

# Deep Space Navigation

NASA Technology Roadmaps Review

Robotics, Communications, and Navigation Workshop

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# Topics to be Covered



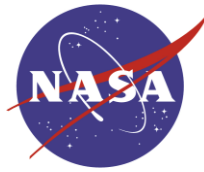
- Information about speaker
- General comments on roadmap
- Comments on roadmap Section 2.1.4
- Radio metric tracking technologies
- Frequency and timing technologies
- Comments on roadmap section 2.1.6
- Communications technologies (brief overview)

# Information about Speaker



- Education
  - B.S., Cornell University, Engineering Physics
  - M.S., Ph.D., Stanford University, Aeronautics and Astronautics
- With Jet Propulsion Laboratory, Caltech, since 1977
  - Various program management, line management, and technical analysis responsibilities in space navigation and mission design
  - Currently, Principal Engineer, Mission Design & Navigation Section
- Associate Editor of
  - Journal of Guidance, Control, and Dynamics, 1983-1990
  - Journal of the Astronautical Sciences, 1980-1983
- Technical committee member
  - American Astronautical Society (AAS) Space Flight Mechanics Committee, 1980-1997; Chairman, 1993-1995
  - AIAA Astrodynamics Technical Committee, 1985-1988; Chairman, 1986-1988
- Associate Fellow, AIAA; Senior Member, AAS and IEEE

## Information about Speaker (Cont'd)



- Author or coauthor of 70+ journal articles or conference papers on space navigation, trajectory optimization, or control theory
- Pertinent recent publications include
  - Wood, L. J., “Interplanetary Navigation,” *Encyclopedia of Aerospace Engineering*, Vol. 5, edited by R. Blockley and W. Shyy, John Wiley & Sons, Ltd., Chichester, UK, 2010, pp. 3071-3084.
  - Wood, L. J., “The Evolution of Deep Space Navigation: 1989-1999,” in *Advances in the Astronautical Sciences: The F. Landis Markley Astronautics Symposium*, Vol. 132, edited by J. L. Crassidis, et al., Univelt, San Diego, 2008, pp. 877-898.
  - Wood, L. J., “The Evolution of Deep Space Navigation: 1962-1989,” in *Advances in the Astronautical Sciences: Guidance and Control 2008*, Vol. 131, edited by M. E. Drews and R. D. Culp, Univelt, San Diego, 2008, pp. 285-308.

# General Comments on Draft Communication and Navigation Systems Roadmap



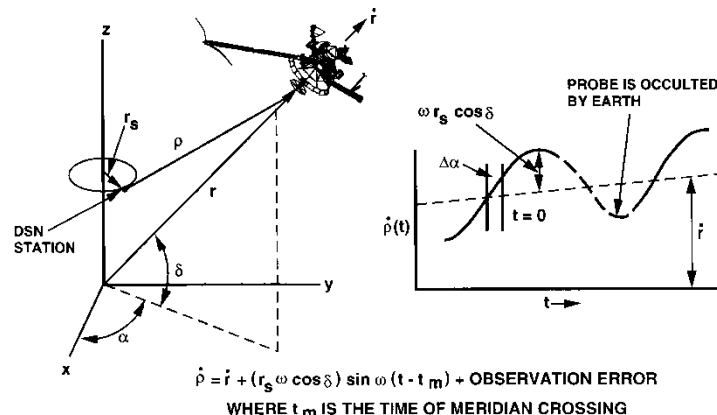
- Section 2.1.4 touches, at least briefly, on many important topics within positioning, navigation, and timing
  - A few important topics are not addressed (see also presentations by MiMi Aung and Al Cangahuala)
  - A few statements made are not correct (see subsequent slides)
- Section 2.1.6 discusses several revolutionary concepts
  - Comments with regard to practicality and breadth of applicability of X-ray and neutrino-based navigation are made later in this package

# Comments on Section 2.1.4

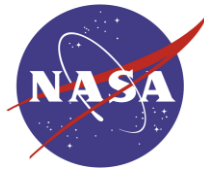


- Text as written (p. 15, ¶2): “Position determination performance is better than 10m at near-Earth distances, and is 10s of km at the distance of Mars.”
- Comments on text:
  - Position determination performance is typically a few km on approach to Mars, using only line-of-sight (Doppler and range) data, with variations due to mission geometry and nongravitational forces acting on spacecraft
  - Once in orbit around Mars, orbit determination accuracies are typically better
  - Broad generalizations about conventional radio metric orbit determination accuracies are difficult to make because of indirect nature of deducing three-dimensional position and velocity from line-of-sight measurements

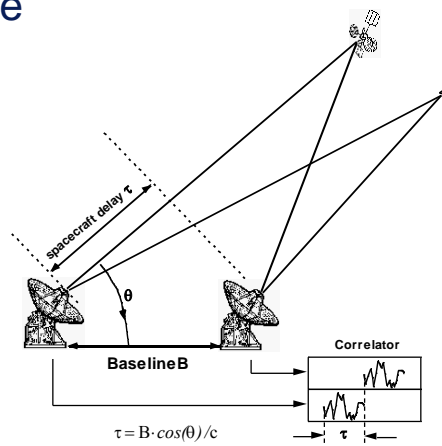
- TWO-WAY RANGE AND DOPPLER DIRECTLY MEASURE LINE-OF-SIGHT COMPONENTS OF SPACECRAFT STATE
- DIURNAL SIGNATURE OF EARTH ROTATION ALSO PROVIDES ANGULAR STATE INFORMATION



## Comments on Section 2.1.4 (Cont'd)



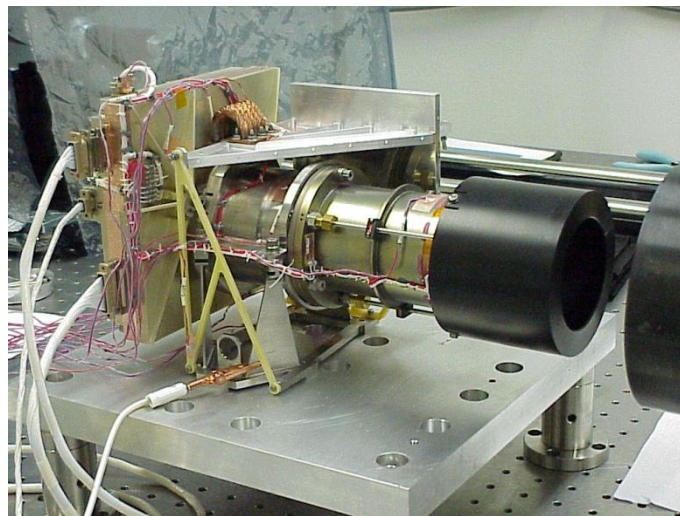
- Text as written (p. 15, ¶2): “The Deep Space Network (DSN) employs a high-accuracy Very Long Base Line (VLBI) method that yields position determination performance of 1km at Mars, a few kilometers at Jupiter, and 100s of km at distances beyond Jupiter.”
- Comments on text:
  - VLBI denotes Very Long Baseline Interferometry; particular form of VLBI of interest (figure below) is called Delta-Differential One-Way Ranging ( $\Delta$ DOR)
  - $\Delta$ DOR can yield position determination performance as good as 250 m at Mars (Mars Exploration Rover results), a few kilometers at Jupiter, and errors that increase linearly with distance beyond Jupiter, but only when used in conjunction with Doppler and ranging data
  - $\Delta$ DOR data are very useful augmentation to Doppler and range data, but are not replacement for these



## Comments on Section 2.1.4 (Cont'd)



- Text as written (p. 15, ¶1): “NASA’s current PNT state-of-the-art relies on both ground-based and space-based radiometric tracking, laser ranging, and optical navigation techniques (e.g. star trackers, target imaging).”
- Comment on text:
  - Optical navigation uses science imaging systems rather than star trackers, because of superior angular resolution and other characteristics of former
  - In addition, dedicated optical navigation camera was flown on Mars Reconnaissance Orbiter as technology demonstration on approach to Mars
    - Mass of 2.8 kg
    - 24  $\mu$ rad pixel size, 1024x1024 pixels
    - Gimbal (plus electronics and bracket) would increase mass by 2.2 kg

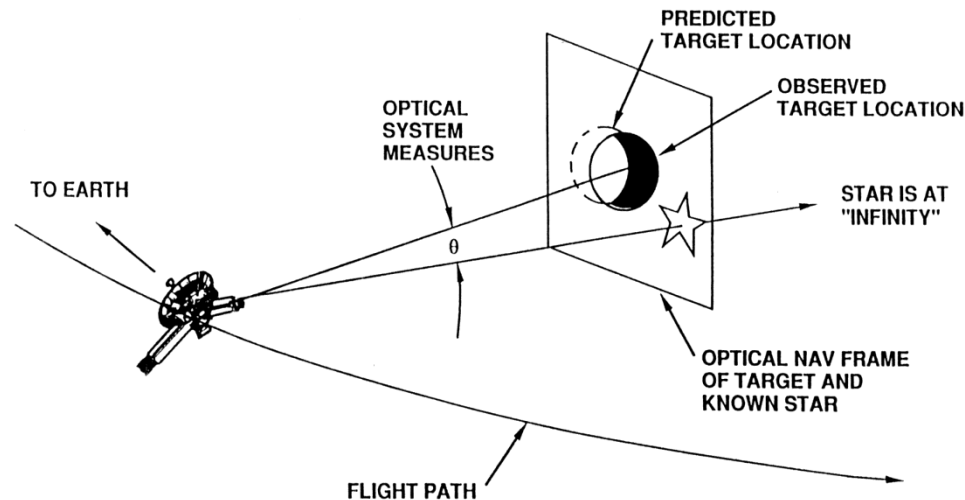


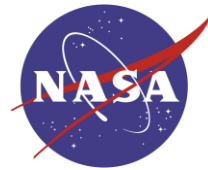


## Comments on Section 2.1.4 (Cont'd)



- Text as written (p. 15, ¶2): “Optical navigation methods yield position determination performance of 1 km at near-Earth distance and 10s of km at Mars distance.”
- Comment on text:
  - Accuracy of optical navigation data depends on distance from target body being imaged, not on distance from Earth
  - Except when viewing natural body subtending many pixels, optical navigation accuracy is better characterized in imaging system-dependent angular terms (e.g., 2-5  $\mu\text{rad}$ ) than in km

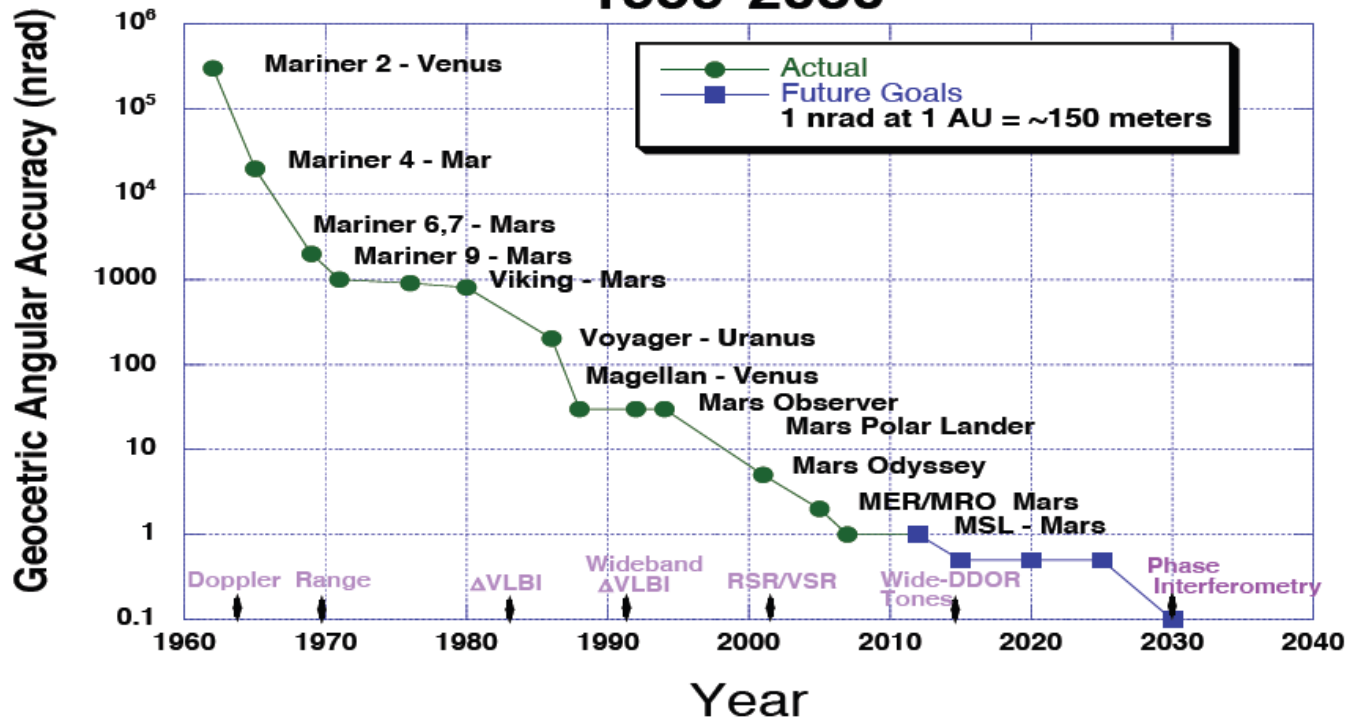




# Tracking Accuracy Improvement over Time

- Ability to determine spacecraft position from DSN radio metric data has improved many orders of magnitude over 50 years, due to major capability additions shown and many incremental improvements
- Far-sighted technology investments were needed to achieve this
- Technology investments are needed to ensure continued success in future

## DSN Absolute Tracking Accuracy 1959-2030

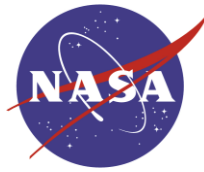


# Ongoing Radio Metric Tracking Improvements



- **Range:** Calibration improvements and hardware upgrades (transponders) can be used to push accuracy down to ~10 cm for missions such as BepiColombo (needed for relativity and solid core gravity mapping investigations) – not funded yet
- **$\Delta$ DOR:** Steady improvements in bandpass separation and width and nonlinear dispersion calibration, recording bit rates, and quasar catalog density and accuracy have reduced absolute angular accuracy to ~200 m on impact plane at Mars, as of today
- **Phase Tracking:** R&D support for Phoenix using Very Long Baseline Array (VLBA) obtained absolute (quasar-relative) angular accuracies of ~150 m on impact plane at Mars (after the fact)
- **Relative Tracking:** Using VLBA phase tracking, Phoenix was tracked with respect to Mars orbiters, 90 days prior to arrival, with accuracies of ~20 m in R&D mode; DSN may be able to provide similar S/C-relative tracking 60 days prior to Mars arrival, with typical  $\Delta$ DOR turnaround times of hours, rather than months – experiments are in preparation
- Further information on radio metric tracking technologies may be obtained from [Charles.J.Naudet@jpl.nasa.gov](mailto:Charles.J.Naudet@jpl.nasa.gov)

# Frequency and Timing Technologies – General Comments on Roadmap



- Section 1.4 does good job of capturing “Top Technical Challenges” categories
- Avoid communication & navigation becoming constraints to missions (1.4.1-2)
  - Major TRL 4-7 advances are needed to make system building blocks available to PNT architecture designs
    - *Operable* frequency standards/clocks for use in space are particularly needed
  - Lower TRL component technology pipeline should be supported at appropriate level
- Minimize latency impact (1.4.3)
  - Need new level of PNT system autonomy
  - Need accurate/stable & reliable frequency standards *in* space environment
- Minimize size, weight, and power (SWAP) and improve performance (1.4.4)
  - Availability of pipeline of space qualified parts/components is critically important
  - SWAP advances *are* technologies in themselves
- Provide integrity of information delivery across solar system (1.4.5)
  - Frequency & timing autonomy results from high clock accuracy/stability plus reliability
  - Lesser clock accuracy/stability encounters limits imposed by remote time/frequency transfer
- Lower life cycle cost of services (1.4.6)
  - Focus on standardized, long-term PNT system infrastructure (relays, satellite constellations at moon or Mars, beacons, etc.)
  - Timescales extended through solar system; distributed timing nodes
- Validate with flight missions (1.4.7)
  - Need well designed validation of family of oscillators/frequency standards/time transfer

# Frequency and Timing Technologies – Responses to Questions Sent to Presenters



- What are top technical challenges?
  - Advance TRL of space frequency standards/clocks to flight (stability, SWAP, & reliability)
    - Latency to deep space means clock accuracy/stability must stand alone
      - Atomic timekeeping is currently not performed beyond Earth orbit (GPS)
    - With less stable oscillators, must rely on remote frequency/time transfer technologies
      - Limits imposed by transmission media: fiber (local), atmosphere, space environment
      - Limits imposed by distance – SNR improves with higher transmission frequency
  - Credible system infrastructure designs/architectures – realistic, meaningful space requirements are needed
  - Broad component advances and availability are needed for oscillators/USOs, space qualified lasers, packaging
    - E.g., laser-cooled microwave or optical clock technology is not feasible for space until qualified lasers exist
- What technology gaps does roadmap not cover?
  - Communication, navigation, and science requirements can differ by many orders of magnitude (milliseconds to picoseconds)
  - Large range of technologies exist commensurate with above requirements: quartz oscillators, atomic (microwave) clocks, atomic (optical) metrology
- What are high-priority technology areas for NASA to take?
  - TRL and SWAP advances of reliable microwave frequency and timing reference sources (resonator and atomic)
  - Lower TRL emphasis (e.g., in optical metrology technology) on reliability and SWAP, as opposed to additional performance

# Frequency and Timing Technologies – Responses to Questions Sent to Presenters (Cont'd)



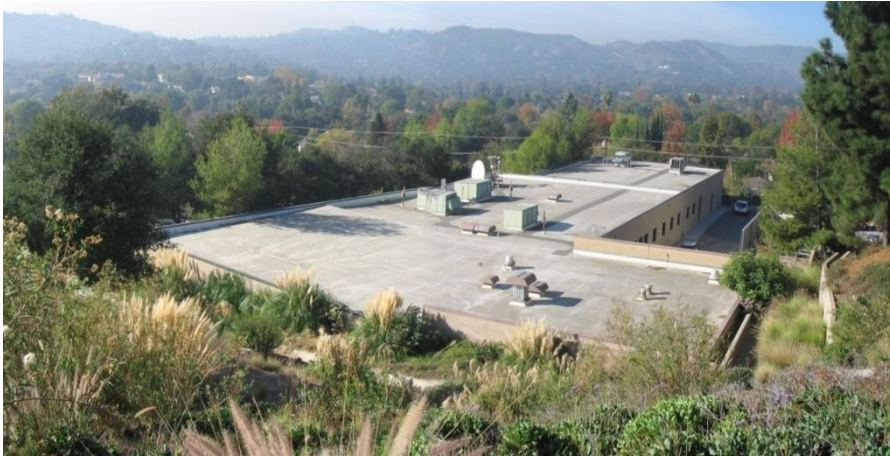
- Do high-priority areas align with NASA's expertise, capabilities, facilities, and role?
  - Yes – JPL has substantial experience in frequency and timing advanced development activities plus Frequency Standards and Test Laboratory (next slide)
- What specific technologies might be called "Game Changing"?
  - UTC level timekeeping in space provides foundation for autonomous PNT capability
  - Most “game changing” capability is expected to result from evolutionary rather than revolutionary advances
    - SWAP and reliability engineering maturation
    - Frequency standard progression: quartz oscillators to atomic (microwave) to atomic (optical)
  - Mercury ion frequency standards have demonstrated very high performance and are amenable to SWAP reductions
  - Note: most revolutionary concepts listed in roadmap have fundamental issues
    - Reference clock is required for space-based X-ray pulsar navigation schemes
    - Quantum entanglement schemes have same atomic coherence limitations as do atomic clocks
- Is any technology area near tipping point?
  - Mercury ion atomic clocks are receiving investment from NASA and DOD (ground at TRL 8, space at TRL 4/5)
  - Need family of clocks demonstrated in flight that span high stability performance/SWAP trade space
- Further information on frequency and timing technologies may be obtained from Robert.L.Tjoelker@jpl.nasa.gov



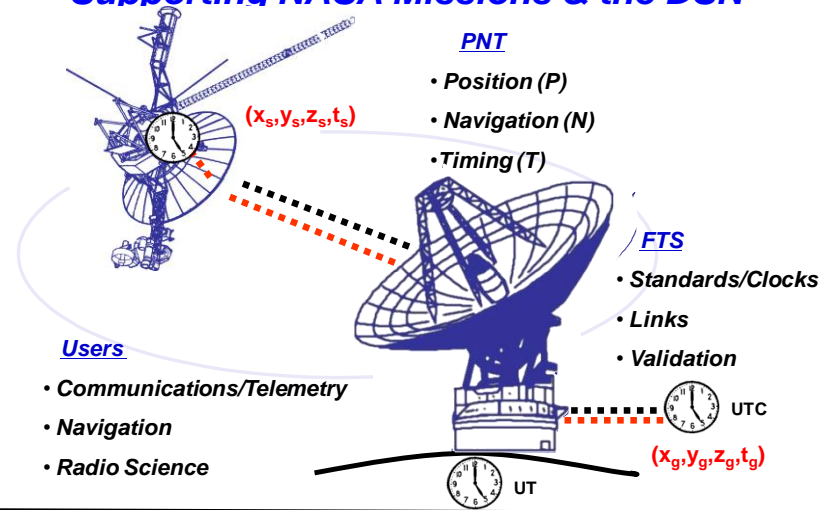
# NASA/JPL Frequency Standards & Test Laboratory

## Frequency and Timing Advanced Instrument Development

### JPL Bldg 298- Frequency & Timing Laboratories



### Supporting NASA Missions & the DSN



### Clock characterization & state-of-the-art references

**Stability Analyzers**

**DSN Clocks**

**Atomic Standards**

**Low Noise Oscillators**

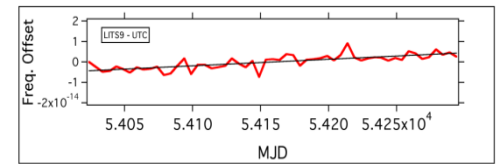
**Thermal & Magnetic Tests**

### Ultra-Stable Atomic Clocks & UTC Timescales

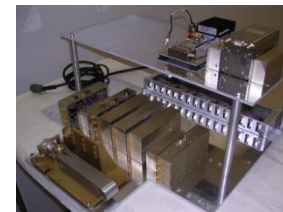
#### Mercury trapped ion frequency standards



**LITS-9:**  
JPL timekeeping



Maintains UTC with single, room temperature clock

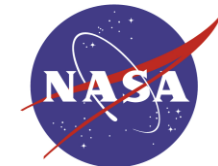


GPS Ion Clock breadboard:  
Earth orbit timekeeping



**NASA Ion Clock:**  
deep space  
timekeeping

## Comments on Section 2.1.6 – X-Ray Navigation



- X-ray navigation faces number of challenges before becoming feasible in deep-space applications:
  - Mass and volume issues: large detector areas are needed for photon detection and arrival timing
  - Difficulty of use in environments with variable dynamics (e.g., orbit insertion, atmospheric flight, landing): long integration times are needed for photon detection and arrival timing
  - X-ray sources need to be found that are sufficiently luminous, stable, and well distributed over sky
- X-ray navigation determines position of spacecraft relative to solar-system barycenter, not relative to destination body, which may have inaccurately determined orbit
  - Consider ongoing New Horizons mission to Pluto (arrival in 2015), as example
  - Pluto's ephemeris at time of encounter is uncertain to 2700 km ( $1\sigma$ ); this may be reduced to about 1600 km ( $1\sigma$ ) with ground-based observing campaign
  - Spacecraft must be delivered to within 100 km ( $1\sigma$ ) of Pluto-relative aimpoint
    - Optical navigation can achieve desired accuracy relative to Pluto
    - Accuracy with X-ray navigation would be limited by Pluto's ephemeris error
  - X-ray navigation would be more applicable to missions where no frame tie is needed, for example, mission to solar gravitational lens foci beyond 548 AU



## Comments on Section 2.1.6 – X-Ray Navigation (Cont'd)



- Dramatic reduction in DSN tracking time and consequent cost saving are sometimes claimed with X-ray navigation
  - DSN coverage is currently driven by telecommunication needs in almost all cases, though
  - Consequently, Doppler data are available at essentially no cost (cannot guarantee this 30 years in future, however)

## Comments on Section 2.1.6 – Neutrino Navigation



- Text states that detection of neutrinos currently requires massive detectors made of thousands of tons of liquid buried in ground
- Main Injector Neutrino Oscillation Search (MINOS) experiment, conducted by Fermi National Accelerator Laboratory, has directed beam of neutrinos 735 km to northern Minnesota mine, where 5000 metric ton underground detector detects muons resulting from neutrino interactions
  - 730 muons were detected in two years
- Neutrino generator and detector sizes and event detection rates are currently many orders of magnitude removed from practicality for either deep space communication or navigation
  - Can radical improvements in neutrino detection rates be achieved, or is low probability of neutrino-matter interactions just inherent property of neutrinos?

# Communications Technologies



- Coverage of deep space communications technologies in roadmap is good
- General areas of particular importance are
  - Moving to Ka-band (higher frequency)
  - Larger space antennas; arrays of ground antennas; improved pointing
  - Higher power flight transmitters
  - Next generation flight transponders
  - Precision radio science integrated into telecom
  - Optical communications