9th International Planetary Probe Workshop
Short Course Toulouse, France

Ultra-Stable Oscillators For Probe Radio Science Investigations

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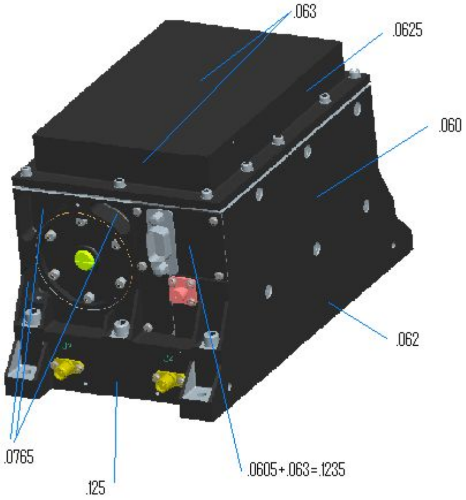
What is a USO

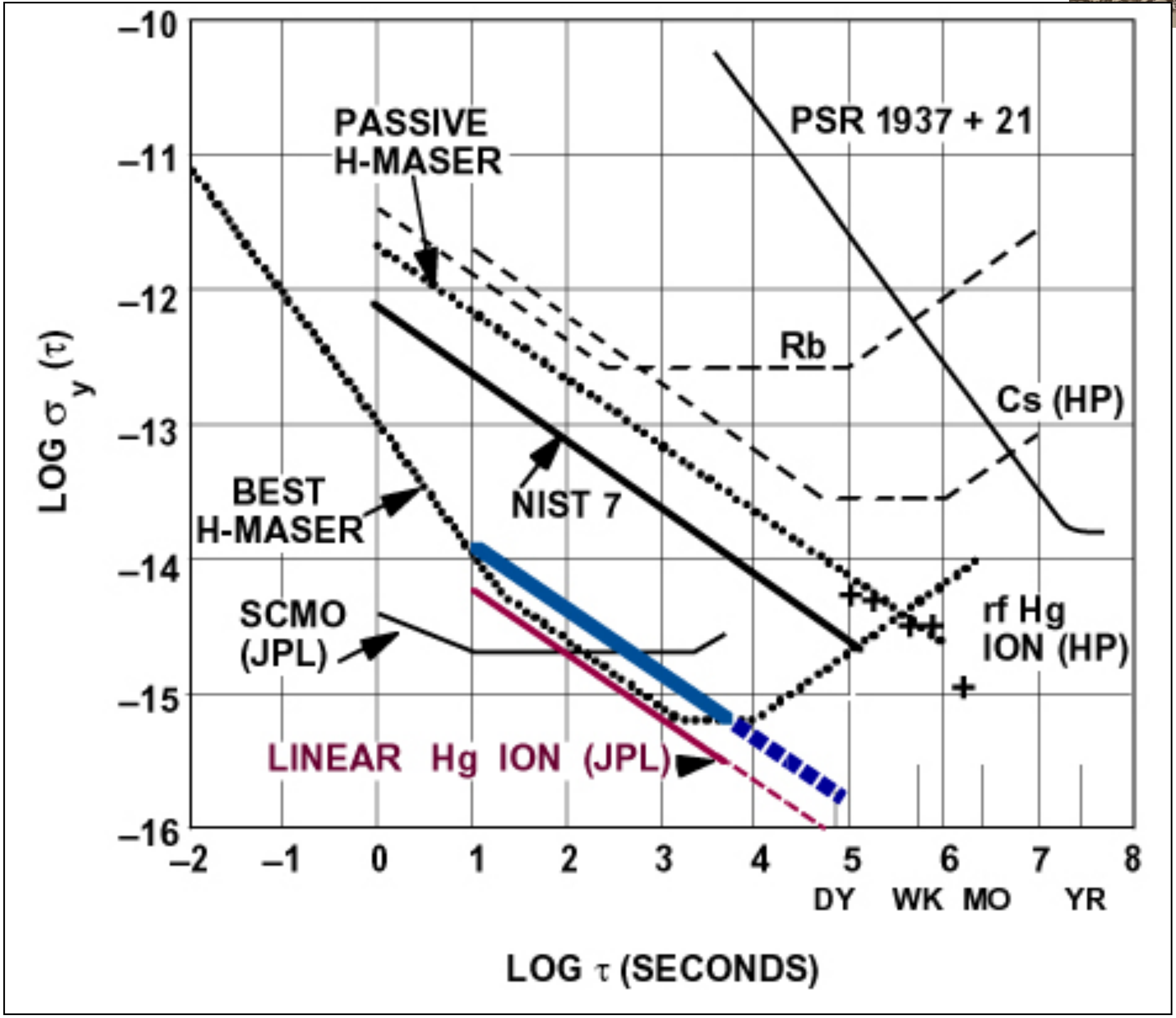
- An Ultra-Stable Oscillator (USO) is
  - A frequency reference
  - A clock
- Stable
- Small
- Sensitive
- A science and an art form
- Flown on spacecraft/probes
- Utilized at ground stations alone or as a cleanup loop
- Eliminates lock-up time on uplink for occultation egress & effect of media on uplink signal
- Enabled significant planetary science investigations



Progress in Timekeeping

Period	Milestone	Accuracy/day
4th millen. BC	Day & night divided into 12 equal hours	
Up to 1280 A.D.	Sundials, water clocks	~1 h
1280 A.D.	Mechanical clock invented	~30 min
1345	Hour divided into minutes and seconds	
15th century	Clock time used to regulate people's work	~2 min
16th century	Galileo times free-fall (first impact on science)	~1 min
1656	Huygens develops pendulum clock	~100 s
1880	Piezoelectric effect discovered Jacques & Pierre Curie	
1910s	Wrist watches become widely available	10^{-3} to 10^{-2} s
1920s	Electrically driven tuning forks	10^{-5} to 10^{-1} s
1921	Quartz crystal clocks	10^{-9} to 10^{-4} s
1949	Atomic clock developed	
1970s	Quartz crystal watches	
1979	**Quartz ultra-stable oscillator flies by Jupiter**	
2005	**Rb Atomic clock delivered to Titan**	
2008	**"Atomic Clock" readied for space missions**	

Accurate Clocks



Acronyms

- XO…………..Crystal Oscillator
- VCXO………Voltage Controlled Crystal Oscillator
- OCXO………Oven Controlled Crystal Oscillator
- TCXO………Temperature Compensated Crystal Oscillator
- TCVCXO..…Temperature Compensated/Voltage Controlled XO
- OCVCXO.….Oven Controlled/Voltage Controlled XO
- MCXO………Microcomputer Compensated XO
- RbXO……...Rubidium-Crystal Oscillator

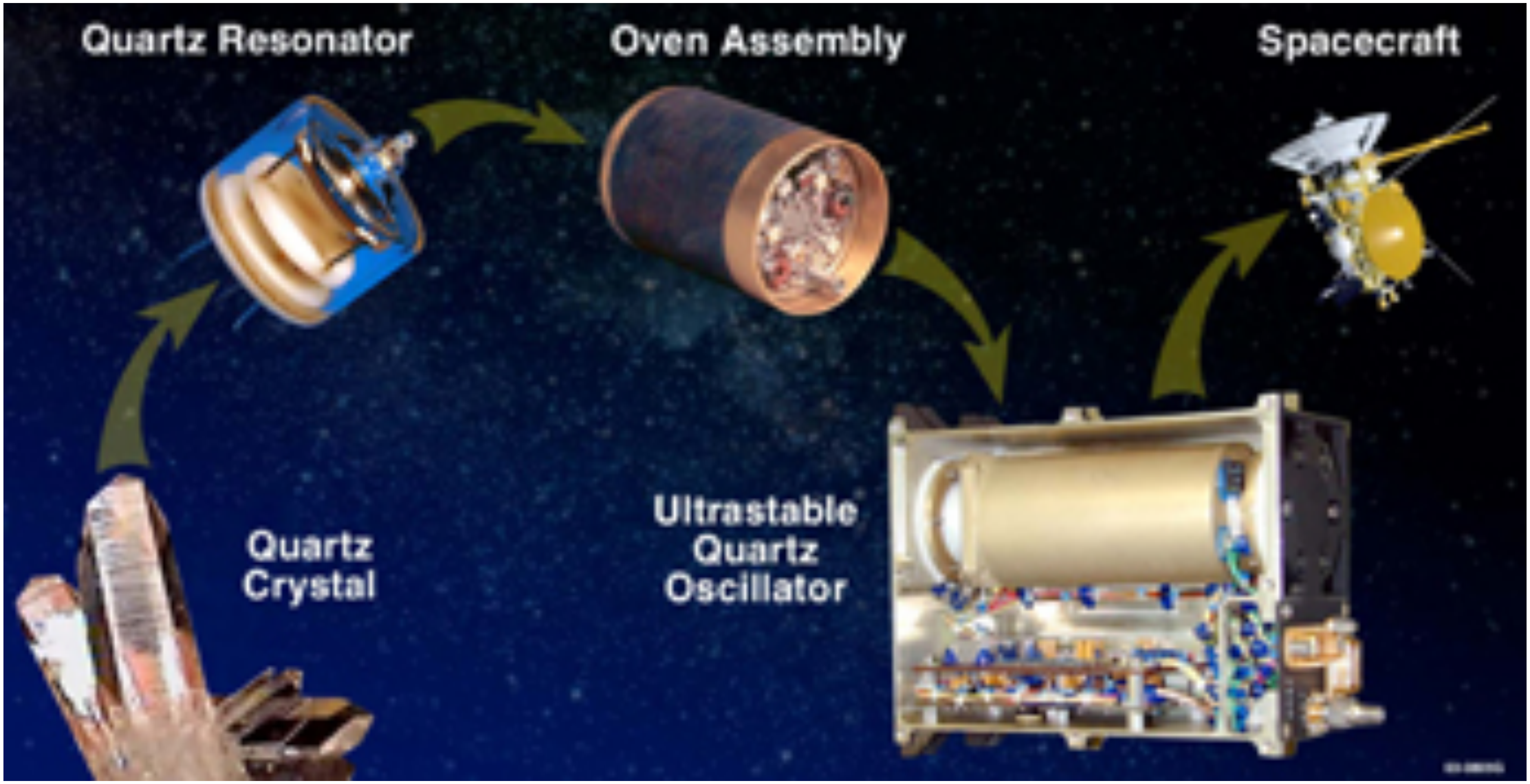
USO History

- The first Ultra-Stable Oscillator (USO) in deep space was flown on the Voyager spacecraft launched in the late 1970s
- Was required in order to meet the stability requirements for the radio occultation experiments
- **Eliminates lock-up time on uplink for occultation egress and**
- **Eliminates the effect of media on the uplink signal**
- Voyager **Radio Science** Team coined the term “USO” and worked closely with Frequency Electronics Inc. (Long Island, New York)
- Voyager II USO is still working
- Voyager I USO ceased operations at age 20+ years
- Typically a single string USO augmented the redundant telecommunications subsystem

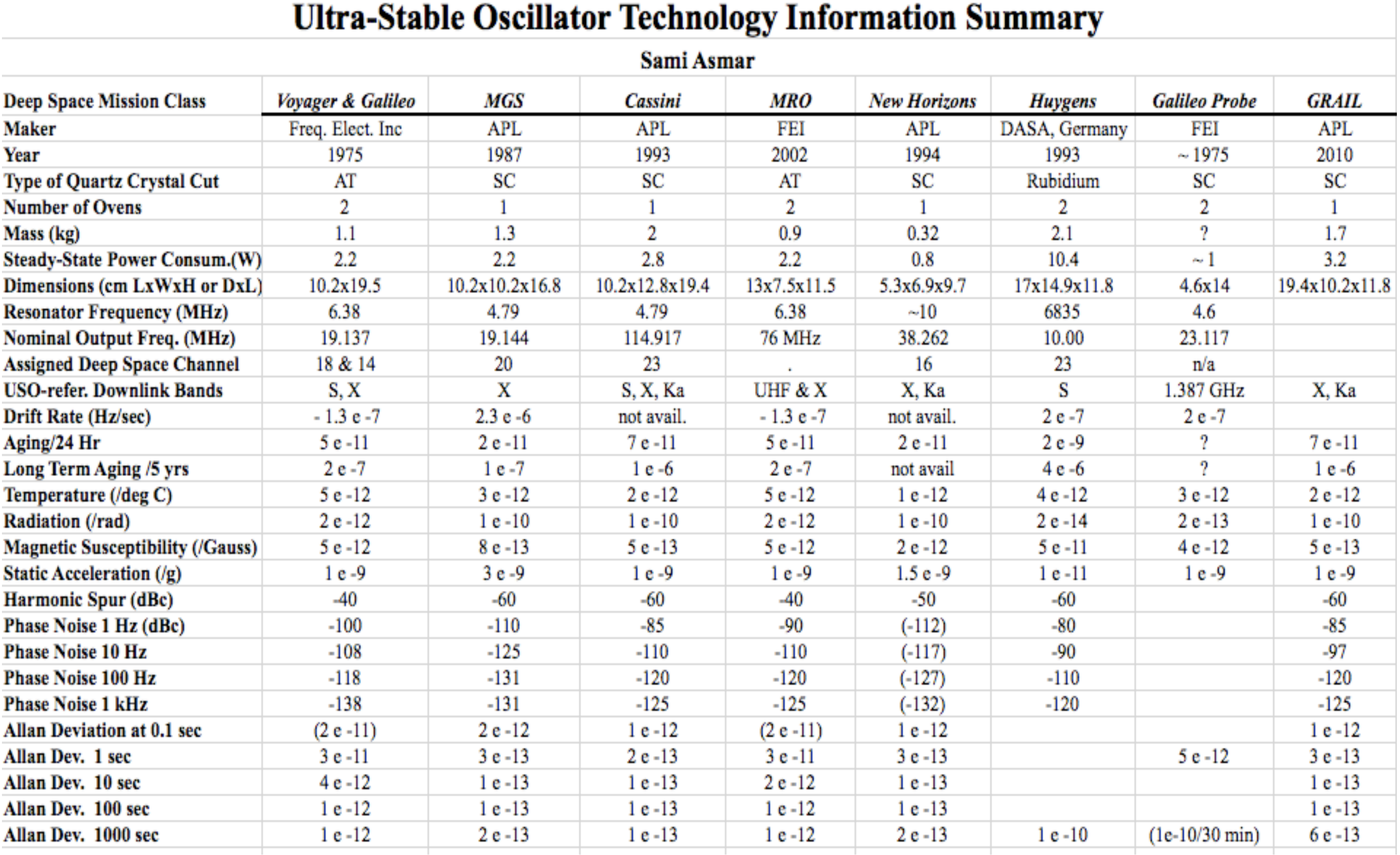
USO Recent History

- USO serial number 4 of the batch of 5 Voyager USOs later flew on the Galileo orbiter
- The Galileo probe was also equipped with an FEI USO procured independently (probe project managed by NASA Ames)
- Currently, numerous missions fly USOs
- MGS & Cassini moved to ~E-13 stability at 100 s from JHU-APL
- Mars Recon. Orbiter returned to FEI E-12 USO
- New Horizons, Stereo, & other APL missions flew APL USO
- GRACE (Earth mission) science required E-13 APL USO
- GRAIL (lunar gravity) is latest to procure top of the line APL USO

From Silicates to Deep Space



Technical Summary



Ultra-Stable Oscillator Technology Information Summary

Sami Asmar

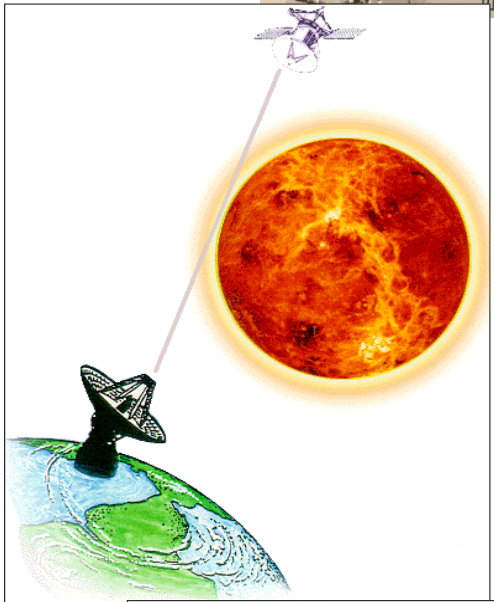
Deep Space Mission Class	*Voyager & Galileo*	*MGS*	*Cassini*	*MRO*	*New Horizons*	*Huygens*	*Galileo Probe*	*GRAIL*
Maker	Freq. Elect. Inc	APL	APL	FEI	APL	DASA, Germany	FEI	APL
Year	1975	1987	1993	2002	1994	1993	~ 1975	2010
Type of Quartz Crystal Cut	AT	SC	SC	AT	SC	Rubidium	SC	SC
Number of Ovens	2	1	1	2	1	2	2	1
Mass (kg)	1.1	1.3	2	0.9	0.32	2.1	?	1.7
Steady-State Power Consum.(W)	2.2	2.2	2.8	2.2	0.8	10.4	~ 1	3.2
Dimensions (cm LxWxH or DxL)	10.2x19.5	10.2x10.2x16.8	10.2x12.8x19.4	13x7.5x11.5	5.3x6.9x9.7	17x14.9x11.8	4.6x14	19.4x10.2x11.8
Resonator Frequency (MHz)	6.38	4.79	4.79	6.38	~10	6835	4.6	
Nominal Output Freq. (MHz)	19.137	19.144	114.917	76 MHz	38.262	10.00	23.117	
Assigned Deep Space Channel	18 & 14	20	23	.	16	23	n/a	
USO-refer. Downlink Bands	S, X	X	S, X, Ka	UHF & X	X, Ka	S	1.387 GHz	X, Ka
Drift Rate (Hz/sec)	- 1.3 e -7	2.3 e -6	not avail.	- 1.3 e -7	not avail.	2 e -7	2 e -7	
Aging/24 Hr	5 e -11	2 e -11	7 e -11	5 e -11	2 e -11	2 e -9	?	7 e -11
Long Term Aging /5 yrs	2 e -7	1 e -7	1 e -6	2 e -7	not avail	4 e -6	?	1 e -6
Temperature (/deg C)	5 e -12	3 e -12	2 e -12	5 e -12	1 e -12	4 e -12	3 e -12	2 e -12
Radiation (/rad)	2 e -12	1 e -10	1 e -10	2 e -12	1 e -10	2 e -14	2 e -13	1 e -10
Magnetic Susceptibility (/Gauss)	5 e -12	8 e -13	5 e -13	5 e -12	2 e -12	5 e -11	4 e -12	5 e -13
Static Acceleration (/g)	1 e -9	3 e -9	1 e -9	1 e -9	1.5 e -9	1 e -11	1 e -9	1 e -9
Harmonic Spur (dBc)	-40	-60	-60	-40	-50	-60		-60
Phase Noise 1 Hz (dBc)	-100	-110	-85	-90	(-112)	-80		-85
Phase Noise 10 Hz	-108	-125	-110	-110	(-117)	-90		-97
Phase Noise 100 Hz	-118	-131	-120	-120	(-127)	-110		-120
Phase Noise 1 kHz	-138	-131	-125	-125	(-132)	-120		-125
Allan Deviation at 0.1 sec	(2 e -11)	2 e -12	1 e -12	(2 e -11)	1 e -12			1 e -12
Allan Dev. 1 sec	3 e -11	3 e -13	2 e -13	3 e -11	3 e -13		5 e -12	3 e -13
Allan Dev. 10 sec	4 e -12	1 e -13	1 e -13	2 e -12	1 e -13			1 e -13
Allan Dev. 100 sec	1 e -12	1 e -13	1 e -13	1 e -12	1 e -13			1 e -13
Allan Dev. 1000 sec	1 e -12	2 e -13	1 e -13	1 e -12	2 e -13	1 e -10	(1e-10/30 min)	6 e -13

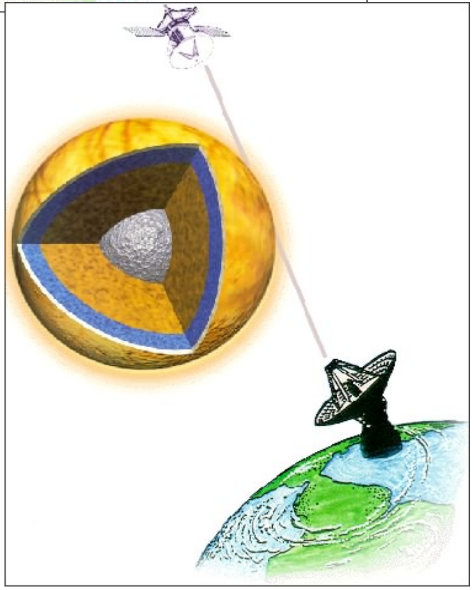
Relevant Highlights

- Quartz crystal resonator is thermally stabilized
  - Two options on market: single over and dual oven
- Mass between 1-2 kg
- Power between 1-3 W
- Best Allan Deviation: ~ 1×10^{-13} at 100 seconds
- Phase Noise: ~ 95 dBc 1 Hz and ~ 140 dBc 1 kHz offset

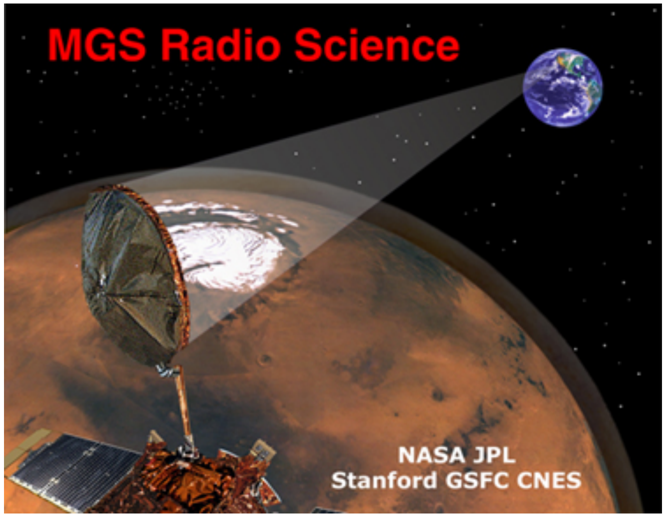
Radio Science

- It became apparent with early planetary missions that occultations by atmospheres would affect the quality of radio signals
- Bothered telecommunications engineers
- But one can study atmospheric properties
- *One person's noise is another's data*
- Now a recognized field in solar system exploration with instrument distributed between spacecraft and ground stations
- Grew to other aspects of planetary science, solar science, and fundamental physics



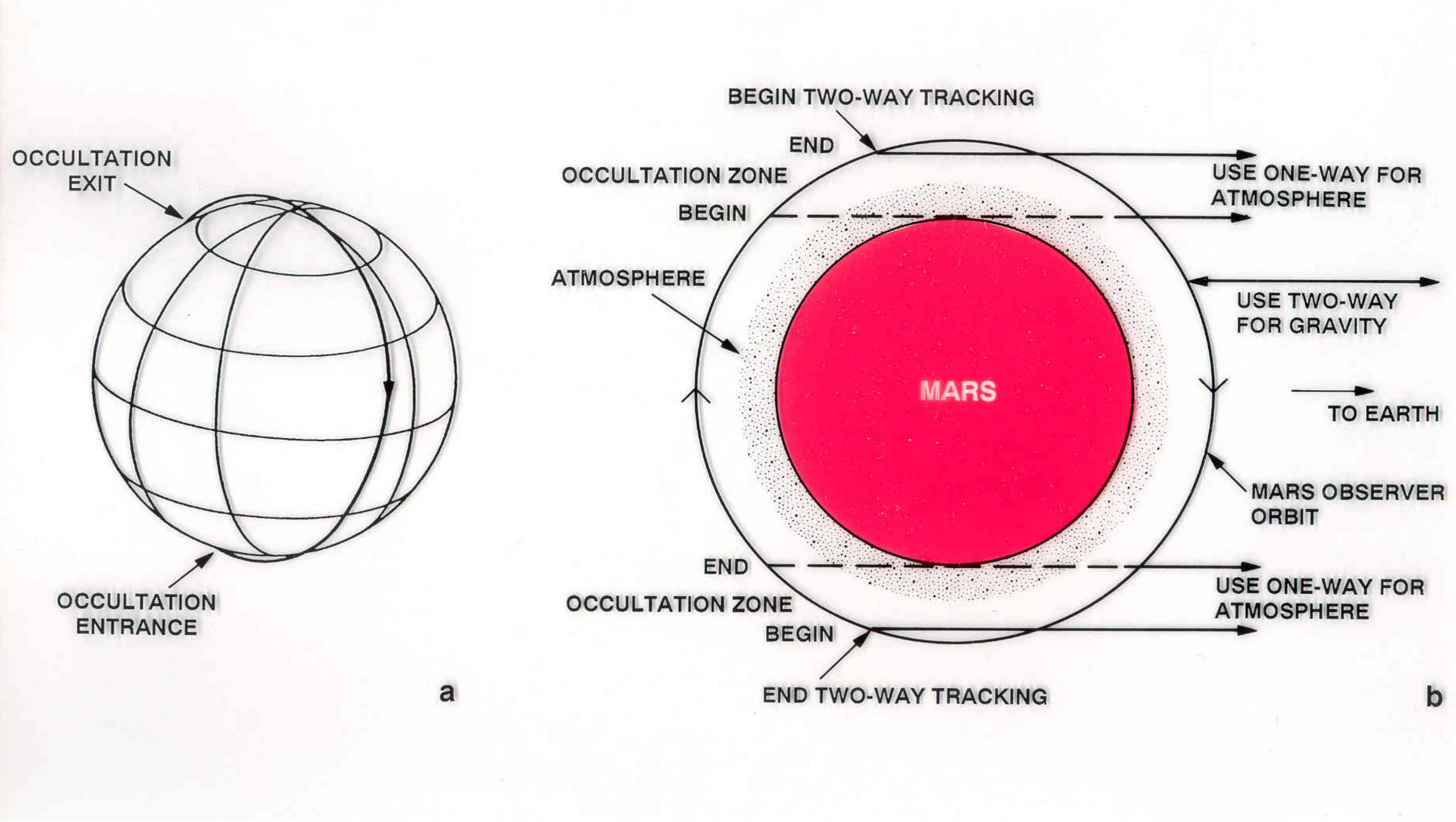


Experiment Types



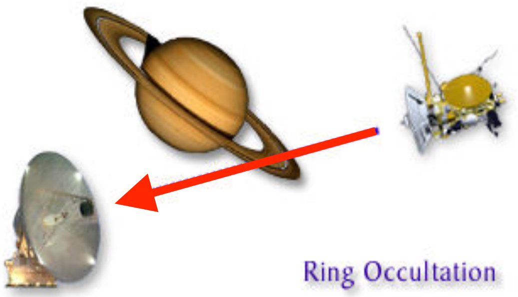
- Propagation
  - Study media
  - Remove the effects of forces
- Gravitation
  - Study forces
  - Remove the effects of media
- One-way: signal referenced to source onboard spacecraft
  - Utilize a USO when available
- Two-way: downlink coherent with uplink signal
  - Three-way: uplink & downlink at different stations
  - Four-way: Used for relay satellites

Signal Modes



Radio Occultations

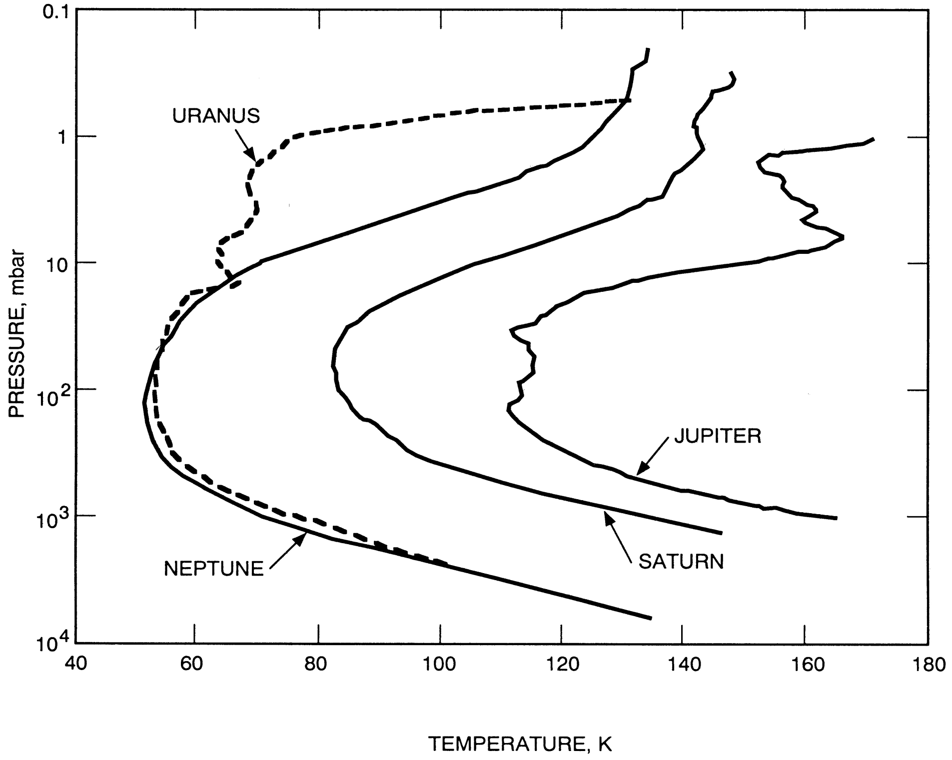
- Study properties of planetary media along propagation path
  - Atmosphere: temperature-pressure profile
  - Ionosphere: electron density
  - Rings: particle structure and size distribution
  - *Byproducts: planetary shapes, planetary surfaces*



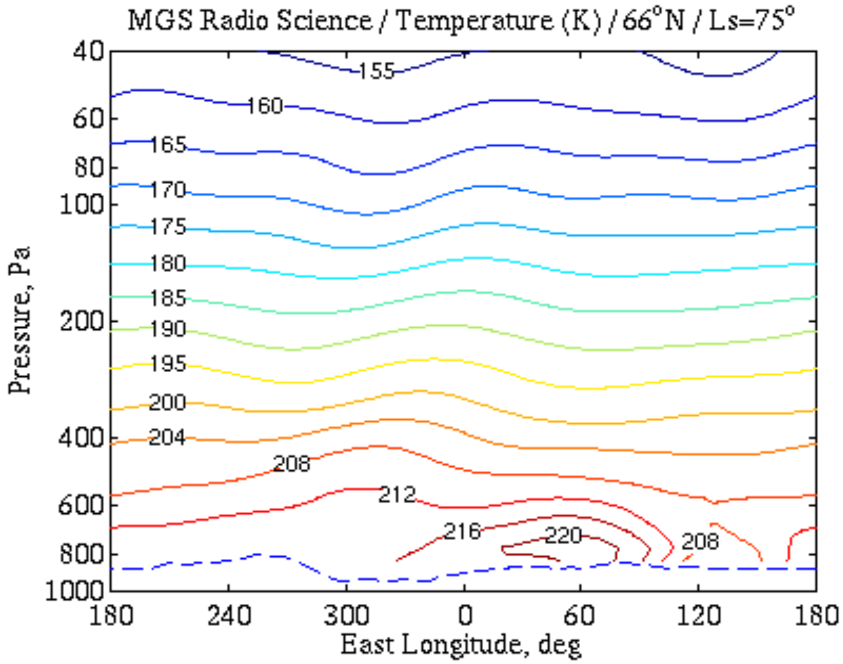
- Observables:
  - Amplitude and **phase**

- **One-way downlink** referenced to an ***Ultra Stable Oscillator***
- Other requirements

Classic Results



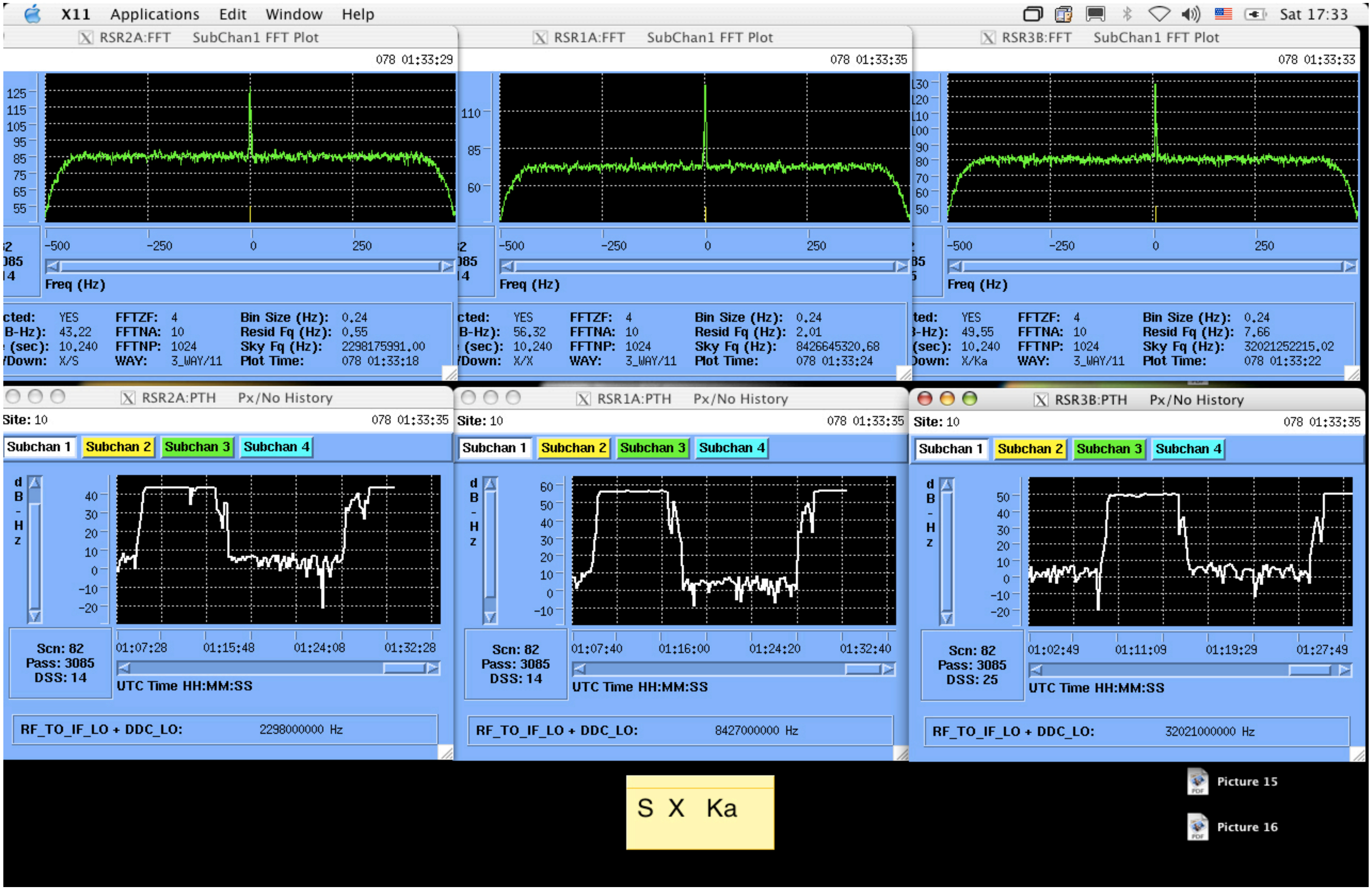
Temperature profiles for the giant planets derived from radio occultation data acquired with the Voyager spacecraft (from Lindal, 1992)



Source: D. Hinson

Three Wavelengths From One USO

Cassini Signals Occulted by Titan



```
RSR2A:FFT   SubChan1 FFT Plot                                  078 01:33:29
cted:       YES      FFTZF:  4          Bin Size (Hz):   0.24
B-Hz):      43.22    FFTNA:  10         Resid Fq (Hz):   0.55
 (sec):     10.240   FFTNP:  1024       Sky Fq (Hz):     2298175991.00
/Down:      X/S      WAY:    3_WAY/11   Plot Time:       078 01:33:18
```

```
RSR1A:FFT   SubChan1 FFT Plot                                  078 01:33:35
cted:       YES      FFTZF:  4          Bin Size (Hz):   0.24
B-Hz):      56.32    FFTNA:  10         Resid Fq (Hz):   2.01
 (sec):     10.240   FFTNP:  1024       Sky Fq (Hz):     8426645320.68
/Down:      X/X      WAY:    3_WAY/11   Plot Time:       078 01:33:24
```

```
RSR3B:FFT   SubChan1 FFT Plot                                  078 01:33:33
ted:        YES      FFTZF:  4          Bin Size (Hz):   0.24
-Hz):       49.55    FFTNA:  10         Resid Fq (Hz):   7.66
(sec):      10.240   FFTNP:  1024       Sky Fq (Hz):     32021252215.02
Down:       X/Ka     WAY:    3_WAY/11   Plot Time:       078 01:33:22
```

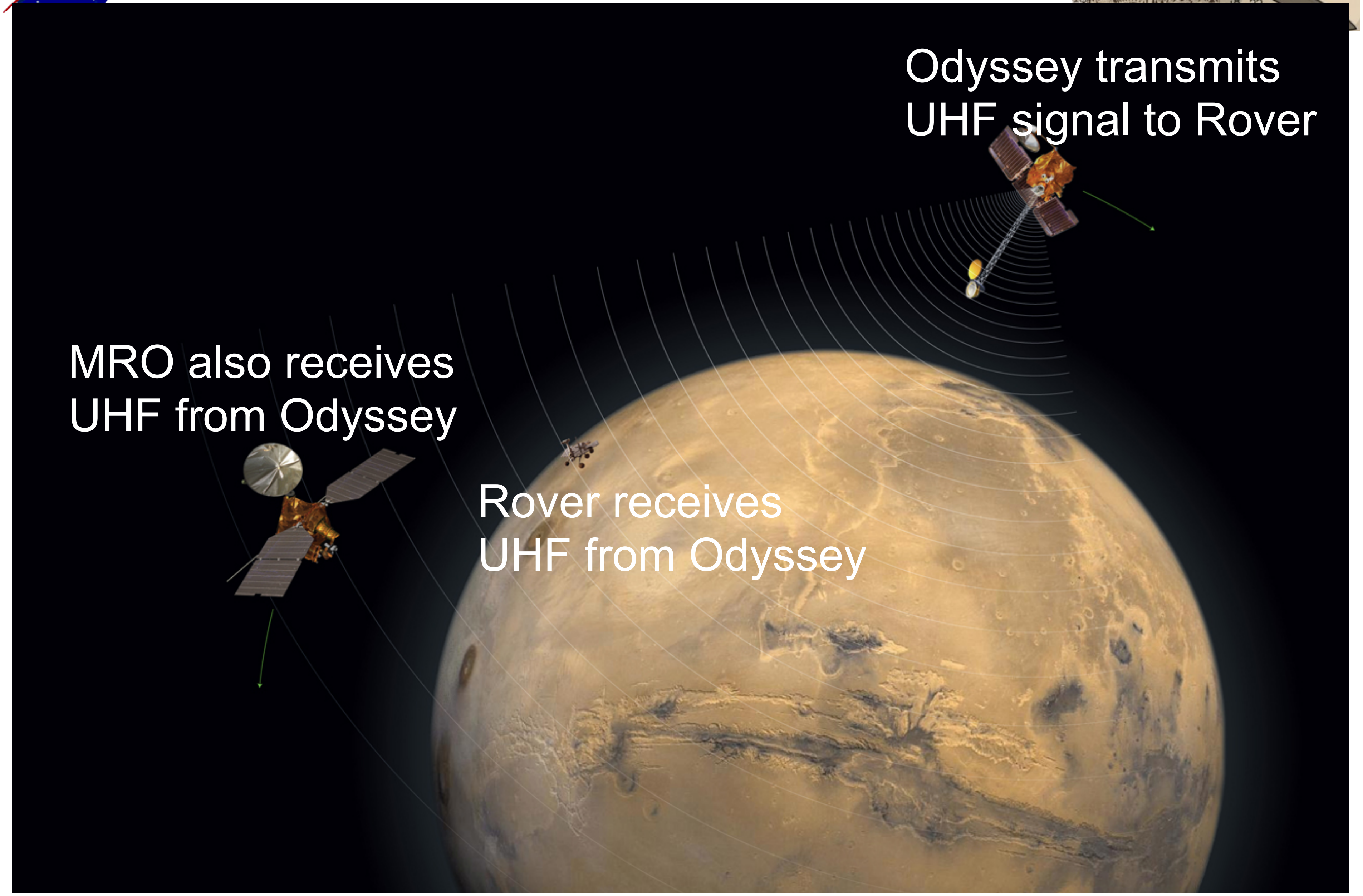
```
RSR2A:PTH   Px/No History
Site: 10                                                       078 01:33:35
Scn: 82
Pass: 3085
DSS: 14
RF_TO_IF_LO + DDC_LO:        2298000000 Hz
```

```
RSR1A:PTH   Px/No History
Site: 10                                                       078 01:33:35
Scn: 82
Pass: 3085
DSS: 14
RF_TO_IF_LO + DDC_LO:        8427000000 Hz
```

```
RSR3B:PTH   Px/No History
Site: 10                                                       078 01:33:35
Scn: 82
Pass: 3085
DSS: 25
RF_TO_IF_LO + DDC_LO:        32021000000 Hz
```

S X Ka

Spacecraft-to-Spacecraft Links Require USOs



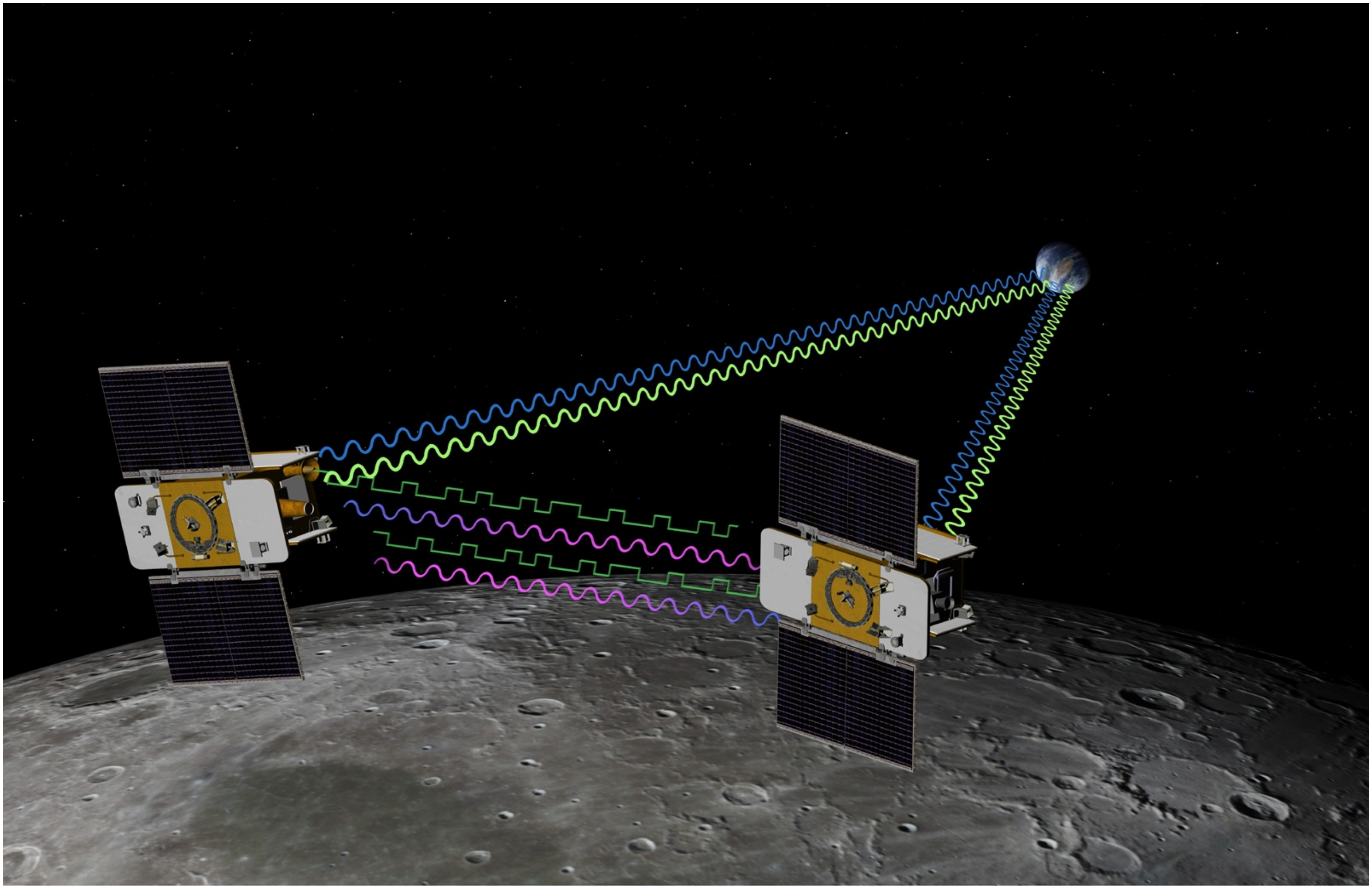
Odyssey transmits UHF signal to Rover

MRO also receives UHF from Odyssey

Rover receives UHF from Odyssey

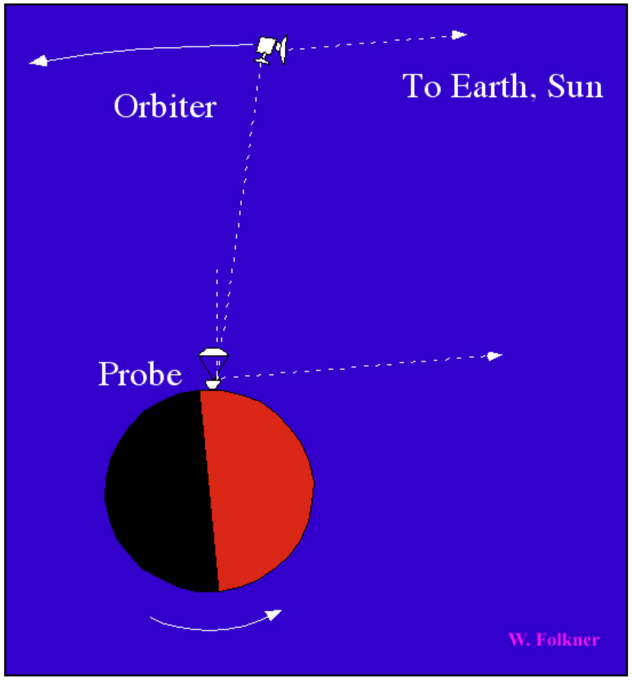
Spacecraft-to-Spacecraft Links Require USOs

GRAIL Reveals Lunar Interior Structure

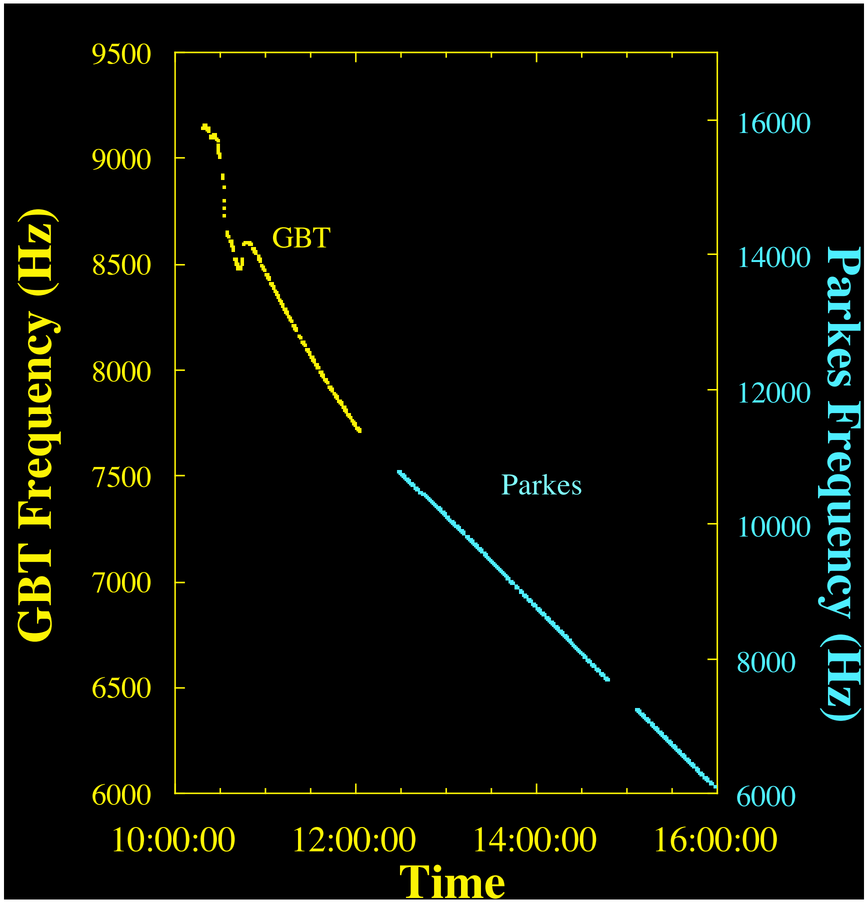


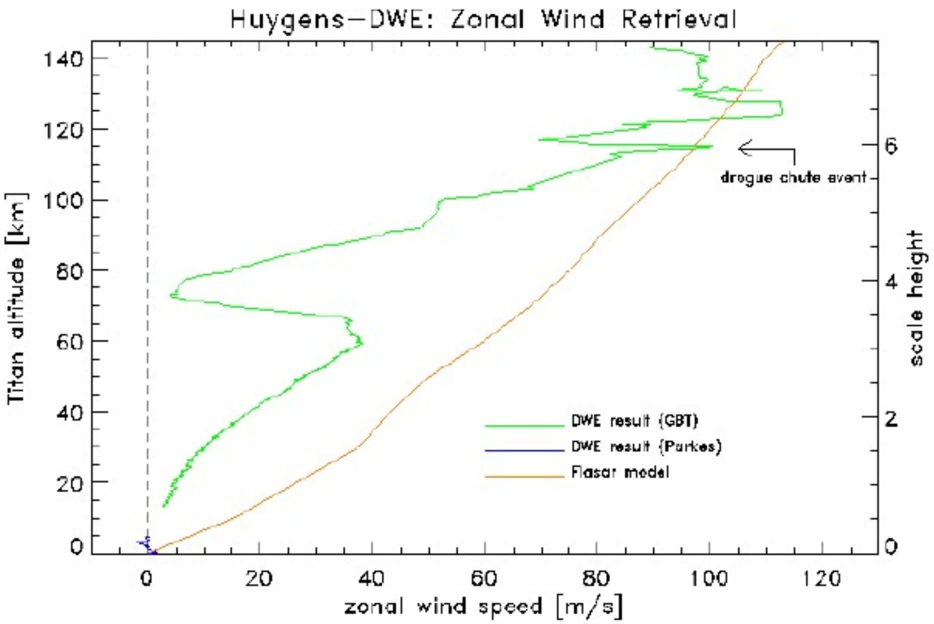
Wind Profiles

- Deduce wind speed and direction from Doppler when probe descends into atmosphere of planet or satellite
  - Huygens Probe at Titan
  - Galileo Probe into Jupiter
  - Russian probes at Venus
- Stable oscillators on probe **and** orbiter
- Possible to receive signal on Earth
  - Huygens Doppler Wind Experiment saved
  - 100-m Green Bank radio telescope and 64-m Parkes radio telescope
  - Zonal winds above boundary layer *prograde*
  - Low-velocity layer between 60-80 km
  - Considerable turbulence above 100 km



Titan Probe Science With USO

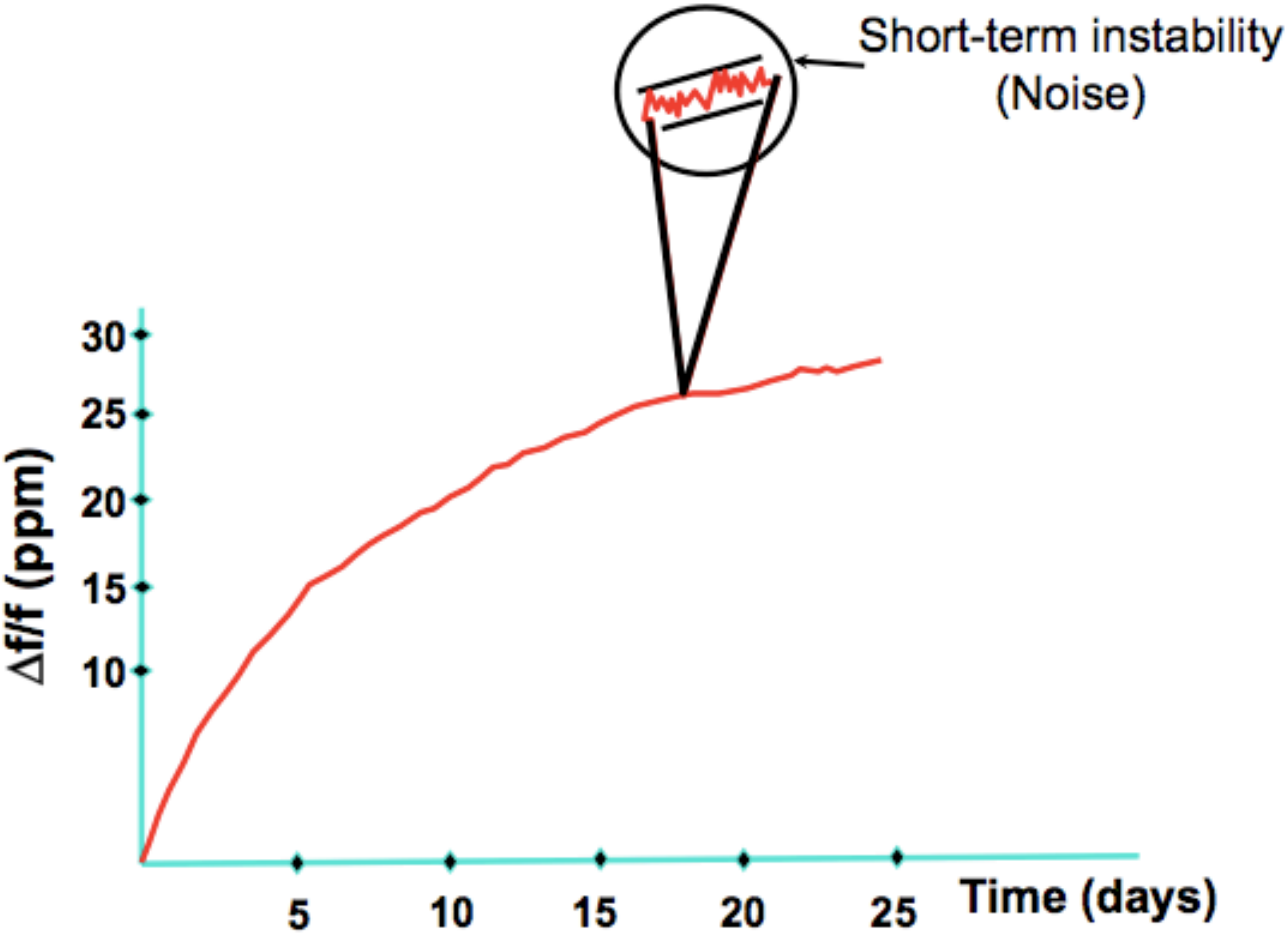




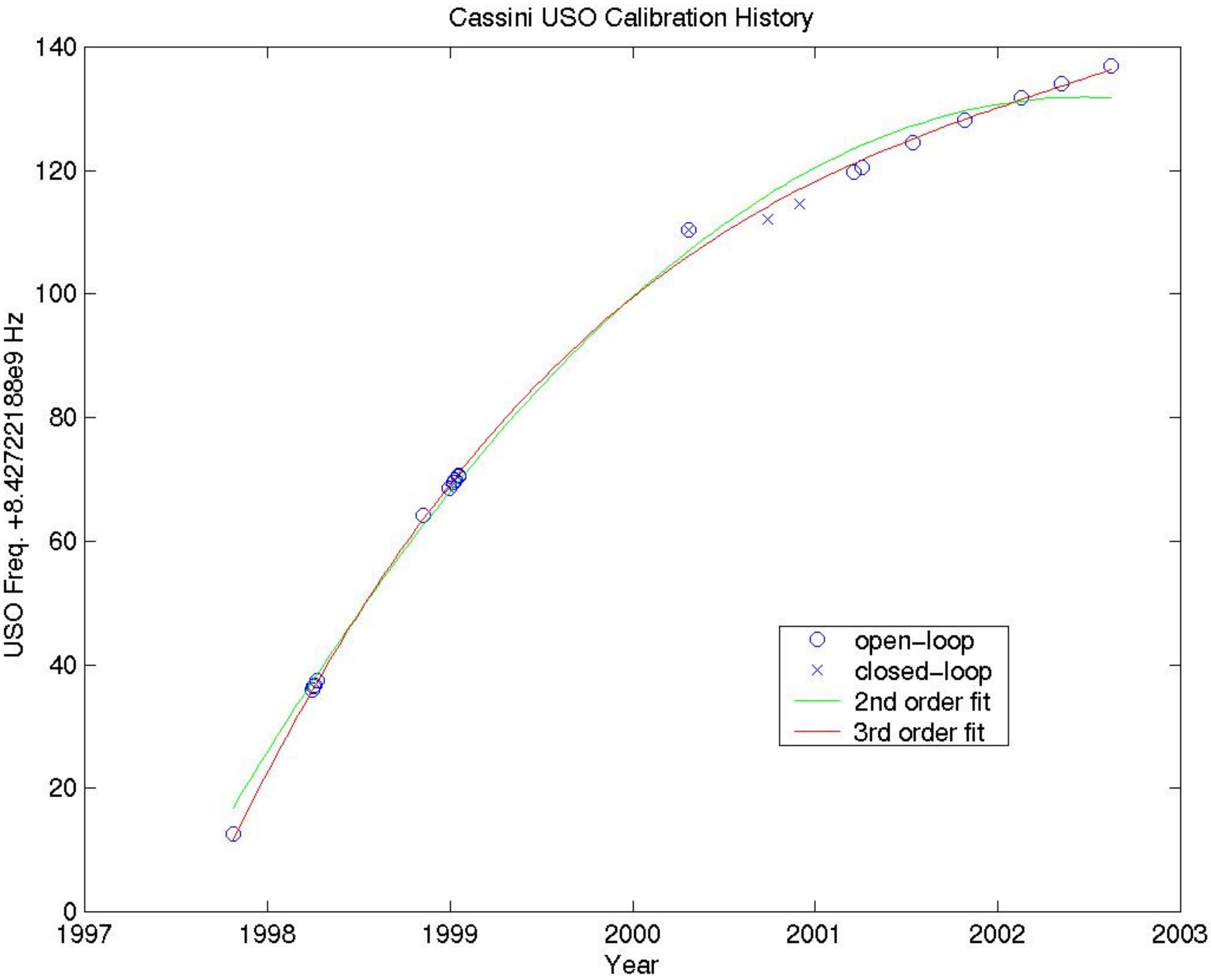
“Ultra Stable”

- USO is characterized by relevant parameters:
  - Allan Deviation at times 1 to1000 s
  - Phase noise at various frequency offsets
  - Long-term drift
  - Several environmental parameters
- For comparison of classes, Allan Deviation at 100 s can act as a summary indicator of quality and captures physics of the device
- Range in stability performance from E-10 to E-13
  - Voyager-era USO has 100-second Allan Deviation of ~E-12
  - MGS-era USO ~E-13 USO (Cassini, GRAIL, …)
  - Mars Odyssey oscillator ~E-11 (SSO!)
  - Huygens RB USO ~E-10 (at time scales a few to 30 minutes)
- Mission planners considering a stable oscillator are in danger of selecting a device that does not meet science requirements but is still designated ultra-stable. Recommend specifying the Allan Deviation at 100 s summary

Quality Indicator



Drift of Cassini USO



Allan Variance

- **Classical variance:**
- Diverges for some commonly observed noise processes, such as random walk, i.e., the variance increases with increasing number of data points

- **Allan variance:**
- Converges for all noise processes observed in precision oscillators
- Simple relationship to power law spectral density types.
- Easy to compute
- aster and more accurate in estimating noise processes than the Fast Fourier Transform.

Allan Deviation

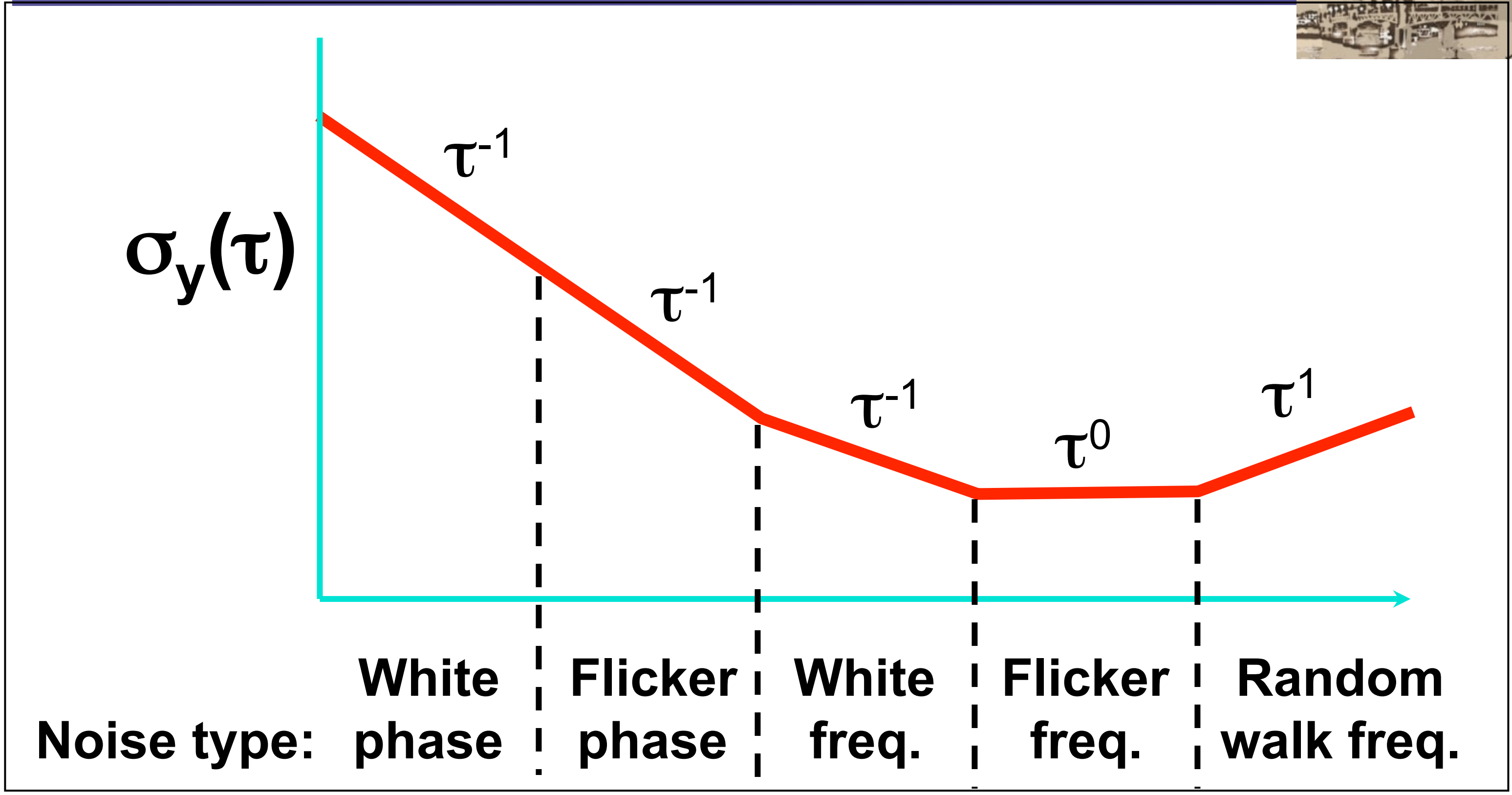
- **Two-sample deviation**
- Square-root of the **Allan variance** is the standard method of describing the short term stability of oscillators in the time domain
- Denoted by $\sigma_y(\tau)$,
- Where

$$\sigma_y^2(\tau) = \frac{1}{2} < (y_{k+1} - y_k)^2 > .$$

- The fractional frequencies, $y = \frac{\Delta f}{f}$ are measured over a time
- interval, τ; $(y_{k+1} - y_k)$ are the differences between pairs of
- successive measurements of y, and, ideally, < > denotes a time average of an infinite number of $(y_{k+1} - y_k)^2$. A good estimate can be obtained by a limited number, m, of measurements (m≥100)

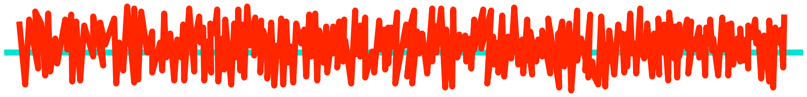
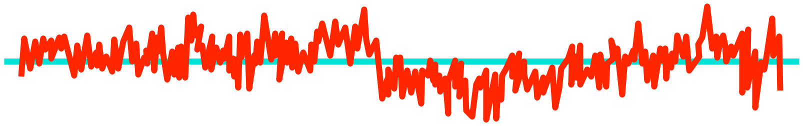
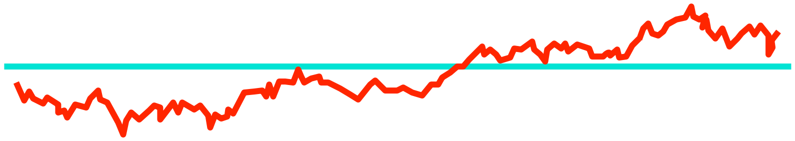
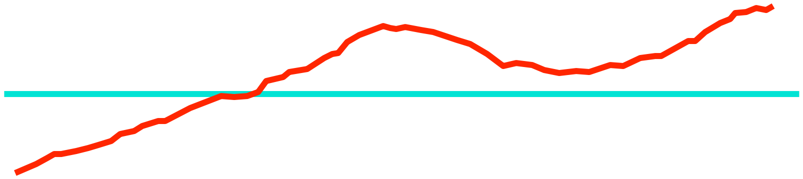
$$\sigma_y^2(\tau) = \sigma_y^2(\tau, m) = \frac{1}{m} \sum_{j=1}^{m} \frac{1}{2} \left(y_{k+1} - y_k\right)_j^2$$

Power Law Dependence



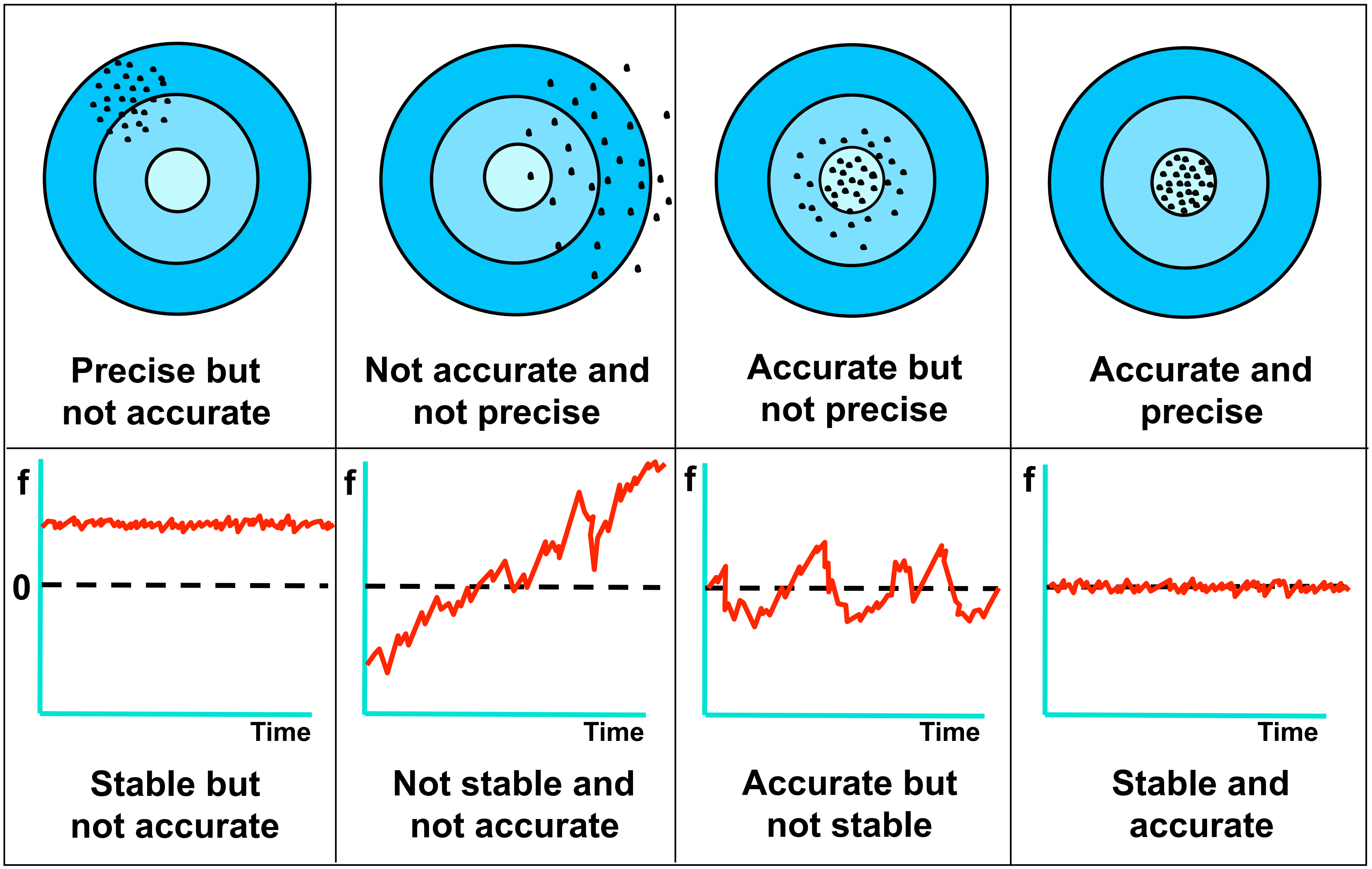
Below the flicker of frequency noise (i.e., the “flicker floor”) region, crystal oscillators typically show τ^{-1} (white phase noise) dependence. Atomic standards show $\tau^{-1/2}$ (white frequency noise) dependence down to about the servo-loop time constant, and τ^{-1} dependence at less than that time constant. Typical τ’s at the start of flicker floors are: 1 second for a crystal oscillator, 10^3s for a Rb standard and 10^5s for a Cs standard.

In Time Domain

Plot of z(t) vs. t	$S_z(f) = h_\alpha f^\alpha$	Noise name
	$\alpha = 0$	**White**
	$\alpha = -1$	**Flicker**
	$\alpha = -2$	**Random walk**
	$\alpha = -3$	

Plots show fluctuations of a quantity z(t), which can be,e.g., the output of a counter (Δf vs. t) or of a phase detector ($\phi[t]$ vs. t). The plots show simulated time-domain behaviors corresponding to the most common (power-law) spectral densities; h_α is an amplitude coefficient. Note: since $S_{\Delta f} = f^{\,2} S_\phi$, e.g. white frequency noise and random walk of phase are equivalent.

Accuracy - Precision - Stability



Precise but not accurate

Not accurate and not precise

Accurate but not precise

Accurate and precise

Stable but not accurate

Not stable and not accurate

Accurate but not stable

Stable and accurate

Quartz vs. Rubidium

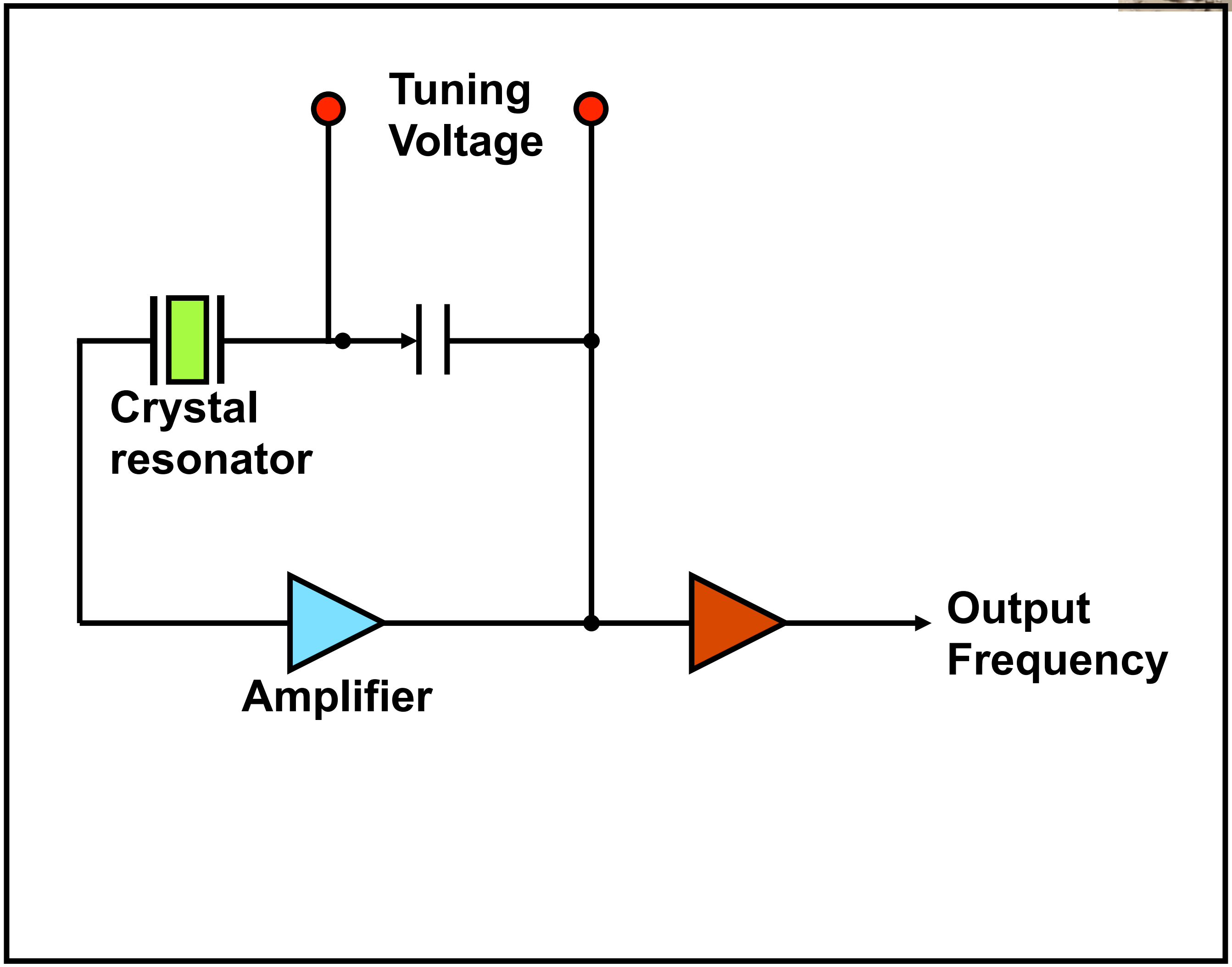
- Choice between quartz crystal oscillators and rubidium atomic oscillators for planetary probes
  - Galileo probe utilized a quartz for Doppler wind experiment
  - Huygens probe to Titan utilized a rubidium oscillator
- **The criterion was the requirement for precision versus accuracy over the available time period**
- Quartz is very precise; reaches high stability after warm up but the absolute value of its output is not accurate due to normal drift
  - Radio Science observations emphasize the relative changes in the output frequency over the duration of the experiment

Quartz vs. Rubidium

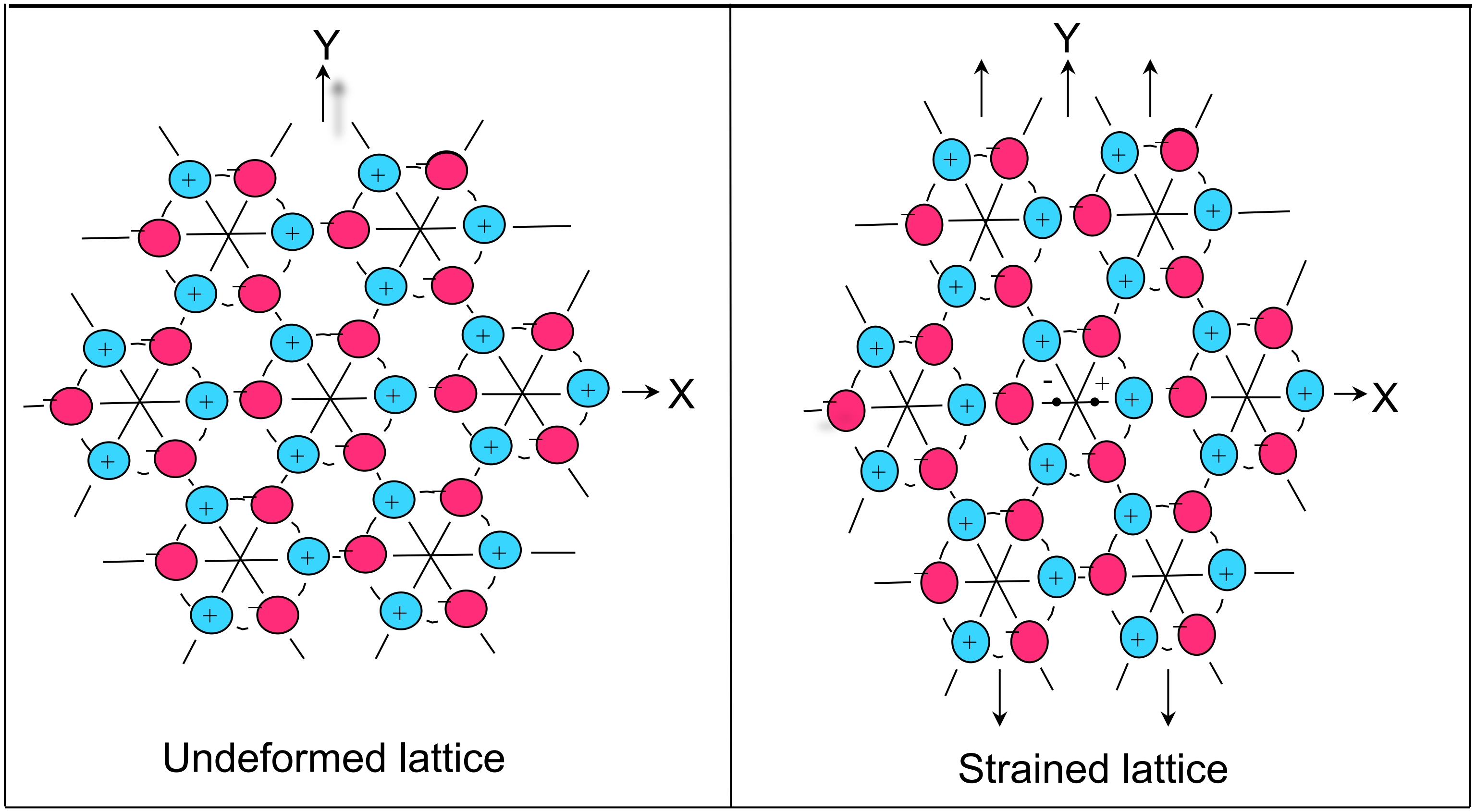
- Rb is tied to the atomic transition line and outputs an absolute and accurate frequency
  - Warm-up period is significantly shorter than quartz warm-up
  - Huygens DWE only ~E-10 accuracy compared to the ~E-13 precision of a quartz – determine the winds to 1 m/s level only

- **Rubidium: nosier but more accurate over short time periods**
- **Quartz: less accurate but more precise over a longer time period**

Quartz


Tuning Voltage
Crystal resonator
Amplifier
Output Frequency

Piezoelectric Effect



Undeformed lattice

Strained lattice

- The piezoelectric effect provides a coupling between the mechanical properties of a piezoelectric crystal and an electrical circuit
- Discovered by the Curie brothers in 1880

Quartz

- Quartz is the only material that possesses the properties:
  - ✓ Piezoelectric ("pressure-electric"; *piezein* = to press, in Greek)
  - ✓ Zero temperature coefficient cuts and stress compensated cut
  - ✓ Low loss (i.e., high Q)
  - ✓ Easy to process
  - ✓ Abundant in nature
  - ✓ Easy to grow in large quantities, at low cost, and with relatively high purity and perfection.

Quartz History

1880	Piezoelectric effect discovered by Jacques and Pierre Curie
1905	First hydrothermal growth of quartz in laboratory by G. Spezia
1917	First application of piezoelectric effect, in sonar
1918	First use of piezoelectric crystal in an oscillator
1926	First quartz crystal controlled broadcast station
1927	First temperature compensated quartz cut discovered
1927	First quartz crystal clock built
1934	First practical temp. compensated cut, the AT-cut, developed
1949	Contoured, high-Q, high stability AT-cuts developed
1956	First commercially grown cultured quartz available
1956	First TCXO described
1972	Miniature quartz tuning fork developed; quartz watches
1974	The SC-cut (and TS/TTC-cut) predicted; verified in 1976
1982	First MCXO with dual c-mode self-temperature sensing

Advantages of SC-Cut

- Thermal transient compensated (allows faster warm-up OCXO)
- Static and dynamic f vs. T allow higher stability OCXO and MCXO
- Better f vs. T repeatability allows higher stability OCXO and MCXO
- Far fewer activity dips
- Lower drive level sensitivity
- Planar stress compensated; lower Δf due to edge forces and bending
- Lower sensitivity to radiation
- Higher capacitance ratio (less Δf for oscillator reactance changes)
- Higher Q for fundamental mode resonators of similar geometry
- Less sensitive to plate geometry - can use wide range of contours

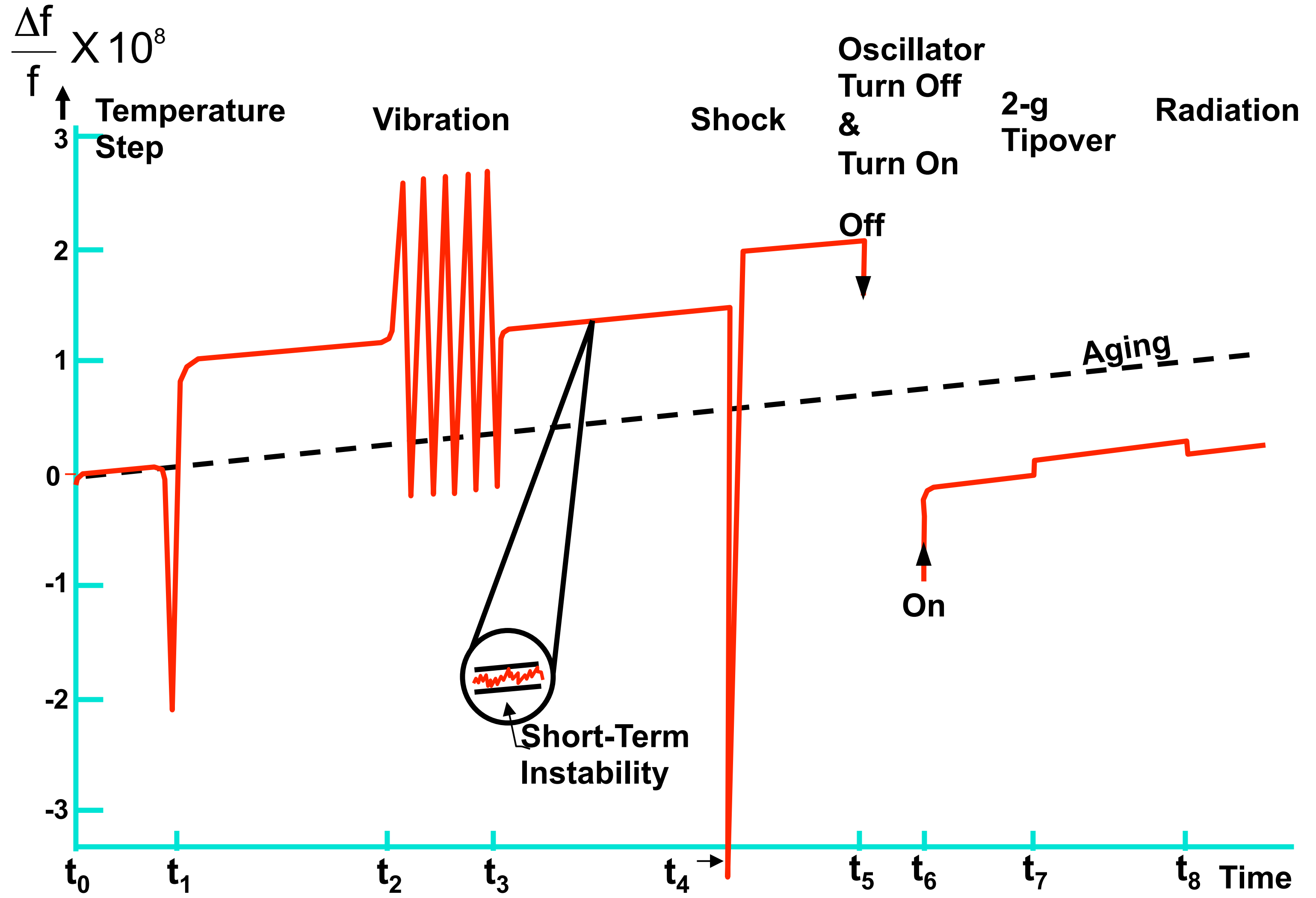
Oscillator Selection Considerations

- Frequency accuracy or reproducibility requirement
- Number and type of users (output lines)
- Environmental extremes
- Power availability
- Allowable warm-up time
- Short term stability (phase noise) requirements
- Size and weight constraints
- Cost
- Other…

Influences on Frequency

- **Time**
  - Short term (noise)
  - Intermediate term (e.g., due to oven fluctuations)
  - Long term (aging)
- **Temperature**
  - Static frequency vs. temperature
  - Dynamic frequency vs. temperature (warm-up, thermal shock)
  - Thermal history ("hysteresis," "retrace”)
- **Acceleration**
  - Gravity
  - Vibration
  - Acoustic noise
  - Shock
- **Ionizing radiation**
  - Steady state
  - Pulsed
  - Photons (X-rays, γ-rays)
  - neutrons, protons, electrons
- **Other**
  - Power supply voltage
  - Magnetic field
  - Atmospheric pressure (altitude)
  - Humidity
  - Load impedance

Frequency-Time-Influence



Aging Mechanisms

- **Mass transfer due to contamination**
  Since $f \propto 1/t$, $\Delta f/f = -\Delta t/t$; e.g., $f_{5MHz} \approx 10^6$ molecular layers, therefore, 1 quartz-equivalent monolayer $\Rightarrow \Delta f/f \approx 1$ ppm

- **Stress relief** in the resonator's: mounting and bonding structure, electrodes, and in the quartz

- **Other effects**
  - Quartz outgassing
  - Diffusion effects
  - Chemical reaction effects
  - Pressure changes in resonator enclosure (leaks/outgassing)
  - Oscillator circuit aging (load reactance and drive level changes)
  - Electric field changes (doubly rotated crystals only)
  - Oven-control circuitry aging

Future Trends I

- Research at JHU-Applied Physics Laboratory developing the next generation USO (funding through JPL technology program)
- A prototype exists for a quartz crystal USO with a **synthesizer** to tune the output frequency in flight
    - USOs are currently tuned once to the specific mission channel
    - There are mission scenarios where a modification of the USO output frequency can help operations
    - A synthesizer-equipped USO provides in situ frequency control
- Taking this concept a step further, a “disciplined” quartz USO can overcome the poorer accuracy in comparison with a rubidium USO
- Modify the output frequency via on-board firmware that monitors the output signal and either decide on the modification or receive commands from a mission team for the modified output frequency
- Now technologically feasible but flight models have not been developed for specific missions yet

Future Trends II

- Reduction in the phase noise of the USO
- Breaking the 5E-14 theoretical limit of quartz crystal oscillator stability can only be accomplished with alternate material and method called “piezoelectric artificials”
- Research has been advanced in identifying the appropriate material that can enable an order of magnitude improvement in oscillator stability
- Such device could begin to rival the use of the ground-based hydrogen masers currently providing the stability and timing reference for two-way Doppler links for most US-developed telecommunications systems
- The future “space clock” has already been demonstrated in the laboratory to achieve E-14 stability (100-second Allan deviation)
  - Space clock technology ready for a flight demonstration

Future Trends III

- Miniaturization
- Spacecraft mass and power resources for small and low-cost missions require a significant reduction of these parameters without sacrificing the stability for science applications
- The E-13 quartz USO which typically weights ~2 kg and requires ~3 W of power in the steady state can now be available with a mass reduced to 0.5 kg and power reduced to ~1 W
- This is achieved by significant simplification in the electronics and number of available output ports
  - Demonstrated with the USO for the Solar Probe mission.

Conclusion

- Stable oscillator for planetary probes are available in several levels of quality, primarily phase stability, spanning three orders of magnitude

- The number of design options for oscillators has increased, offering lower cost and mass and sufficient stability performance for non-scientific applications

- New trends potentially offer exciting devices capable of benefiting from superior accuracy and stability with electronic disciplining of the output signal of quartz crystal oscillators.

- Fly USOs!
- When possible, fly science-Quality USOs.
  - They will be of utility for science, navigation, and telecommunications

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