Low Mass Radio Science Transponder – Satellite TRL Raising Mission for LMRST

Solar System Navigation and Radio Science

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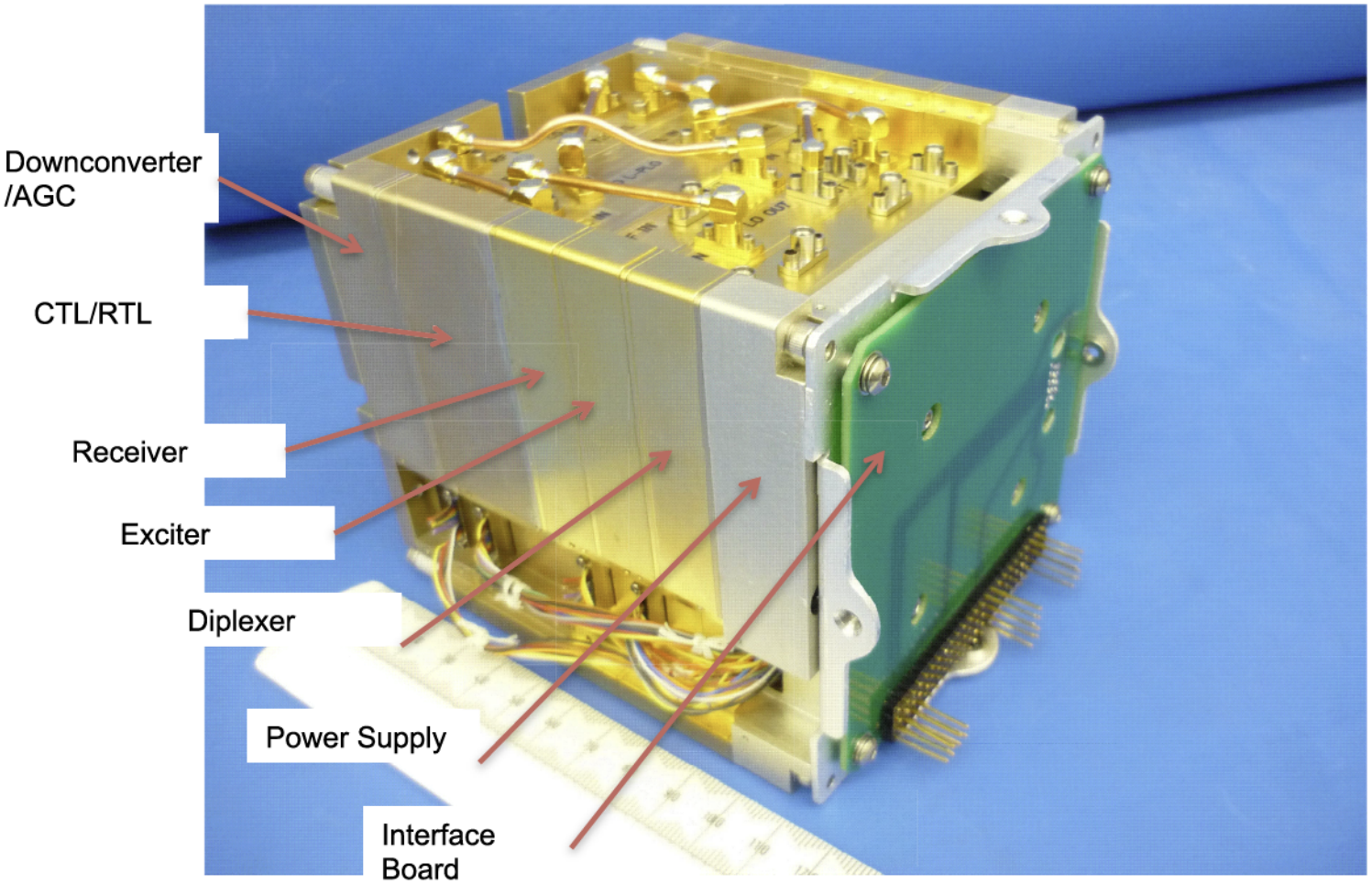
Low Mass Radio Science Transponder

- Doppler and Ranging turnaround transponder
  - No onboard precision reference needed
  - Developed as Radio Science Transponder Instrument (RSTI)
- Low Tech – does only that with minimal parts
  - Adding low rate command and telemetry under discussion
- X and Ka-Band options, can mix
- TRL raising LMRST-Sat mission, CLI, late '14
  - 1U form factor
  - ~1 Kg
  - 8 W when active
    - Short arcs / low duty cycle reasonable
  - Earth orbit demo
  - 1 m. desired ranging accuracy
    - Better with careful antenna placement

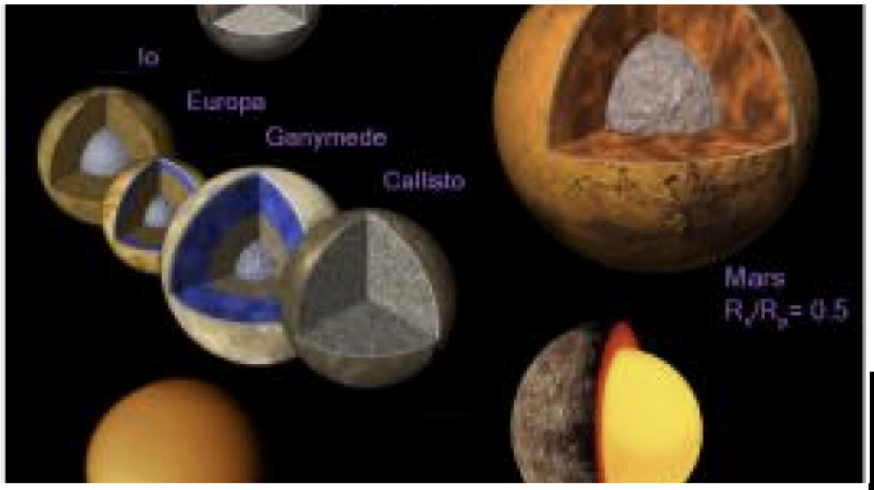
X/X-band LMRST



Deep Space Science

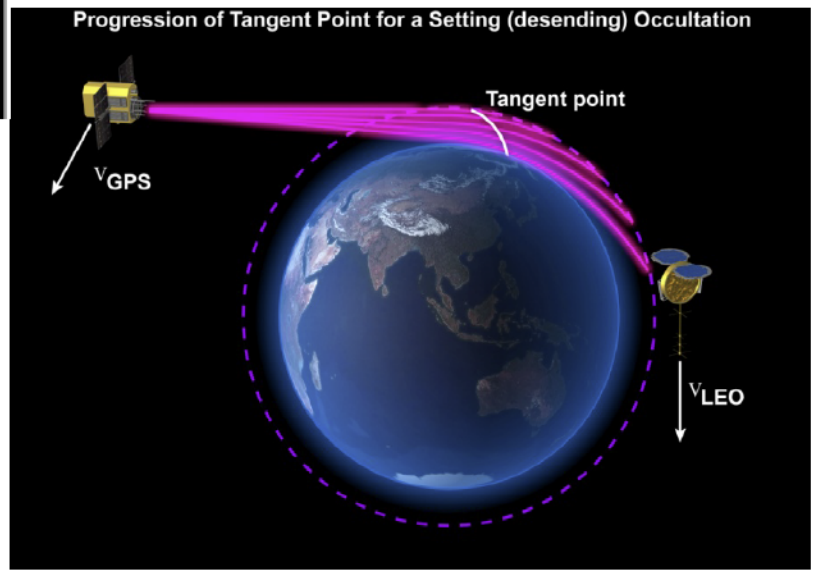
- Gravity Fields
- Atmospheres – Media
- Calibration Target / Source

Deep Space Science



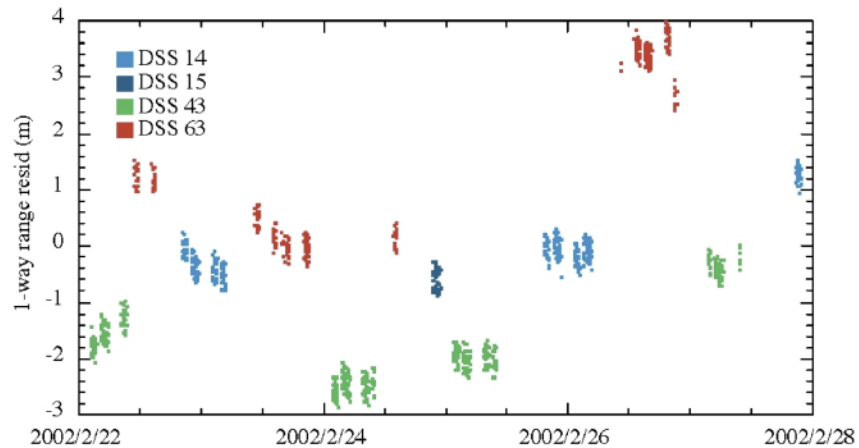
Planet/Moon Gravity Fields

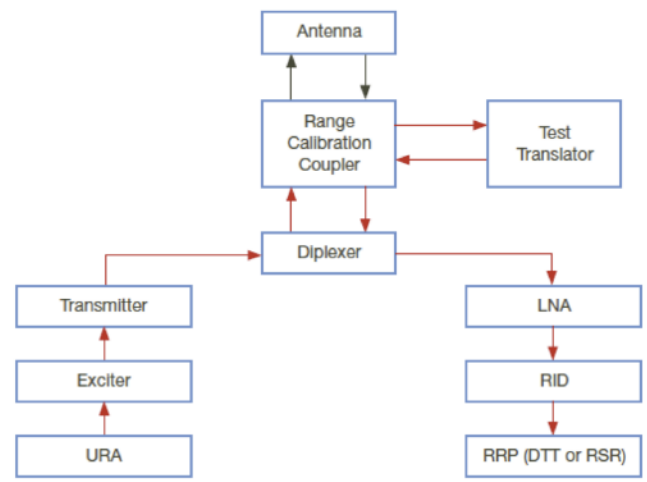
Atmosphere/Ionosphere Profiles



DSN Calibration Target

- X-Band uplink ranging system gives different bias each time configured
  - Error should be 30-50 cm not 1.2 m.
- Cannot separate from other error sources to deep space targets
- Ground calibration facilities are problematic
  - Low elevation angles
  - Single site
- Space-based platform at this cost are only recently plausible due to nanosat technology and inexpensive secondary-payload launches.





Deep Space Navigation

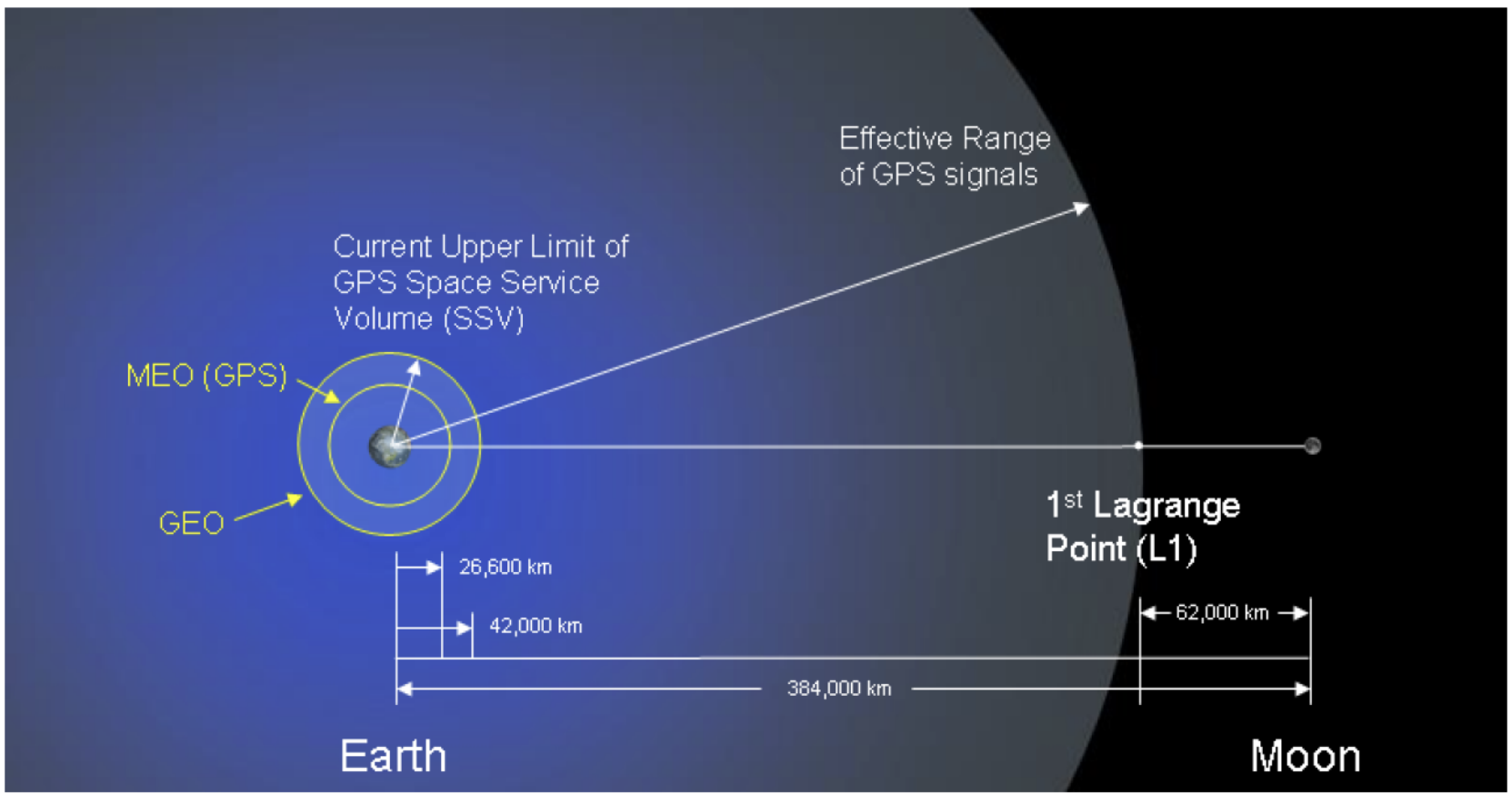
- These five tasks need to be performed for successful navigation, be it on Earth or in interplanetary space:

Task	Example on Earth (Hiking)	Example in Deep Space
(1) Obtain a Map	Obtain road map, digital map database	Develop planetary ephemerides
(2) Develop a Travel Plan	Select trail(s) to reach destination, estimate arrival time	Select orbit(s) to reach destination planet/asteroid, calculate arrival time
(3) Take Meaningful Measurements	Note time arrived at significant landmarks, note direction with a compass	Use radio signals and/or optical measurements to compute spacecraft position and velocity.
(4) Calculate One's Position	Compare actual arrival time at waypoint to predicted time	Estimate size, shape and orientation of orbit
(5) Select a New Optimal Route	Walk faster/slower, change direction	Change orbit using propulsion system

- Tasks 1-2 are done pre-launch, the others from launch to end-of-mission.
  - Information from Dr. Alberto Cangahuala, JPL, "Deep Space Navigation 101"

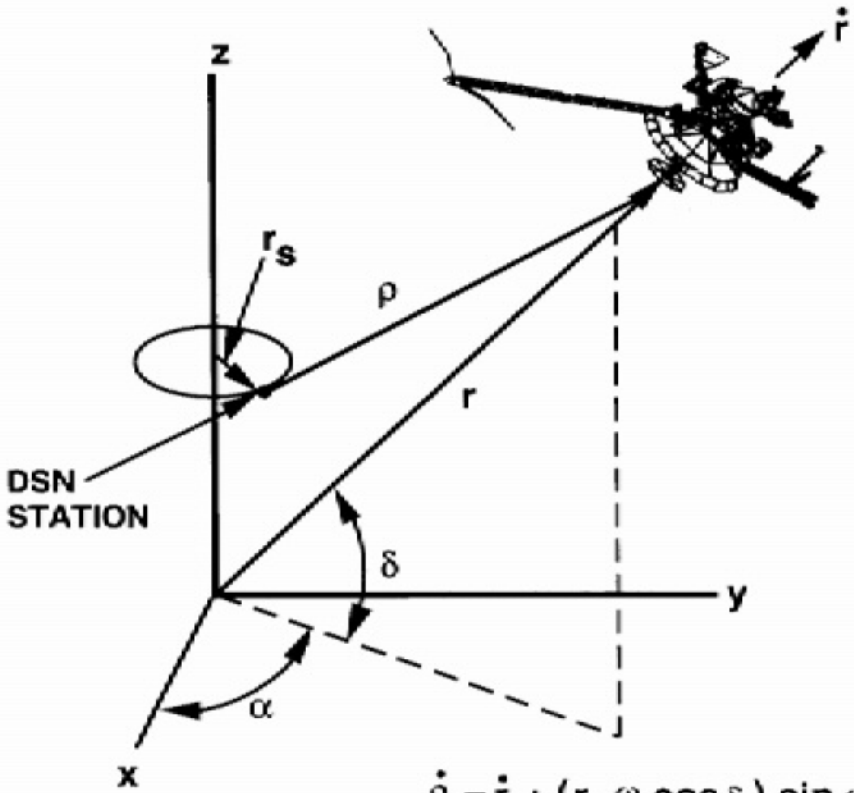
Navigation with GPS beyond Earth Orbit … and on to the Moon

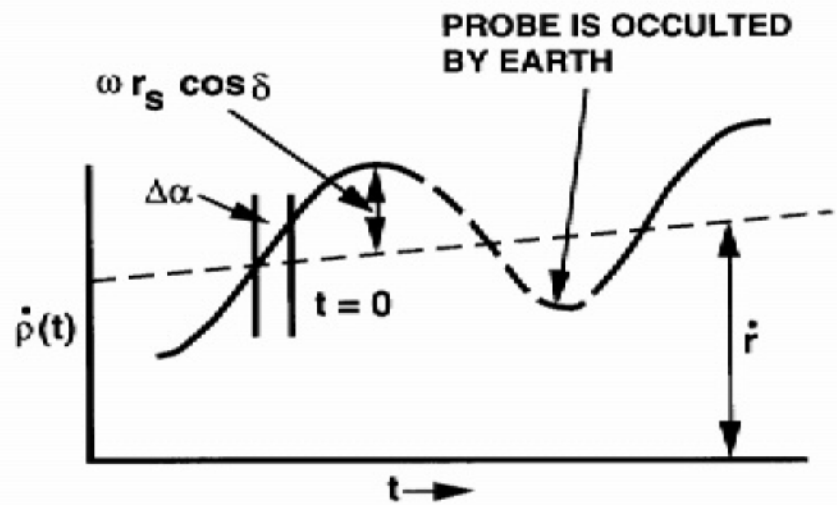
- GPS signals effective up to the Earth-Moon 1st Lagrange Point (L1)
  - 322,000 km from Earth
  - Approximately 4/5 the distance to the Moon
- GPS signals can be tracked to the surface of the Moon, but not usable with current GPS receiver technology



Navigation Measurements:

- TWO-WAY RANGE AND DOPPLER DIRECTLY MEASURE LINE-OF-SIGHT COMPONENTS OF SPACECRAFT STATE
- DIURNAL SIGNATURE OF EARTH ROTATION ALSO PROVIDES ANGULAR STATE INFORMATION





$$\dot{\rho} = \dot{r} + (r_s \omega \cos\delta) \sin\omega (t - t_m) + \text{OBSERVATION ERROR}$$

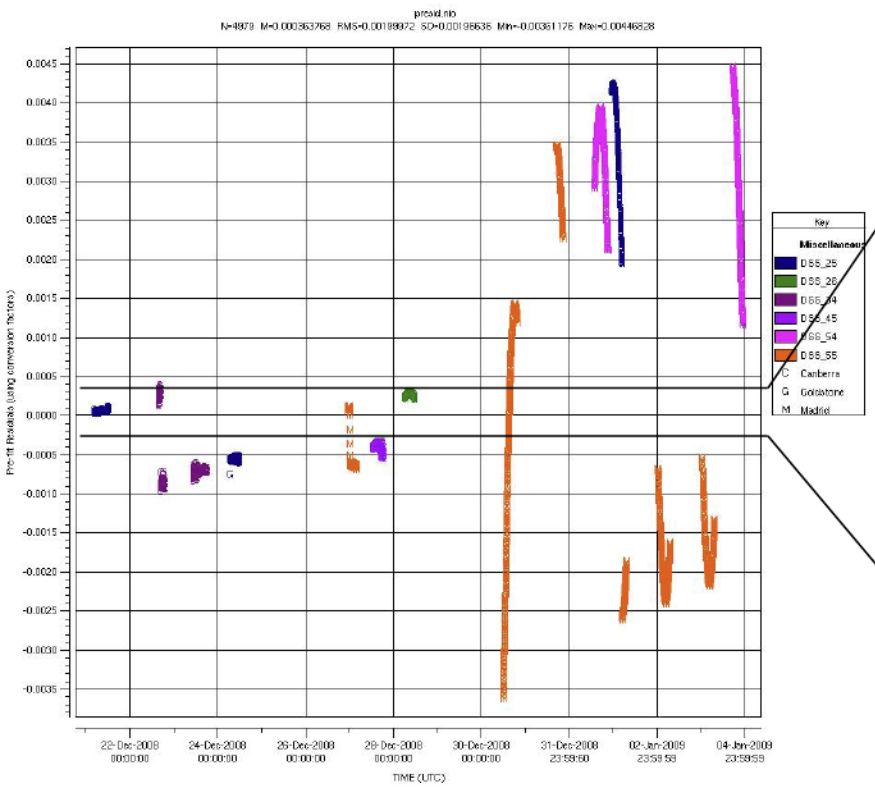
WHERE t_m IS THE TIME OF MERIDIAN CROSSING

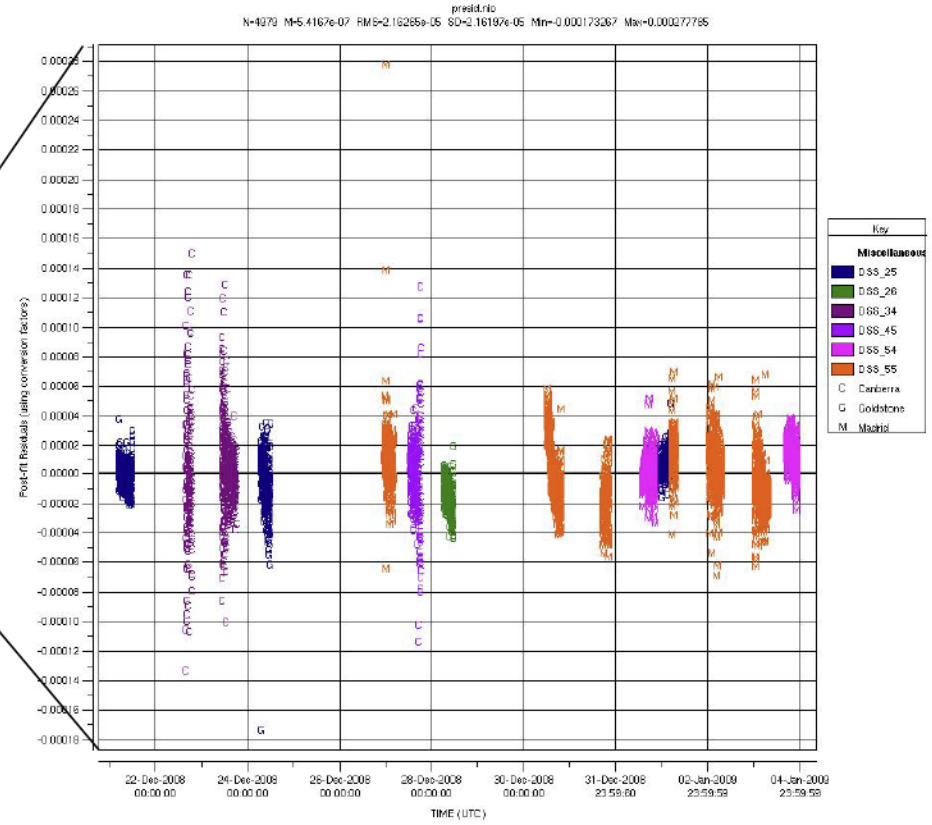
‘Calculating One’s Position’ - Orbit Determination

1. Start with initial guess of spacecraft position, velocity, and associated dynamic parameters,
2. Numerically integrate equations of motion to get position and velocity as a function of time
3. Form data residuals:
   - (What I observered) - (What I thought I was going to observe)
4. Perform least squares fit
   - Adjust trajectory and associated parameters to minimize sum-of-squares of residuals of all available data
5. Iterate on (1-4) until residuals in (3) are small, due to random noise
   - <u>Least squares solution also produces uncertainties on parameters estimated</u>
     - Very important to determine how good the fit is, and evaluating results to decide whether or not to perform maneuvers

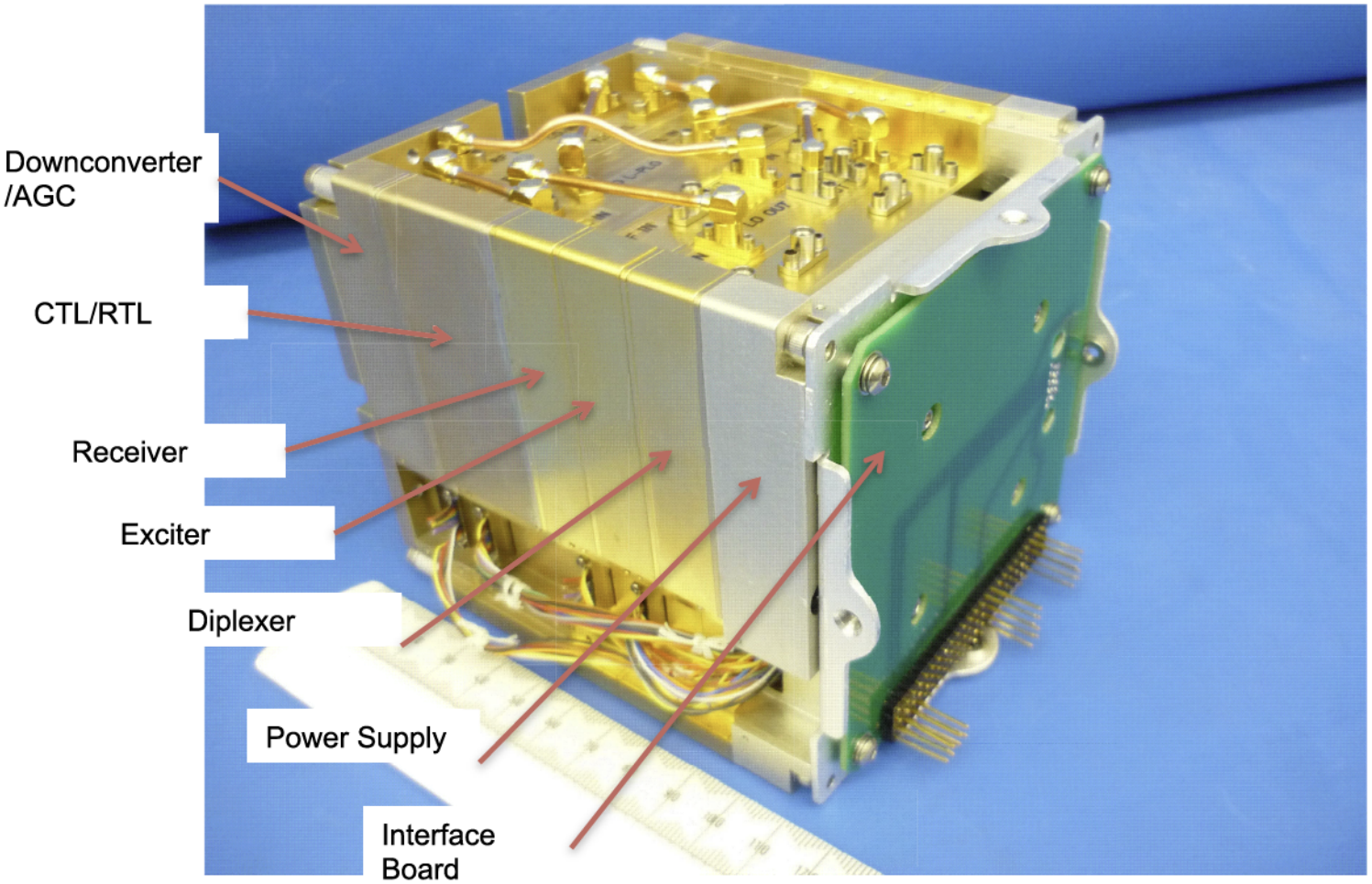
Software used to perform these steps takes into account hundreds of effects that determine station locations and spacecraft in inertial space as well as perturbations to the radio signals and images.

Orbit Determination –
Pre-fit (L), Post-fit (R) Doppler Residuals



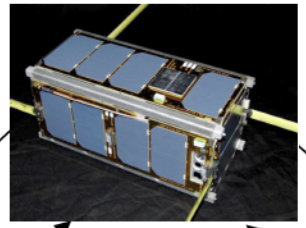


X/X-band LMRST



LMRST-Sat Operations Concept

LMRST-Sat



Orbit :
- NCLI opportunity changed to > 1000 km -> 2014

Command and Control:
- TT&C on UHF
- Coordinate LMRST op. with DSN

X-Band Downlink

X-Band Uplink

Telemetry UHF

Commands UHF

Frequency:
- X/X system prototyped for DRDF
- X/Ka for TDM

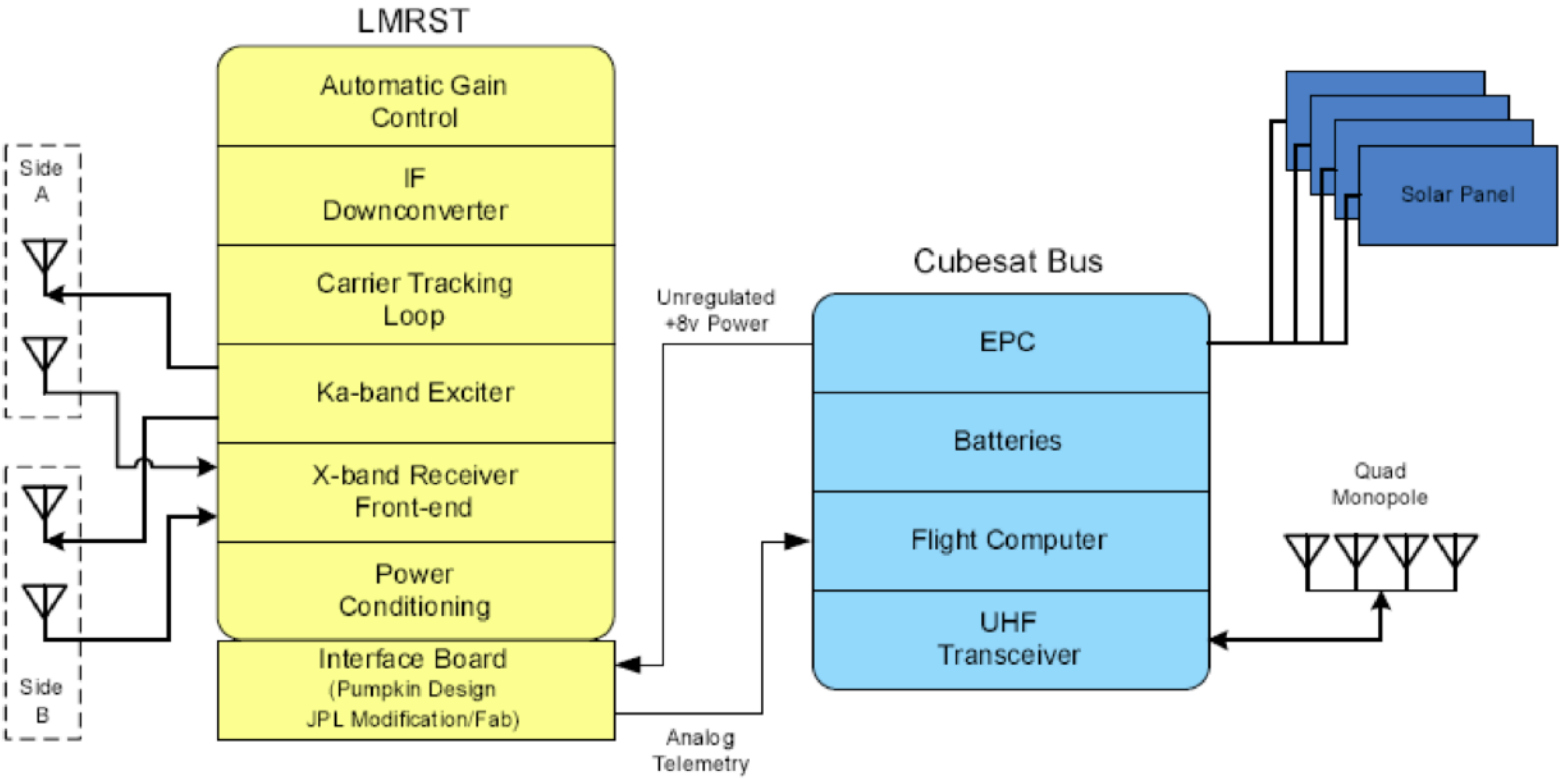
DSN Antennas

Ground Sites

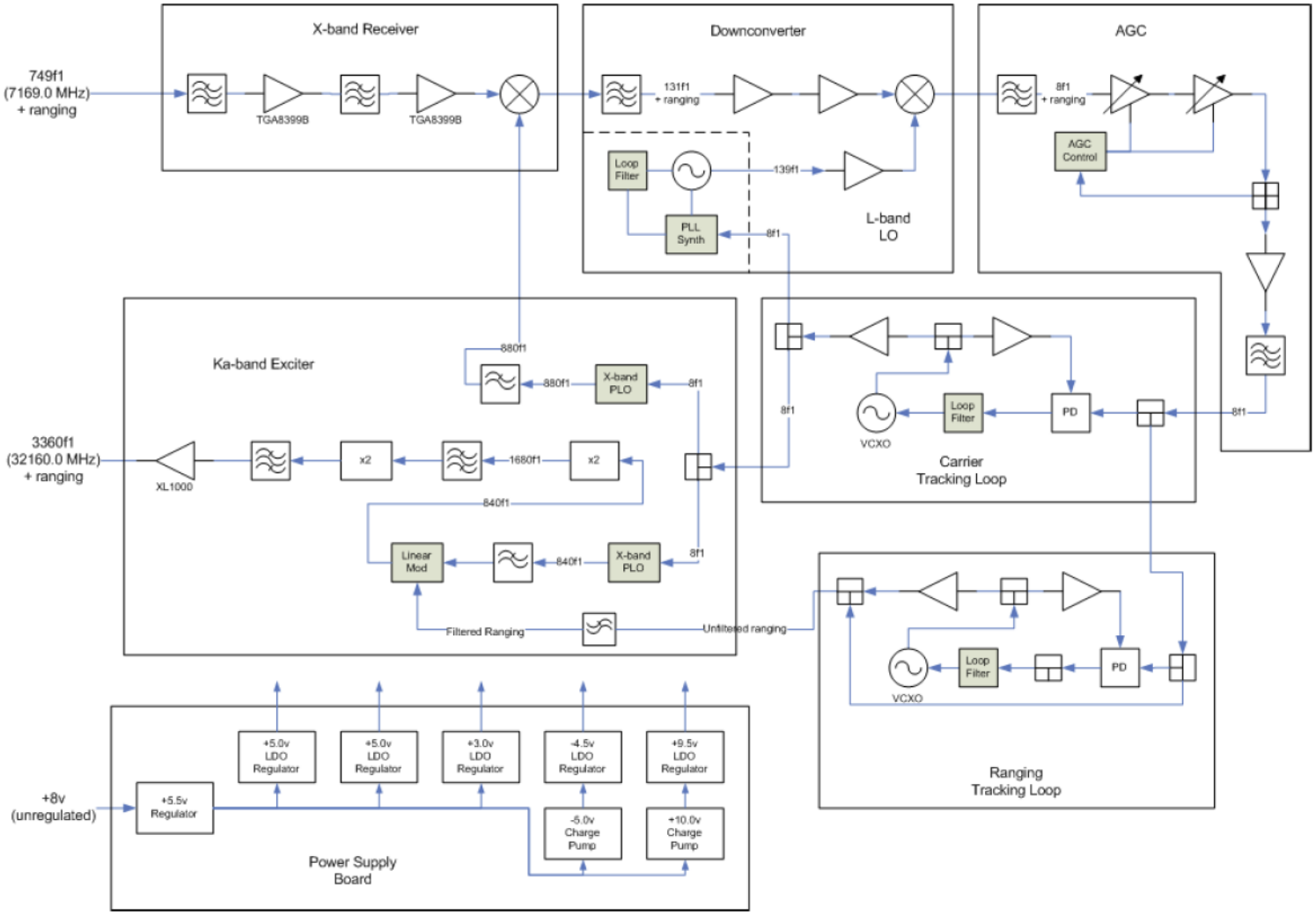
System L1 Requirements

- *LMRST-Sat* shall consist of a LMRST suitable for operation in low earth orbit hosted by a CubeSat bus.
- *LMRST* shall provide an X-Band uplink, X-Band downlink Doppler and ranging capability with 20 centimeter turn-around ranging precision.
- *LMRST-Sat* shall be positively controlled via the CubeSat bus via UHF TT&C.

System Design



X/Ka-band LMRST

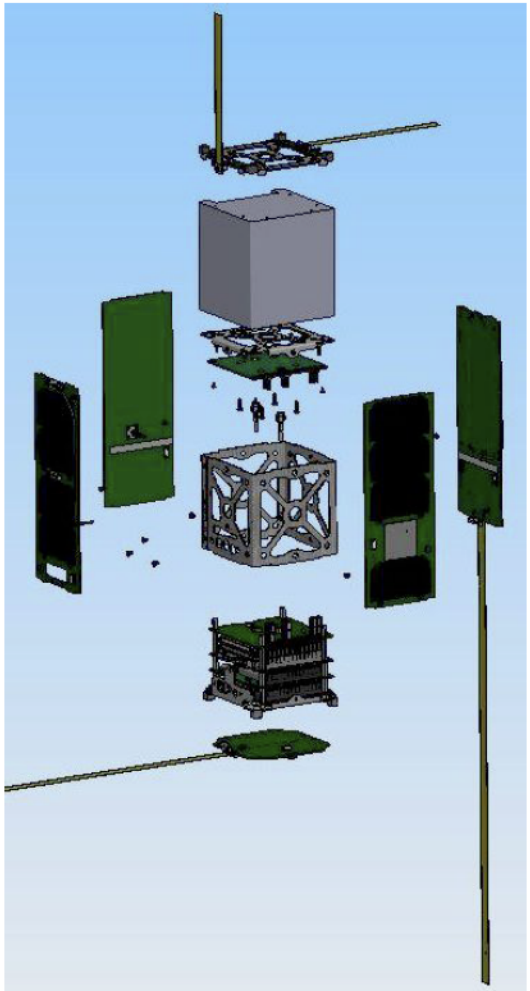


LMRST-Sat Timeline

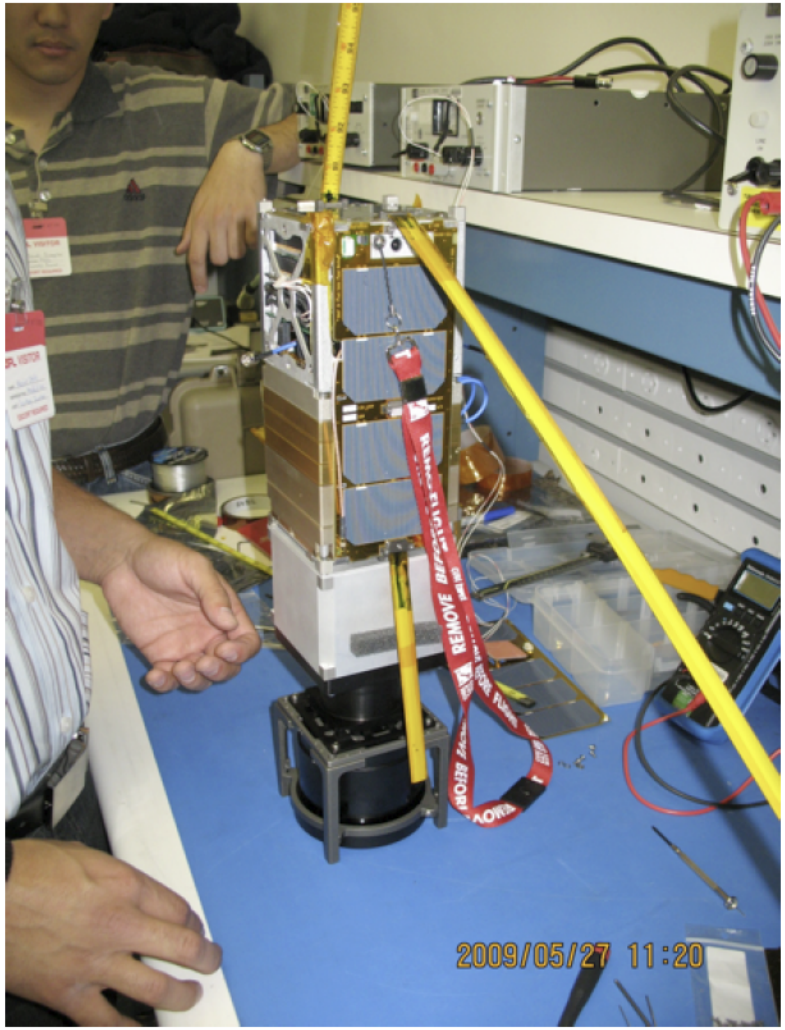
- Fall ‘07 proposed to DRDF
- Spring ‘08 funding - $167K
- Spring ’09 Integrated testing w/ Stanford SSDL
- Fall ‘09 poster
- Fall ‘10 NCLI award of launch
- Spring ‘11 TDM proposal
- FY’12 R&TD - $134K
- FY’13 R&TD pending – flight qual.
- ‘14 projected launch, operations

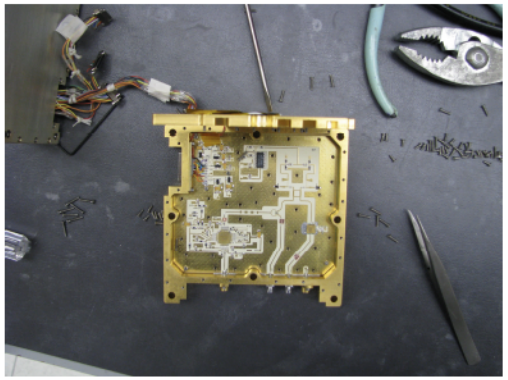
Building LMRST-Sat

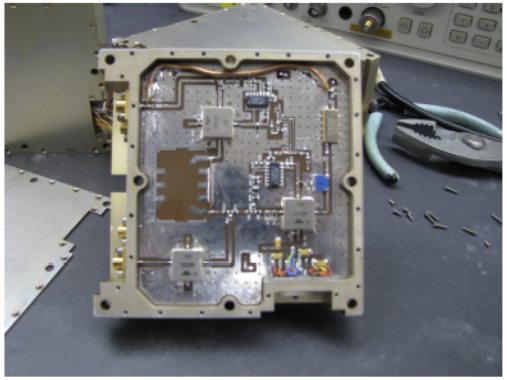
- LMRST – JPL repackaged existing breadboard X-Band RSTI into 1U form factor.
- Stanford SSDL / Pumpkin, Inc. – 1U spacecraft bus with VHF/UHF command / telemetry communications, power management, payload on/off switch, telemetry monitors
- Mechanical interface by standard
- Electrical interface by agreement
- Completed LMRST-Sat is 2U.

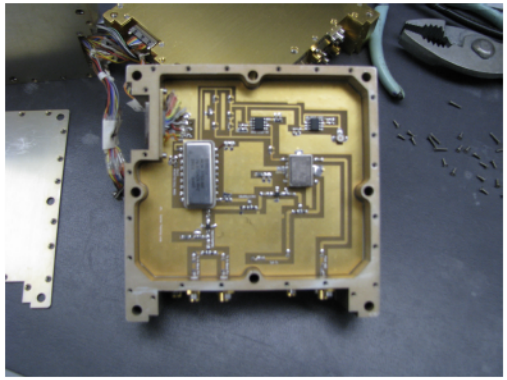


Testing LMRST-Sat



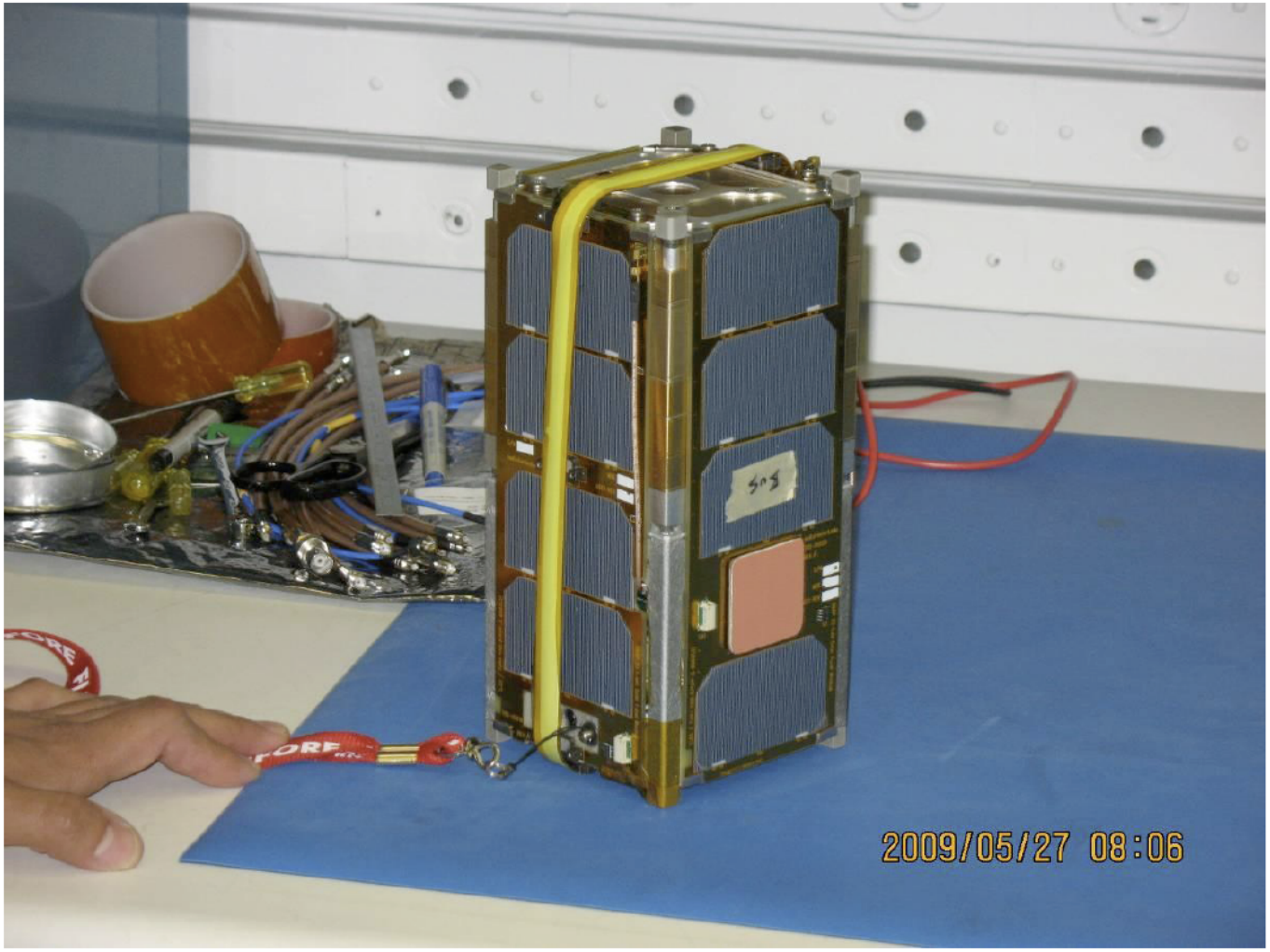






High Value to Cost Missions

TRL-Raising S/C prototype



LMRST Planned Future

- Originally Intended as a Radio Science Instrument
  - (originally called RSTI)
- As a low mass, low power tag along to
  - Mars surface
  - Europa – hostile!
  - Mercury
- Does
  - Navigation
  - Gravity field measurements
  - Body motions, cores (landed)

LMRST nano-Future

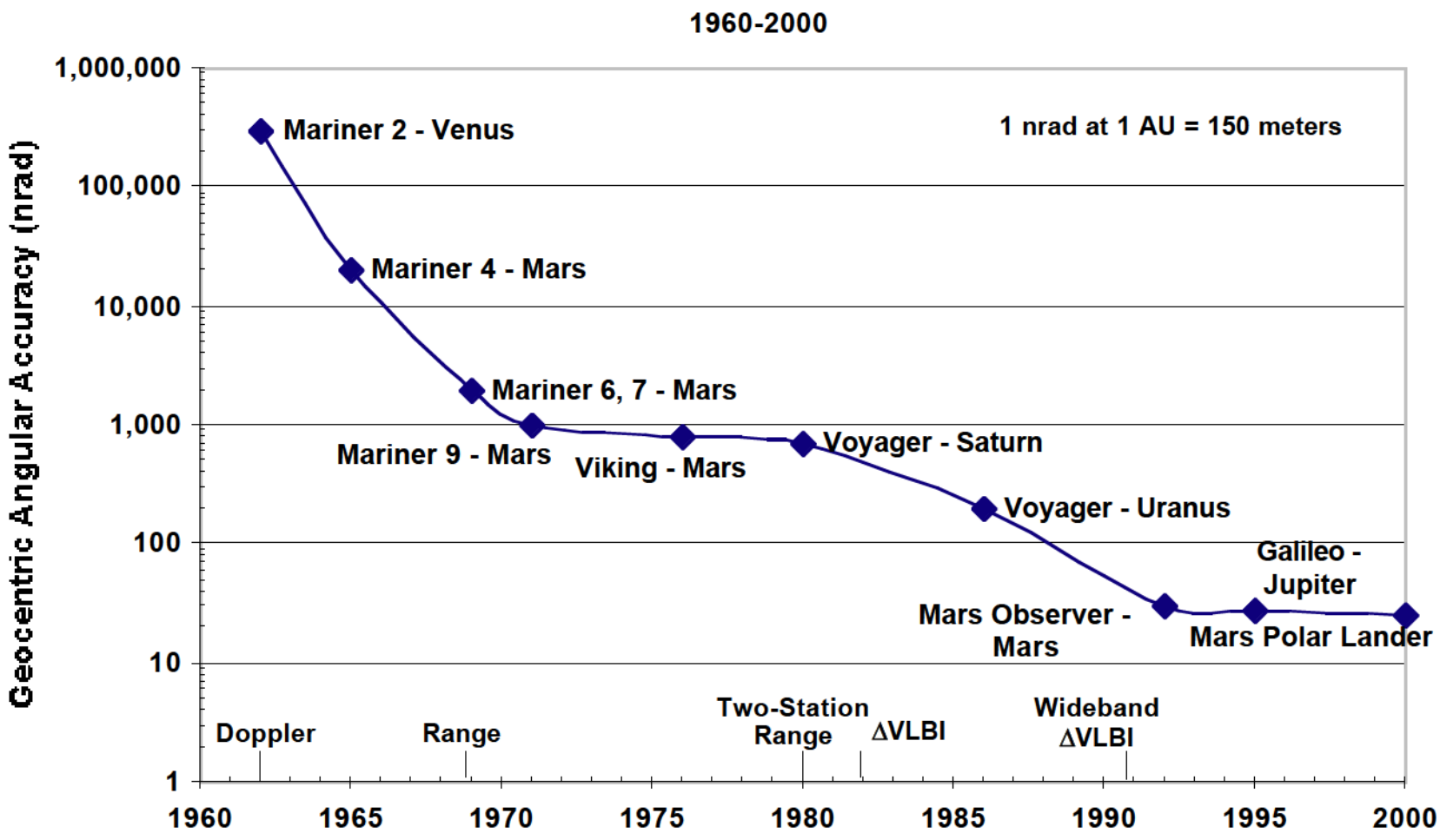
- An available, viable navigation solution for deep space nanoSpacecraft
- Ground network: the DSN or other (rather large) station
  - Limitations are onboard power and ground scheduling
  - Low duty cycle adequate
- Engineering *goals*
  - 0.5U
  - ~3W (current exciter)
  - PA (5W out for ~15W in)
  - Adding telemetry/command for TT&C not difficult
  - ~$50K unit cost

LMRST-Sat Prioritized Issues

- TT&C
- ISS Orbit
- LMRST Issues
- Key Personnel
- Frequency Coordination
- SSDL ITAR
- ATLO FY13
- Phase E
- SURP GPS Tertiary and dual frequency antenna & 3U
- The Establishment
- SmallSat Community

Backup

Deep Space Navigation System:
Evolution of DSN Navigation System Accuracy

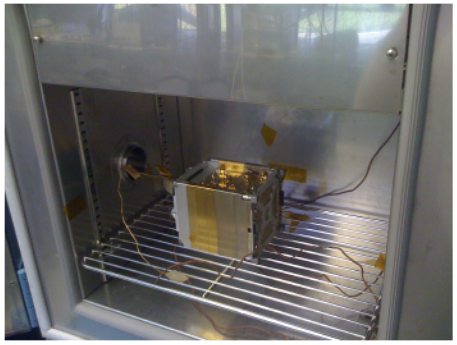


Link Capabilities

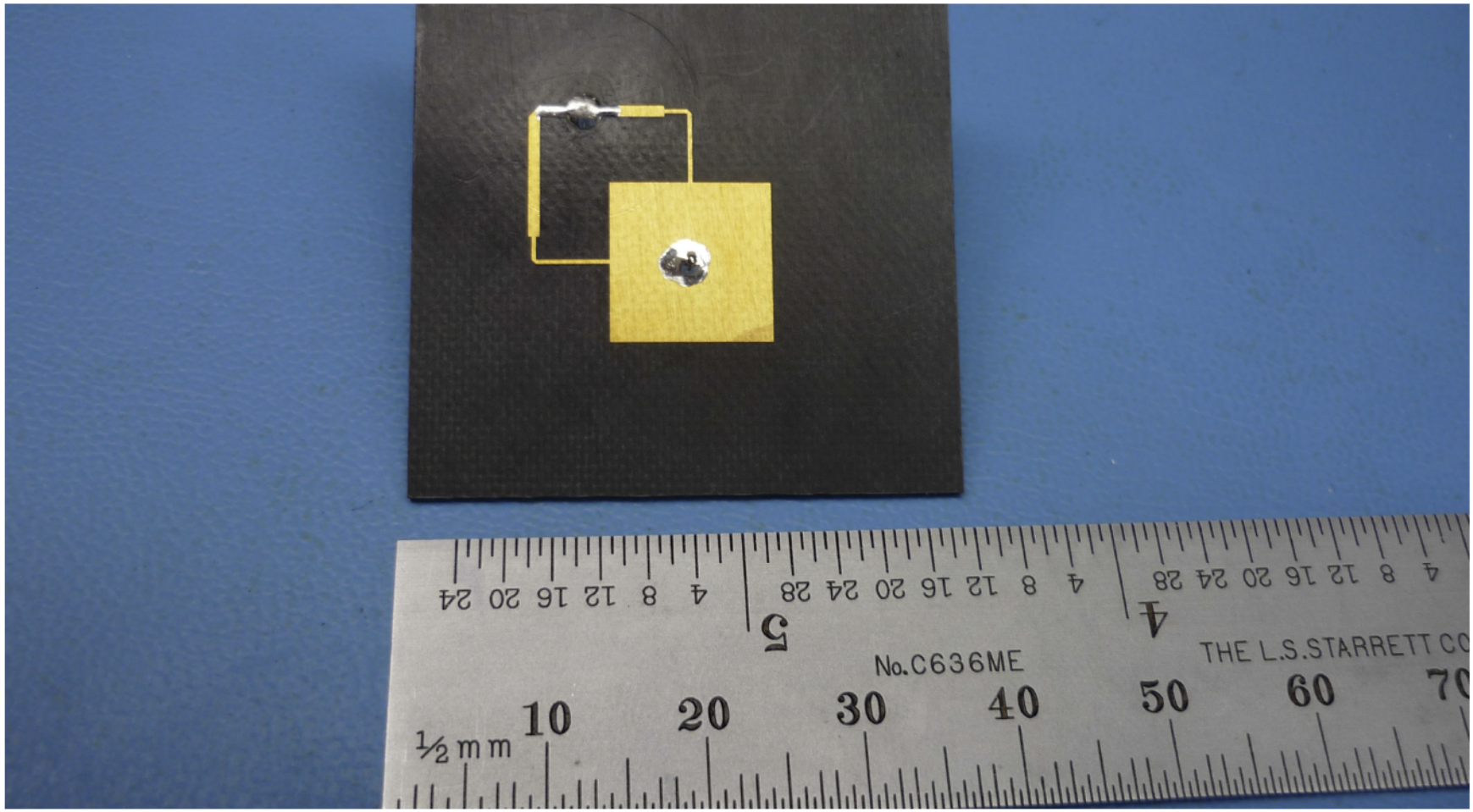
LMRST Deep Space Downlinks					
From		GEO	Lunar	NEO/Mars	Asteroids
To		V-Sat class	V-Sat class	DSN	DSN
Transmitter power, watts		0.01	1	5	5
Frequency, GHz		8.425	8.425	8.425	8.425
Transmit antenna gain, dBi		0.0	0.0	2.0	4.0
Transmiter EIRP, dBm		9.5	29.5	38.5	40.5
Earth Radius, km		6378.1	6378.1	6378.1	6378.1
Slant range, AU		0.000323	0.003	1.5	3.0
Path loss, dB		-204.6	-223.1	-277.9	-283.9
Isotropic signal at Receive antenna, dBm		-195.1	-193.6	-239.4	-243.4
Receive dish diameter, m.		1.5	1.5	34	34
Receive antenna efficiency		0.5	0.5	0.5	0.8
Receive Antenna Gain, dBi		39.4	39.4	66.5	68.6
Prec at LNA input, dBm		-156.8	-155.4	-173.5	-175.1
Receive Noise Figure, dB		1.0	1.0	0.5	0.5
Sky Temperature, K		100	100	100	100
Receiver G/T, dB/K		15.8	15.8	44.6	47.1
CNR, dB/Hz		19.3	20.8	3.8	2.2
beamwidth, deg.		1.4	1.4	0.06	0.06
	Morehead is 4 dB down from DSN 34				
	Ka is 12 dB down from X- plus inefficiencies plus lower RF				
	Uplinks are not power limited				
	Block V DR locks on 1 Hz BW at 7 dB-Hz, use RSR open loop below that to 3 dB-Hz or less				
	Modest gain at S/C possible (3-5 dB)				

LMRST-Sat Technology

- RSTI development
  - TRL 3 = Breadboard
- DRDF packaged a complete 1U LMRST
  - TRL 4 = "Laboratory Environment"
- Thermal cycling on that LMRST and analogy to GRAIL RSB TV
  - TRL 5 = "Relevant Environment"
    - Outgassing not important to LMRST
    - Multipaction, Corona not a concern at 10 dBm power levels
- Proposed environmental tests on LMRST-Sat
  - TRL 6 = "System in Relevant Environment"
- On-orbit experiments
  - TRL 7 = "System prototype in operational environment"

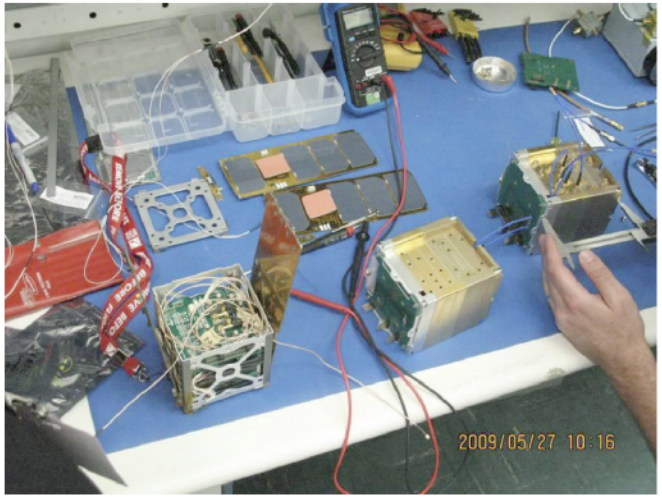


X-Band Patch Antenna

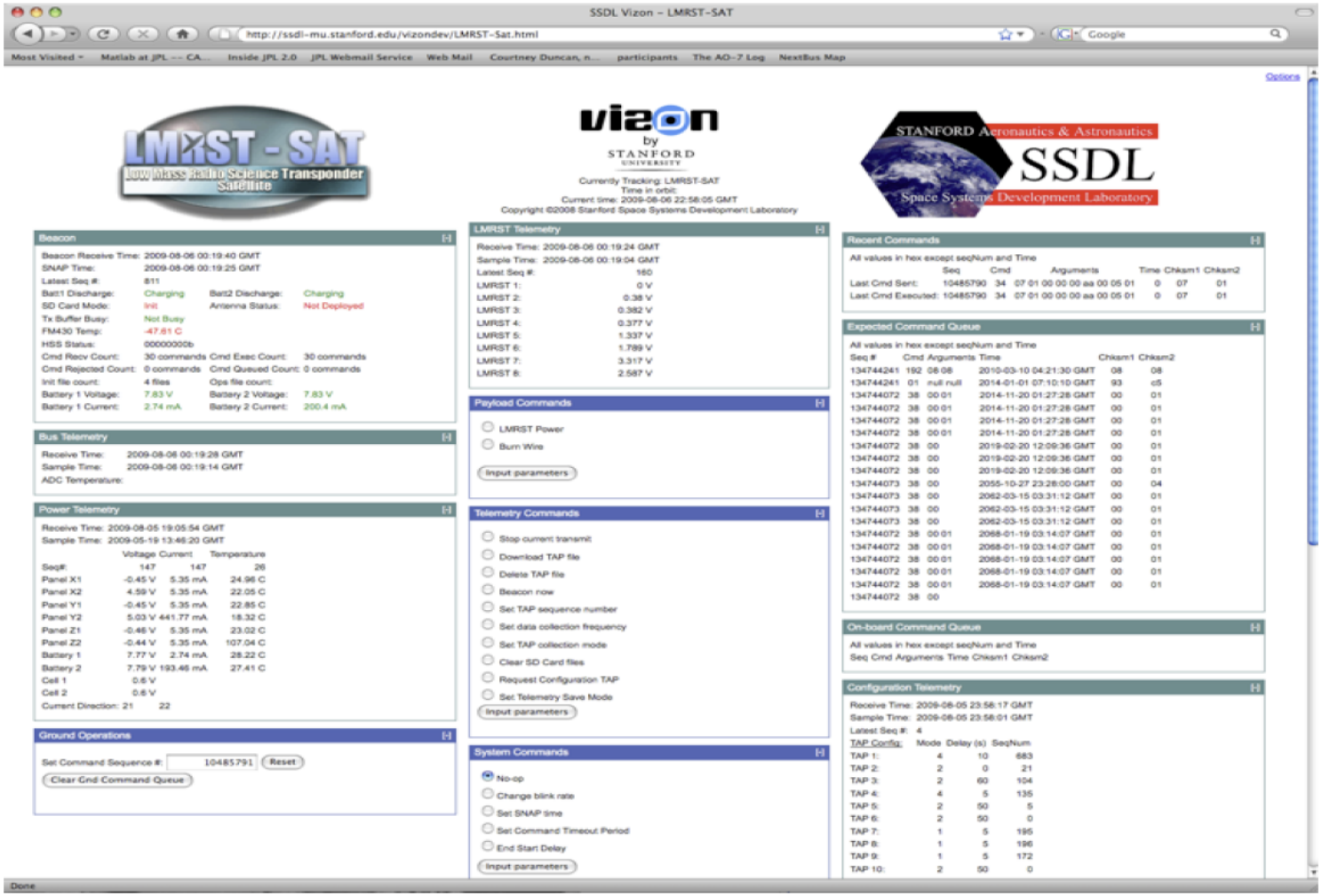
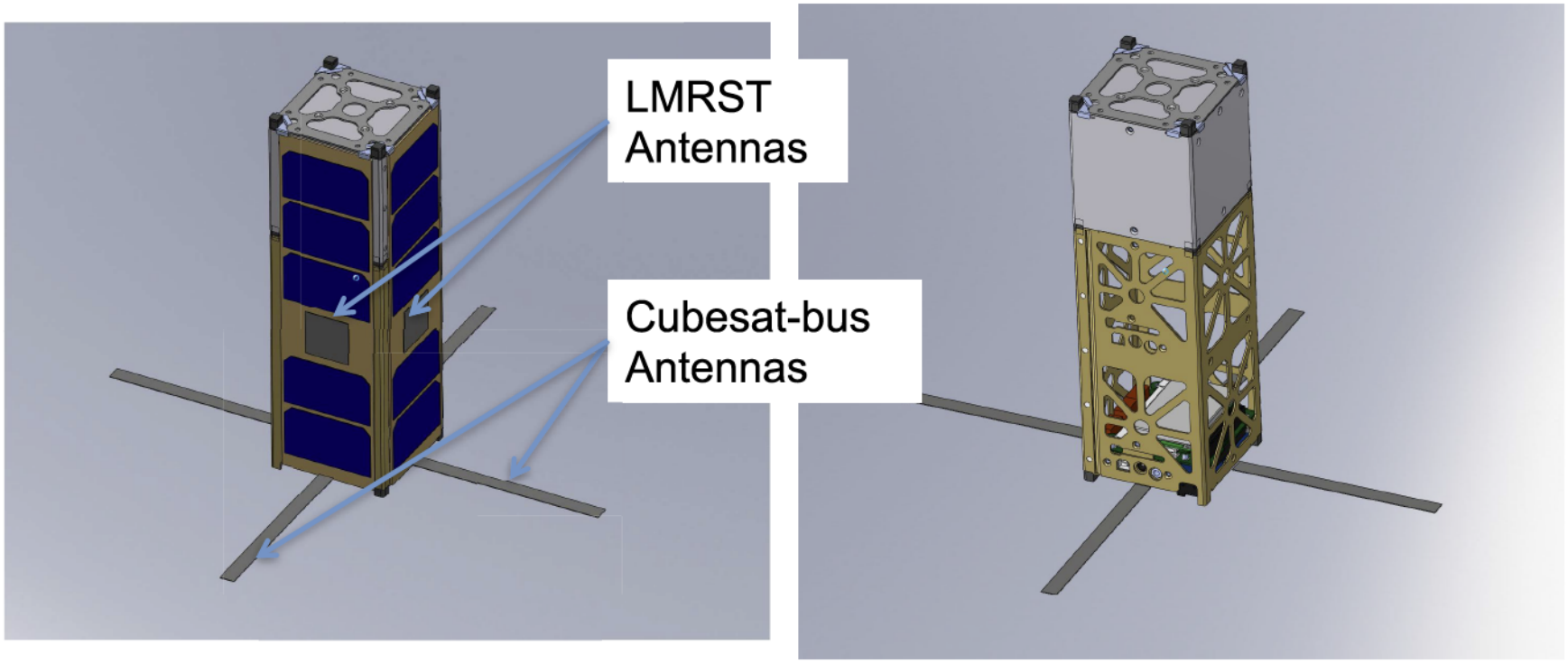


Building LMRST-Sat

- JPL provided requirements document, MEI specification, interface chassis
- SSDL provided as-built CubeSat documentation, detailed ground and flight operating instructions, operational theory
- Integration and integrated testing performed in *one day* at JPL with several participants from each institution. Antenna deployment test included.



LMRST-Sat Telemetry Display



New 3U LMRST-Cubesat