Report from JPL Frequency Standards Test Laboratory

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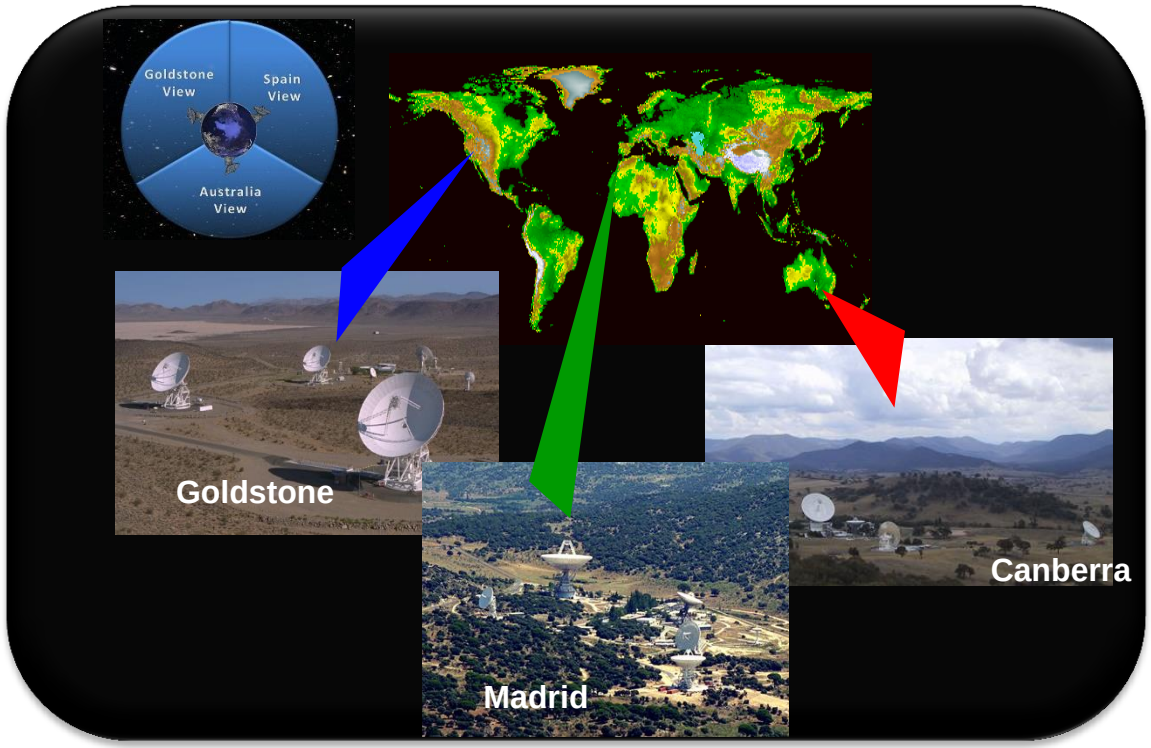
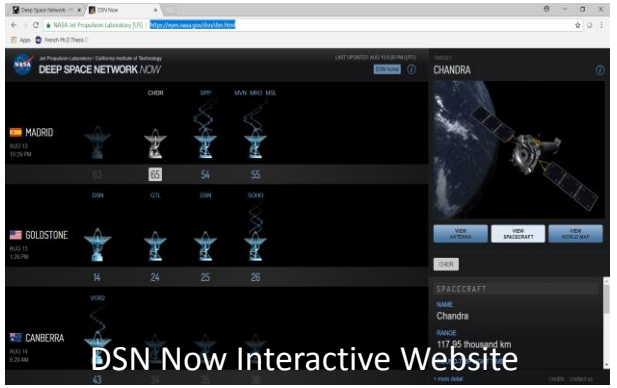
Frequency And Timing Advanced Instrument Development Group

Jet Propulsion Laboratory
California Institute of Technology

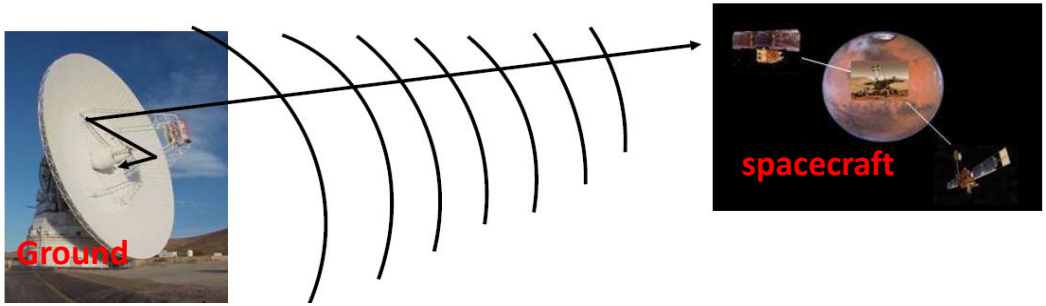
JPL is a federally funded research and development center managed for NASA by Caltech. The Jet Propulsion Laboratory is a unique national research facility that carries out robotic space and Earth science missions. JPL developed and manages NASA's Deep Space Network, a worldwide system of antennas that communicates with interplanetary spacecraft.

NASA/JPL Deep Space Network and Exploration





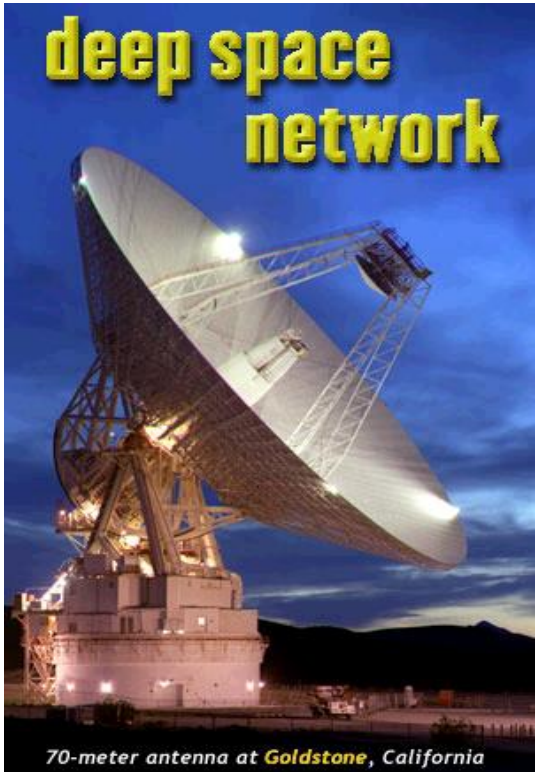
DSN Now Interactive Website



https://www.nasa.gov/
https:/www.jpl.nasa.gov/
https://deepspace.jpl.nasa.gov/

DSN Frequency & Timing System (FTS)

@ Goldstone, Canberra, Madrid



22 antennas on 3 sites,

- ***Mojave Desert, California***
- ***Madrid, Spain***
- ***Canberra, Australia***

(Each site with distances up to 30 km)

Photonic Frequency Links (fiber distr.)

Integrated Master Clocks

DSN Hydrogen Masers

Frequency & Time References:

- Focus on high stability <12 hours
  - transit times of solar system
  - require knowledge of Offsets from UTC

Main Users:

- Radio Science & Astronomy
- Navigation
- Antenna Pointing
- Telemetry

Main System Components

- Atomic Standards & Frequency Distribution
  - Two H-masers plus backup per complex.
- Master Clock & Timing Distribution
- GPS CV receivers for time synchronization
- (GPS CP receivers for ionosphere corrections)
- Phase Calibration System S,X band
- Performance Measurements
  - Time Analyzer
  - Frequency Stability Analyzer

DSN Frequency & Timing System (FTS)

Frequency Standards Test Lab @ JPL

State-of-Art Clock Technologies and Characterization

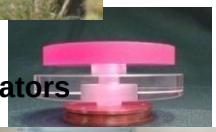
Stability Measurements

DSN Clocks

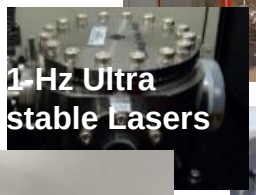
GPS Antennas

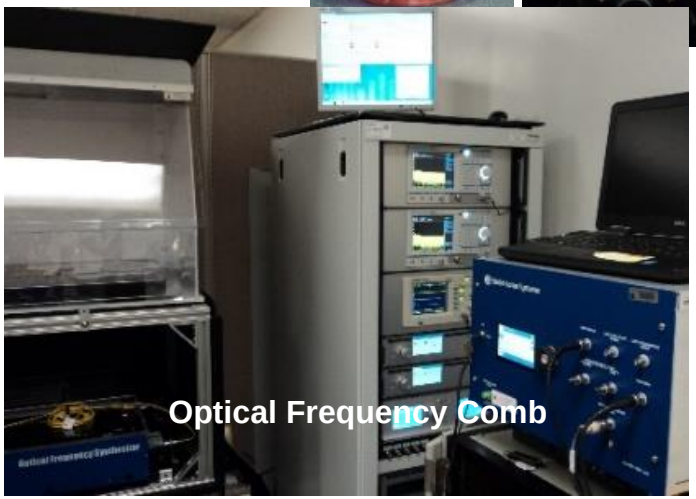
Environmental Tests

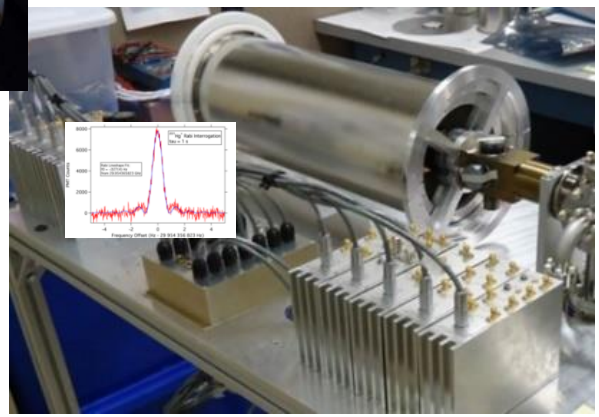
Atomic Standards



Low Noise Oscillators



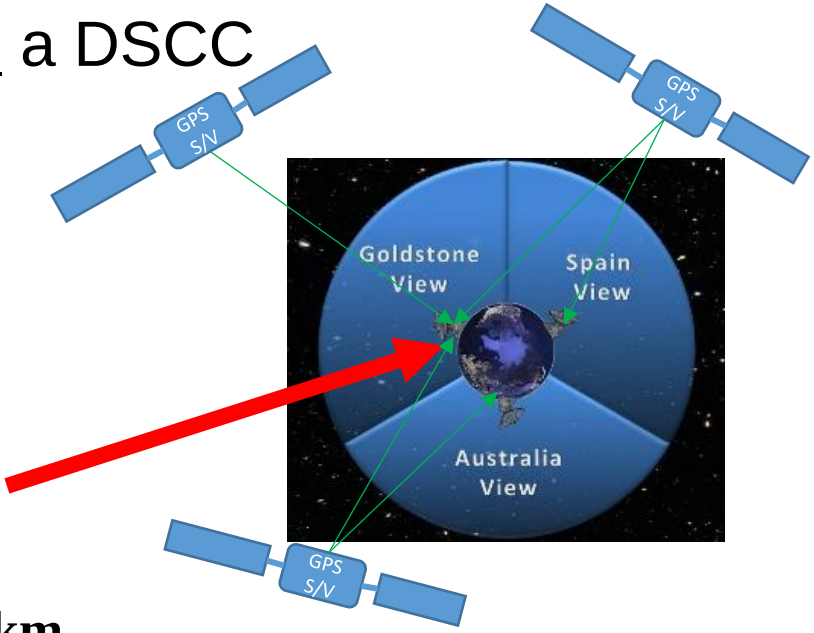




Ultra-Stable Hg+ Clocks (LITS-10-12)
(NASA, DOD, ESA, Commercial)

Distributed Frequency & Timing within a DSCC

Goldstone, California



DSS-14 70 m

Low TC Fiber cable

Central Control Room

- **Atomic standards**
- **Master Clock**
- **GPS (All-in View)**

Low TC Fiber cable

15 34 m HEF

6 km

13 km

12 26 m

4 km

8 km

34 m BWG 24

APOLLO Site

16 km

34 m BWG **(Stabilized Link)** 25

34 m BWG 26

13 34 m BWG R&D

2 km

34 m 28

DSS-14

Antennas = 9

Number of timing users ~ 100

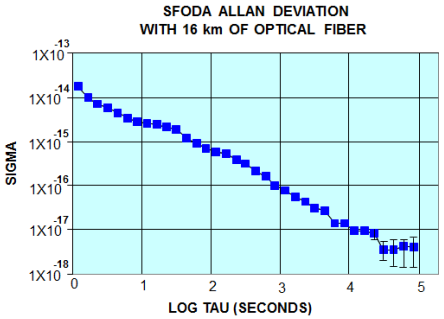
Maximum distance ~ 30 km

(Unless indicated, standard telecom fiber cables are used)

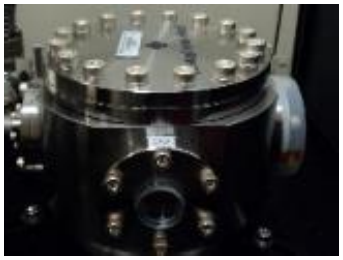
GPS utilization and fiber-link timing in FTS-DSN/FSTL

- Central Frequency standards & Clock calibrated to UTC(k)
  - All-in/Common View Comparison (primary)
  - Steering to UTC(k)
    - Manually change frequency (operational)
    - Manually input linear drift rate(in test)
    - Automatic linear drift rate removal (in test)
  - Carrier-Phase+PPP Comparison(in test)
- Advanced Optical Oscillator (in FSTL)
  - 1Hz commercial ultra stable laser as optical clean up oscillator.
  - Optical frequency comb convert to RF
  - Low drift rate material (operational) study
  - Steering to UTC(k) via CP+PPP using JPL's 30s and 300s GIPSY product (Future)

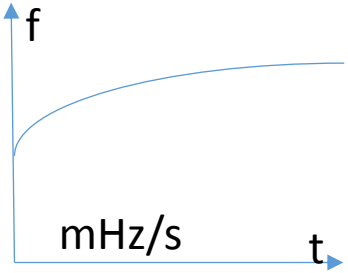
- Fiber Freq Dissemination (within 1 local complex)
  - RF over optical carrier (primary)
  - research



- Fiber Time Dissemination (within 1 local complex)
  - Master Clock and TCTs
  - 30ps resolution



1-Hz Ultra stable Lasers



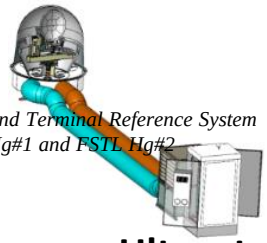
NASA/JPL Mercury Trapped Ion Clocks

- **Long life, continuous, high stability operation**
- **Mercury Linear Ion Clock Paths and Applications:**

1. Ultra-Stable Performance: UTC timescales, ESA ACES mission

"Compensated" Multi-pole ion clock technologies:

- 10^{-16} at 1 to 10 days, drift ≤ 10^{-17}/day.
- 10^{-15} short term stability (~1 sec) via super LO's.

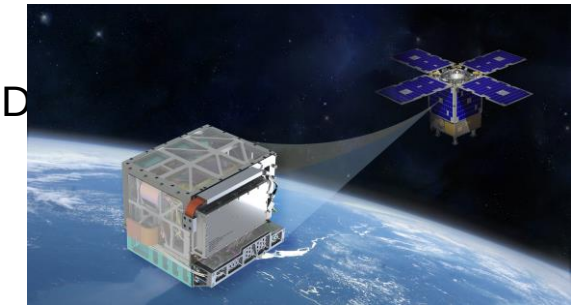


FSTL Ground Terminal Reference System
FSTL Hg#1 and FSTL Hg#2

Ultra stable ion clock

2. Space: DSAC Technology Demonstration Mission (TRL 5-7),

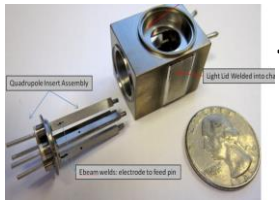
- Quartz USO based LO's.
- NASA Deep Space: ~ 20W and 5 kg goal
- GNSS (MAFS) : ~ 1x10^{-13} short term, 10^{-15} at 1 to 10 D
- Science and other apps….



DSAC

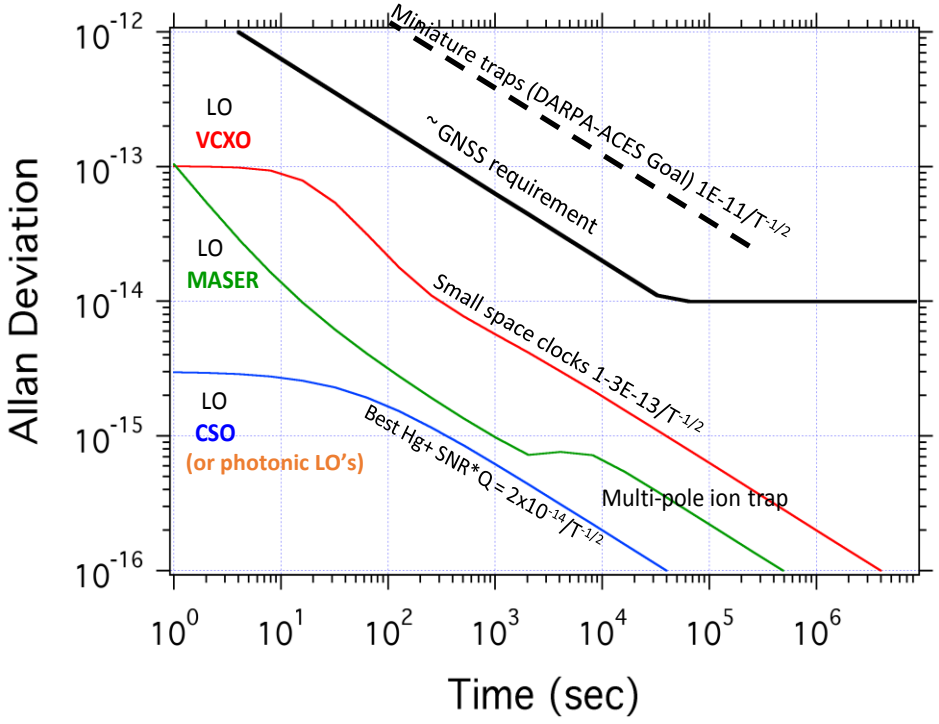
3. Miniature, low power: DARPA ACES program

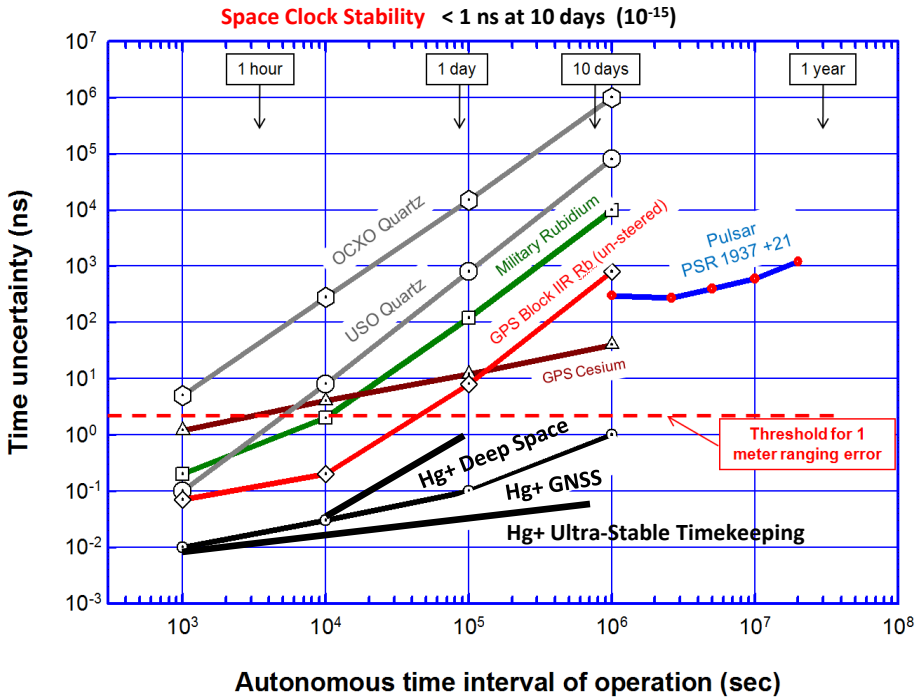
- 30 cm^3 scale ion trap
- Miniature UV light sources and LO's



<30 cm^3

Various Hg+ Standard Implementations with differing Local Oscillators



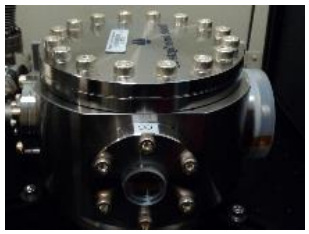


(No drift removal)

GPS Disciplined High Performance Local Oscillator for Deep Space Navigation and Science

- H-Maser steered to UTC(k) via All-in-View GPS comparison
  - Manual Loop (Human input linear drift removal in Microsemi H-Maser), approaching operational in DSN
  - Auto Loop (test in FSTL)
- H-Maser Steered to UTC(k) via GPS Carrier-Phase+PPP comparison
  - Auto Loop, architecture under development in FSTL.
- Photonic Local Oscillator (PLO), i.e. 1Hz-ultra stable laser, steered to remote clocks
  - With optical frequency comb,
  - linear drift removal hardware development
  - calibration of drift (all in FSTL)
- Low drift operational PLO study,
- simplified operational, long life frequency comb study.

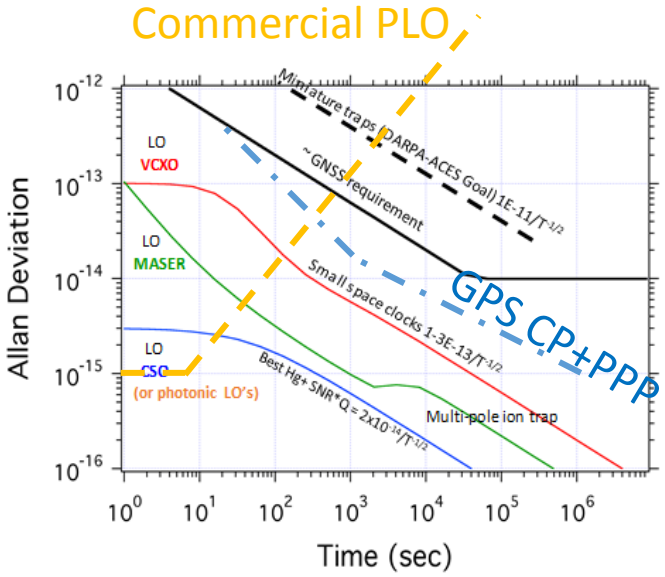
Optical Frequency Comb



1-Hz Ultra stable Lasers

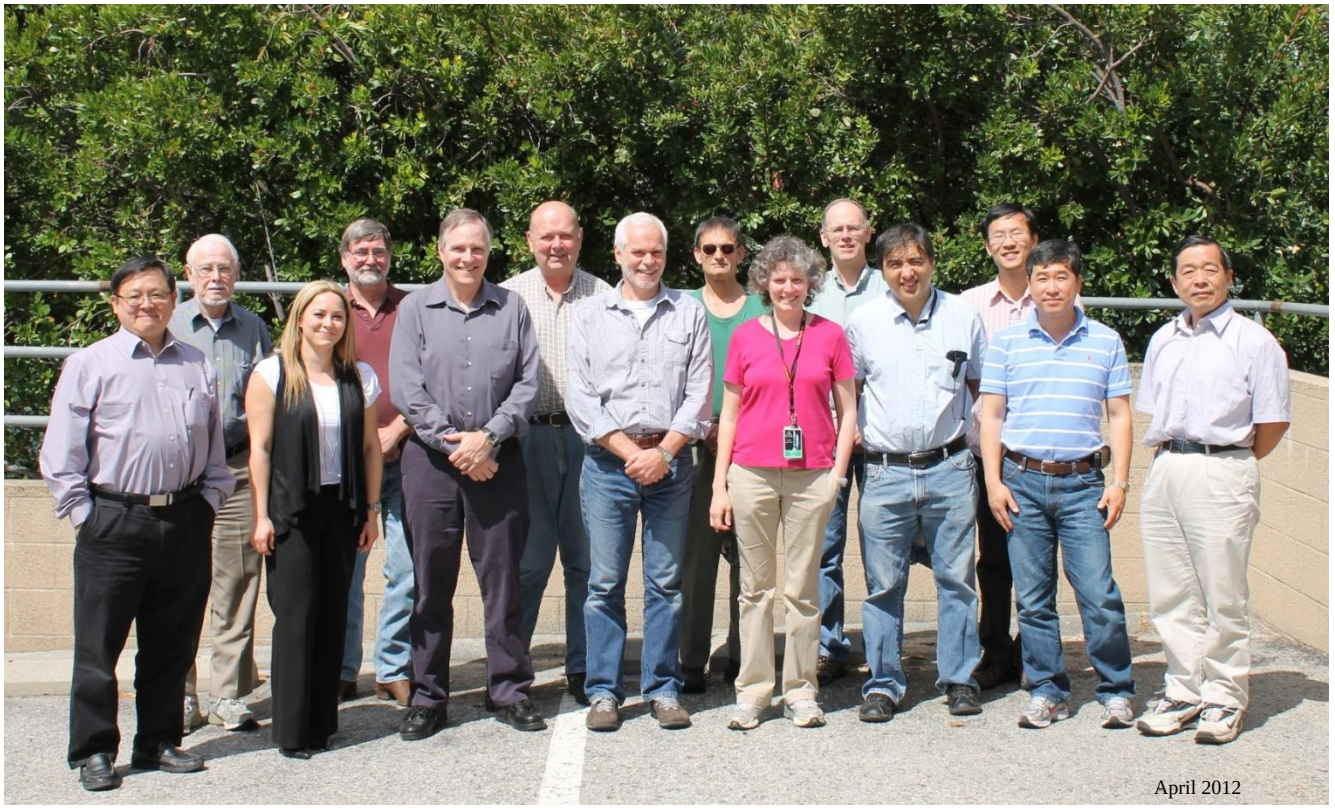
Goal/Challenge:

1. Operational Lower drift?
2. Close GPS calibration fast



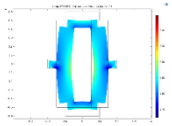
Frequency & Timing Advanced Development Group (335E)

Technical Group Supervisor: Dr. Robert Tjoelker



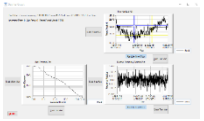
Left to Right: Rabi Wang, Bob Hamell (retired), Narine Knadzhyan (transferred), Blake Tucker, Bob Tjoelker, Bill Diener, John Lauf, Chuck Greenhall, Daphna Enzer, Eric Burt, Jorge Gonzalez, Lin Yi, Yong Chong, Shouhua Huang. (missing: Al Kirk, Jan Magnuson).

Recent Frequency and Timing Student Interns



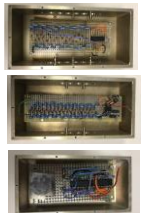
Jacob Harburg (16,17)
Cornell U. (Jr. and Sr.)
Now at MIT Lincoln

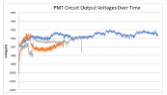
- NI-FPGA based Atomic clock controller (JPL new technology report, i.e. NTR)
- Thermal and mechanical simulation of ultra-stable Fabry-Perot cavity



Michael Toennies (17)
U. Of Michigan (Sr.)
Now at Boeing

- Low SWaP-C Ka-band Synthesizer (IFCS 2018, conference paper)
- Ultra-low power Atomic clock controller with single IC. (JPL NTR)
- Real-Time Frequency Analyzer User Interface (JPL NTR)

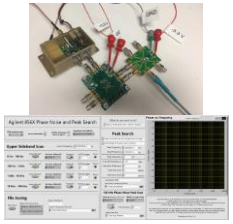




Joseph Zuckerman (17)
Harvard U. (Jr.)

- Low power high voltage electronics (DARPA project)
- Low power ion trapping electronics. (DARPA project)
- Low power field emitter electronics. (DARPA project)

Calvin Lin (17)
Stanford U.(Jr.)



- Ka-band Comb generation electronics (DSN project)
- Amplitude-Phase Noise Instr. control software (JPL NTR)

Andrei Isichenko (18)
Cornell U.(G.)

- Mercury clock DUV optical source monitoring system (TBD)
- 1310nm Piezo/Stage based fiber stabilized distribution with CW and pulsed laser (TBD)

Thank you