Low Mass Radio Science Transponder – Navigation Anywhere

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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

– Information 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 1\textsuperscript{st} 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 - large antenna, pointing
  - 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:

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

- 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.

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 observed) - (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
   – Least squares solution also produces uncertainties on parameters estimated
     • 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

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

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

DSN Antennas
Ka-Band Downlink
X-Band Uplink

Telemetry UHF
Commands UHF

Ground Sites

5/23/11
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
  – ~$50K unit cost
## Link Capabilities

<table>
<thead>
<tr>
<th>LMRST Deep Space Downlinks</th>
<th>GEO</th>
<th>Lunar</th>
<th>NEO/Mars</th>
<th>Asteroids</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>From</strong></td>
<td>V-Sat class</td>
<td>V-Sat class</td>
<td>DSN</td>
<td>DSN</td>
</tr>
<tr>
<td><strong>To</strong></td>
<td>Transmitter power, watts</td>
<td>0.01</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Transmit antenna gain, dBi</td>
<td>Transmit antenna gain, dBi</td>
<td>0.0</td>
<td>0.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Transmitter EIRP, dBm</td>
<td>Transmitter EIRP, dBm</td>
<td>9.5</td>
<td>29.5</td>
<td>38.5</td>
</tr>
<tr>
<td>Earth Radius, km</td>
<td>Earth Radius, km</td>
<td>6378.1</td>
<td>6378.1</td>
<td>6378.1</td>
</tr>
<tr>
<td>Slant range, AU</td>
<td>Slant range, AU</td>
<td>0.000323</td>
<td>0.003</td>
<td>1.5</td>
</tr>
<tr>
<td>Path loss, dB</td>
<td>Path loss, dB</td>
<td>-204.6</td>
<td>-223.1</td>
<td>-277.9</td>
</tr>
<tr>
<td>Isotropis signal at Receive antenna, dBm</td>
<td>Isotropis signal at Receive antenna, dBm</td>
<td>-195.1</td>
<td>-193.6</td>
<td>-239.4</td>
</tr>
<tr>
<td>Receive dish diameter, m.</td>
<td>Receive dish diameter, m.</td>
<td>1.5</td>
<td>1.5</td>
<td>34</td>
</tr>
<tr>
<td>Receive antenna efficiency</td>
<td>Receive antenna efficiency</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Receive Antenna Gain, dBi</td>
<td>Receive Antenna Gain, dBi</td>
<td>39.4</td>
<td>39.4</td>
<td>66.5</td>
</tr>
<tr>
<td>Prec at LNA input, dBm</td>
<td>Prec at LNA input, dBm</td>
<td>-156.8</td>
<td>-155.4</td>
<td>-173.5</td>
</tr>
<tr>
<td>Receive Noise Figure, dB</td>
<td>Receive Noise Figure, dB</td>
<td>1.0</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>Sky Temperature, K</td>
<td>Sky Temperature, K</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Receiver G/T, dB/K</td>
<td>Receiver G/T, dB/K</td>
<td>15.8</td>
<td>15.8</td>
<td>44.6</td>
</tr>
<tr>
<td>CNR, dB/Hz</td>
<td>CNR, dB/Hz</td>
<td>19.3</td>
<td>20.8</td>
<td>3.8</td>
</tr>
<tr>
<td>beamwidth, deg.</td>
<td>beamwidth, deg.</td>
<td>1.4</td>
<td>1.4</td>
<td>0.06</td>
</tr>
</tbody>
</table>

- 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
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 (DDOR) - 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

- $\Delta_{\text{VLBI}}$
- *DELTA-DIFFERENCED ONE-WAY RANGE: $\Delta_{\text{DOR}}$*
- *DELTA-DIFFERENCED ONE-WAY DOPPLER: $\Delta_{\text{DOD}}$*

- REFERENCE FRAME:
  - DISTANT QUASARS DEFINE BEST KNOWN INERTIAL REFERENCE FRAME
  - MODERN SPACE GEODETIC TECHNIQUES MEASURE AND DESCRIBE EARTH ROTATION IN THIS FRAME
  - DIFFERENTIAL MEASUREMENT TIES S/C INTO THE QUASAR REFERENCE FRAME

- INCREASED ACCURACY DUE TO ERROR CANCELLATION:
  - CLOCKS
  - PROPAGATION MEDIA
  - PLATFORM ERRORS (BASELINE KNOWLEDGE)

- CURRENT 30 NRAD ACCURACY
- 1-10 NRAD FUTURE CAPABILITY

\[
\Delta \rho_{\text{s/c}} = B \cos \theta_{\text{s/c}} + c (\Delta \tau_{\text{clock}} + \Delta \tau_{\text{inst}} + \Delta \tau_{\text{media}}) + \text{NOISE}
\]

\[
\Delta \rho_{\Omega} = B \cos \theta_{\Omega} + c (\Delta \tau_{\text{clock}} + \Delta \tau_{\text{inst}} + \Delta \tau_{\text{media}}) + \text{NOISE}
\]

‘Delta-DOR Demo’
Navigation Measurements: Optical Navigation
Deep Space Navigation System:
Evolution of DSN Navigation System Accuracy

1960-2000

- Mariner 2 - Venus
- Mariner 4 - Mars
- Mariner 6, 7 - Mars
- Mariner 9 - Mars
- Viking - Mars
- Voyager - Saturn
- Voyager - Uranus
- Mars Observer - Mars
- Galileo - Jupiter
- Mars Polar Lander

1 nrad at 1 AU = 150 meters

Geocentric Angular Accuracy (nrad)


Doppler  Range  Two-Station Range  ΔVLBI  Wideband ΔVLBI