National Aeronautics and Space Administration

Time Measurement and its Importance for Navigation

Tomas J. Martin-Mur

Jet Propulsion Laboratory
California Institute of Technology

ISSI/HISPAC Forum on "Understanding Gravity"
Bern, December 4, 2013

Navigation and Timing

- Precise timing has always been a very important tool for navigation
  - Dead-reckoning: time as a measure of distance

- When precise determination of the longitude was sought, the best solution found was based on precise clocks

John Harrison's marine timekeeper number 4 (H4), was deemed to be just 5.1 seconds slow after a two-month transatlantic voyage

The Celestial Clock

- For a long time the best known clock was the Earth itself.
  - The mean solar time at the Greenwich meridian was the base for GMT.
- In 1926 the concept of Universal Time (UT) was introduced.
  - Despite its name, it was still based the rotation rate of the Earth and the proper time at the Earth's surface.
- Ephemeris Time was introduced as the independent variable for the motion of bodies in the barycentric space-time frame of reference.
  - As used by JPL, it is synonymous with the coordinate time of the general theory of relativity.
- The invention of atomic clocks provided a means of timekeeping more accurate than the Earth rotation.
  - Coordinated Universal Time (UTC) was introduced to be consistent with the time measured by atomic clocks.

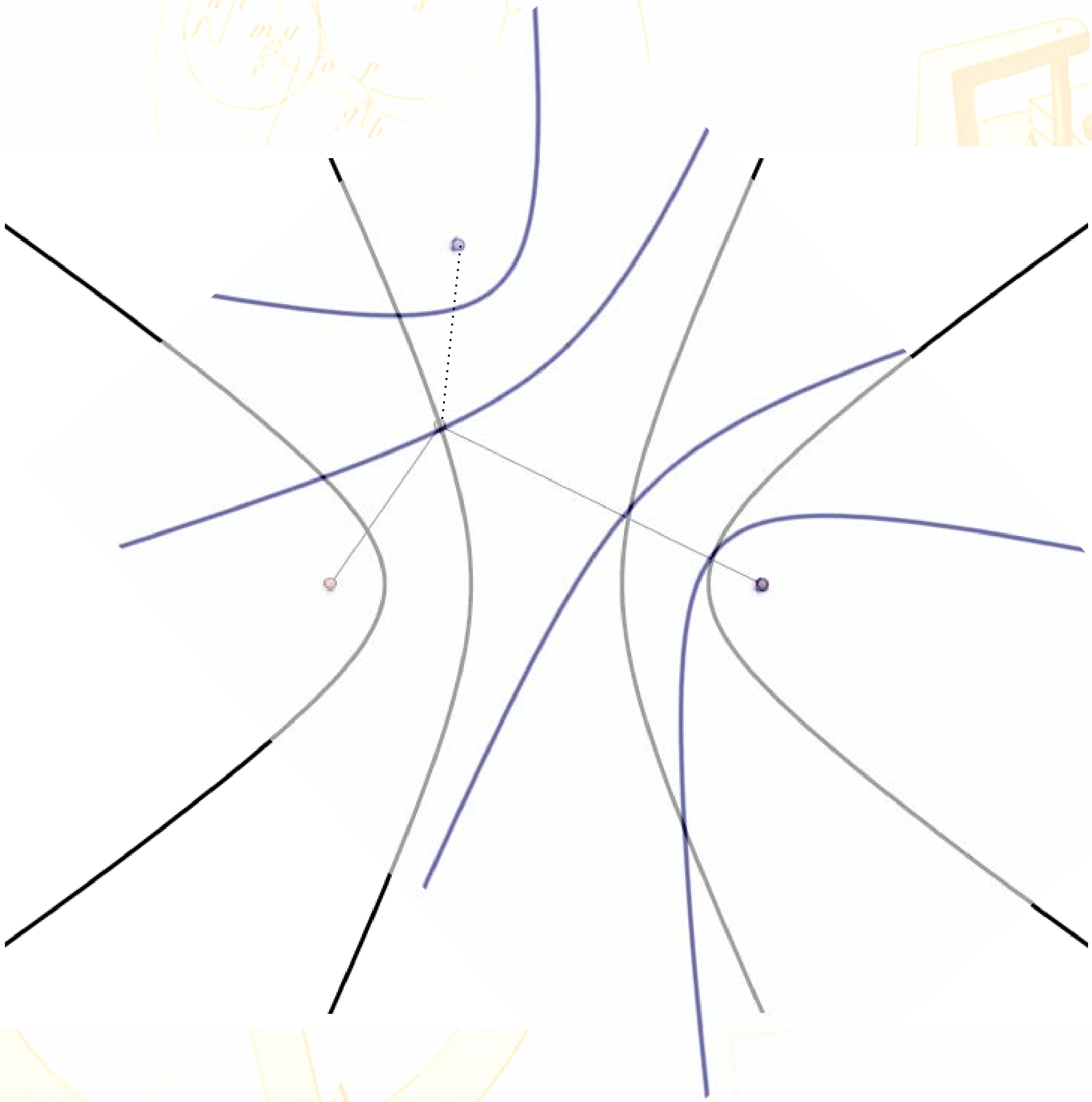
Using Time to Navigate on Earth

- Radio signals based on precise clocks and frequency standards have been used for quite some time to navigate on the surface of the Earth:
  - Gee, Decca, LORAN, Omega, TRANSIT, GPS, GLONASS, Galileo

- All of these systems use the fact the speed of light is constant in order to determine position by measuring the difference in arrival time of radio signals from separate sources
  - The position of the radio sources had to be known precisely
  - The clocks of the radio sources have to be synchronized precisely

- With time, the radio sources were moved from the surface of the Earth to artificial satellites orbiting it, and atomic clocks were use a as time and frequency references.

The Principle of Hyperbolic Navigation



- Hyperbolas are the locus of points with a constant difference in distance to the to foci
- The position of the radio sources define the foci

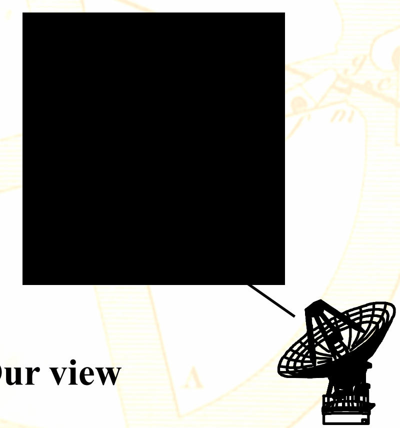
- Comparing signals from three sources we can find our location on a surface
- Comparing four signals we can find our location in space

Navigating in Space

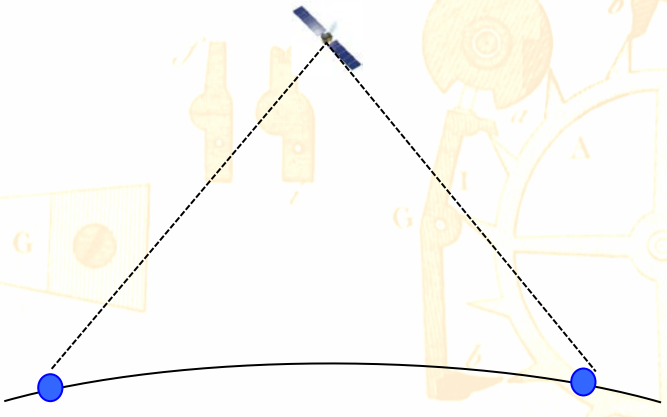
- Near-Earth spacecraft navigation can be performed using GPS
- There is no GPS in deep space
  - We need to use big ground antennas to track the spacecraft
  - We use both distance and rate measurements, and differenced time of arrival measurements
    - They are all based on precise time and frequency systems at the ground stations
  - One-way measurements are also possible if the spacecraft is equipped with a precise clock
  - Optical navigation can also be used, either in cruise or near targets

Measuring Round-Trip Light Time

- Planetary distances result in light times of minutes to hours
- When calculating distances you have to know at what time the signal was transmitted by the ground station, at what time it was transponded by the spacecraft, and at what time it was received by the station.
- A station at the Earth surface moves at hundreds of m/s due to the rotation of the Earth.
- But it moves at about 30 km/s due to the movement of the Earth around the Sun.



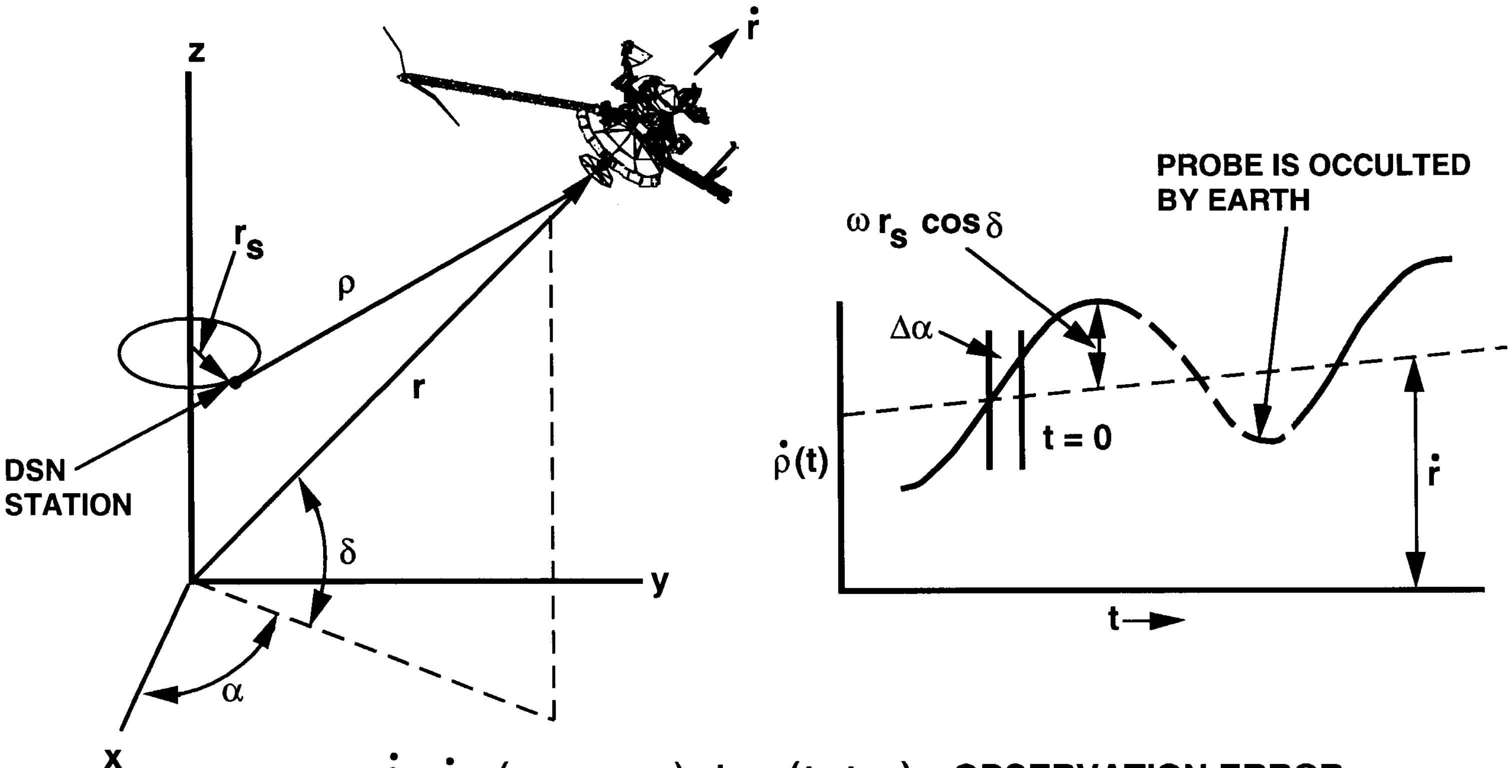
Our view



A solar system inertial view

Line-of-Sight Radiometric 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



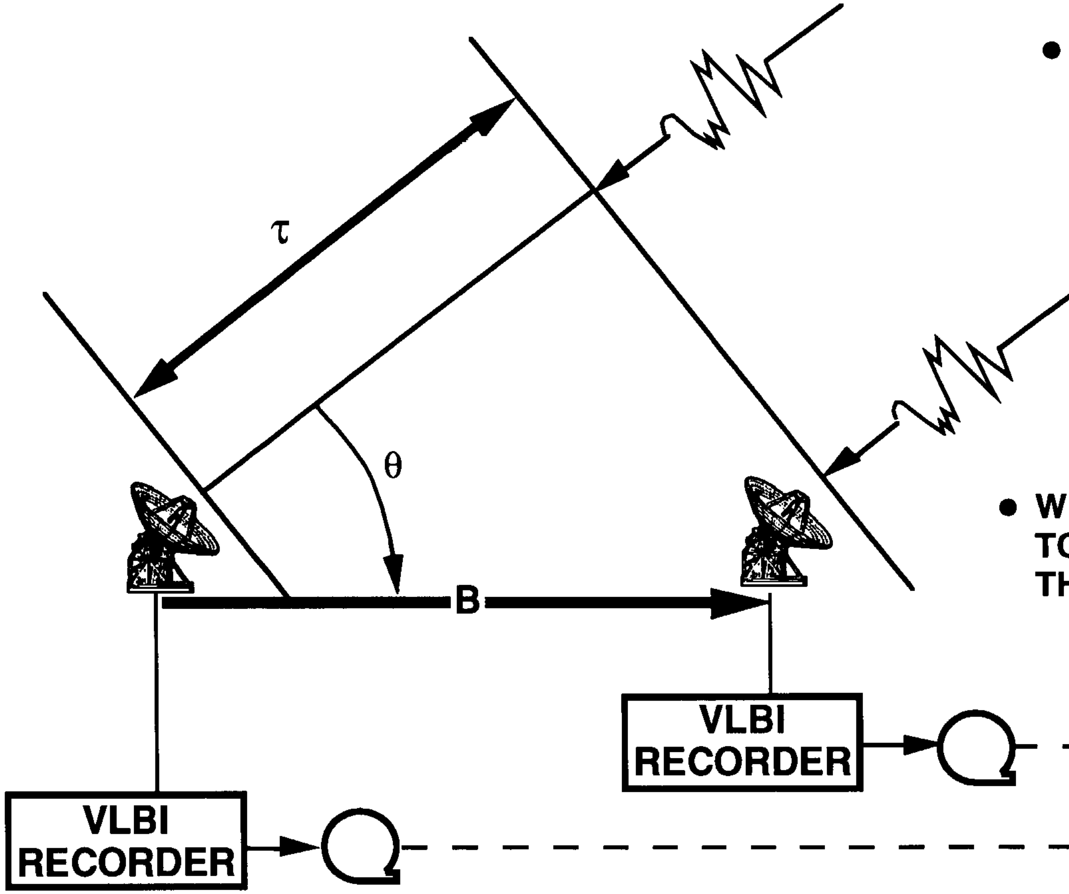
$$\dot{\rho} = \dot{r} + (r_s \omega \cos\delta) \sin \omega (t - t_m) + \text{OBSERVATION ERROR}$$

WHERE t_m IS THE TIME OF MERIDIAN CROSSING

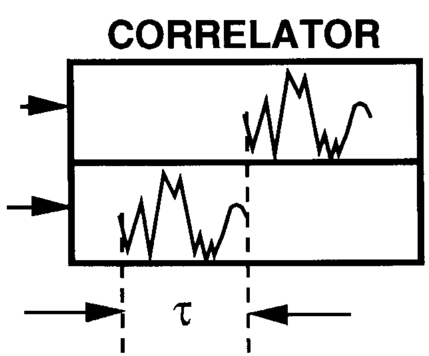
Very Long Baseline Interferometry

- VLBI ALLOWS DETERMINATION OF GEOMETRIC DELAY FOR NOISELIKE SOURCES BY CROSS-CORRELATING THE RECEIVED RADIO SIGNALS AT TWO STATIONS

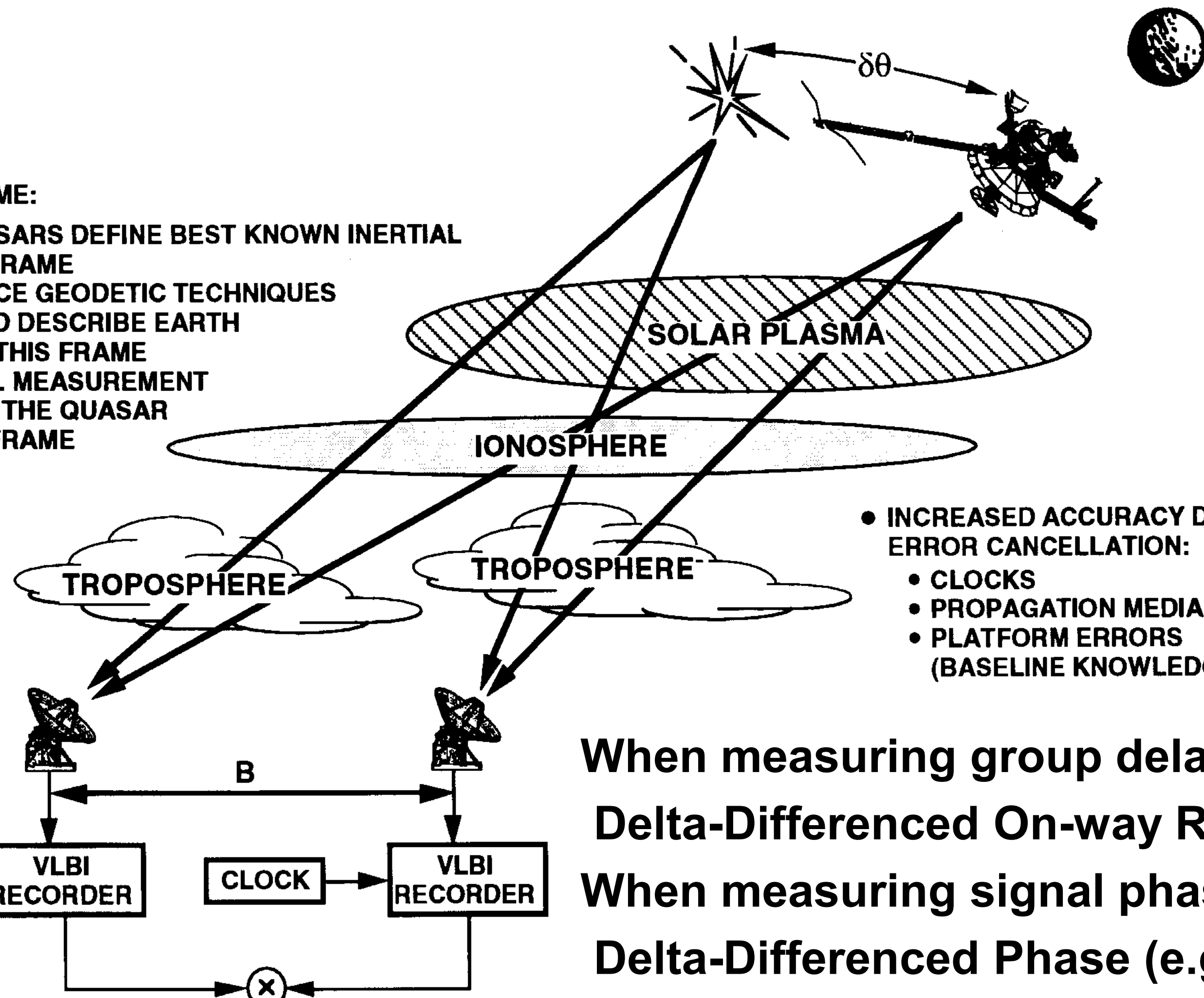
- EXTRAGALACTIC QUASARS PROVIDE A DENSE AND HIGHLY STABLE INERTIAL REFERENCE FRAME FOR NAVIGATION



- WIDE-BANDWIDTH RECORDING IS REQUIRED TO PROVIDE HIGH SNR DETERMINATION OF THE CROSS-CORRELATION DELAY



Differenced Interferometric Measurements



- 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)

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

$$\Delta\rho_{Q} = B \cos\theta_{Q} + c\,(\Delta\tau_{clock} + \Delta\tau_{inst} + \Delta\tau_{media}) + \text{NOISE}$$

When measuring group delay:

Delta-Differenced On-way Range, ΔDOR

When measuring signal phase:

Delta-Differenced Phase (e.g. VLBA)

Effects Accounted for in Measuring Light Time

- Geometry:
  - Spacecraft motion and its associated dynamical models
  - Planetary and small body ephemeris
  - Earth orientation
  - Plate motion
  - Tidal displacement
  - Position of the ground station with respect to a local geodetic network
- Relativity:
  - Proper time at the source of the time signal
  - Signal bending due to space-time wrapping by gravity
- Media effects:
  - Tropospheric delay
  - Ionospheric delay
  - Interplanetary plasma delay
- Equipment delays
- Measurement time tag errors

What Is Being Measured?

- Short answer: Light times
- Long answer: The time-tagged phase of the returned signal
  - The returned signal is compared with a signal generated at the ground station in order to measure the phase difference between the two.
  - The reference signal is based on a precise frequency and timing system.
  - The total phase of the incoming signal is reconstructed by adding the reference signal and the differenced signal.
- Doppler measurements are based on the phase of the carrier signal and constructed by counting the number phase cycles received over a given count time.
- Range measurements are based on modulating the carrier with lower frequency tones that allow for a wider ambiguity resolution.

Obtaining Measurement Residuals

- For Doppler light times are calculated for the start and the end time of the count interval, in order to obtain the corresponding transmission times.
- Using the transmitted frequency history, the number of transmit cycles is calculated
- The measurement residual is the difference between the observed number of cycles and the number of cycles transmitted, multiplied by the transponding ratio.
  - The transponding ratio is used to separate the uplink and the downlink signal so they do not interfere with each other
- For range the measured Doppler is used to calculate the instantaneous range phase at the measurement time.
- The light time is calculated in order to obtain the range phase at the transmission time
- The measurement residual is the difference between the observed range phase and the transmitted range phase

The Foundation of It All: Clocks

- The Deep Space Network tracking stations are equipped with very stable atomic time and frequency reference systems
  - Each deep space complex has four atomic frequency standard.
  - One of them at each site, usually a hydrogen maser, serves as the source for all coherent, precision frequencies and provides the reference for the station master clock.
  - Each site synchronizes its clock with the NIST realization of UTC via common-view GPS signals.

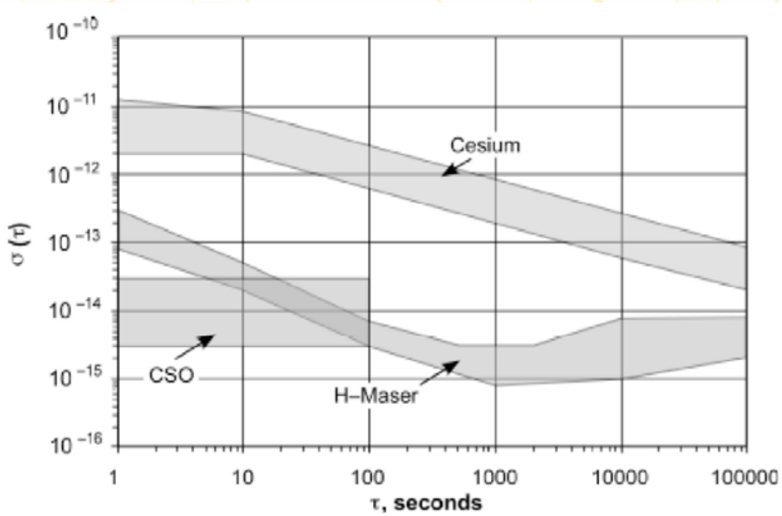


Table 1. DSN Frequency Standard Performance.

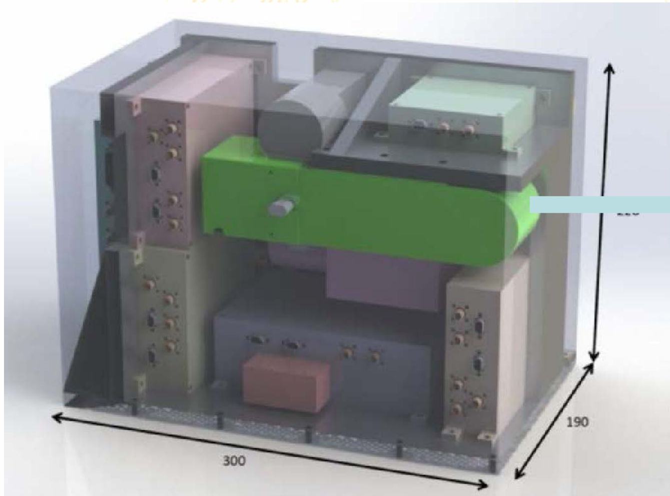
Parameter	Value
Frequency Offset Relative to UTC	
Worst Case	$<9 \times 10^{-13}$
Typical	$<3 \times 10^{-13}$
Resolution reconstructed by analysis (3 σ)	$<1 \times 10^{-13}$
Fractional Frequency Drift	
Specified	1×10^{-13} /10 days
Typical	$<3 \times 10^{-14}$ /10 days
Setability	10 ns
Offsets from UTC	
Requirement	< 3 μs
Resolution from UTC, reconstructed by analysis (3 σ)	< 1 μs

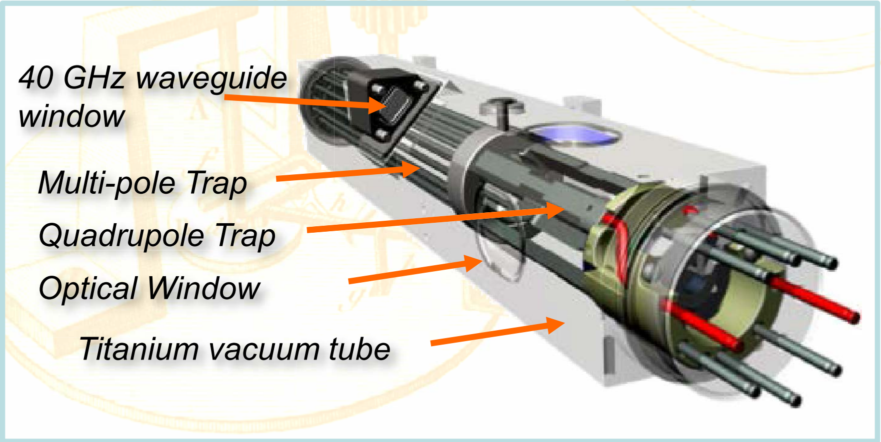
From DSN document 810-005 304A

Spacecraft Clocks

- If a precise time reference is available at the spacecraft, it can be used to obtain one-way radiometric measurements, either at the spacecraft or at the ground station.
- This can free ground resources, allowing a ground antenna to serve more than one spacecraft.
- It can support precise spacecraft-to-spacecraft tracking.
- It can support autonomous navigation that is not limited by round-trip delays.

JPL's Deep Space Atomic Clock (DSAC)



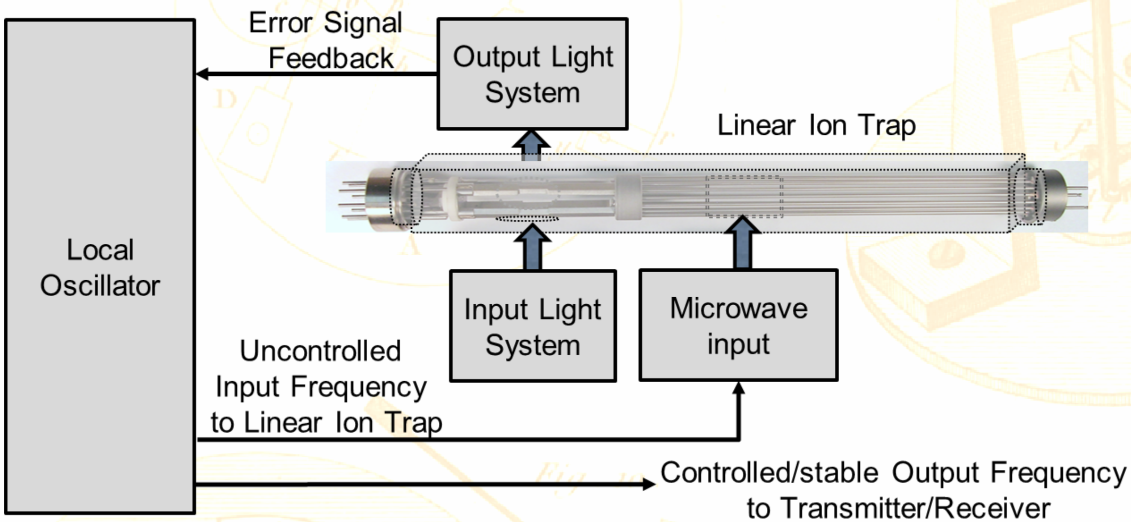


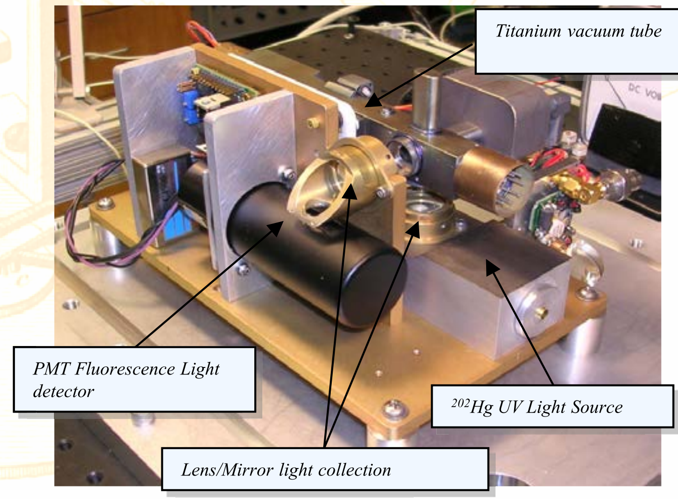
- DSAC is a small, low-mass mercury-ion clock suitable for deep space flight.

- DSAC's Technology Demonstration Mission flight in 2015 will enable a customized 5 kg/20 W clock for future deep space flight opportunities.

Courtesy of Todd Ely, DSAC's TDM Principal Investigator

DSAC Technology & Operation





Ion Clock Operation

- Short term (1 – 10 sec) stability depends on the Local Oscillator
- Longer term stability (> 10 sec) determined by the “atomic resonator” (Ion Trap & Light System)

Key Features for Reliable Use in Space

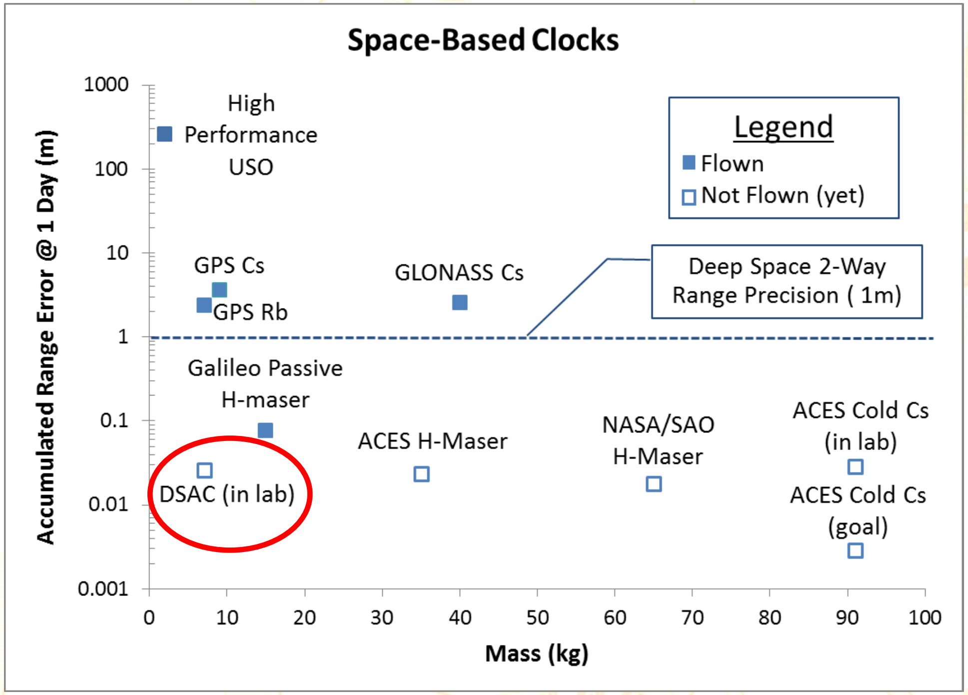
- No lasers, cryogenics, microwave cavity, light shift, consumables
- Low sensitivity to temperature changes, magnetic fields, radiation, zero-g

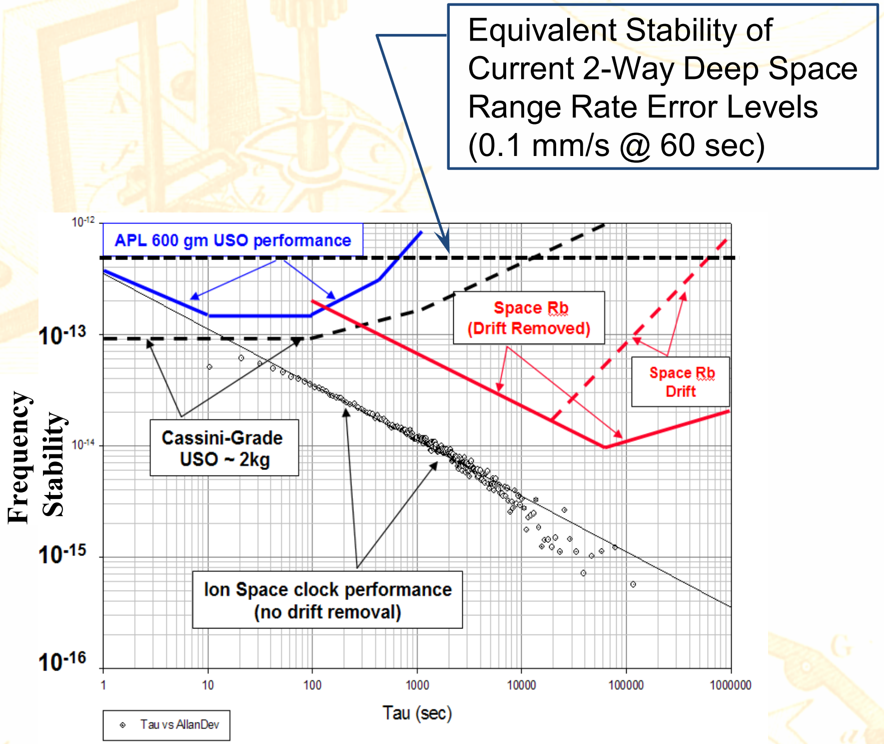
Ion Clock Technology Highlights

- State selection of 10^6-10^7 $^{199}Hg^+$ trapped ions via optical pumping from $^{202}Hg^+$
- High Q microwave line allows precision measurement of clock transition at 40,507,347,996.8 Hz
- Ion shuttling from quadrupole to multipole trap to best isolate from disturbances
- 1-2 UV photons per second scattered
- Ions are in an uncooled buffer-gas (Ne) (as opposed to other atomic clocks)

Courtesy of Todd Ely, DSAC’s TDM Principal Investigator

DSAC vs Other Space-Based Clocks





DSAC is expected to outperform any other space based oscillator/clock on a per mass basis. Combined with its long-life potential, DSAC is an ideal technology for infusion into deep space exploration as well GNSS applications

Courtesy of Todd Ely, DSAC's TDM Principal Investigator

X-Ray Spacecraft Navigation

- Some pulsars are known for having very stable periodic X-ray pulses, with long-term stability similar to that of atomic clocks
- By measuring the time of arrival of the pulse, and comparing it with a ground generated prediction, it is possible to know the position in the direction to the pulsar.
- By combining three or more pulsars, it could be possible to determine the 3-D position of the spacecraft
- Current challenges for this technology are:
  - The generation of pulse timing predicts at the required accuracy
  - The considerable collection area needed to detect the X-ray photons at the spacecraft
  - The need to point the collector to different directions to obtain a 3-D fix
  - The need to accurately time tag the arrival time of the pulse at the spacecraft.
- Accuracies in the 5 km range may be possible when using a 150 m^2 detector and an on-board atomic clock

Conclusion

- Precise timing is the enabler for precise radiometric navigation.
- It also enables radio science, allowing for the accurate determination of the ephemeris and gravity fields of the solar system bodies.
- In the future we expect to see spacecraft carrying deep space atomic clocks that can be used for autonomous operations and for spacecraft-to-spacecraft tracking.

- Ephemeris
- Measuring distance by measuring time dead reckoning and light time
- Time systems
- GPS, GLONASS, Galileo
- Radiometric measurements
- Deep space network
- Range
- Doppler
- VLBI measurements
- Light time equation
- Relativistic corrections to time
- USO and other spacecraft clocks
- DSAC
- X-ray Nav
- IMUs – fiber optic gyroscopes
- Gravity