We’re not at NASA to get rich.
If you want me to talk for an hour…

Microwaves: Communications and Navigation in Deep Space … even in nano-SpaceCraft

C. Duncan
2014 October 2
San Bernardino Microwave Society
Corona, California

Two and a Half Conference Talks
and some other stuff

- LMRST – Navigation Anywhere, May 2012
- Iris Transponder – comm and nav in deep space, August 2014
- Link tutorial and notes from LunarCubes talk, November 2014
- Amateur Radio thoughts
- Unreleased stuff you might find interesting

Low Mass Radio Science Transponder – Navigation Anywhere

C. Duncan
2012 May 30
Session C.3.2
1st Interplanetary CubeSat Workshop
Cambridge, Mass.

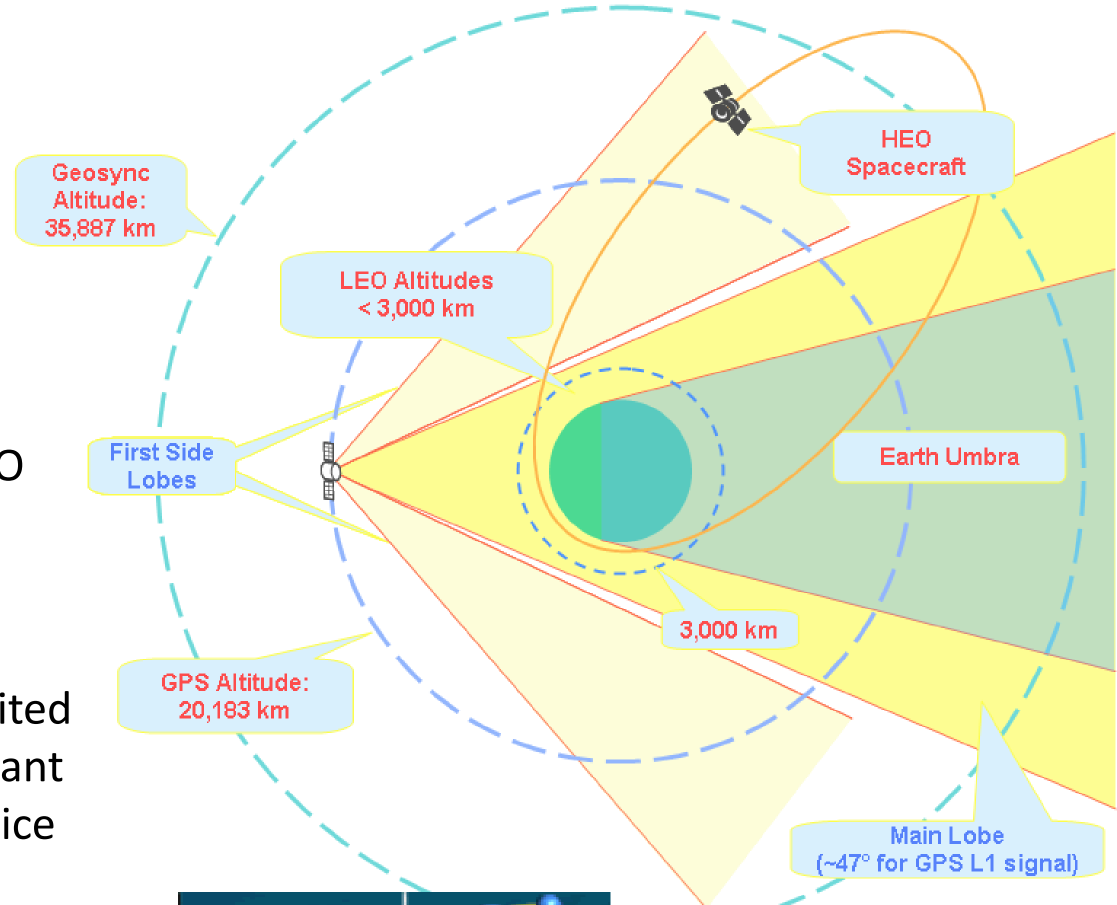
GPS only goes so far

Designed for earth surface and up to 3000 km above -- LEO

Navigation with GPS beyond LEO

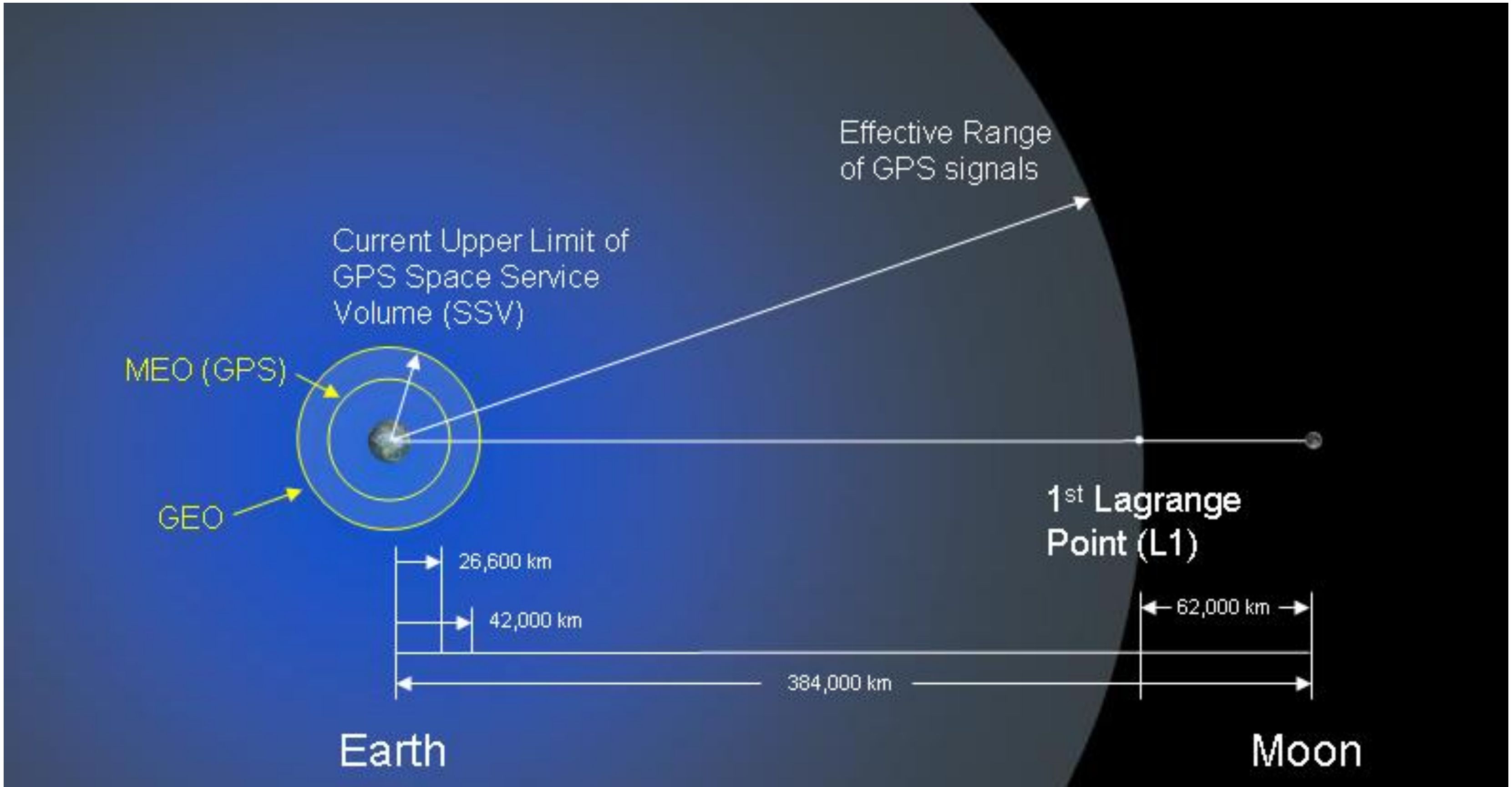
- GPS Terrestrial Service Volume
  - –Up to 3000 km altitude
  - –Many current applications
- GPS Space Service Volume (SSV)
  - –3000 km altitude to GEO
  - –Many emerging space users
  - –Geostationary Satellites
  - –High Earth Orbits (Apogee above GEO altitude)
- SSV users share unique GPS signal challenges
  - –Signal availability becomes more limited
  - –GPS first side lobe signals are important
  - –Robust GPS signals in the Space Service Volume needed
  - –NASA GPS Navigator Receiver in development

  - –Info from Dr. Scott Pace – NASA PNT Advisory Board



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



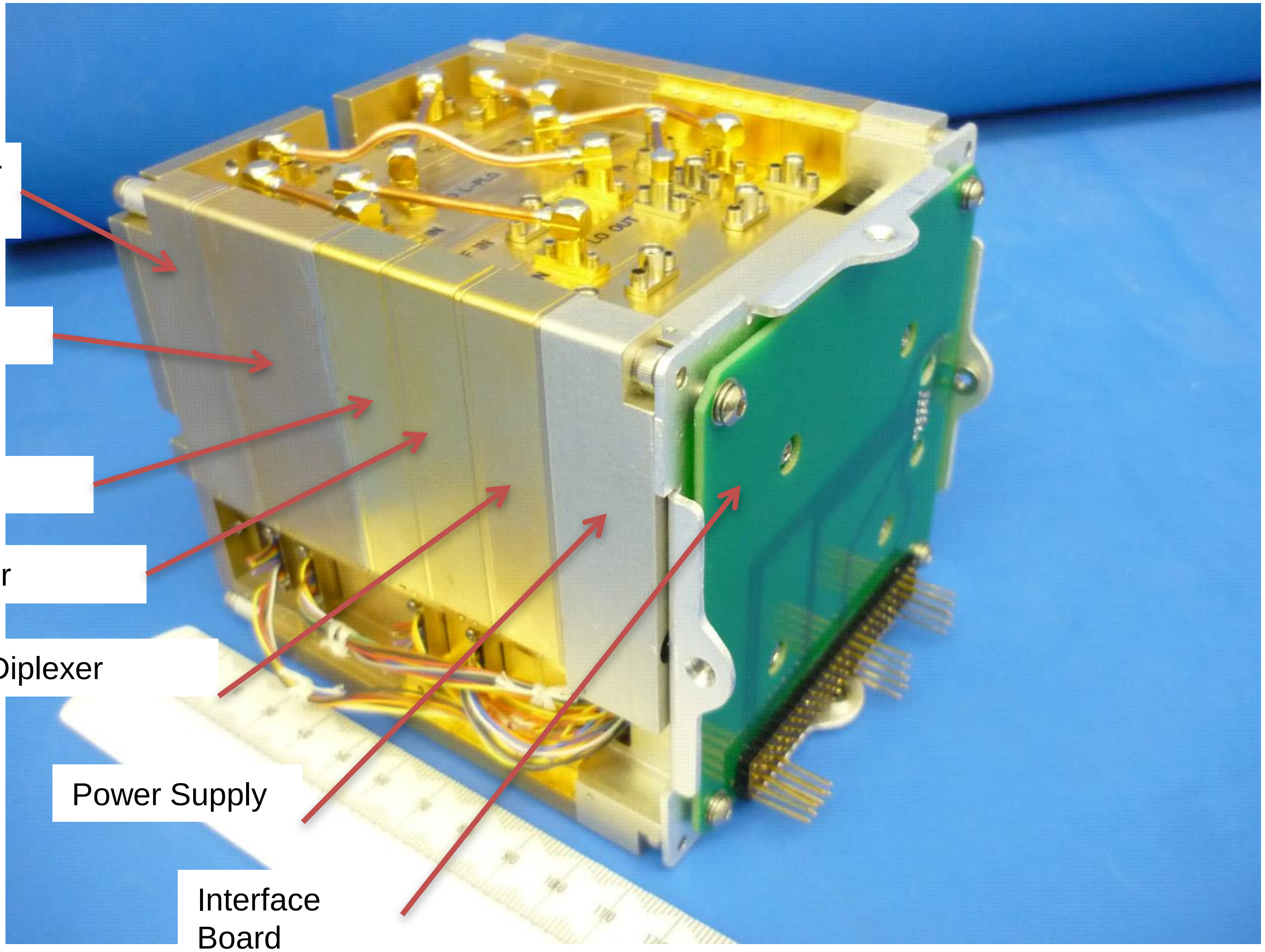
Beyond 3000 km…

- Forget about all those rumors/studies of GPS transmit antennas on the top, or sidelobes, or GPS at the moon.
  - It can be made to work up to a point but it's the wrong general approach
  - Don't try it on a nanoS/C that's going anywhere beyond 3000 km
  - Unless it is your entire mission

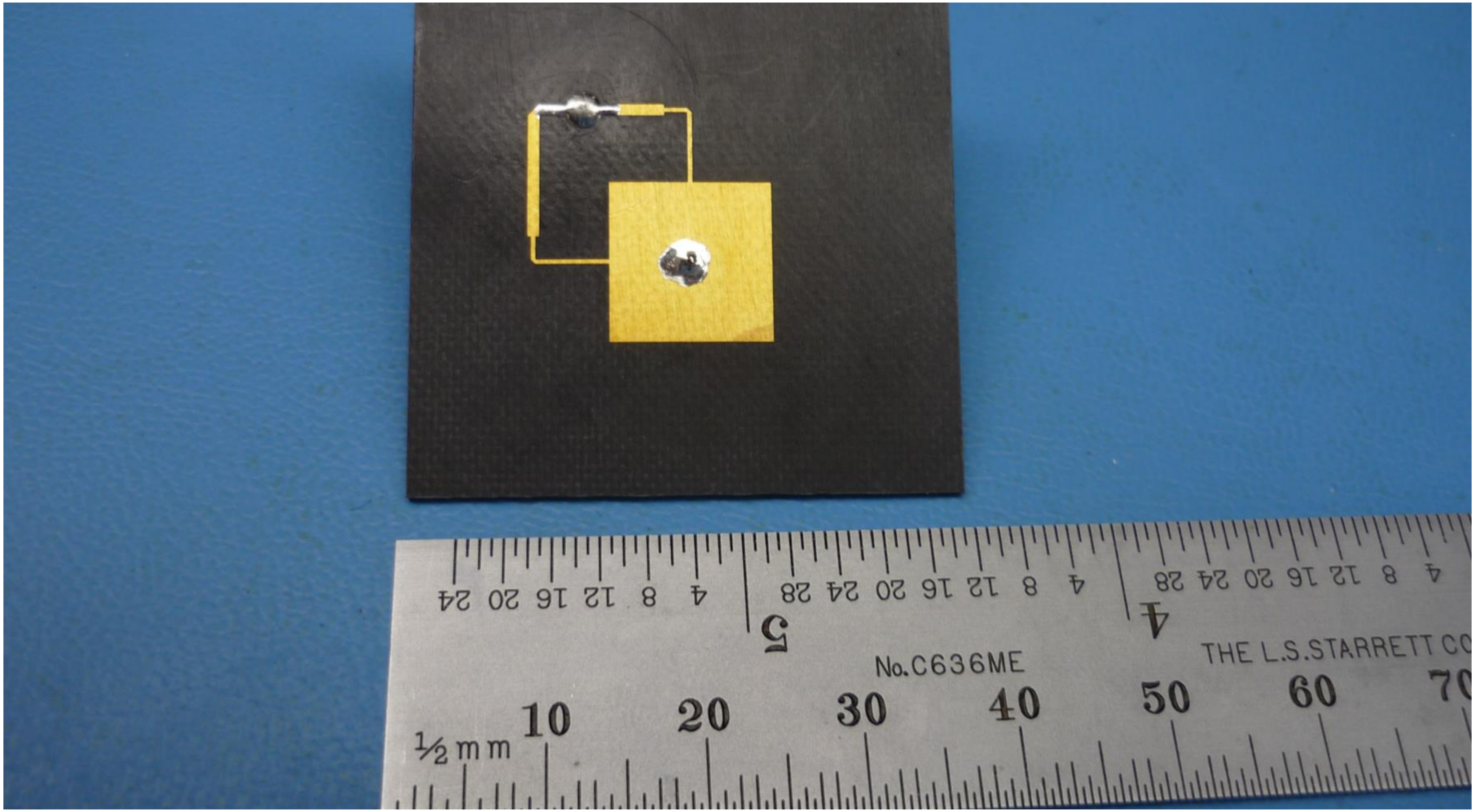
Low Mass Radio Science Transponder

- Doppler and Ranging turnaround transponder
  - No onboard precision reference needed
- Low Tech – does only that with minimal parts
- 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

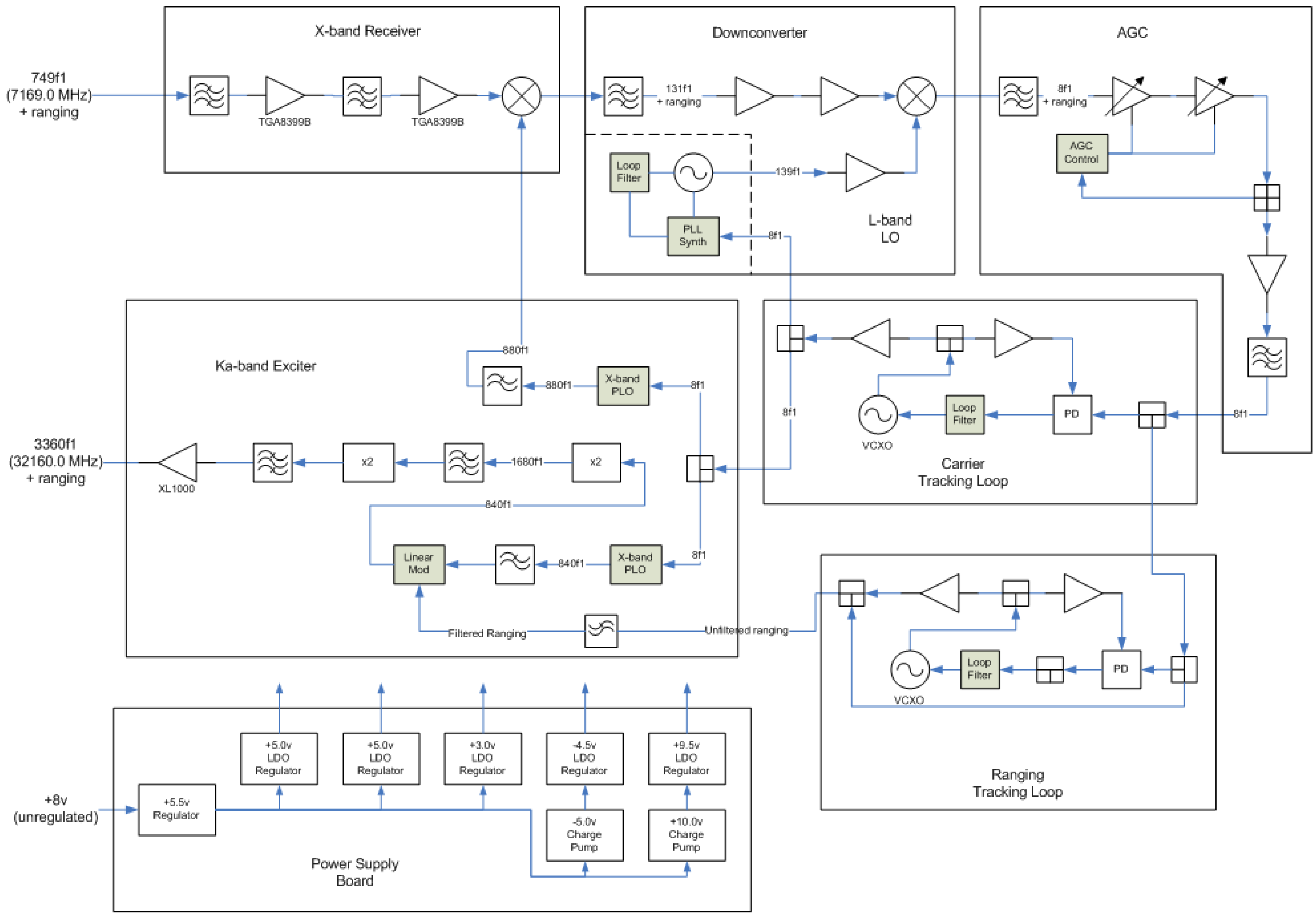
X/X-band LMRST



X-Band Patch Antenna



X/Ka-band LMRST



Deep Space Navigation Components

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

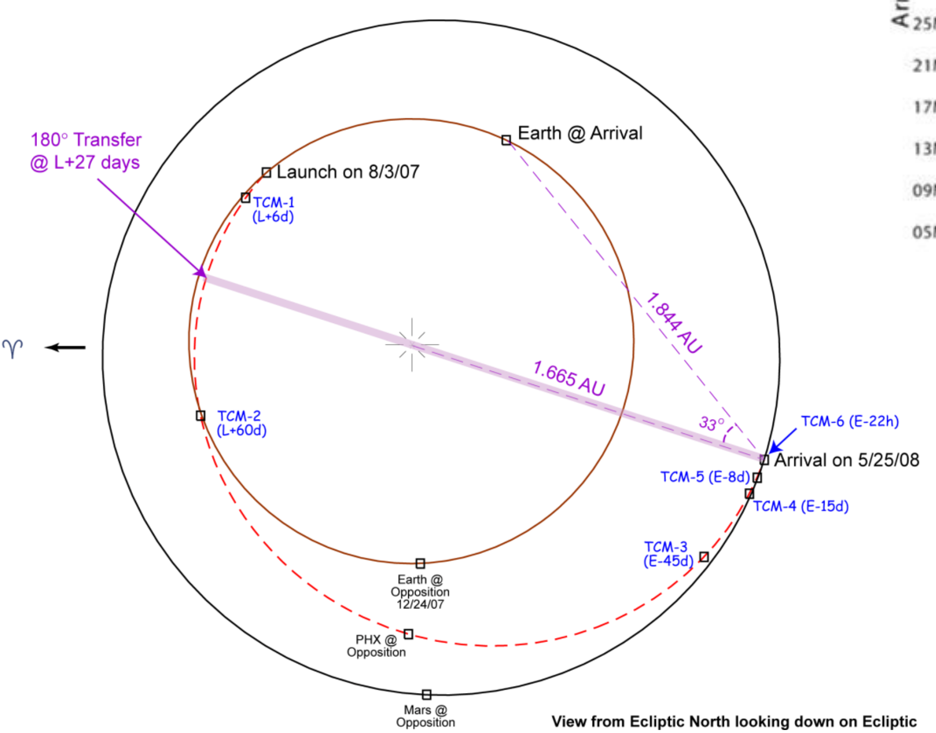
Task	Example on Earth (Hiking)	Example in Deep Space
(1) Obtain a Map	Obtain road map, digital map database	Develop planetary ephemerides
(2) Develop a Travel Plan	Select trail(s) to reach destination, estimate arrival time	Select orbit(s) to reach destination planet/asteroid, calculate arrival time
(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

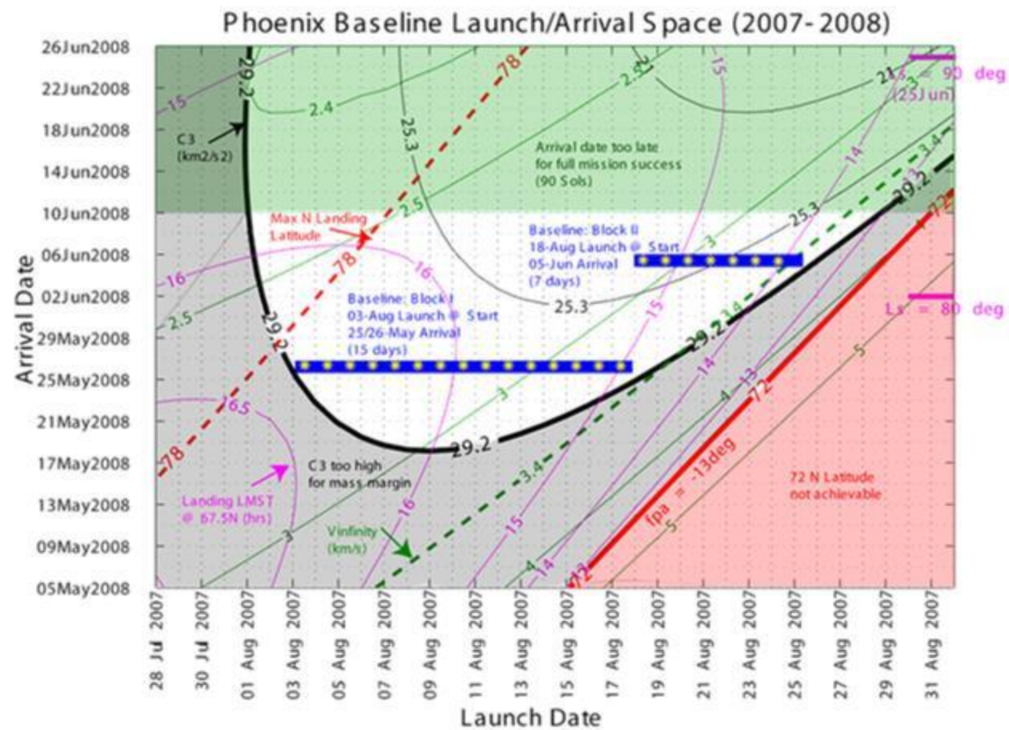
- Tasks 1-2 are done pre-launch, the others from launch to end-of-mission.
  – Information from Dr. Alberto Cangahuala, JPL, “Deep Space Navigation 101”

Example Trajectory: Phoenix Earth-Mars

Launch/Arrival considerations are varied, and their interplay very important to understand

(Comm, Power, Science, etc.)

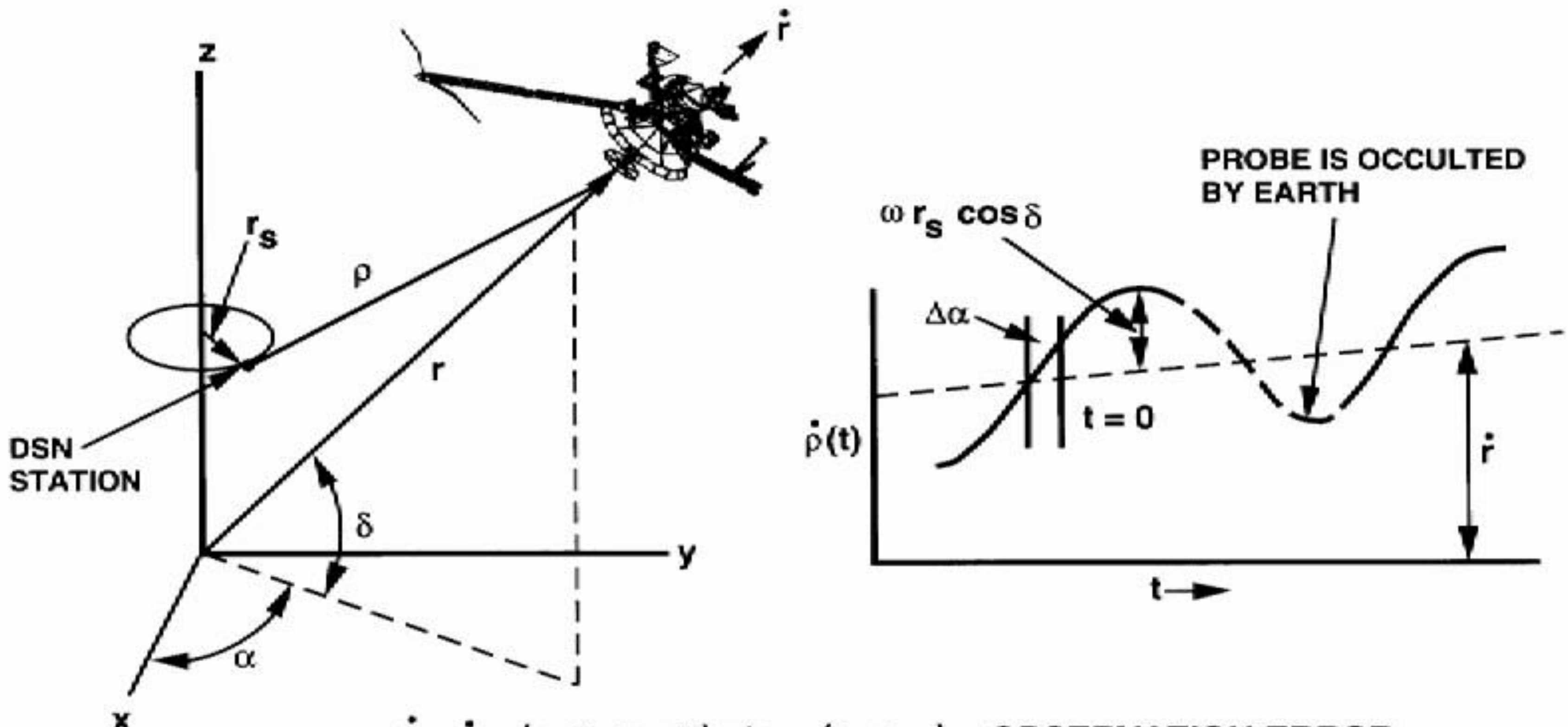




Interplanetary Cruise Activities (correction maneuvers, calibrations, rehearsals)

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

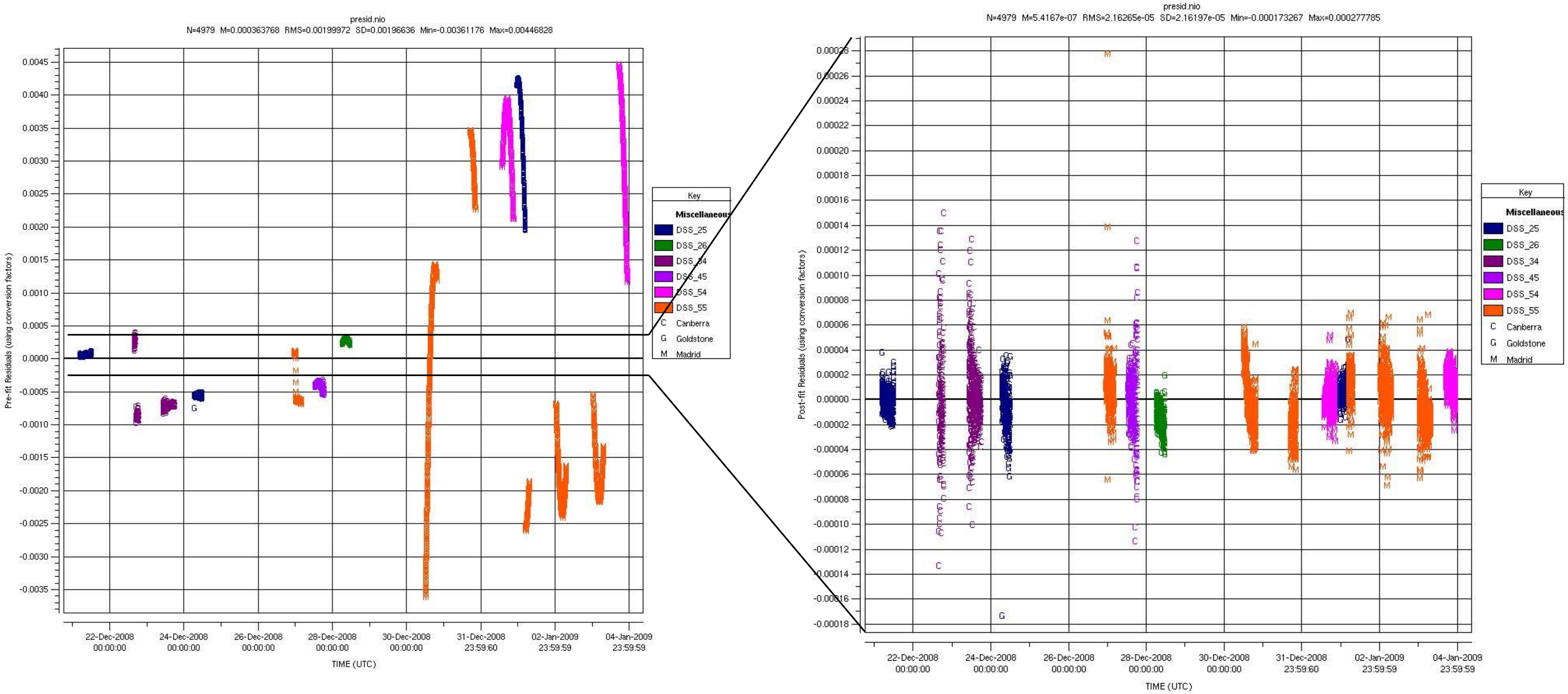
Recall parallax – we exploit 'velocity parallax' to infer 'plane of sky' position [Refs. 1, 2]

‘Calculating One’s Position’ - Orbit Determination

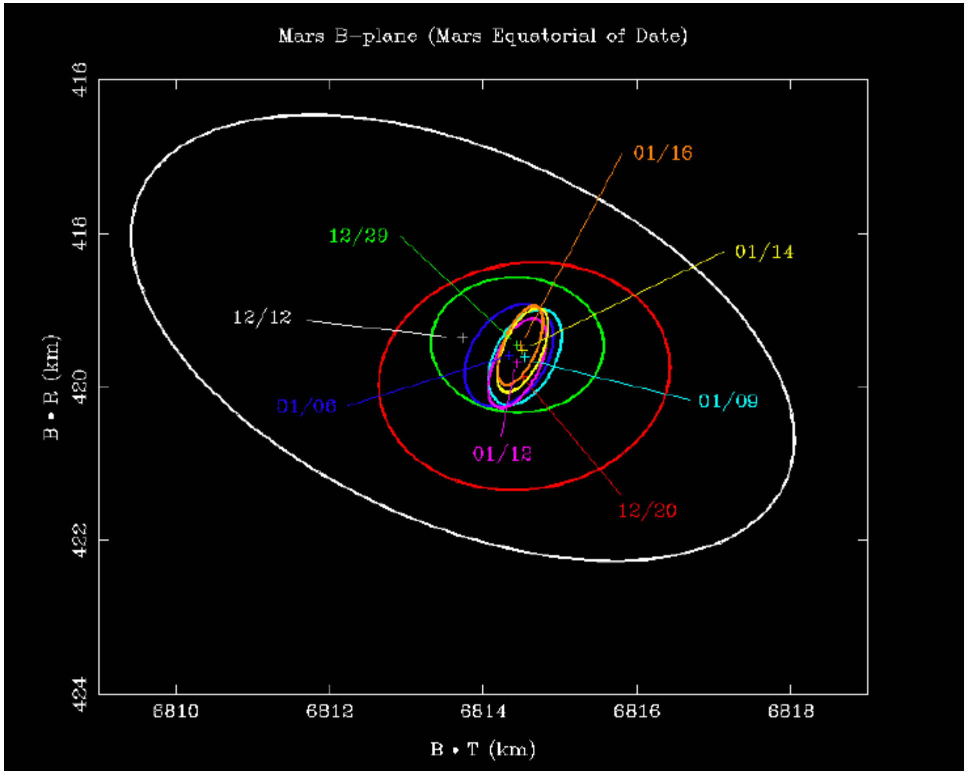
1. Start with initial guess of spacecraft position, velocity, and associated dynamic parameters,
2. Numerically integrate equations of motion to get position and velocity as a function of time
3. Form data residuals:
   – (What I observered) - (What I thought I was going to observe)
4. Perform least 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.

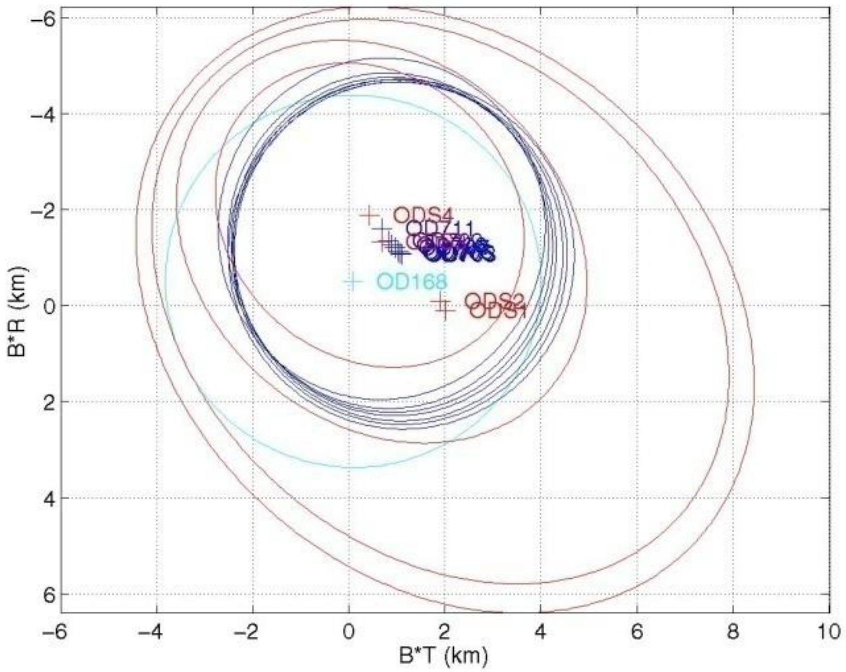
Orbit Determination –
Pre-fit (L), Post-fit (R) Doppler Residuals



Orbit Determination – Consistency Tests



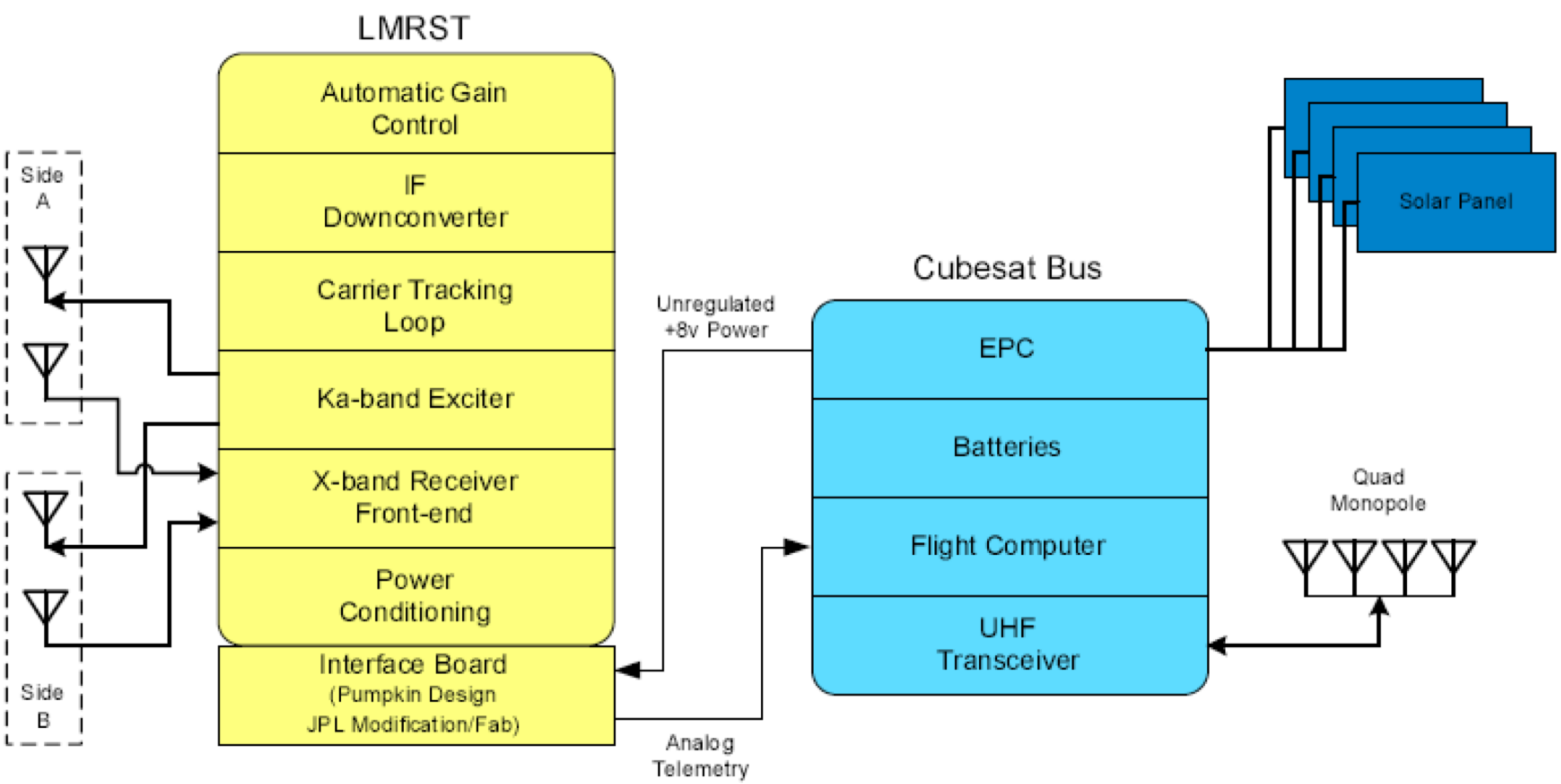
- **Different solution types plotted to targeting plane**
  - **Varying data types, data weights, arc lengths, modeling, etc.**



- **Analysts study groupings and relative behavior of different solutions to confirm intuition about spacecraft dynamics and quality of inputs (tracking data, telemetry, etc.)**

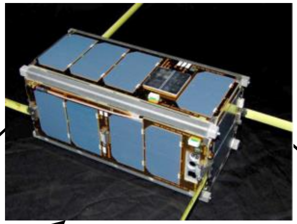
High Value to Cost Missions
TRL-Raising S/C prototype

System Design



LMRST-Sat Operations Concept

LMRST-Sat



Orbit :

- NCLI opportunity is to ISS-like LEO on CRS-3

Command and Control:

- SSDL facilities for all C&C
- DSN and Stanford coordinate Ops

Ka-Band Downlink

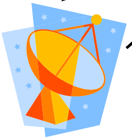
X-Band Uplink

Telemetry UHF

Commands UHF

Frequency:

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



DSN Antennas

Ground Sites

Doesn't this remind you of the 10 G contest with Cactus liaison?

LMRST Planned Future

- 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 your (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
  - ~$100K unit cost

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)

Conclusion

- Your mission will need to do *something* like this
- LMRST is ready made for nanoSats – exists today
  - Can be proposed now while TRL raising is in progress
  - Can adapt to mission needs and scale
- JPL does deep space navigation
  - Understands the data types and algorithms

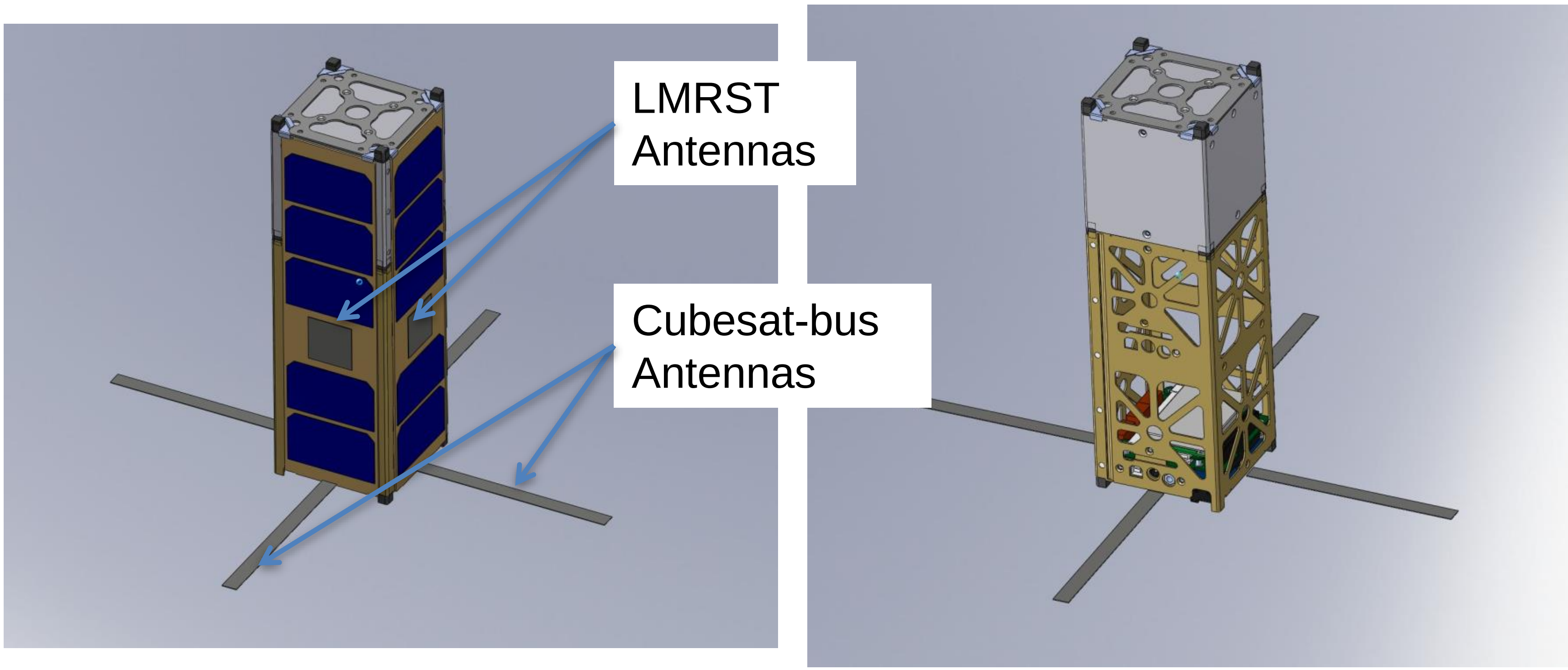
LMRST-Sat now set for launch in August 2015

Backup

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"

New 3U LMRST-Cubesat



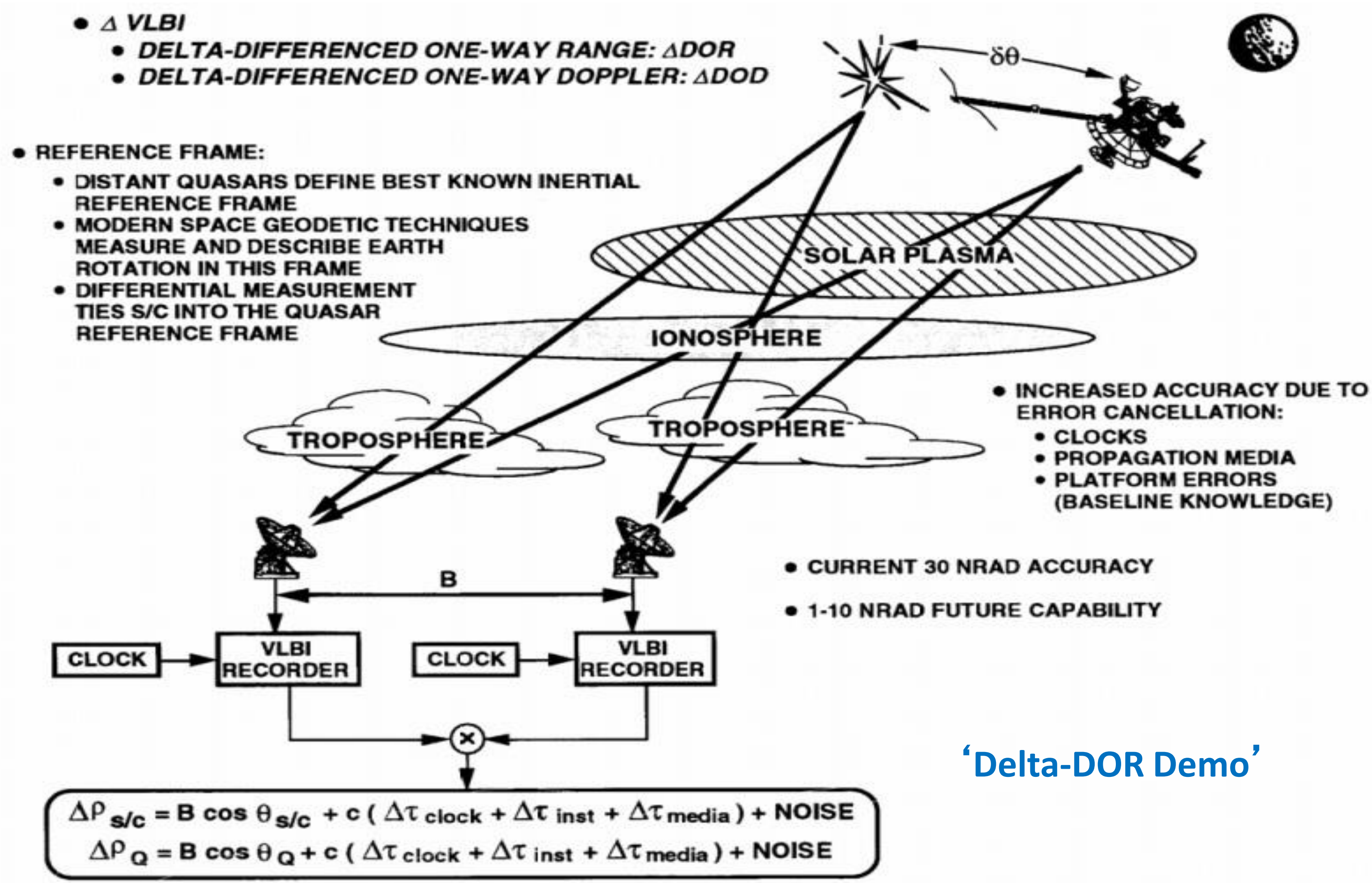
Doppler and Range

- Two-way Doppler (F2) data:
  - F2 measurements are made when a single tracking station radiates a signal to a S/C which in turn multiplies the received signal by a constant (turn-around ratio) and sends the signal back to the transmitting station. The signal frequency is Doppler shifted on both the up and down-link paths.
  - Primarily measures the line-of-sight component of the S/C velocity. With a long enough tracking pass, the S/C right ascension and declination can also be measured, although usually with less accuracy.
  - Units of hertz (Hz). 1.00 Hz = 17.76 mm/s for X-band uplink/downlink.
  - Assumed 1-sigma noise = 5.6 mHz (0.1 mm/s)
- Range (SRA - Sequential Ranging Assembly) data:
  - Range measurements are the round-trip light time for a signal to propagate between a ground station and S/C and measures the line-of-sight component of the S/C position.
  - The ranging signal consists of a sequence of sinusoidal tones phase modulated on the carrier.
  - Units of “range units” (RU). 1.00 RU = 0.142 meters.
  - Assumed 1-sigma noise = 14 RU (2 m)

Navigation

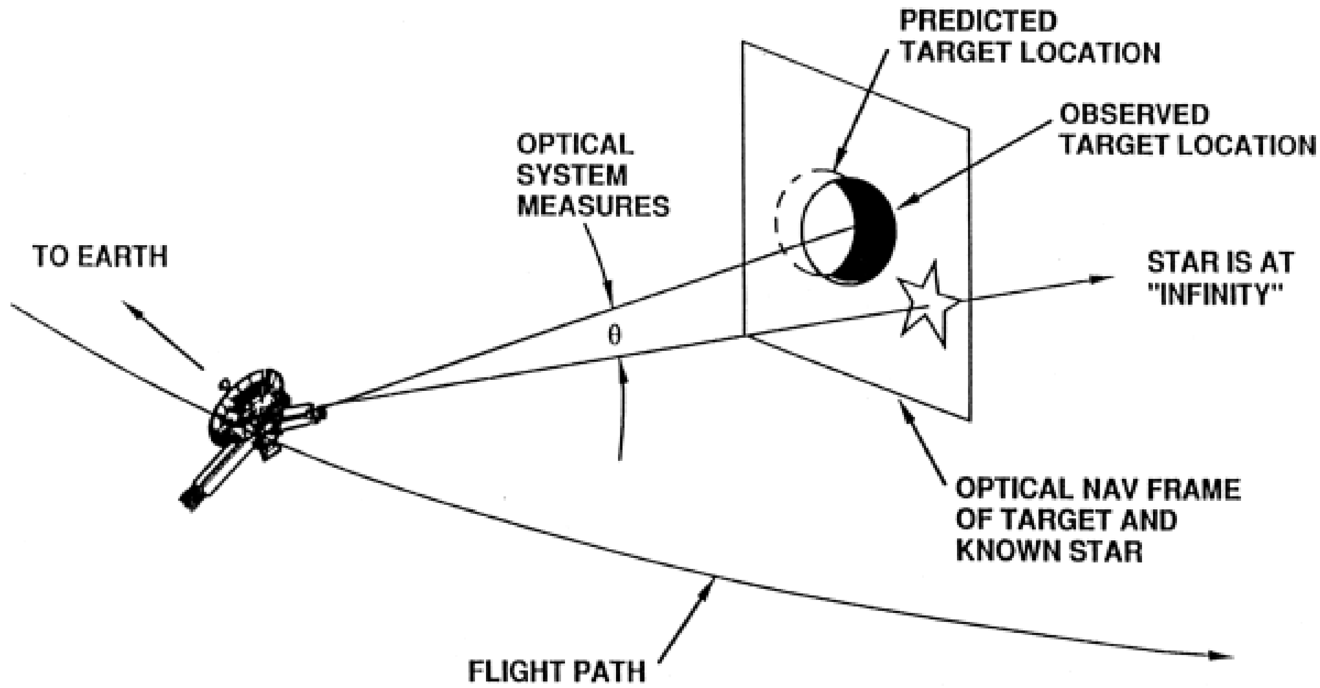
- Flying the spacecraft from launch to end of mission
  - Reconstruction of position and velocity up to current time (orbit determination)
  - Predict future path of spacecraft
  - Compare actual course with planned course, and make course adjustments as necessary (flight path control)
- Orbit determination
  - Use tracking data to compute spacecraft's current trajectory
  - Radiometric data types
    - Doppler - measures line-of-sight velocity of spacecraft relative to tracking station
    - Range - measures line-of-sight distance of spacecraft relative to tracking station
    - Delta Differential One-way Range (ΔDOR) - measures plane-of-sky angle between spacecraft and a baseline between two tracking stations
  - Optical data
    - Uses onboard camera to measure angle between spacecraft and target body
- Flight Path Control
  - At predetermined times in the mission, compare predicted course with actual course
  - If outside of tolerance, compute maneuver to re-target
  - Can optimize current and future maneuvers to minimize fuel usage
  - Keep track of fuel usage

Navigation Measurements: Delta-DOR

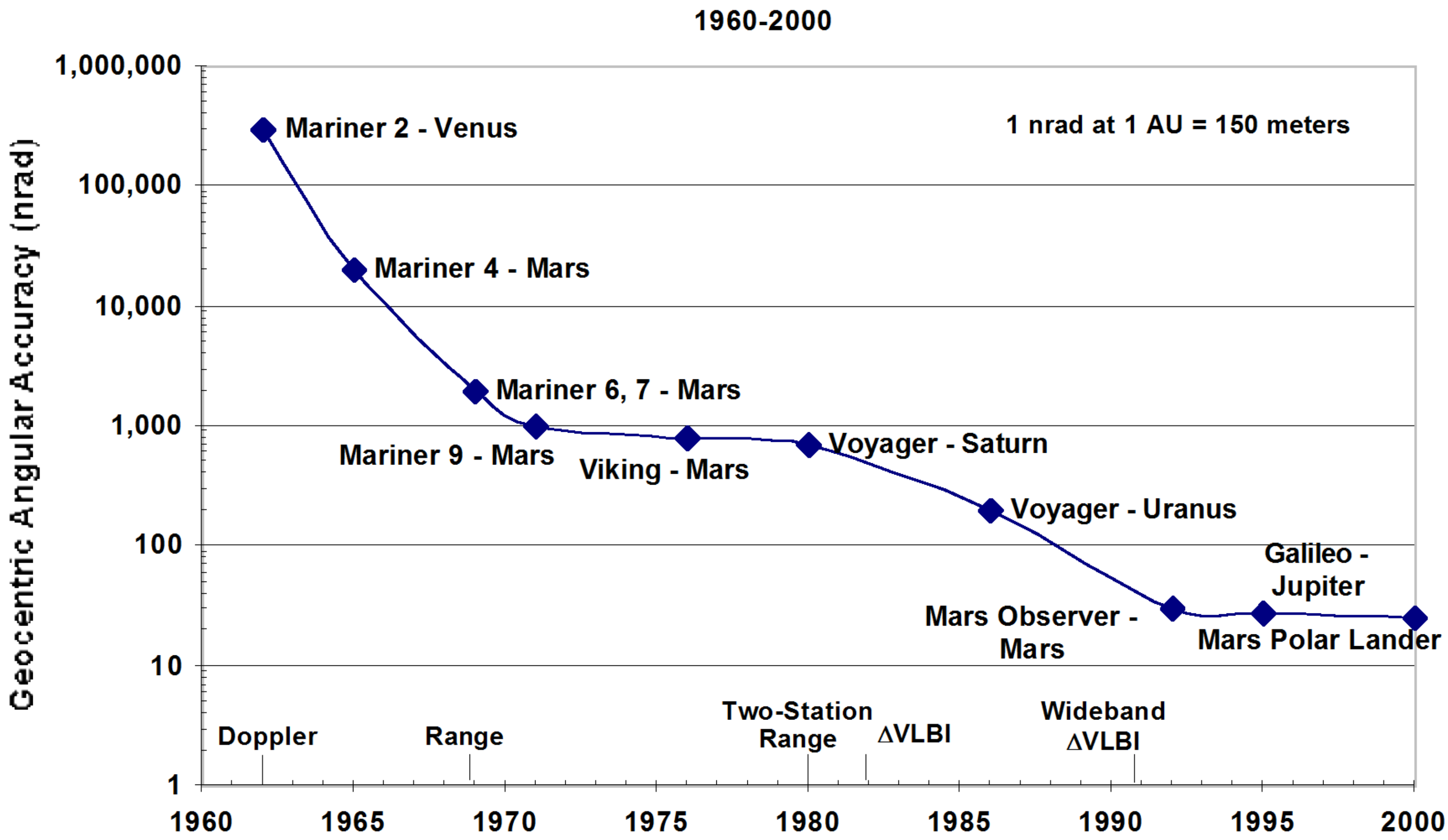


'Delta-DOR Demo'

Navigation Measurements: Optical Navigation



Deep Space Navigation System:
Evolution of DSN Navigation System Accuracy



Iris Transponder Communications and Navigation from Deep Space

Courtney Duncan
Amy Smith
Fernando Aguirre
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2014 August 6
28th Annual AIAA/USU Conference on Small Satellites
Utah State University, Logan, Utah, USA
With amateur radio additions for SBMS 2014 October 2

Government sponsorship acknowledged.

Transponders

- Transmit and receive simultaneously
  - 100% duty cycle for hours during navigation passes
  - No GPS in deep space, users participate by receiving *and transmitting*
- Coherent turnaround – Doppler and Ranging
  - Long navigation passes (hours)
- Commands up / Telemetry down
- Subcarriers and residual carrier
- Data rates vary with range

- *Note the differences between transponders and more familiar data-only transceivers*

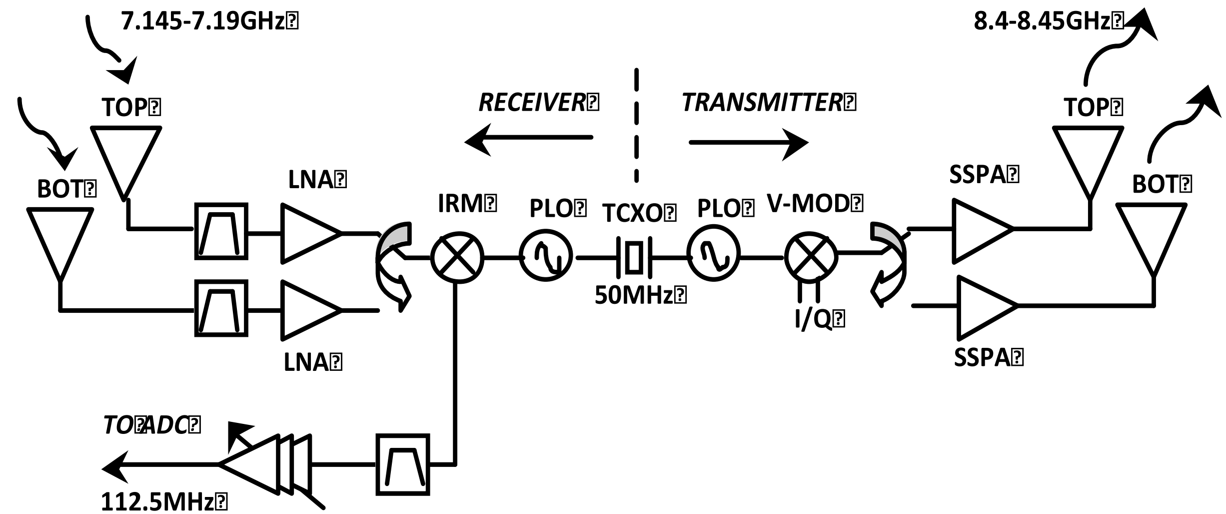
- When navigating on Earth or in Earth orbit using GPS
  - Transmit and receive are 100% duty cycle, but
  - GPS users are receive-only, not needing much power

Iris Transponder for Deep Space

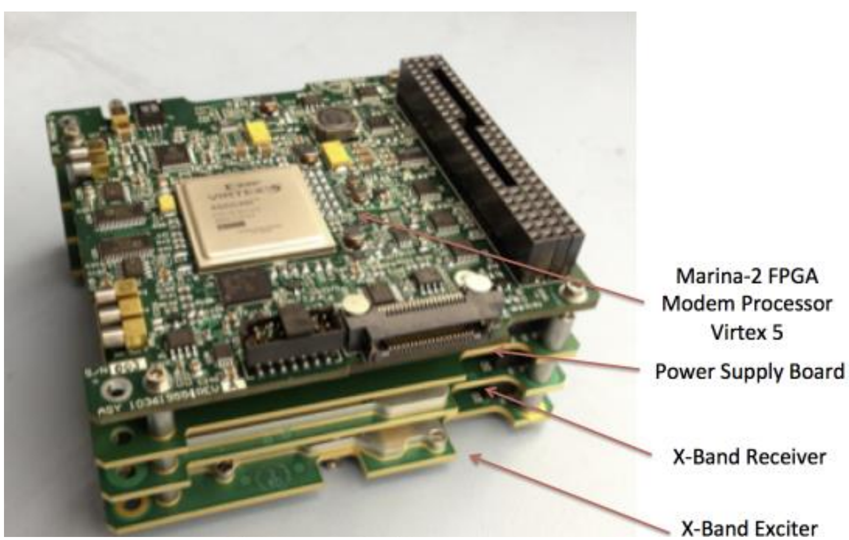
- JPL and others build transponders for deep space missions
  - Not small or low power enough for a CubeSat or nanoSat form factor
  - Until now
- Iris is CubeSat Compatible – 0.5 kg, 0.5U
  - Four stacked boards in current version, 0.4U
- Iris is DSN Compatible – CCSDS, transponder
  - Also intended for proximity operations – (planned)

Iris Architecture

RF Block Diagram:



Iris Prototype Stack

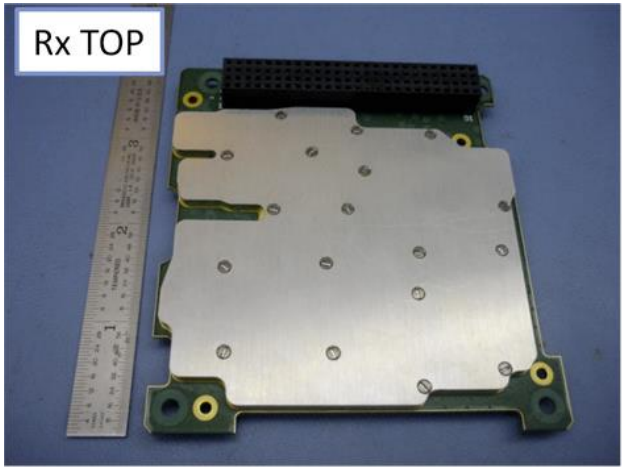


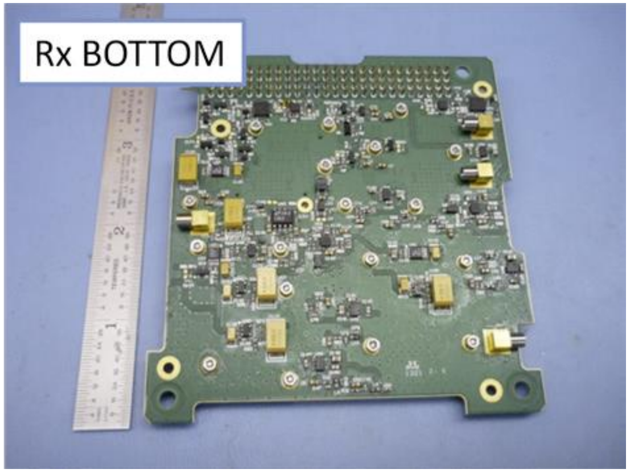
All functions and PLOs under FPGA control
All signal processing at baseband in FPGA
- generation of transmit I/Q
- processing of 112.5 MHz receive IF

Commercial Parts for INSPIRE mission

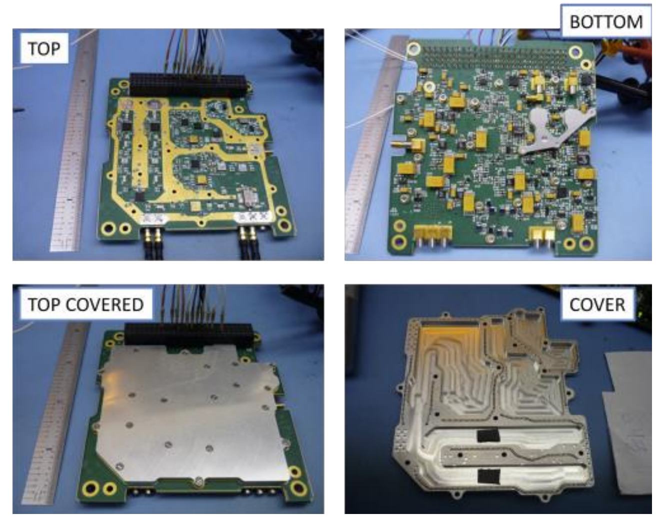
Receiver

- Converts 7.2 GHz uplink to 112.5 MHz IF
  - X-Band channel/frequency selection under FPGA control
  - 15 MHz IF bandwidth
  - -130 dBm sensitivity
  - 5 dB noise figure
- Two selectable low noise amplifiers
  - Top and bottom antenna
- Quadrature (subharmonic) sampled at 12.5 Msps





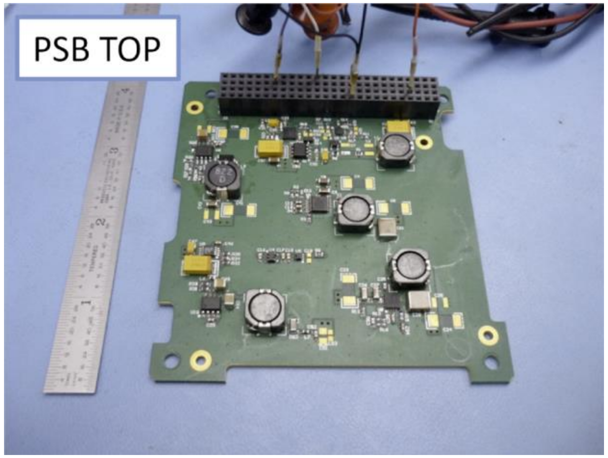
Exciter



- 8.4 GHz carrier PLL
  - X-Band vector modulator
  - Quadrature baseband at 2 MHz
- 50 MHz TCXO
- DACS for PLLs (TX and RX)
- Two selectable power amplifiers
  - Top and bottom antenna
- 30 dBm (1 W.) output possible
  - Can be biased back depending on mission needs
  - For INSPIRE, 23 dBm selected
- PA Heat dissipation
  - 3 W thermal at final amplifier (but only one at a time)
- “Exciters” usually drive high power amplifiers
  - This is CubeSat compatible, 1-2 W *is* “high” power

Power Supply Board

- Converts CubeSat bus to voltages used internally
  - 7.4-8.3 VDC nominal input
  - Separate RF and digital rails
  - Inrush limited to 3 A
  - FPGA, RX, and TX boards separately powerable
- Because *transponders* run nominally for hours at 100% duty cycle for navigation passes, an ultra low power “cellphone-like” receive mode is not as useful
  - But receive-only is still lower power
- To be upgraded to “radiation tolerant”



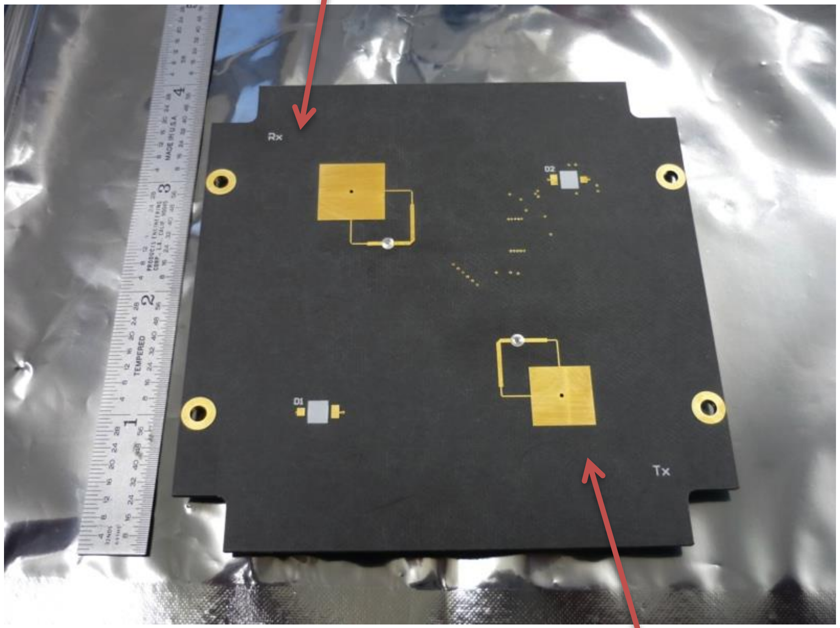
DC Input Table, W.	INSPIRE V1	INSPIRE V2 (WC)	Goal
FPGA & PSB	2.6	2.6	1.5
plus Receive	6.4	6.4	4.0
Full Transpond @ 0.3 W	12.75	12.75	10.0
Full Transpond @ 1.0 W	15.2	15.2	11.0
Full Transpond @ 2.0 W		18.9	15.0
Ka-Band @ 2.0 W		> 21.0	< 20.0

Low Gain Antenna

RHCP, each:

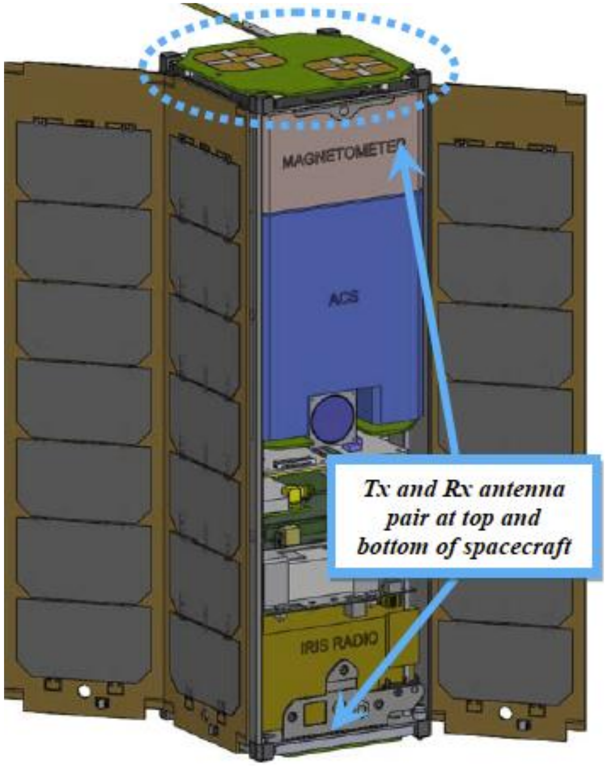
- 300 Mhz 3 dB bandwidth
- 80 degree 3 dB beamwidth
- 5 dB boresite gain

Receive Patch, 7.2 GHz >35 dB isolation



Accommodation for sun sensor

Transmit Patch, 8.4 GHz



Antenna placement on top and bottom of INSPIRE spacecraft

Baseband Functions, Common

- All baseband functions are implemented digitally in FPGA code and can be modified
  - In-flight modification capability planned
- Phase Lock Loop (PLL) programming, Tx and Rx
- Automatic Gain Control (AGC)
  - RF chain analog using PWM to op amp
  - Digital in later stages in baseband
- C&DH interface: Serial Peripheral Interface SPI
  - Command and telemetry dictionary planned for softcore in FPGA

Baseband Functions, Navigation

- Phase coherence downlink with uplink
  - 880/749 for standard X-Band – others possible
- Ranging tone or PN code passthrough
  - Non-regenerative
  - Regenerative (planned)
- Delta DOR tones (planned)
  - 19 MHz

Baseband Functions, Modems

- Uplink
  - Carrier
  - Subcarrier, 16 KHz
  - BPSK bit sync
  - Buffering
    - Multimission Telecommunications Interface (MTIF) SDST heritage
  - Deframing (in C&DH on INSPIRE, planned for softcore in FPGA in V2)
    - 2072 bit frame (smallest CCSDS frame size) on INSPIRE (other frame sizes planned)

Baseband Functions, Data & Modems

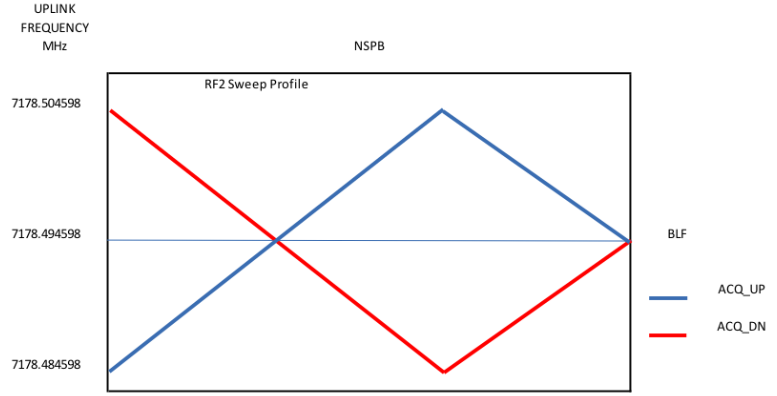
- Downlink
  - Carrier
  - Subcarrier (25 KHz, 281.25 KHz, others possible)
  - Framing (in C&DH on INSPIRE, planned for softcore in FPGA in V2)
    - 2072 bit frame on INSPIRE (other frame sizes planned)
  - Buffering and Coding in MTIF
    - Reed Solomon RS (255,223)) other schemes and interleave depths available
    - Convolutional (R=1/2, K=7), two symbols per bit
    - Turbo Coding available: 1/2, 1/3, 1/6
    - PN Coding available
  - BPSK
  - Direct carrier modulation
    - Suppressed carrier (π/2 mod. index)
    - Residual carrier (π/3 mod. index)

Iris Data Specifications

- Data Rates
  - Uplink
    - 1000 bps on 16 KHz subcarrier
    - Full range (planned) subcarrier and non subcarrier
    - FIRECODE (special but valid CCSDS frame)
  - Downlink
    - 62.5, 250, 1000, 4000 bps on 25 KHz subcarrier
    - 16000, 64102 bps on 281.25 KHz subcarrier
    - 260416 bps direct on carrier
    - Full range in factors of 2 (planned)
      - Up to > 4 Mbps
      - < 62.5 bps using tones

DSN Compatibility

- ConOps
  - Keep in mind two way light time delays of seconds to minutes (Earth orbit light time is milliseconds)
  - Find the downlink in plane of sky and frequency
  - Sweep the uplink across expected acquisition range
    - Up and/or Down (diagram)
  - Watch downlink frequency move to coherence with uplink
  - Reacquire downlink
  - Record navigation measurements
    - Doppler only for carrier coherence
    - Tones or PN code for ranging
  - Downlink Telemetry
  - Uplink Commands



Uplink Acquisition Sweep Pattern

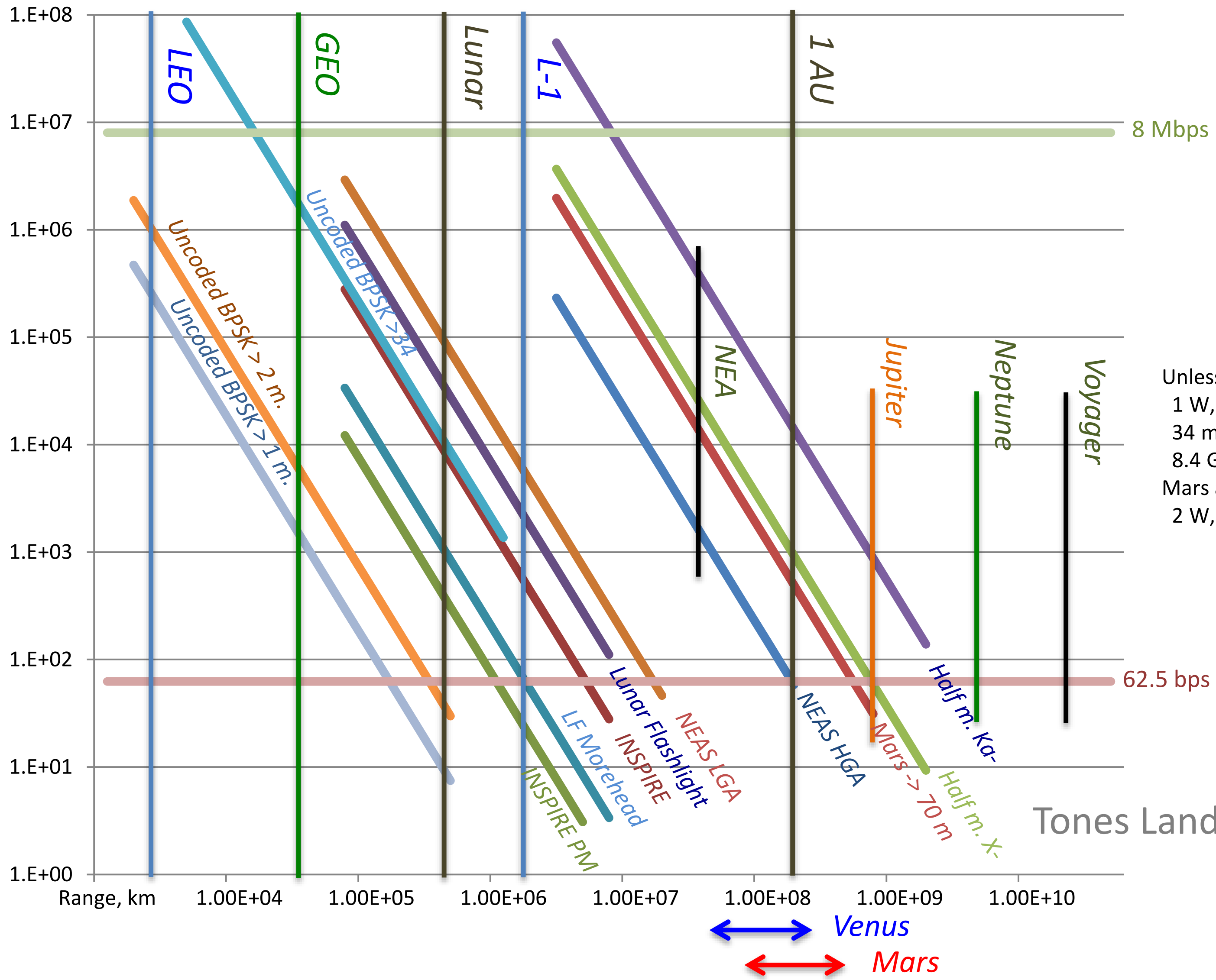
Deep Space Navigation Data Types

- Doppler
  - Most useful when there is Doppler "signature" as orbiting or passing a planet or moon
  - Easiest – nominal transponder operation
- Ranging
  - Gives absolute range from station to spacecraft
  - Sequential tones or PN (pseudo-noise)
  - Non-regenerative (implemented) or regenerative (planned)
- Delta DOR (planned)
  - Gives plane-of-sky location of spacecraft
  - Involves multiple ground stations slewing between spacecraft and quasars with spacecraft sending "tone" modulation
- Iris supports all

Projected Capabilities

- Frequency Bands
  - Ka-Band – more bandwidth available, higher gain antennas possible
  - UHF / S-Band – proximity operations
- Digitally implemented feature upgrades
  - As presented
- 2 W RF out baseline
  - Thermal design cooperation with spacecraft
  - Consideration of driving a higher power tube
    - But remember, these are CubeSats / nanoSats
    - You may really have a bigger mission and need a bigger comm/nav system

Iris Downlink Rates



Unless otherwise noted:
1 W, Conv. K=7, r=1/2
34 m, 45K
8.4 GHz
Mars and beyond:
2 W, Turbo 1/6 1728

Missions Planning on Iris

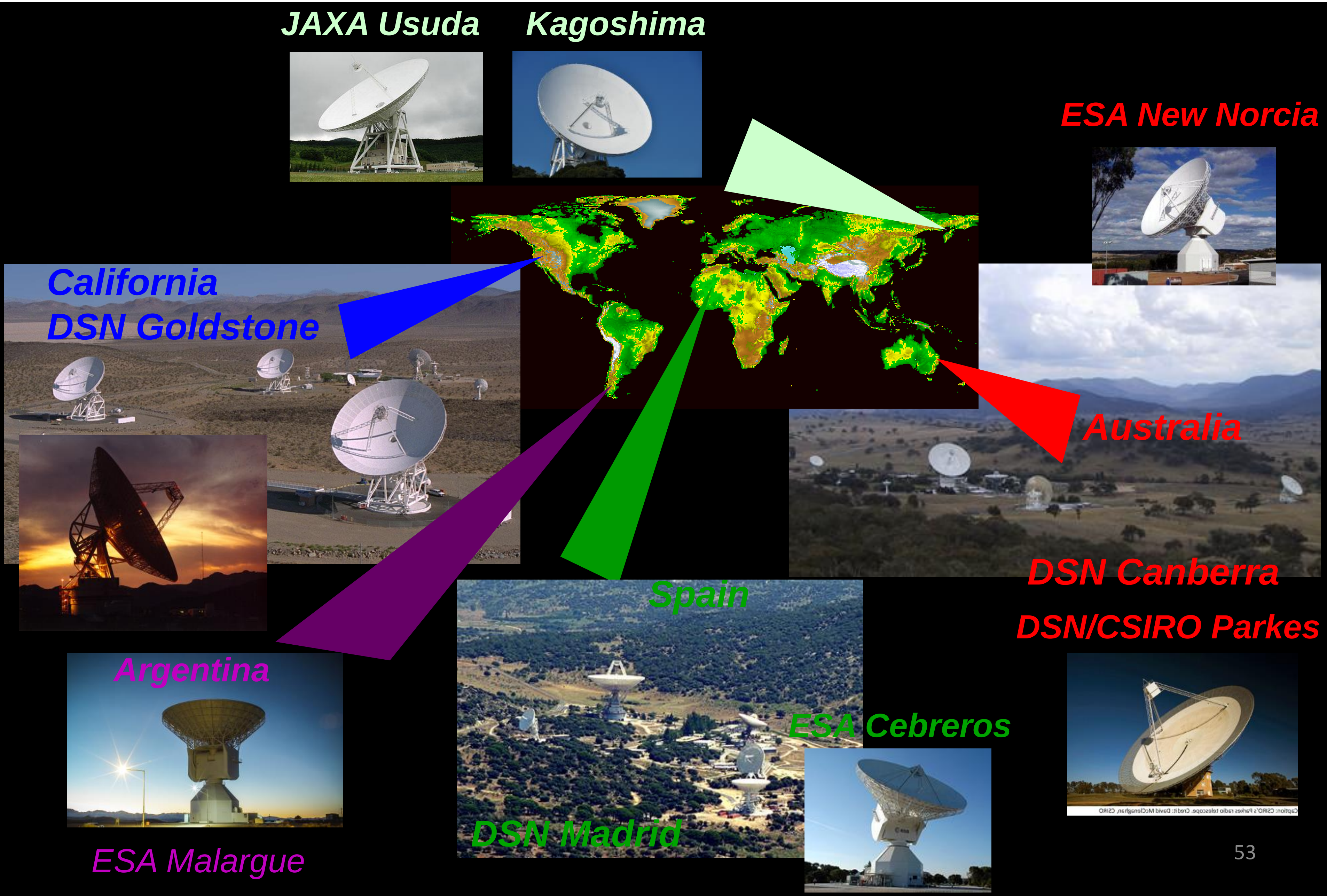
- INSPIRE – delivered 6/30/14
  - Earth escape, operate to 1.5 M km (0.01 AU)
  - Waiting on Earth Escape manifest
- Baselined for EM-1 launch in 2017
  - Lunar Flashlight*
    - Lunar south pole science with solar sail
  - NEAScout*
    - Fly by Near Earth Asteroid with solar sail
  - Bio Sentinel*
    - Interplanetary radiation effects on yeast
  - Heliophysics CubeSat*
    - LCAS AO out now

*Mission Concept – Pre-decisional – for Planning and Discussion Purposes Only

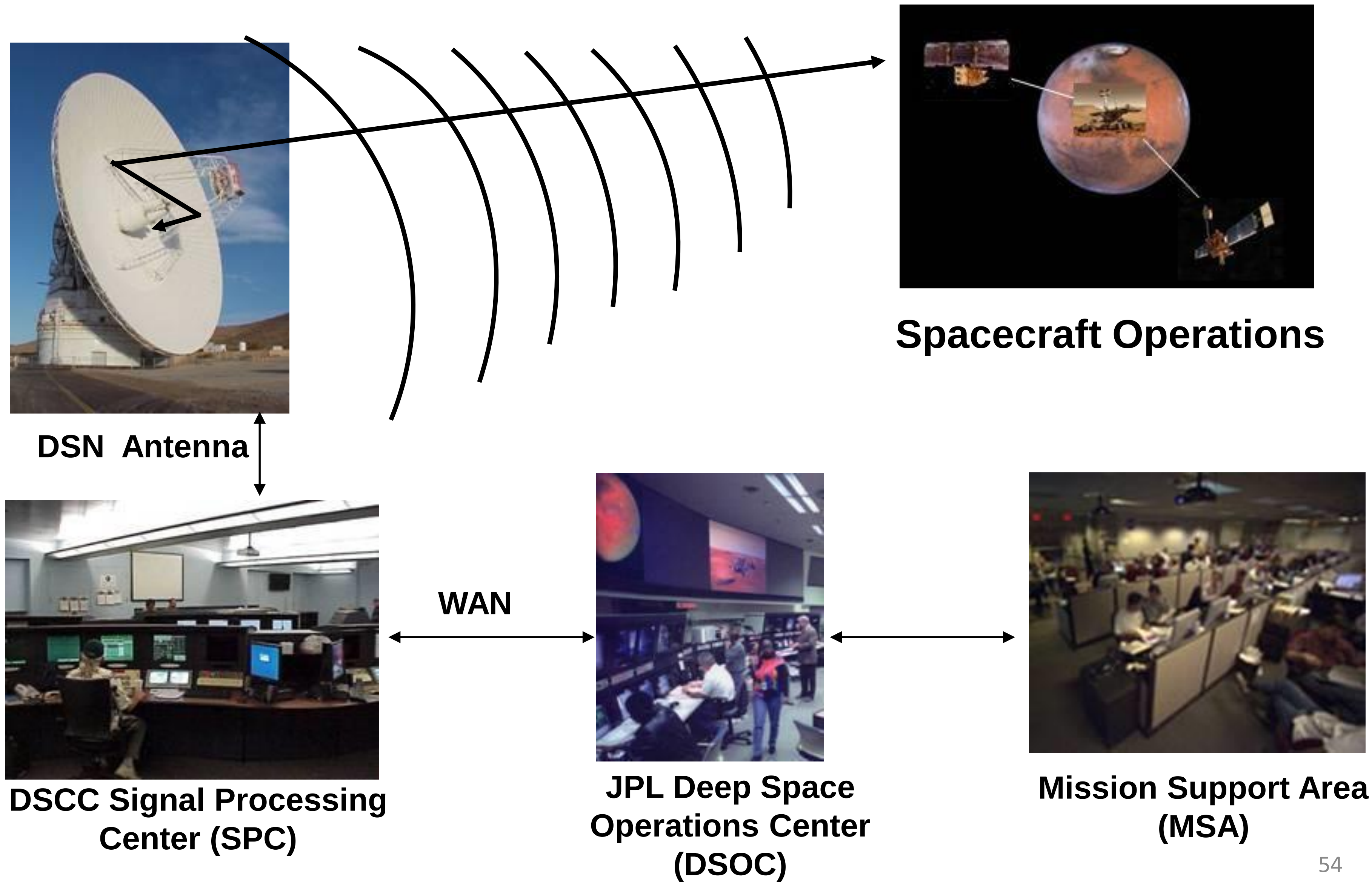
DSN

- DSN wants to support all deep space missions
  - Business and technical issues being worked in the community now
  - Don’t assume it’s too expensive or inaccessible
  - JPL contact is Kar-Ming Cheung
- DSN is the earth station partner that makes deep space operations possible
  - 34 and 70 m apertures – high gains
    - Precision pointing
  - Quiet front ends – 45K *system* noise temperature
  - High uplink power – 20 KW
  - High performance coding and other modulation schemes, > 10 dB of further improvements

Deep Space Network (DSN): Comprises DSN and Partner 34-70m tracking sites around the globe to provide continuous communication and navigation support



The Big Picture



DSN Collaborators

- Non DSN ground stations should be DSN compatible for interoperability
  - Small number of missions to deep space, multiple standards don't make sense
  - Community needs to be able to help / rescue each other, at least technically
- Steps towards compatibility
  - X-Band, receive 8.4 GHz data
    - CCSDS back-ends (can be implemented in digital IFs)
  - Good clock on ground to participate in navigation
    - Ideally collaborate with JPL navigators
  - 7.2 GHz uplink for command / navigation
    - Licensing
  - Ka-Band 32/34 GHz

Summary

- Iris is a DSN Compatible, CubeSat Compatible transponder intended for deep space mission communication and navigation
  - Support for at least inner solar system missions on nanoSats
    - Different missions will need different antennas – stabilization strategy
  - Evolving product, improved capabilities in progress as discussed
  - Commercialization is in progress for lower cost, higher availability
- Deep Space missions should use or be compatible with DSN
  - Including non DSN ground stations intended for this purpose

Iris (Ιρις)

- As a goddess, Iris is associated with communication, messages, the rainbow and new endeavors.
- “Little Sister” to Electra

Iris V2 Transponder for Lunar Missions

Courtney Duncan
Jet Propulsion Laboratory, California Institute of Technology

The 4th International Workshop on LunarCubes (LCW 4)
Sunnyvale, California
October 7-10, 2014

<snip>

Link Tutorial

- Data Rate = f(distance, apertures, power, other)
- Approach here, for back of the envelope, is to
  - Start from a known, well calculated budget
  - Assume all else (“other”) remains the same
    - Including efficiency – coding – frequency, see notes
  - Extrapolate to other apertures, powers, distances
- Data Rate= f(distance, apertures, power)

$$R_d = \frac{kPA_sA_g}{r^2}$$

Link Tutorial

$$R_d = \frac{kPA_sA_g}{r^2}$$

where

R_d	data rate
A_g	effective aperture ground antenna
A_s	effective aperture spacecraft antenna
r	ground – spacecraft distance
k	constant from base calculation Includes all “other”

Or, in dB: (see Backup for dB conversions)

$$R_{d\text{-}dB} = K + 10\log(P) + 10\log(A_s) + 10\log(A_g) - 20\log(r)$$

“Effective Aperture” is a function of antenna size, design, and efficiency.
Receiving is also affected by “system temperature” which varies widely.

Link Tutorial Examples

- Starting point
  - Iris V2 @ 2W (33 dBm) X-Band
  - LGA antenna (5 dB when pointed)
  - 34 m DSN aperture
  - Lunar distance
  - *100,000 bps*
- Back of the envelope deltas
  - 70 m DSN aperture = A_gx4 = data x4 = 400 kbps
  - 1W power out = P/2 = data/2 = 200 kbps
  - Go to L2 = $(384000 / 444000\ \text{km})^2$ = 150 kbps

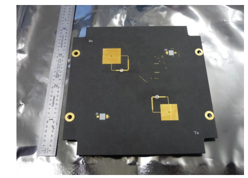
Ground Antennas

- DSN 34 m
  - ~68 dBi
  - And cryogenic front end too, low system temperature is good
- Morehead 21.6 m
  - ~64 dBi*
  - down factor of > 2.5
- Wallops 11 m
  - ~58 dBi*
  - down factor of > 10
- Sat Terminal Dish 1.2 m
  - ~39 dBi*
  - down factor of > 800

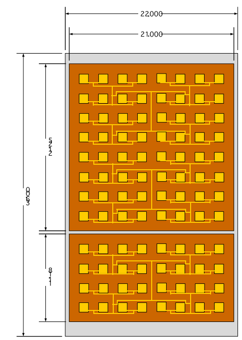
(roughly to scale)

* everything else being the same
“>” because system temperatures are higher

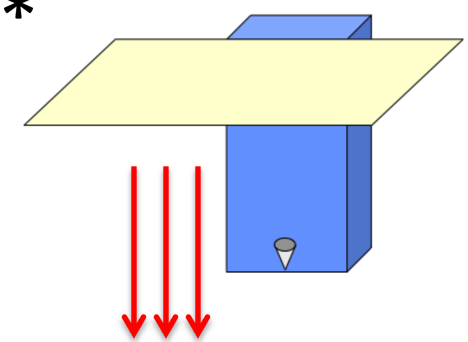
Iris Antennas



- Iris stock LGA patch
  - 5 dBi



- 20x30 cm MGA 64 patch array*
  - 22 dBi
  - factor of 50 improvement



- 3x 20x30 cm HGA reflectarray*
  - 29 dBi
  - factor of 250 improvement

*Pre-development investigation for various missions

Notes - Coding

- In Data & Modems slide it mentioned Reed-Solomon, Convolutional, and TurboCoding
  - These are complex schemes that improve data throughput significantly, > 10 dB, which is why they are used and necessary for deep space
  - Proprietary, optimized implementations
  - If you don't use coding, reduce all bit rates by at least a factor of ten
- Encryption
  - Supportable, but not in discussion at this time

Notes - Navigation

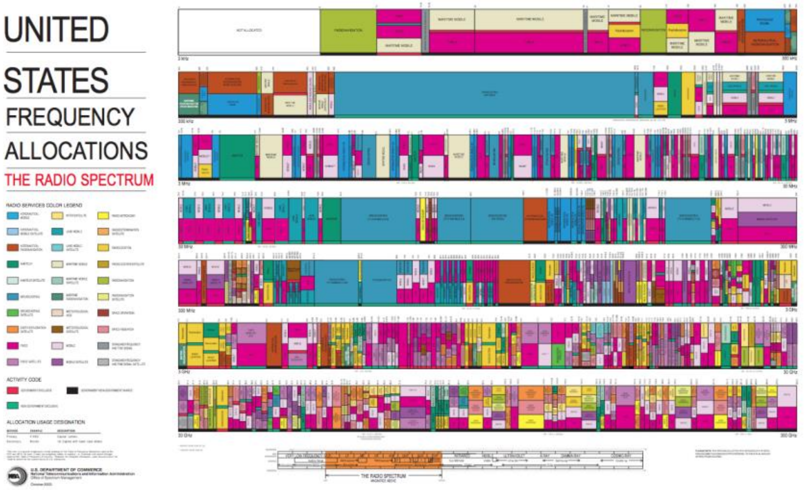
- Two-way, “long” tracks needed for Doppler / Ranging
  - Onboard oscillators for one-way nav data types not good enough (in CubeSat sizes) yet
  - Track length and signal quality depend on navigation requirements
    - ~km level on or near the moon very navigation, and mission design, intensive
  - Covariance of specific lunar navigation problems beyond the scope of this presentation
  - Navigation still available at signal levels below that required to support 62.5 bps link
- The lunar comm problem also includes nav (no Lunar GPS yet)
  - Infrastructure is similar
  - Additional equipment, track time planning, and processing needed
- Distinction between comm and nav:
  - Comm recovers bits, recovery at some bit error rate “good enough” typically ppm level
  - Nav measures the *edges of the bit transitions* and carrier phase as precisely as possible any degradation (clock instability, interference) *at all* degrades
  - These are fundamentally different measurements made on the same signals

Notes – Frequency

- Link Tutorial is at X-Band (8.4-8.5 GHz)
- For *aperture to aperture* data capacity goes **up** with square of frequency
- For other designs (LGA, yagis, arrays) data capacity goes **down** with square of frequency
- For *aperture to "other" it's a* ***wash***, to first order
- Examples
  - Ka-Band parabola to parabola, 16x better
  - UHF omni to omni, 400x better

Notes - Regulations

- Spectrum allocation situation has not changed since last year, nor is it likely to change radically in the foreseeable future
- Get your frequency story straight early
- Apply for your channel(s) before funding arrives!



Hams have it good!

(As long as they remain hams about it.)

Notes – Uplink

- The DSN has 20 KW uplink capacity at X-Band
  - (80 KW at S-Band for Voyager extension)
  - (500 KW for Solar System Radar)
- This is 10,000 times (40 dB) higher than the downlink, give or take
- So we don't worry about the uplink – plenty of power on the earth
- But, a commercial or university solution will be different
  - Few hundred watts good for university, -20 dB_{DSN} (or a ham)
  - Few KW good for commercial, -10 dB_{DSN}

Notes - Crosslinks

- People often have the idea of improving the situation by having assets talk to each other in "proximity"
  - Mars is so far away, that's a good idea
  - The moon is different
- The Iris to Iris bit rate earth to moon distance (the tutorial example) is
  - X-Band 0.002 bps at X-Band
  - UHF is 0.8 bps (see Notes – Frequency)
- Lunar Proximity (~2000 km separation)
  - X-Band 70 bps
  - UHF 32 kbps
  - OK for point to point, networks, clusters meshes, but:
  - Want to string out 200 equidistant relays between here and the moon?
    - And station keep them?
- Conclusion – Earth resources can be really classy, for lunar

Amateur Radio

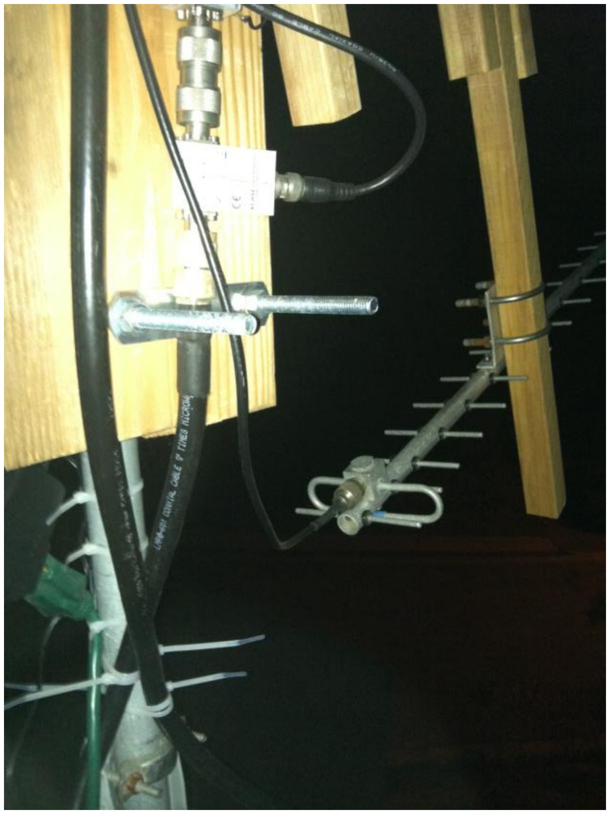
MicroWave Contesting

- Mars is -.5 to 1.5 Astronomical Units Away, typically 1.0 at arrival.
- 149,000,000 km
- 149,000,000 points for a QSO
- One way light time > 8 minutes.
  - So you have to judge on the spot whether it’s worth the ~20 minutes it will take to complete the exchange.
- Moon is ~384,000 km. 1.2 seconds

EME…

23cm35 Fixed Elevation - ~13 deg.

Cable Xperts



Lab Jumper 0.5 dB

Half Inch 0.05 dB

7/8 Heliax

WebCAM Views

Day

Night

WebCAM Moon Views

2M12 at upper left