Combined Observational Methods for Positional Awareness in the Solar System (COMPASS): Applications of VLBI Beacons in Cislunar Space

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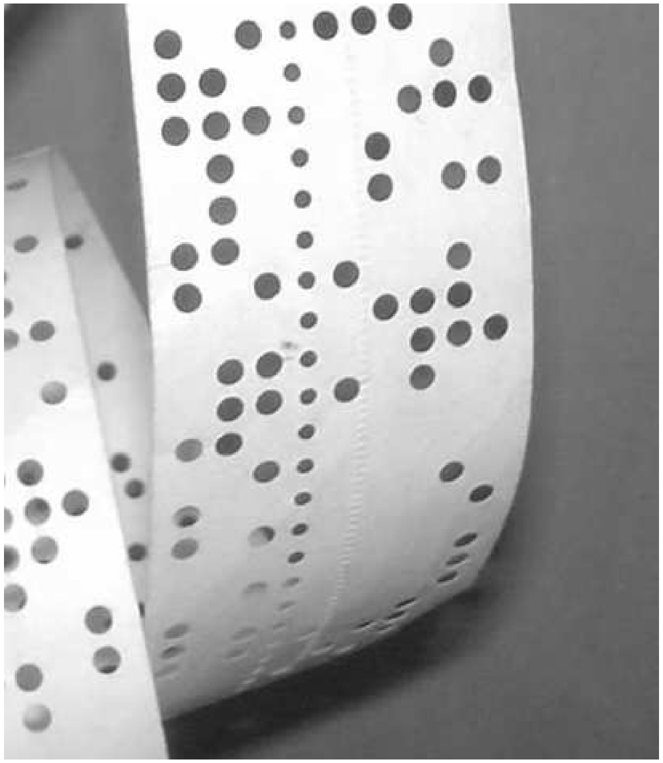
October 7, 2019

Journées 2019 “Astrometry, Earth Rotation and Reference systems in the Gaia Era”

It all Started with Punched Paper Tape



VLBI to the Lunar ALSEPS

- In the mid-1970's I worked with Bob King at MIT in Irwin Shapiro's Group.
- His office had a back-section **filled** with punched paper tape.
- That was the ALSEP VLBI phase data [King et al., 1976].
  - Later on, the paper tape started cracking, which was a problem.
- A very narrow bandwidth (kHz) S-band transmitter was used to determine relative positions of the ALSEPS on the Moon to "about 30 m along the earth-moon direction and about 10 m in each of the two transverse coordinates."
- No quasars were involved in this VLBI!
- Now, we are going back to the Moon. How can VLBI help with this effort? And, how much better can we do after decades of techncal development?

Extending the Space Service Volume (SSV) to CisLunar Space

NASA, Other Space Agencies, and Industry are planning for a vast increase in operations in Cislunar Space

- Lunar Orbital / Surface Operations
  - The Gateway will require accurate backup navigation, and will likely host many free-flying Small-Sat / CubeSat missions. These will all need positional awareness.
  - Lunar surface operations (rovers, hoppers, construction) will have very similar requirements to Formation Flying.
  - Again, requirements can be as low as 1 meter absolute positioning and cm-level relative navigation.
  - Operations on the Far Side or in Permanently Shadowed Regions will require PNT extension.
- Planetary Defense.
  - There is interest in the NASA Planetary Defense Office in “tagging” Potentially Hazardous Objects (PHO) with beacons or transponders.
  - This will fit naturally into COMPASS operations, although PD will set stringent limits on beacon longevity, and will require more power than CisLunar beacons.

COMPASS - Extending the Space Service Volume to the Moon with Centimeter Level Positioning

- A CisLunar SSV will clearly involve use of the GPS
  - This will be “over-the-shoulder,” and will be limited by the Geometrical Dilution of Precision (GDOP) this causes.
  - A single point GPS extension, say at the Gateway or at a Lagrange point, will help availability but will not solve the GDOP problem.
- For Lunar Surface Operations, laser retroreflectors will provide highly accurate ranging, but limited positioning.
- And, of course, there are existing NASA Spacecraft Tracking assets for high value and crewed missions.
  - These are not set up to handle hundreds or thousands of spacecraft.
- There is, however, another **existing** International infrastructure that can observe spacecraft in CisLunar Space - the VLBI Global Observing System (VGOS).
  - VGOS was developed with the strong participation and support of the Goddard VLBI Group.
  - The existing and planned VGOS network **can** track 1000’s of spacecraft in CisLunar space (and beyond), **if** these spacecraft carry suitable VLBI beacons.
  - This has been done using legacy VLBI with, e.g., Huygens in the Titan atmosphere. The TRL is high.
- COMPASS (Combined Observational Methods for Positional Awareness in the Solar System) is our proposal to use Ultra-Wide-Band (UWB) Beacons for routine positional awareness in CisLunar space and beyond.

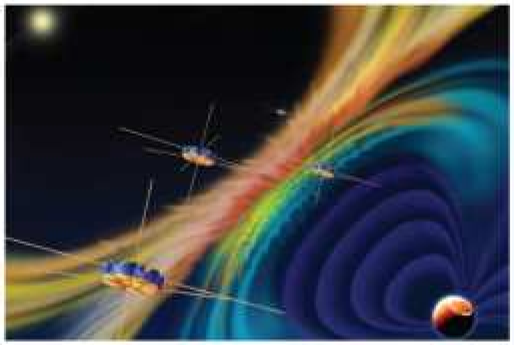
Recent SSV Experiences: NASA MMS Mission

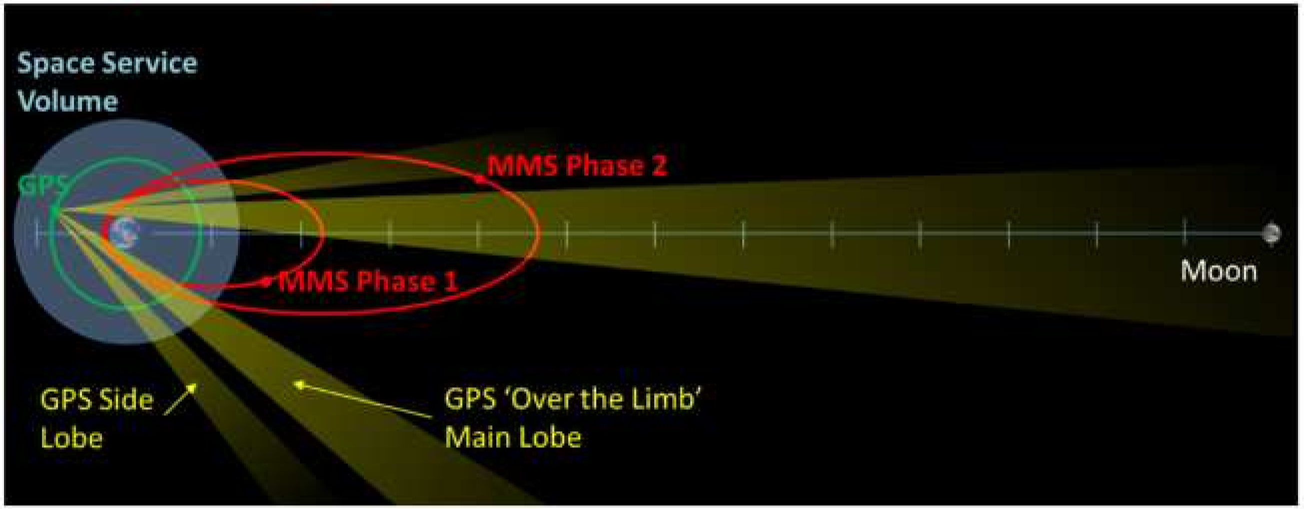
Magnetospheric Multi-Scale (MMS)

- Launched March 12, 2015
- Four spacecraft form a tetrahedron near apogee for performing magnetospheric science measurements (space weather)
- Four spacecraft in highly eccentric orbits
  - Phase 1: 1.2 x 12 Earth Radii (Re) Orbit (7,600 km x 76,000 km)
  - Phase 2B: Extends apogee to 25 Re (~150,000 km) **(40% of way to Moon)**

MMS Navigator System

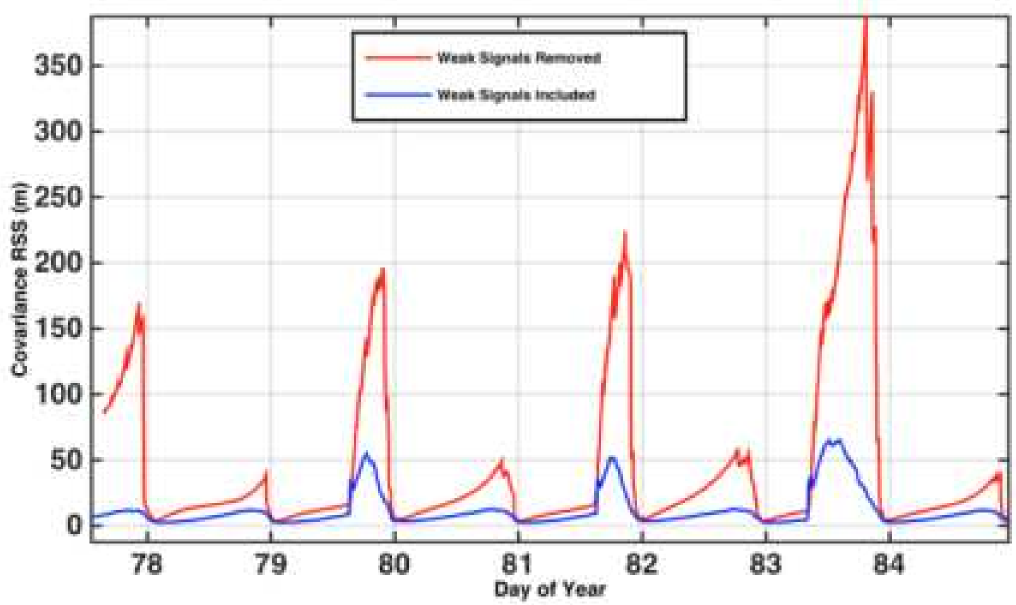
- GPS enables onboard (autonomous) navigation and near autonomous station-keeping
- MMS Navigator system exceeds all expectations
- At the highest point of the MMS orbit Navigator set Guinness world record for the highest reception of signals and onboard navigation solutions by an operational GPS receiver in space
- At the lowest point of the MMS orbit Navigator set Guinness world for fastest operational GPS receiver in space, at velocities over 35,000 km/h





(Courtesy Benjamin Ashman, GSFC.)

MMS SSV Lessons Learned.



MMS response to apogee maneuvers with side-lobe signals (blue) and without (red)

Over the Shoulder GNSS can approach Dekameter accuracy at CisLunar distances using sidelobe signals, which substantially improve GNSS availability and GDOP in CisLunar Space. (Courtesy Benjamin Ashman, GSFC.)

Tracking Lunar Spacecraft with Very Long Baseline Interferometery (VLBI)

Why VLBI?

- VLBI offers a number of attractive features for a cislunar positional awareness system.
  - Differential dual-frequency VLBI can potentially provide 10 muas angular accuracy, corresponding to $\sim$ 2 cm transverse positional accuracy at the lunar distance.
  - The terrestrial parallax would provide $\sim$1 meter radial position estimates.
  - The angular noise floor, from ICRF work, is maybe a factor of 5 better, or 8 cm at the Moon.
  - An SEFD of 1000 JY or less would enable integration times of a few seconds even with transmitter power of a few milliwatts.
- COMPASS therefore proposes that VLBI be used for routine positioning of the coming flood of cislunar smallsats. .
- CisLunar COMPASS will develop a chipsat sized "navigation patch" to allow for routine smallsat navigation support.
- In parallel with this a registry should be established to give deep space small sats a unique identifier, which should be integrated into the navigation system and broadcast by each beacon.
  - This would function something like the MAC address in terrestrial wireless networks.

How Would COMPASS Work?
(and this is where we need advice and comments!)

- A UWB navigation beacon would be developed.
- There would be a Registry, which would assign a unique identifier (ID) to each spacecraft (or each navigation beacon).
  - I would suggest a 24 bit (16,777,216 numbers) address space for "future proofing."
  - Ideally, the ID would also map into a DTN ID and even maybe a IPv6 address suffix.
- The Navigation Beacon would broadcast a beacon signal (including its ID) on a regular basis.
  - The beacon code format will be chosen to interoperate with local communications and relative navigation needs.
  - The beacon would be ruggedized to potentially outlast the mission (especially for Lunar surface use).
  - Optical retroreflectors could be included to meet colocation needs, particularly for lunar surface missions.
- The terrestrial VGOS network would observe the beacon catalog on a regular basis (daily or weekly).
- The goal would be to obtain a observation with $\lesssim$ 10 seconds of observing, and observe at least 10 (and ideally many more) beacons in one beam.
- 1000 spacecraft would thus require order 1000 seconds per day, perhaps repeated a few times per day.
  - This could be worked into many regular observing sessions.

VLBI Lunar Beacon SNRs

- The basic equation [Pogrebenko et al., 2004] is

$$SNR = t_{int} \frac{\eta \, \pi \, D^2}{4 \, kT_{sys}} \left(\frac{P \, G_{transmit}}{4 \, \pi \, f \, R^2} \right) \quad (1)$$

  where η is the net VLBI efficiency, k the Boltzmann constant, T_{sys} the system temperature, D the antenna diameter, R the distance to the source, and P the transmitter power. f is the UWB loss factor, about 11.3 for 802.15.4a.

- We assumed the availability of two VLBI antennas,and typical values for the 25 meter VLBA telescopes.
  - For the VLBA, T_{sys} = 26.6 K and η = 0.55

- The VLBA could in theory detect a 1 milliWatt UWB transmitter at the lunar distance with 1 second integrations and an SNR of 10.
  - This needs to be tested.

- As a broadband source, the navigation beacon would be a 0.4 milliJansky radio source.

- 10 μas (0.05 nanoradians) VLBI angular accuracy has been demonstrated with dual frequency phase referenced differential VLBI.
  - That is equivalent to $\sim$2 cm transverse and $\sim$1 meter radial positioning on the Moon.
  - Note that near the Lunar limb “transverse” and “radial” may not be aligned with the Lunar topography.

802.15.4-a UltraWideBand RF Protocol Being Evaluated for VLBI Positional Awareness

- At 3-10 GHz, there is the potential of using 802.15.4-a. There is COTS industrial equipment available that supports:
  - Centimeter level real time range accuracy.
  - Support for up to 11,000 communications nodes.
  - Coherent receivers that support real time ranging.
  - Native Support for store and forward communication.
- This is all based on nanosecond pulses with a 3.9 MHz (or higher) pulse repetition rate in 500 Mhz or 1 GHz channels.
- We propose consideration of this protocol as a possible candidate for deep space.
- For a variety of reasons, terrestrial WiFi - 802.11a (C band) or 802.11b (S band) - is not nearly as suitable for use as a deep space standard.

802.15.4a Channel Assignments.

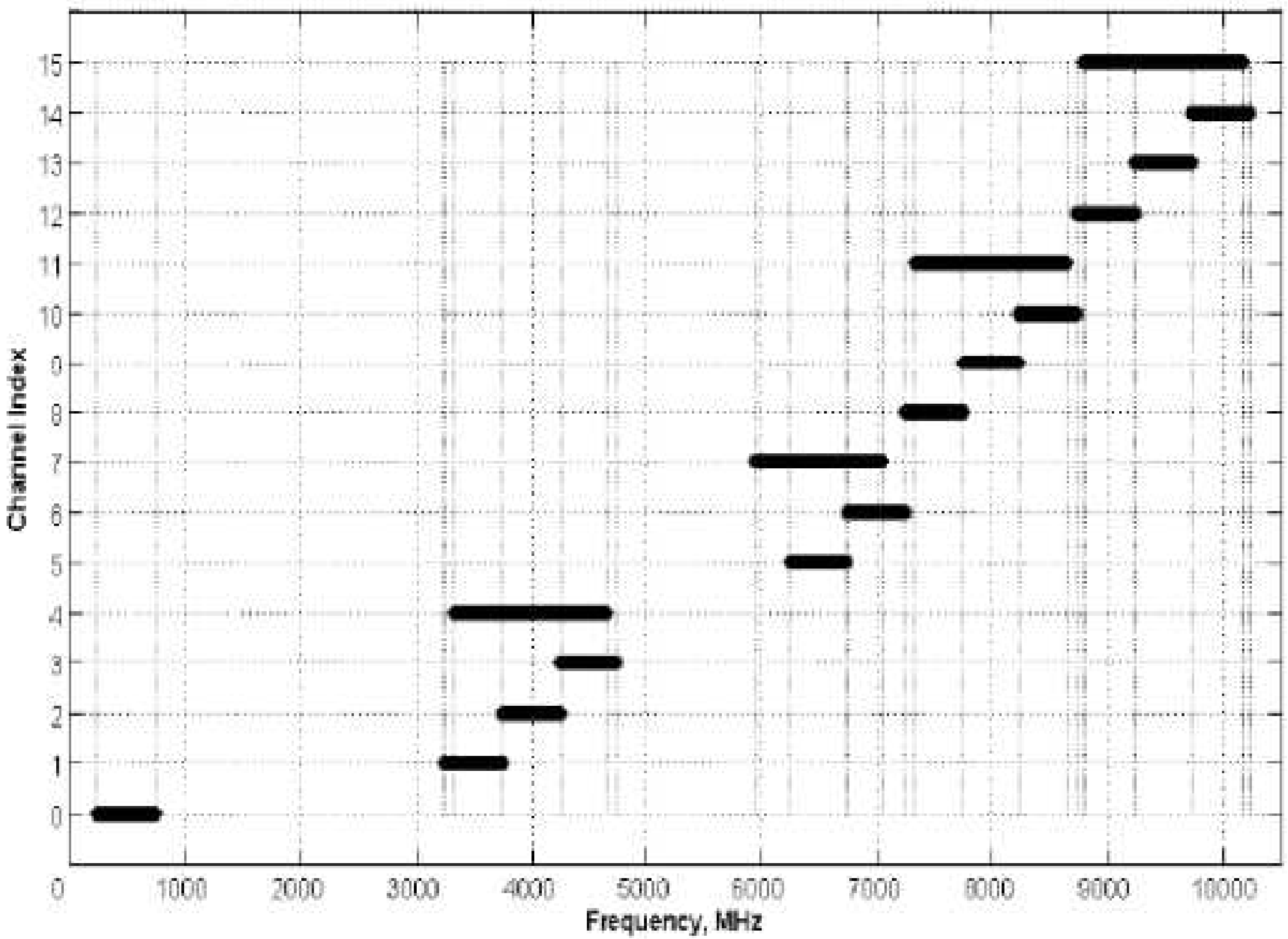
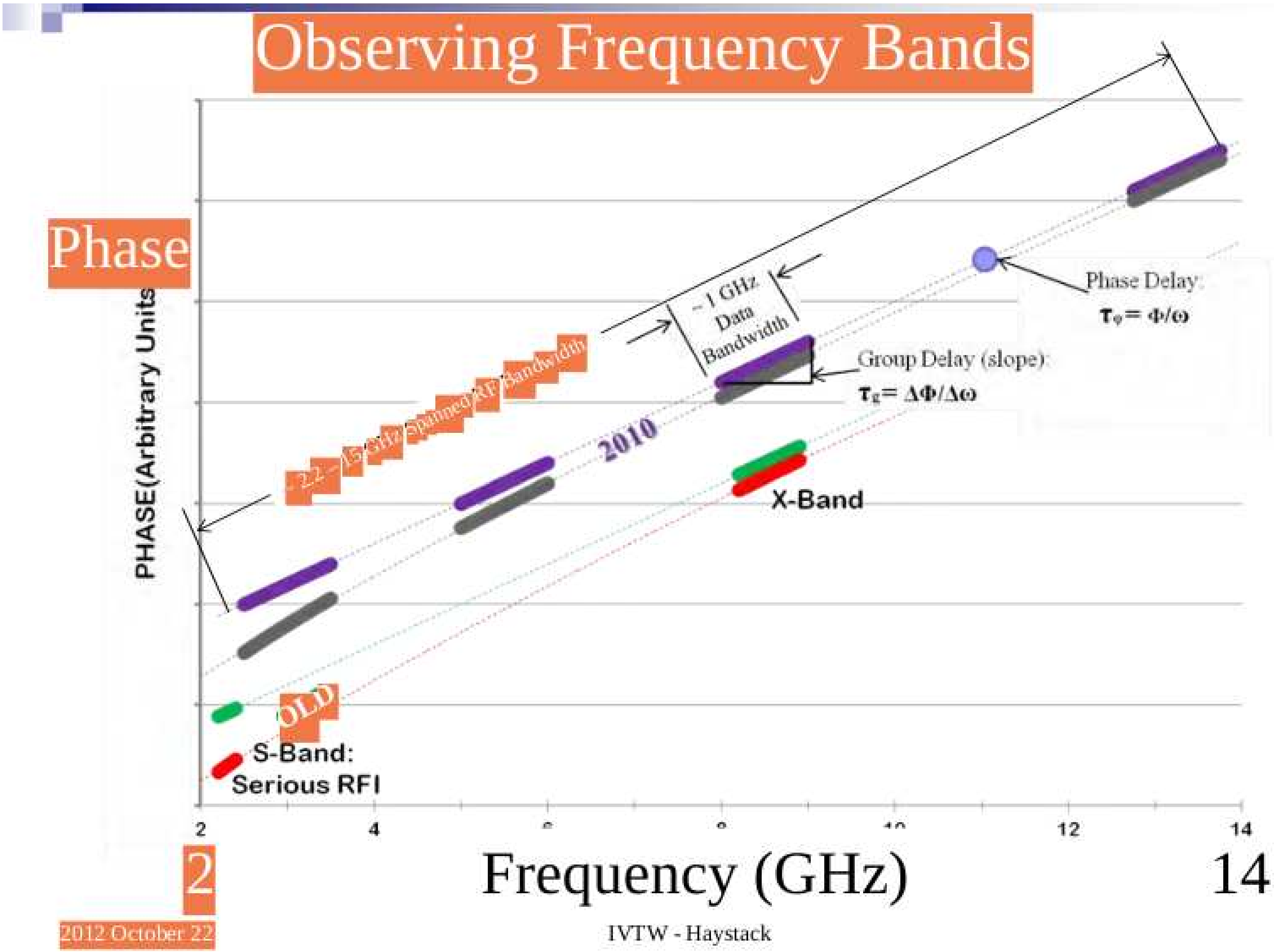


Figure 16-12—HRP UWB PHY band plan

This spread in frequency, and even some of the frequency channels, is very close to the new VGOS frequency choices.

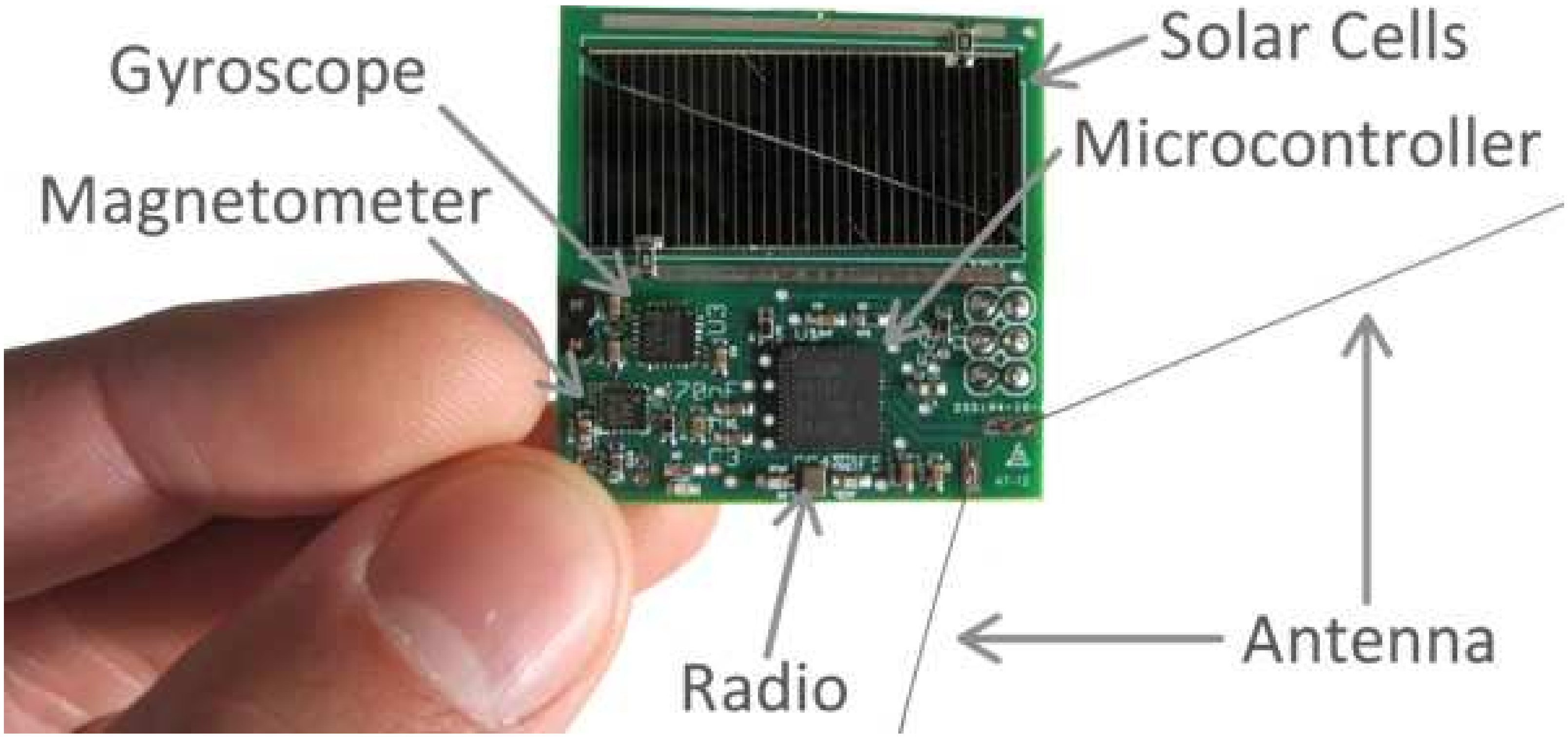
Possible VGOS Channel Assignment.



Source: Arthur Niell Presentation.

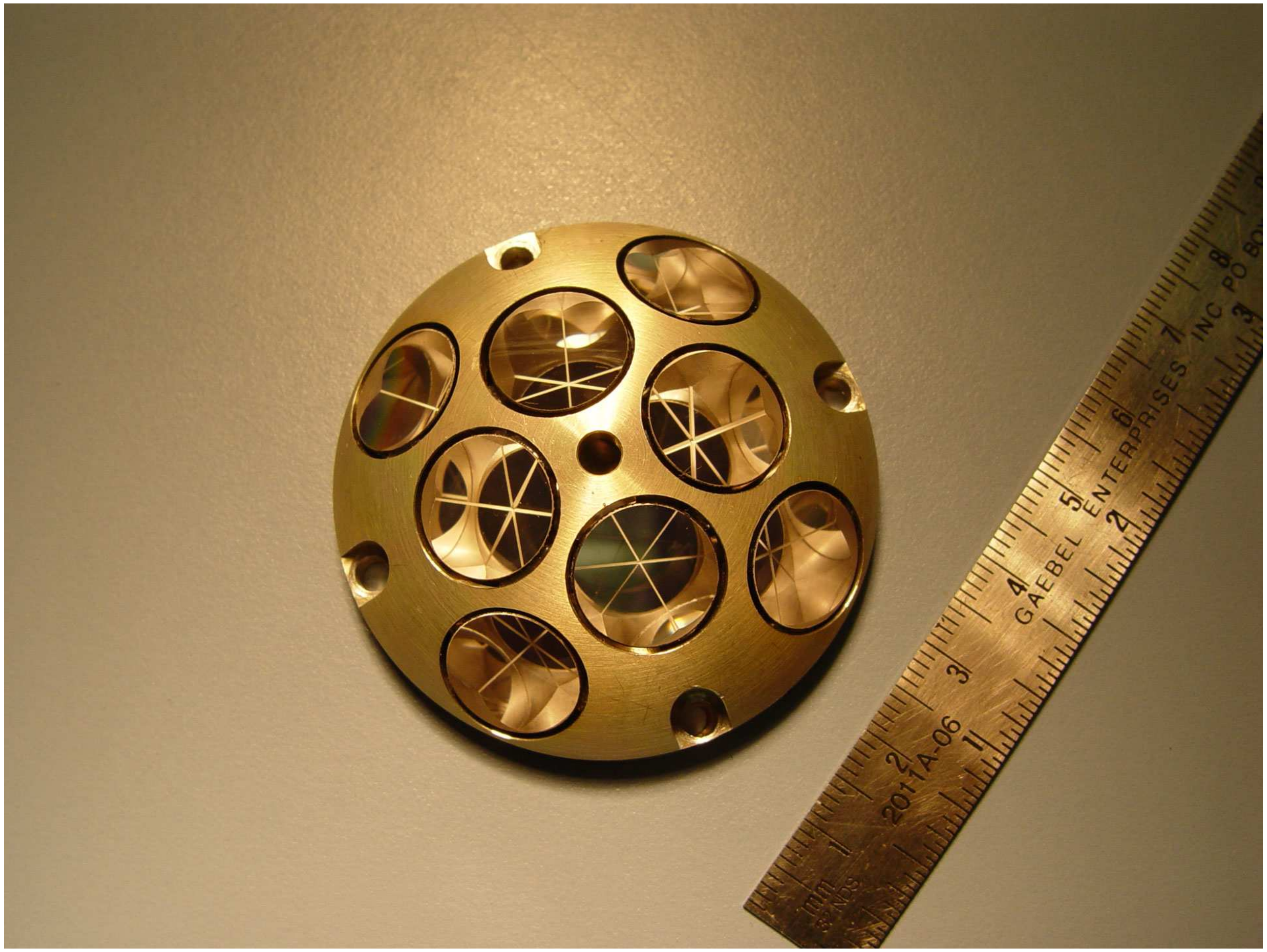
A Landed Surface Geodetic Station

A Chipsat.



The Cornell “Sprite” Chipsat is about the size of a pure VLBI beacon. Image is from Manchester et al. [2013].

The “Beresheet” Retroreflector (made here at GSFC).



Combine this Retroreflector with a VLBI beacon and (ideally) a suitable GPS receiver. Result: A lunar geodetic station with VLBI, LLR and GPS collocation not much larger than a cell phone!

A Lunar Penetrator capable of implanting a VLBI beacon on the Moon

A Lunar ballistic penetrator developed by Transorbital Corporation and the Polish Academy of Sciences.

What Science can be Provided by a Lunar Surface VLBI Beacom?

- First, we simply want to demonstrate the technology works, and the best way to do that is to collocate a VLBI beacon and a LLR retroreflector.
- But there is science that can be done.
  - Surface VLBI would immediately tie the lunar reference frame into the ICRF. Current Lunar-ICRF ties are indirect.
  - There are two major lunar coordinate systems, Principal Axis (PA) and Mean-Earth-Rotation Axis (MER), which differ by about a km. LLR coordinates are basically in the PA system, while cartograpers (and LRO) want a MER frame. Currently, the MER frame is calculated from the PA frame and lunar models, with an accuracy of order 1 m.
  - VLBI Beacons would provide the obliquity and mean Earth direction directly, thus providing a direct MER-PA frame tie.
  - VLBI-LLR geodetic observatories would make it possible to extend the LLR reference frame all near-side surface or orbital operations.
  - Plus, VLBI beacons could improve the determination of the Lunar ephemeris.

Lunar Science with Beacons: Linking the Lunar and Planetary Reference Systems

- LLR observations do not directly observe the Sun or the planets.
- However, the LLR system is connected to the barycenter through oservations of solar perturbations. The largest such variation is
  - δ r = -2996 $\cos 2$ D km
  - Where D is the synodic phase angle between the Sun and the Moon as seen from the Earth.
- Surface VLBI would **directly** observe the mean motion of the Moon, and would be able to **directly** connect the Lunar and Planetary frames.
- The small gravitomagnetic terms,
  - δ r = -7.28 $\cos$ D m - 6.54 $\cos 2$ D m
- are absorbed in the frame tie and thus obscured by the larger Newtonian perturbation. These might be accessible from a combined **long duration** LLR-VLBI observing series.
- There are numerous tidal terms in the orbit and Libration of the Moon.
- Typically the ability of VLBI to observe longitude terms and LLR to observe radial terms should be comparable. VLBI will be more directly able to observe terms in latitude or inclination. The real issue will be the duration of the observations, to separate terms close in frequency.

Conclusions

- There is increasing interest in spacecraft, and in particular small spacecraft, operations in cislunar space, and on the lunar surface.
- VLBI Navigation beacons should become routine in Lunar exploration to provide lunar positioning..
  - In cislunar space, these beacons can be very low mass and low power.
  - A very demanding customer will be the Gateway itself and SmallSats near the Gateway.
  - Such beacons can also support “tagging” of potentially hazardous Asteroids for planetary defense.
- There is serious science that can be done with VLBI beacons, especially from the lunar surface.
- We are looking for contributors and partners for this effort.

References

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