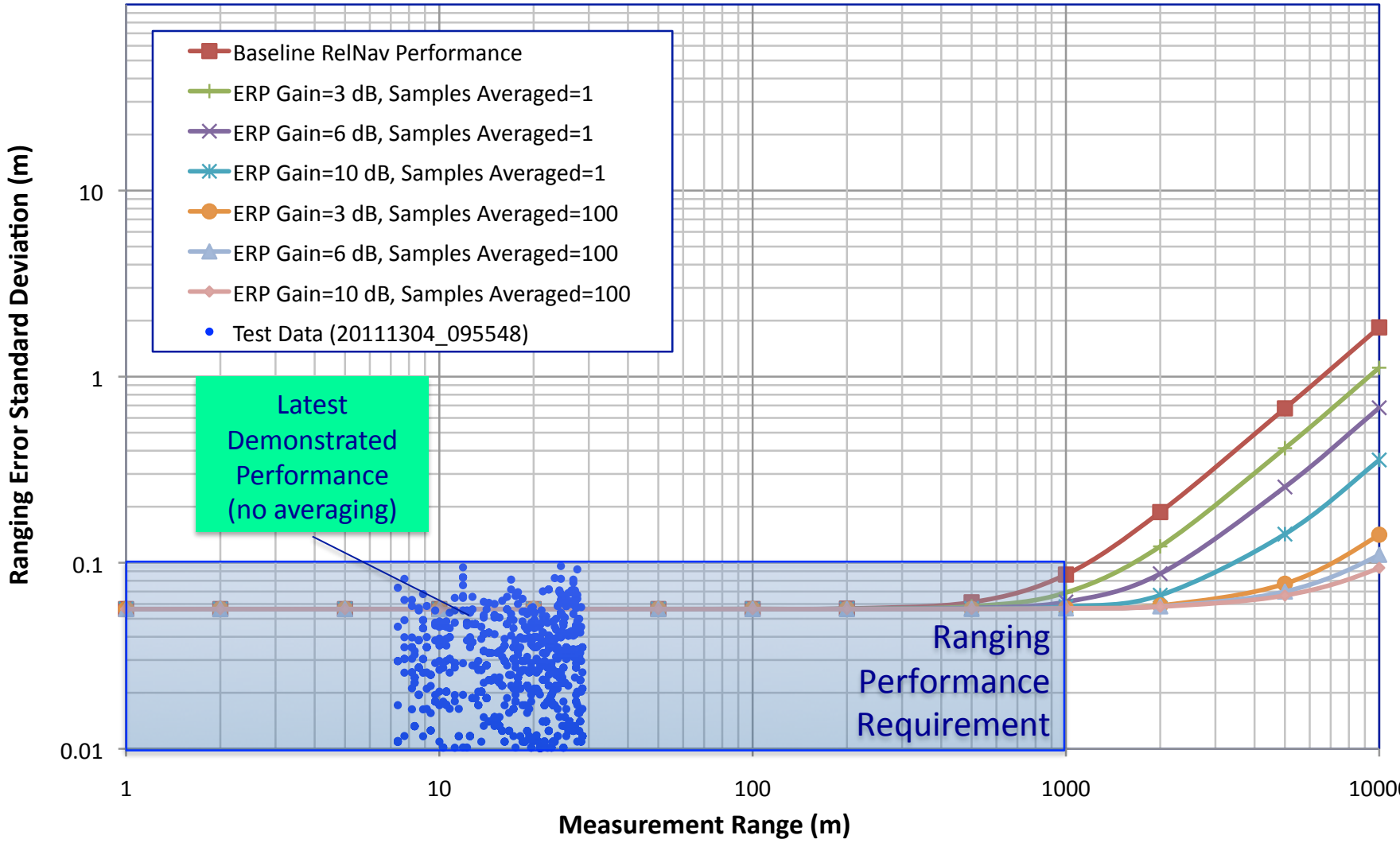
Current RelNav Ranging Performance (110413)



RelNav for CubeSat

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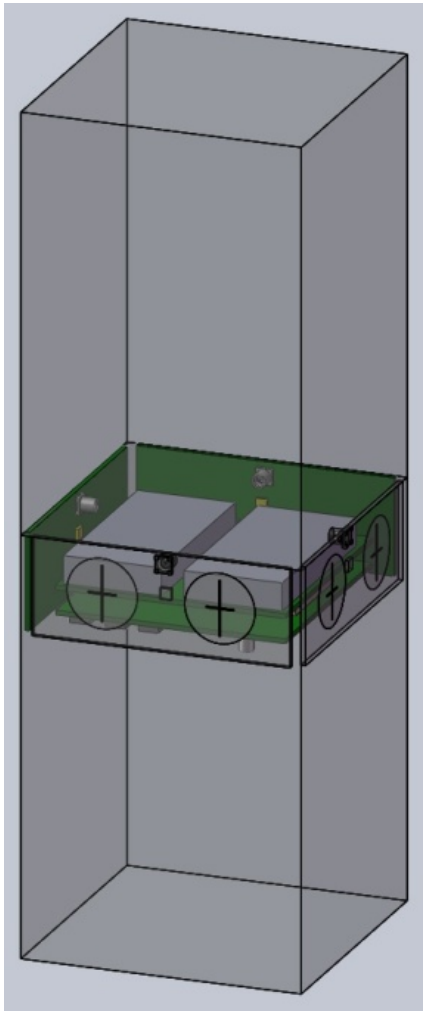
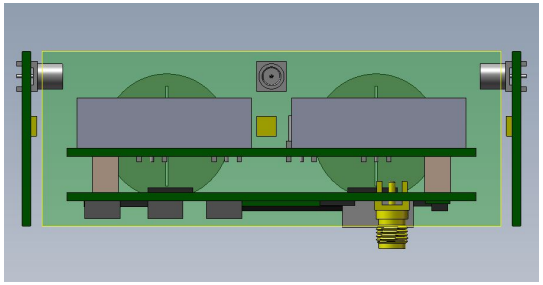
- **CubeSat RelNav Configuration**
  - 8-element (4x2) RHCP antenna array
  - Integrated <0.5ppm oscillator and ability to interface to higher precision onboard clock
  - Data link encrypted with AES-256
- **CubeSat RelNav SWaP Estimate**
  - Size: module is 35mm high => 0.35 U
  - Mass: < 0.4 kg
  - Power: 2.5W average, 5W peak
    - 3 element Cluster with 1Hz update rate on range, and attitude, with data communications 50% of remaining time
    - Data throughput: 6 Mbps





RelNav Communications Bandwidth

- **SDR Enables Multiple Modes of Communication**
  - Current ranging messaging supports channel rate of ≈ 400kbps
  - Reconfiguring the SDR for data-only communication can very readily provide a channel data rate of up to 12Mbps
    - >11dB SNR provides 10^{-7} bit error rate (BER)
    - Forward Error correction can be added to reduce BER at lower SNRs
- **Simple approach relies on Time Division Multiple Access (TDMA) for satellite-satellite communications**
  - If needed, CDMA can be used at the expense of more correlators in radio processors (potential SWaP impact)

CubeSat RelNav Operating Profile

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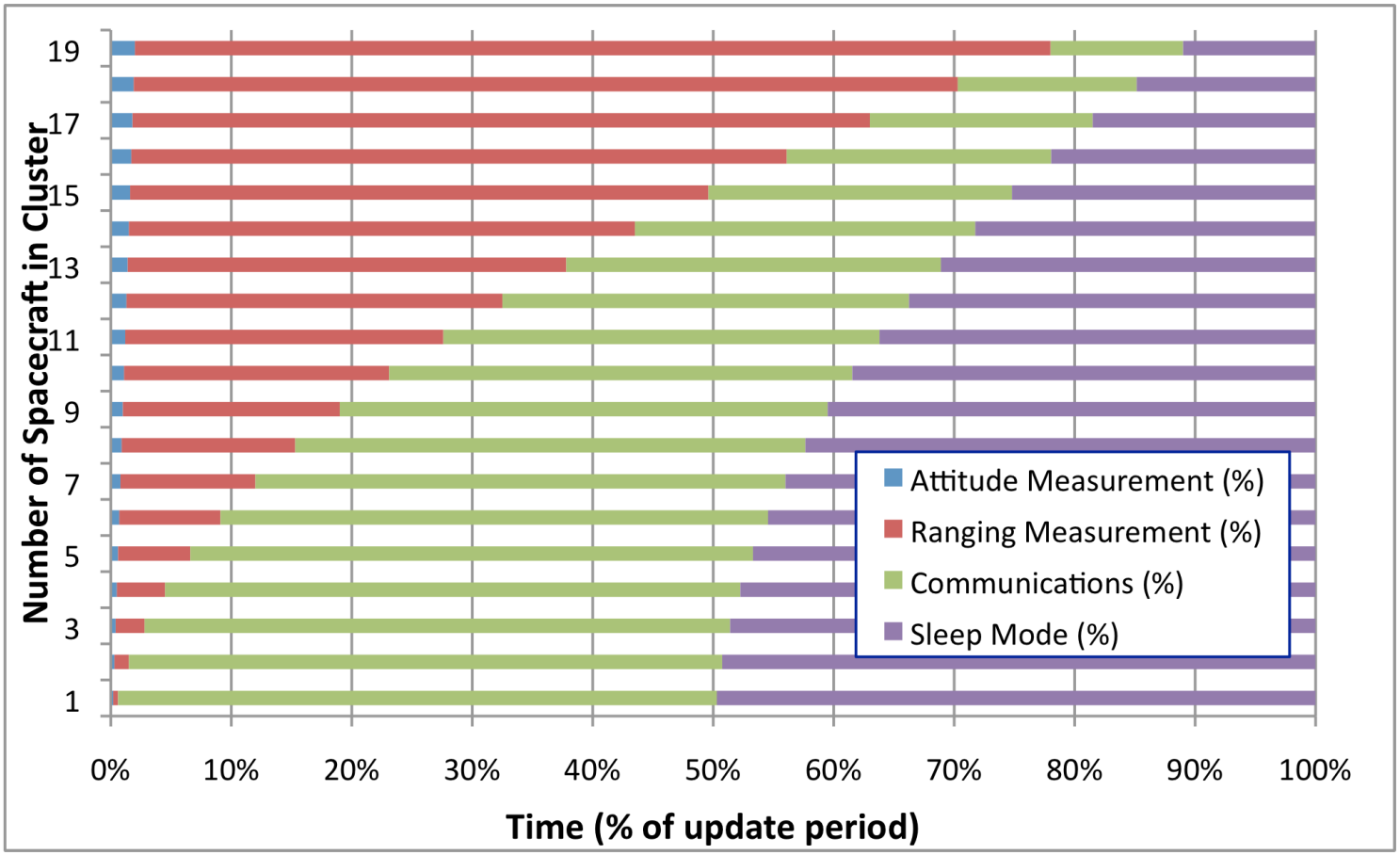
- **Operating Parameters**
  - System measures attitude and range between all satellites in 2 seconds (0.5 Hz update rate)
  - 50% of time remaining after measurements used for data comm



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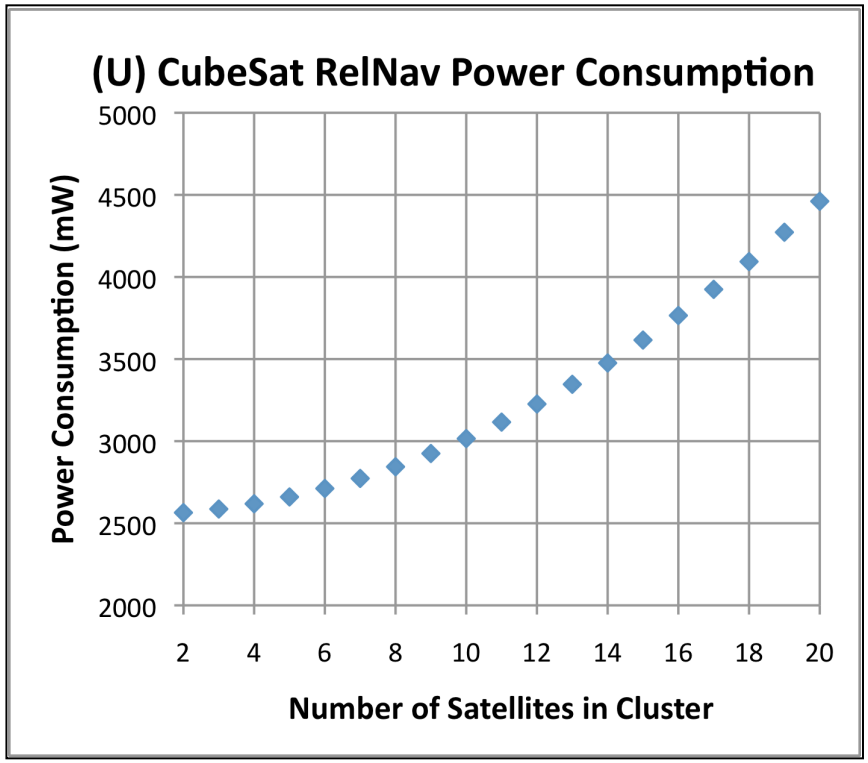

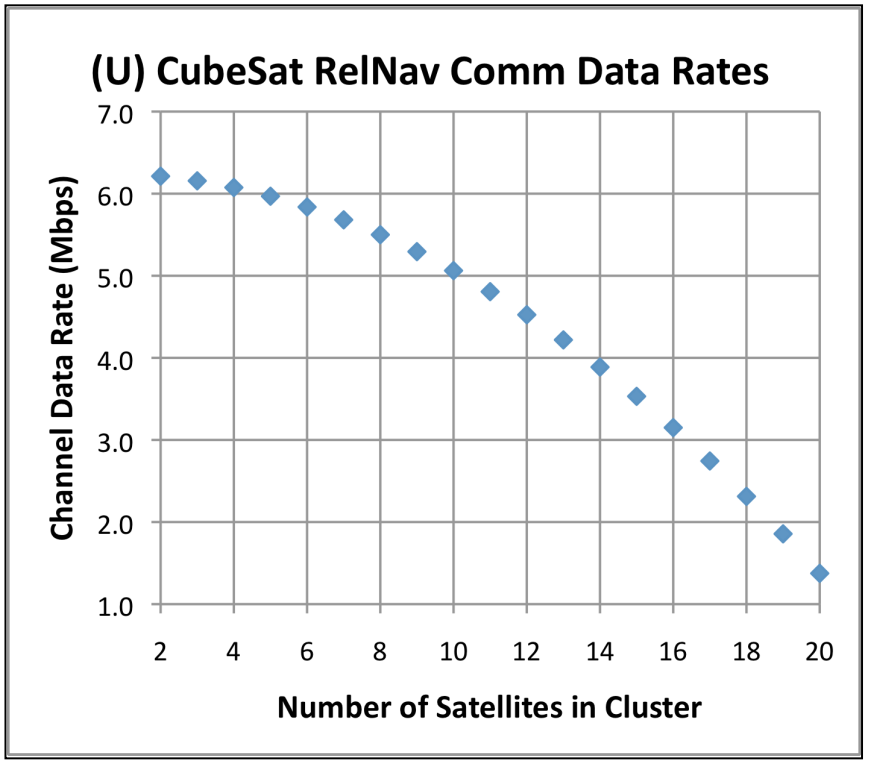

Summary Program Status & Plan

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- **Development Status**
  - Fully functional brassboard prototype
  - Attitude measurements demonstrated to requirements
  - Ranging measurements demonstrated to requirements
    - Comm crosslink @ 400kbits/second demonstrated
- **Future Plans**
  - Fabricate prototype & EM of CubeSat scale RelNav system
  - Demonstrate high-speed communications capability
  - Perform additional testing to verify performance over operating conditions
  - Incorporate kinematics to increase precision and accuracy
  - Explore other applications for TUI's RelNav SDR Technology