



Sync Sources: GNSS and Atomic Clocks

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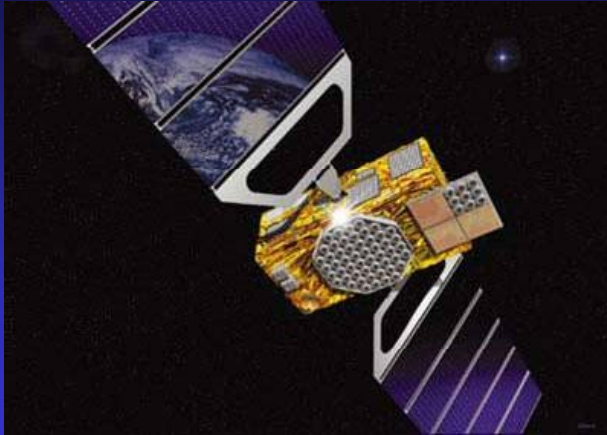
Sync Sources: GNSS and Atomic Clocks

- **GNSS Systems**
- **GPS Status and Future**
- **GNSS Failure Modes**
- **Atomic Clocks**
- **Conclusions & References**

GNSS Systems Now On-Orbit

- GPS – U.S.– 29 Operational Satellites
- Glonass – Russia – 14 Operational Satellites + 3 Commissioning
- Galileo – EU – 2 Experimental
- Compass/Beidou – China – 1 Experimental

Where is GNSS Going?



Galileo (EU)

- Test Sats launched (not representative of the final Sat)
- IOC: 2012-2015?

GLONASS (Russia)

- Revitalization of Glonass; 17 Sats operational now
- FDMA to TDMA Upgrade being considered

Up-Coming GPS-like GNSS & Space-based Augmentation

China

- 1st, was part of EU's Galileo GNSS
- Since March 07, building own GNSS "Compass"

India

- 1st, was part of Galileo -
- Now joined GLONASS

Japan

- Part of US GPS,
- Building Figure-8 GNSS-GPS augmentation using Quasi-Zenith Satellites

Far Future

Cislunar and beyond Moon orbit GNSS

Ground and Space-based Augmentation Systems (DGPS - SBAS) for Civil Aviation globally:

US - WAAS

EU - EGNOS

Japan - MSAS

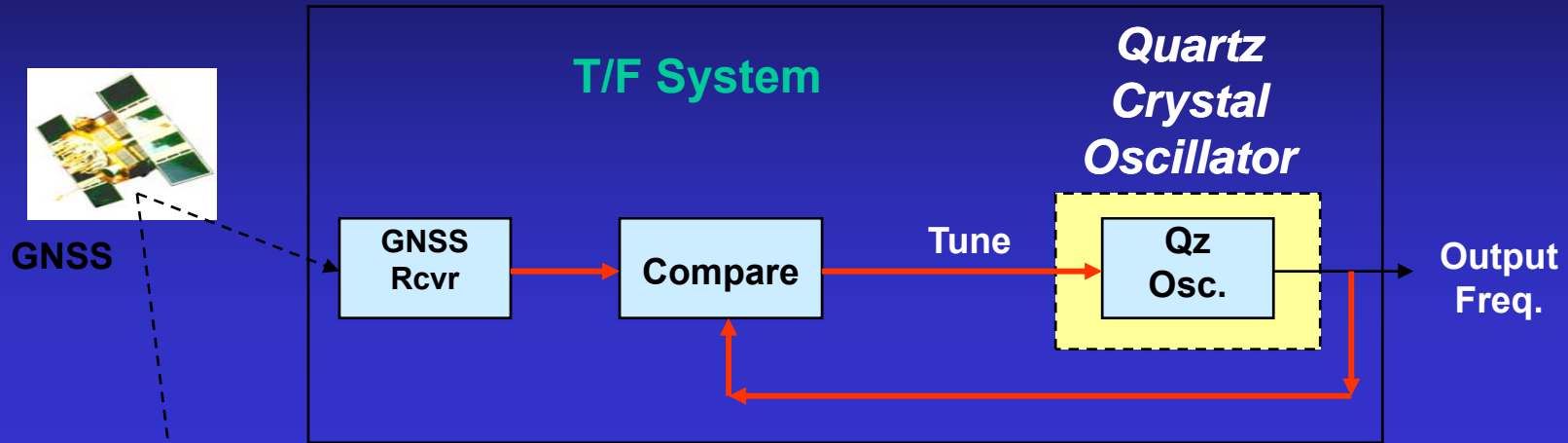
China/India - GAGAN

Courtesy H. Fruehauf, ViaLogy LLC

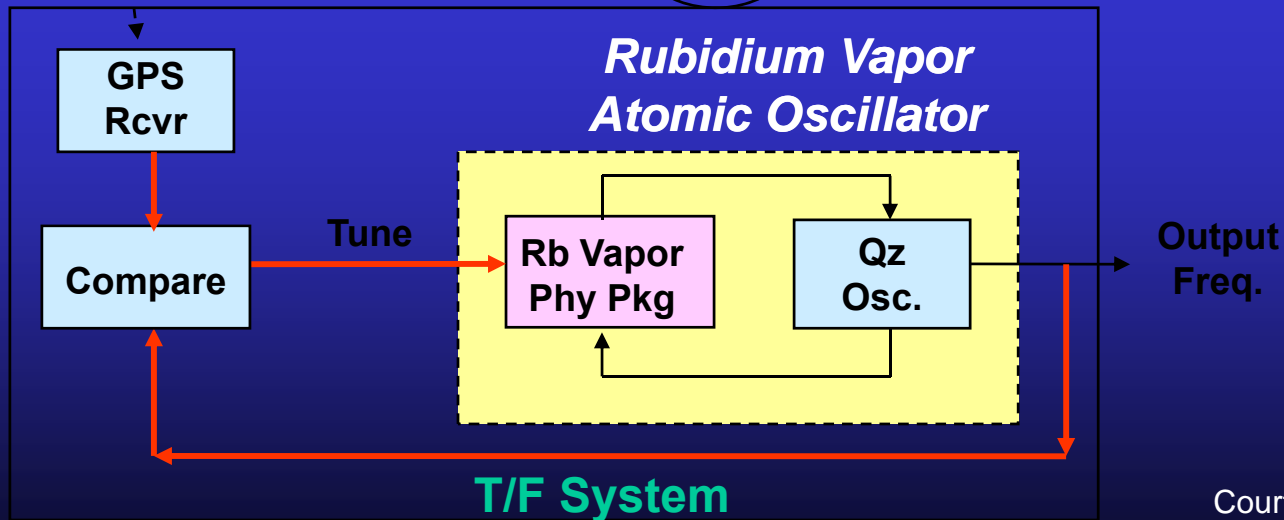
GNSS Systems: General Properties

- Position, Navigation, Timing (PNT)
- Four + synchronized timing signals from known locations in space required for navigation
- Two + frequencies measure ionosphere
- Control, Space, User Segments
- Open and Restricted Services

GNSS-aided Time and Frequency Systems



Or...



- *Rb oscillator 100 to 1000 times better Holdover Performance*

Courtesy H. Fruehauf, ViaLogy LLC

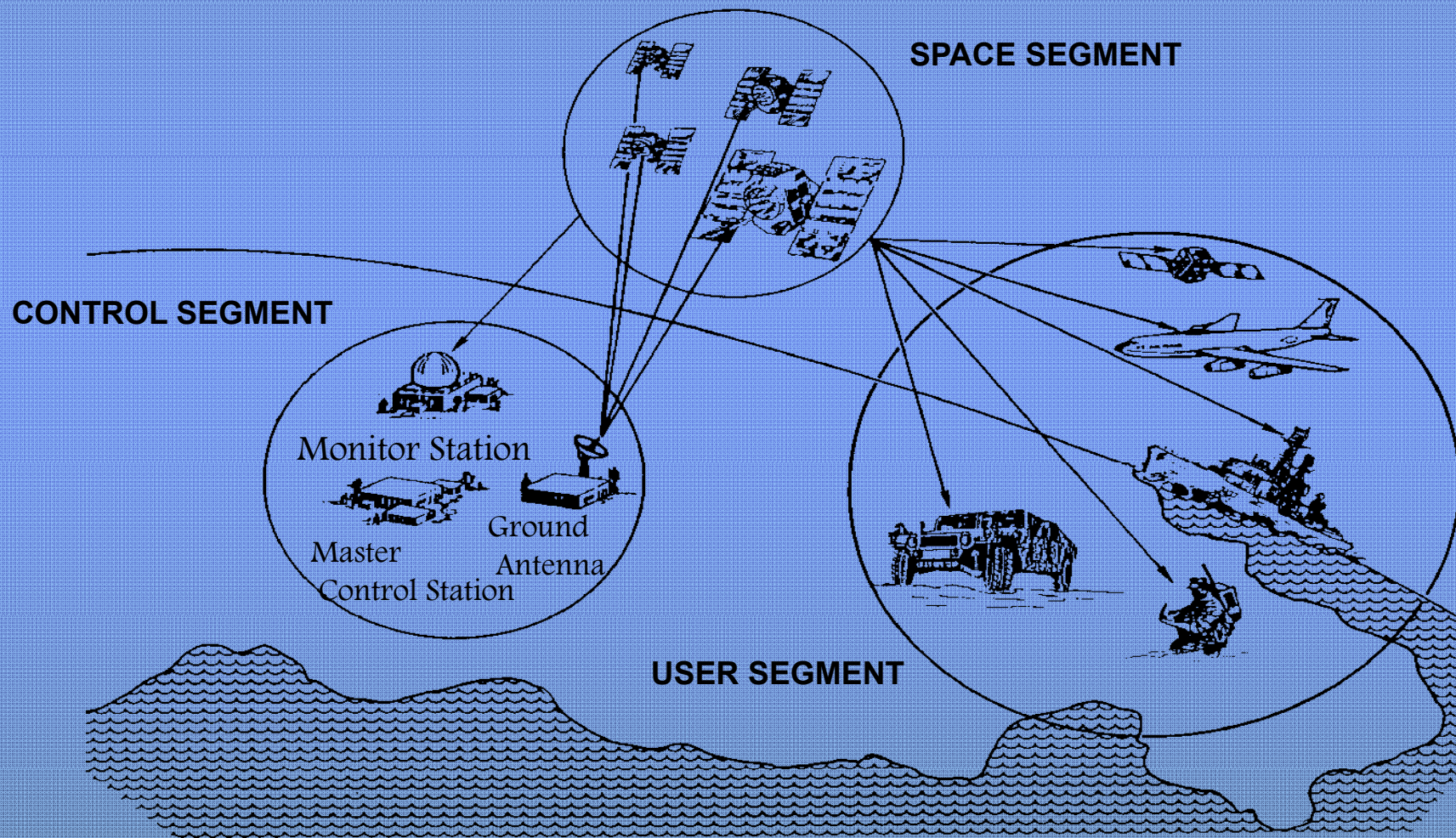
GNSS for Telecom Timing

- Antenna required
 - Top of building implies space rental, lightning issues
 - Through window gives limited visibility, sats come and go, GEOs are fixed
- Receiver needs Qu or Rb oscillator
 - Provides signal, steered to sats
 - Stability/cost trade-offs
- Telecom timing signals required
- Error/failure/attack mitigation
 - RAIM
 - Duplicate/backup timing

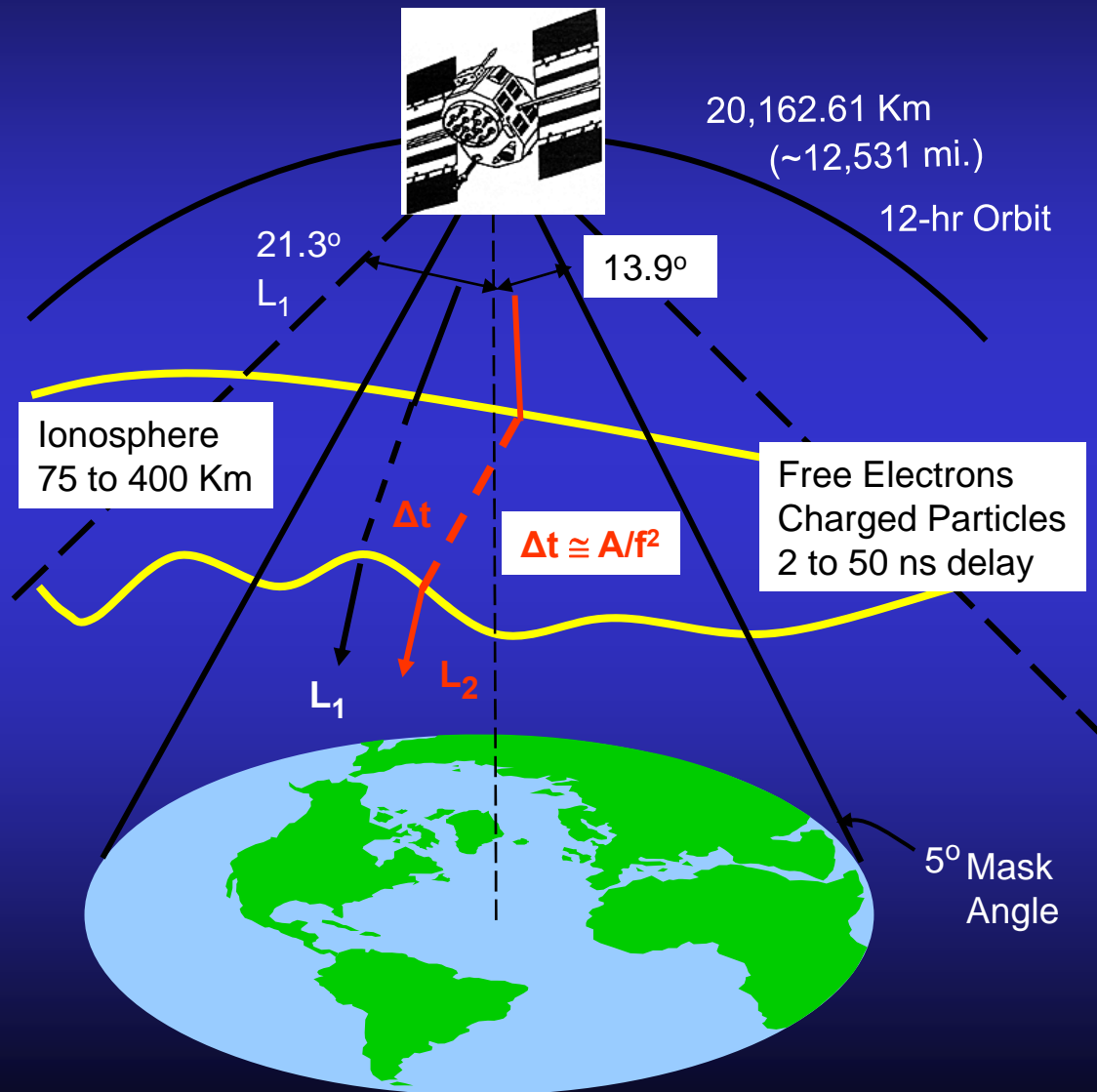
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GPS (GNSS) System Configuration - Three Major Segments



GPS Satellite Signals



- L₁ 1575.42 MHz
C/A-Code 1.023 Mcps,
P-Code 10.23 Mcps
Data 50 bps
- L₂ 1227.6 MHz
P-Code 10.23 Mcps
Data 50 bps
- Four Satellites
needed for
3-D navigation
- Maximum Doppler
Shift
between Satellites
~ ± 6KHz

Courtesy H. Fruehauf, ViaLogy LLC

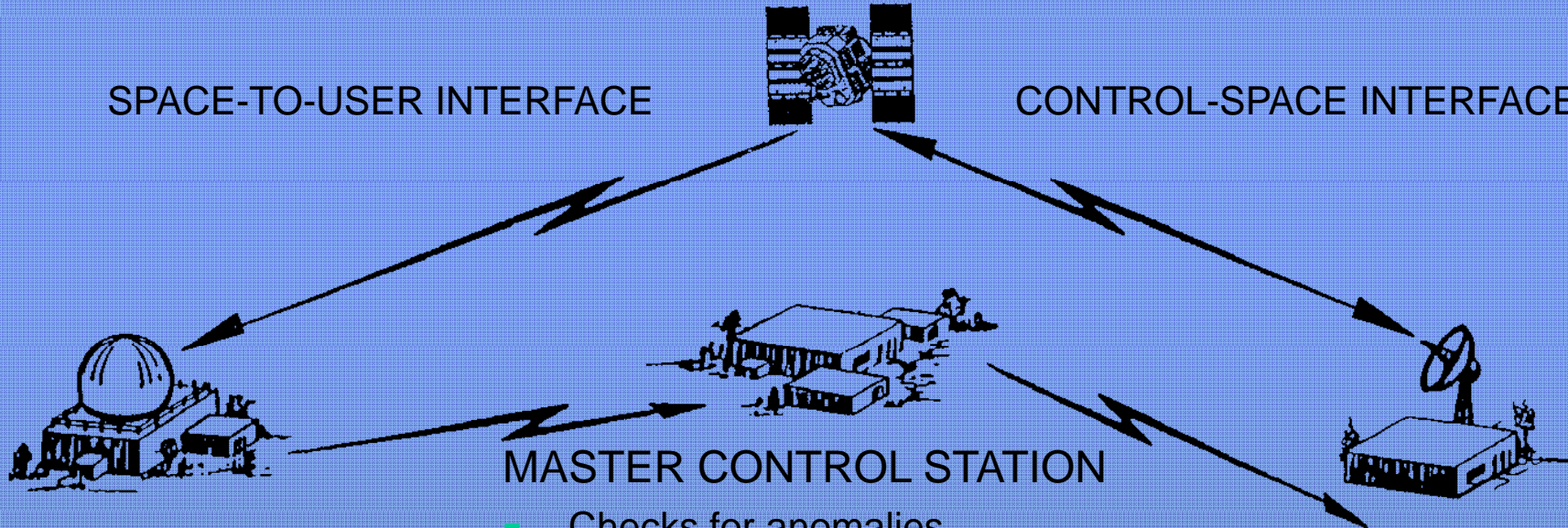
Control Segment

SPACE VEHICLE (SV)

Broadcasts the SIS PRN codes, L-band carriers, and 50 Hz navigation message stored in memory

SPACE-TO-USER INTERFACE

CONTROL-SPACE INTERFACE



MONITOR STATION

- Sends raw observations to MCS

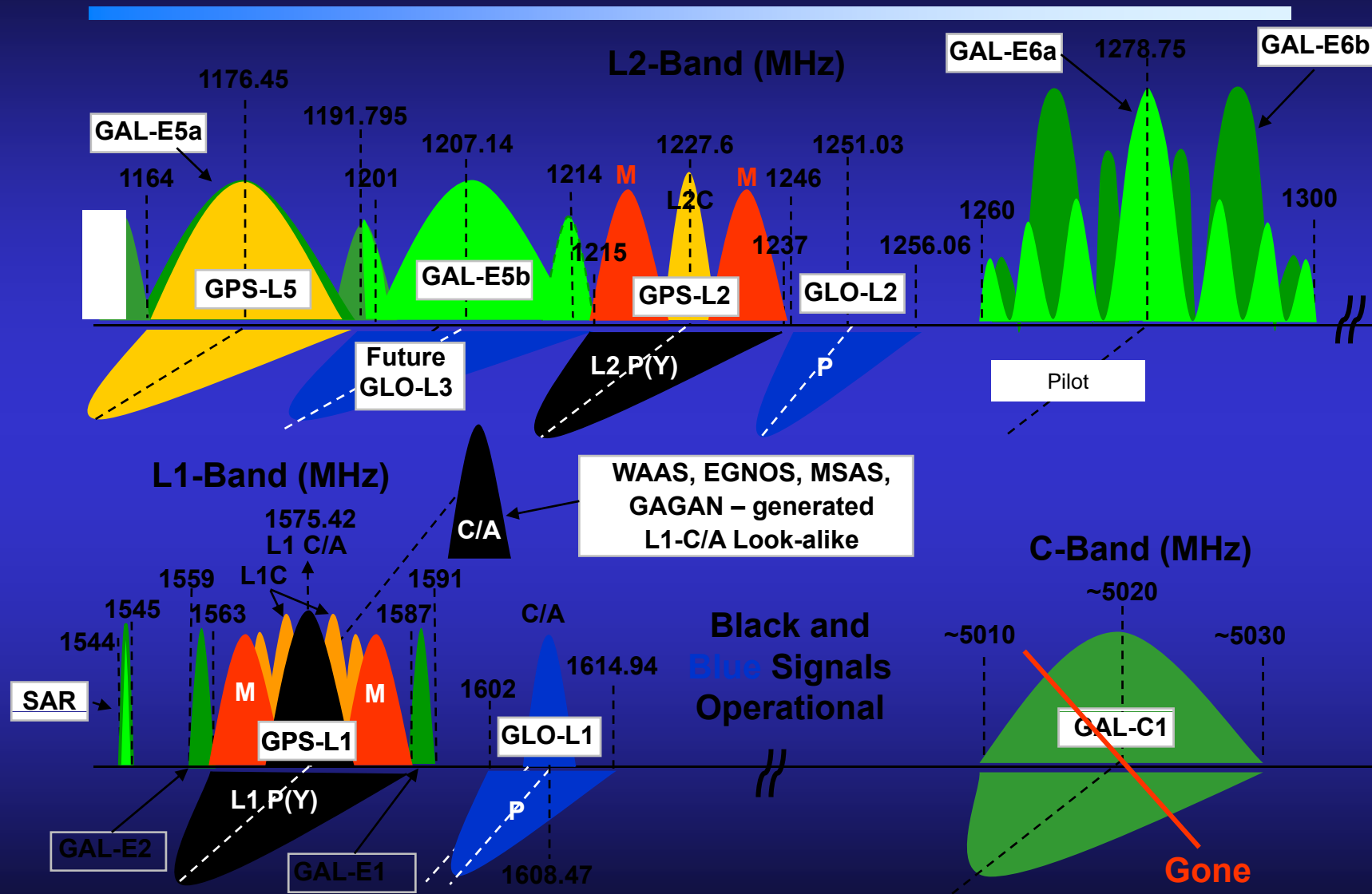
MASTER CONTROL STATION

- Checks for anomalies
- Computes SIS portion of URE
- Generates new orbit and clock predictions
- Builds new upload and sends to GA

GROUND ANTENNA

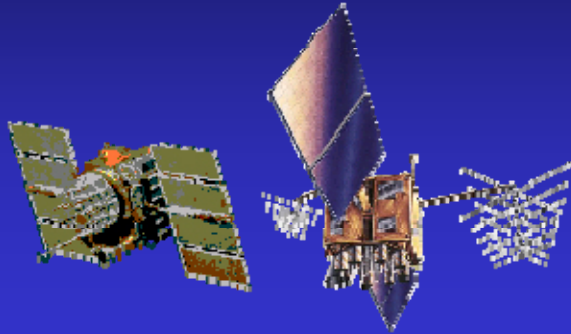
- Sends new upload to SV

Present & Upcoming GPS, Glonass & Galileo Signals

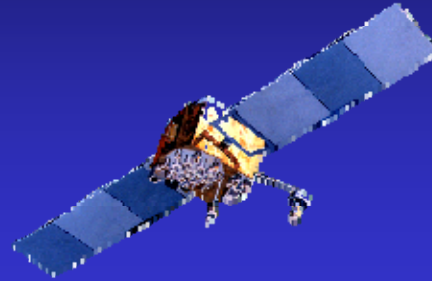


GPS Modernization Plan

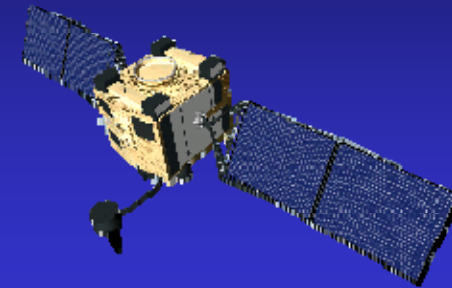
Block IIA/IIR



Block IIR-M, IIF

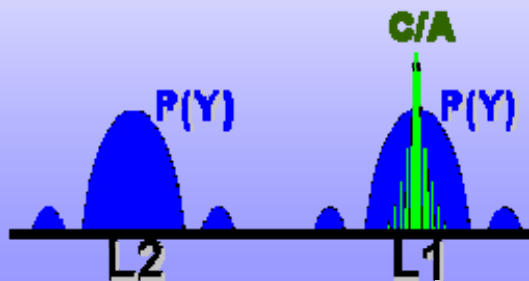


Block III



IIA / IIR: Basic GPS

- C/A civil signal (L1C/A)
- Std Service, 16-24m SEP
- Precise Service, 16m SEP
 - L1 & L2 P(Y) nav

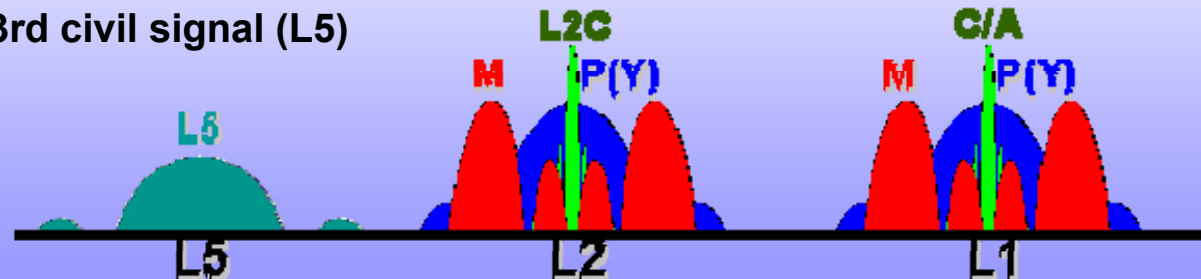


IIR-M: IIA/IIR capabilities &

- 2nd civil signal (L2C)
- New military code
- Flex A/J power (+7dB)

IIF: IIR-M capability plus

- 3rd civil signal (L5)



III: IIF capabilities &

- Improved civil signal (L1C)
- Increased accuracy (4.8-1.2m)
- Evaluating integrity improvements
- Navigation surety
 - Increased A/J power (+20 dB)

GPS III

- Concept Definition completed in 2005
- Contract issued 2008
- GPS-III (2013 ? -): New features are being considered to increase reliability and accuracy
 - Faster time to alert or correct failures (integrity)
 - More accuracy
 - More availability
 - Increased signal strength

GNSS Interoperability Issues

- Coordinate System
 - GPS and Galileo plan on using the same system: ITRF
 - Glonass uses a slightly different system
- Time Scale
 - GPS and Galileo have agreed to transmit the GPS/Galileo Time Offset (GGTO)
 - Goal: an objective of **three nanoseconds** (one meter) accuracy for the GGTO message has been accepted
 - Glonass uses a different time scale, though known relationships are kept within bounds
- Signal Compatibility
 - Generally all systems can be received by the same system

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Failure Modes

- GPS best feature and worst problem: it is extremely reliable
- Satellite failure modes can produce signals with large errors
 - Receiver Autonomous Integrity Monitoring (RAIM) should compare all satellite signals and discard errors
 - System design should compare GPS-based clock to local signals
- Receiver problems
 - Satellites set unhealthy should not be used
 - Firmware errors and wrong interpretations of specs
 - Ionosphere/troposphere models
 - Leap seconds
- Jamming: intentional and unintentional

GNSS Signals Are Vulnerable to Jamming

- Signals can be easily jammed
- Several incidents of accidental jamming
- Most telecom receivers can go into holdover for at least a week with few ill effects
- Wireless base-stations can be affected adversely

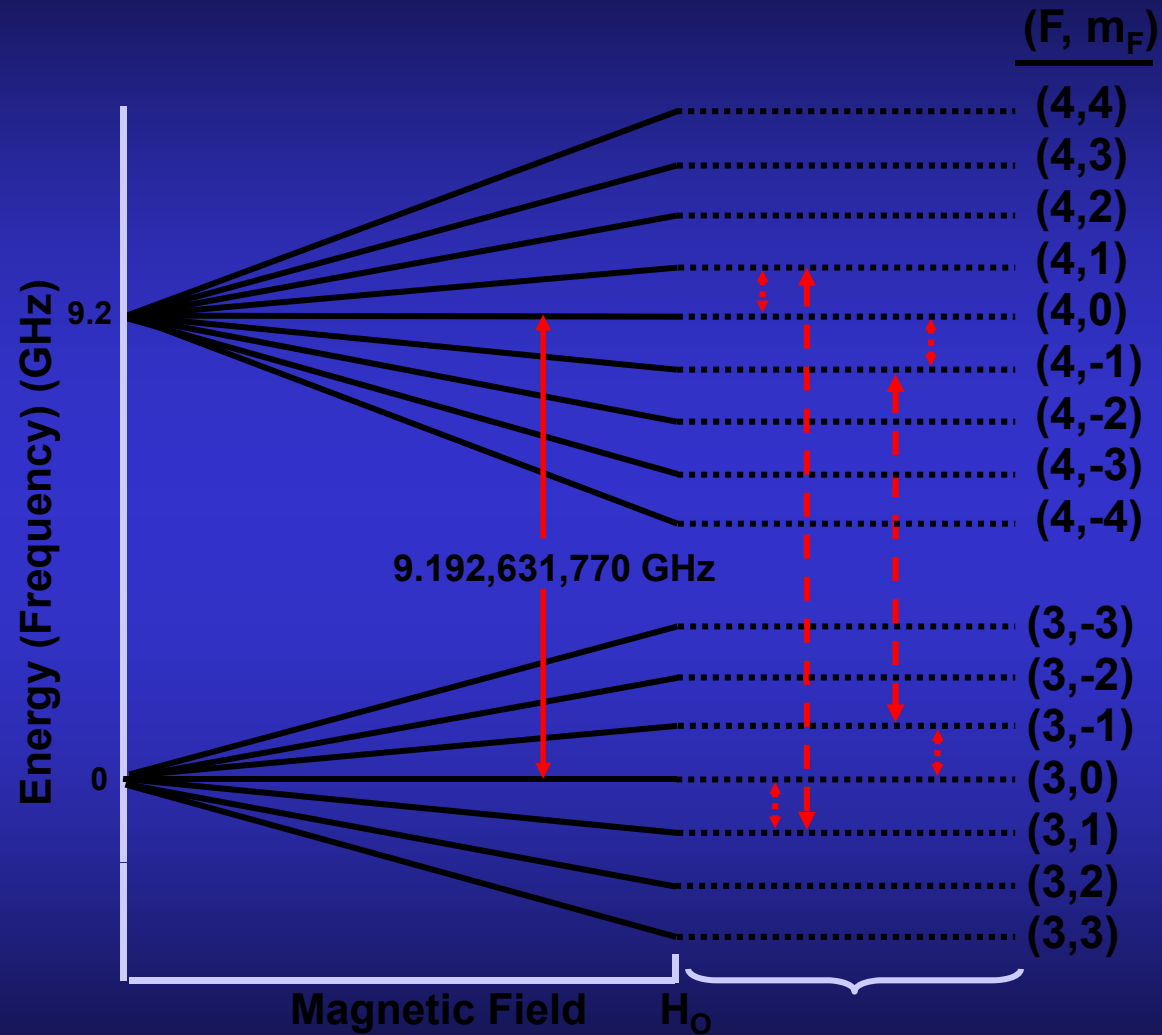
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Atomic Frequency Standards

1. Atoms have discrete energy levels
2. Atoms change energy levels by emitting or absorbing a photon at the right frequency
3. Frequency is proportional to energy difference:
 $\Delta E = h\nu$
4. An atomic clock produces a frequency which is locked to an atomic transition from one energy level to another

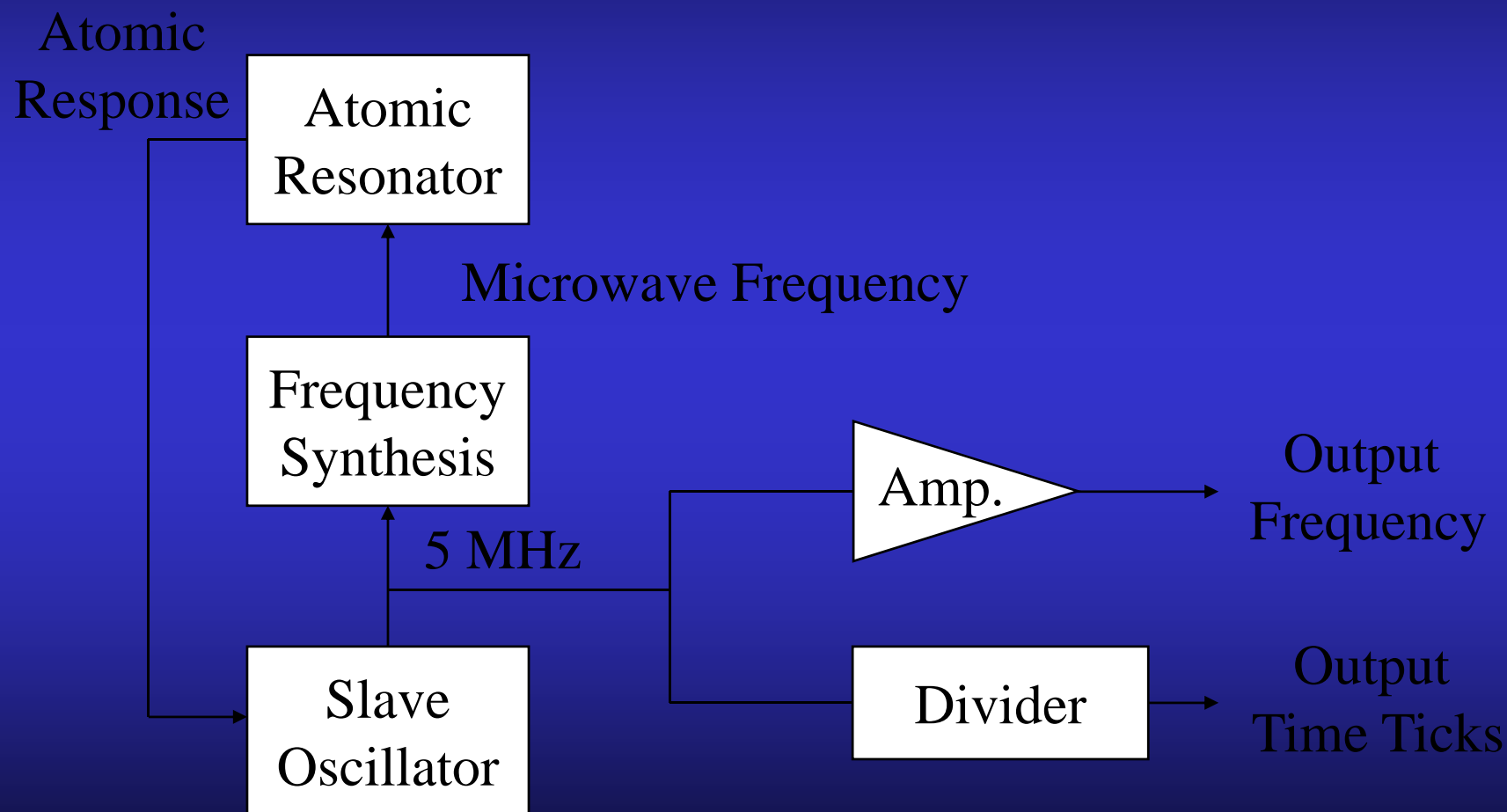
Energy Levels for the Cs Atom



Basic Passive Atomic Clock

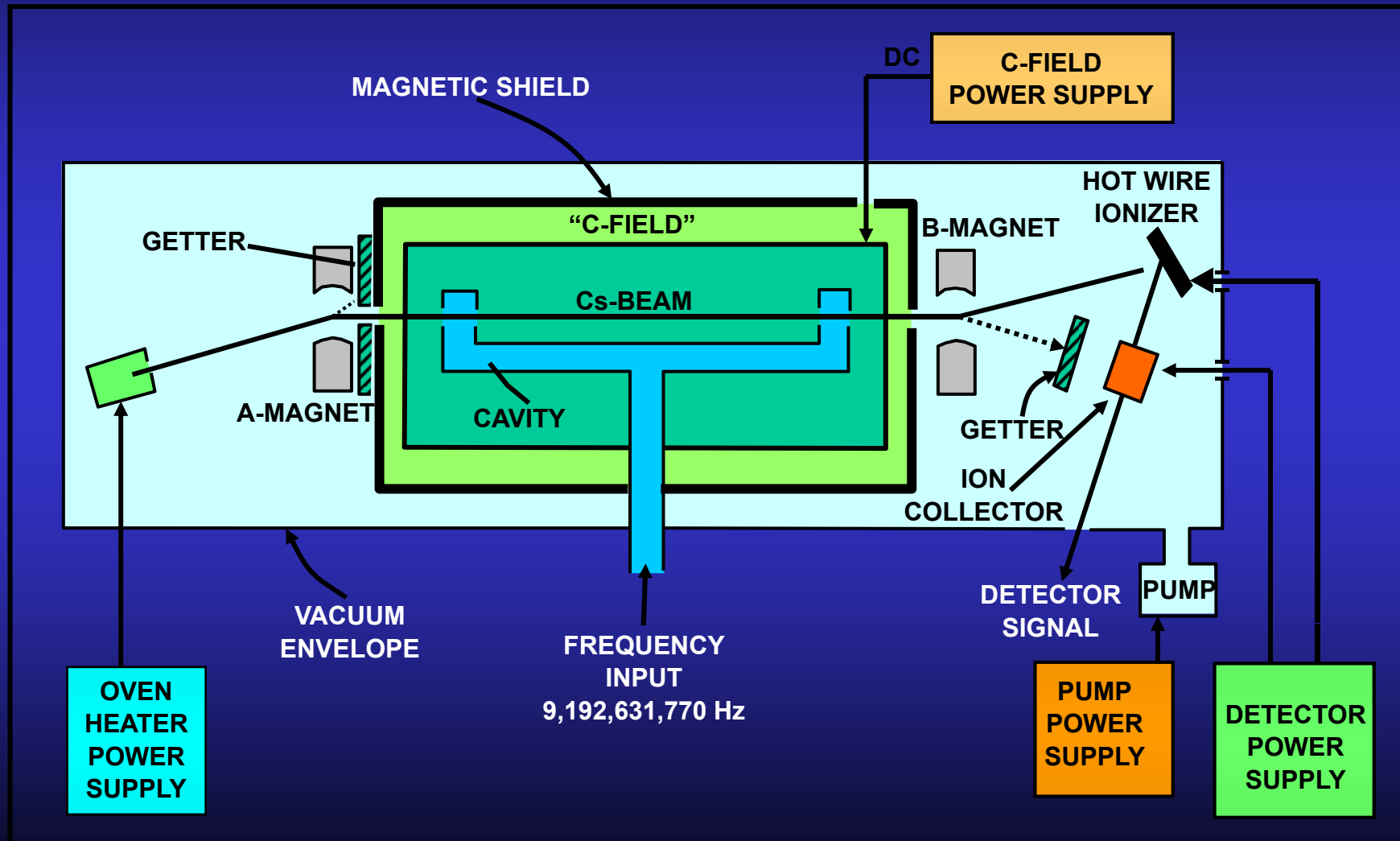
- Obtain atoms to measure
- Depopulate one hyperfine level
- Radiate the state-selected sample with frequency ν
- Measure how many atoms change state
- Correct ν to maximize measured atoms in changed state

Block Diagram of Atomic Clock *Passive Standard*

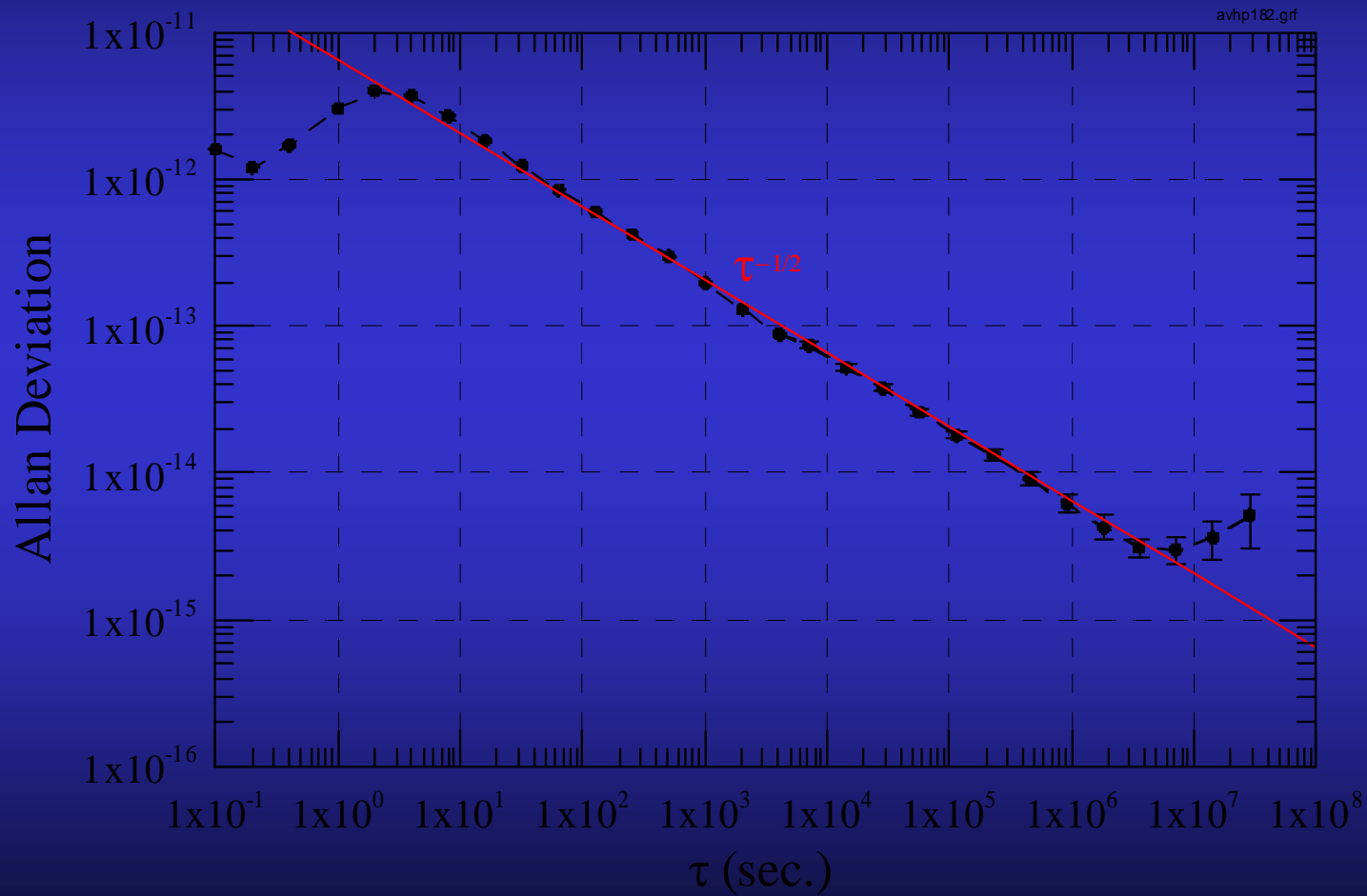


Cesium Standard

(Thermal Beam)

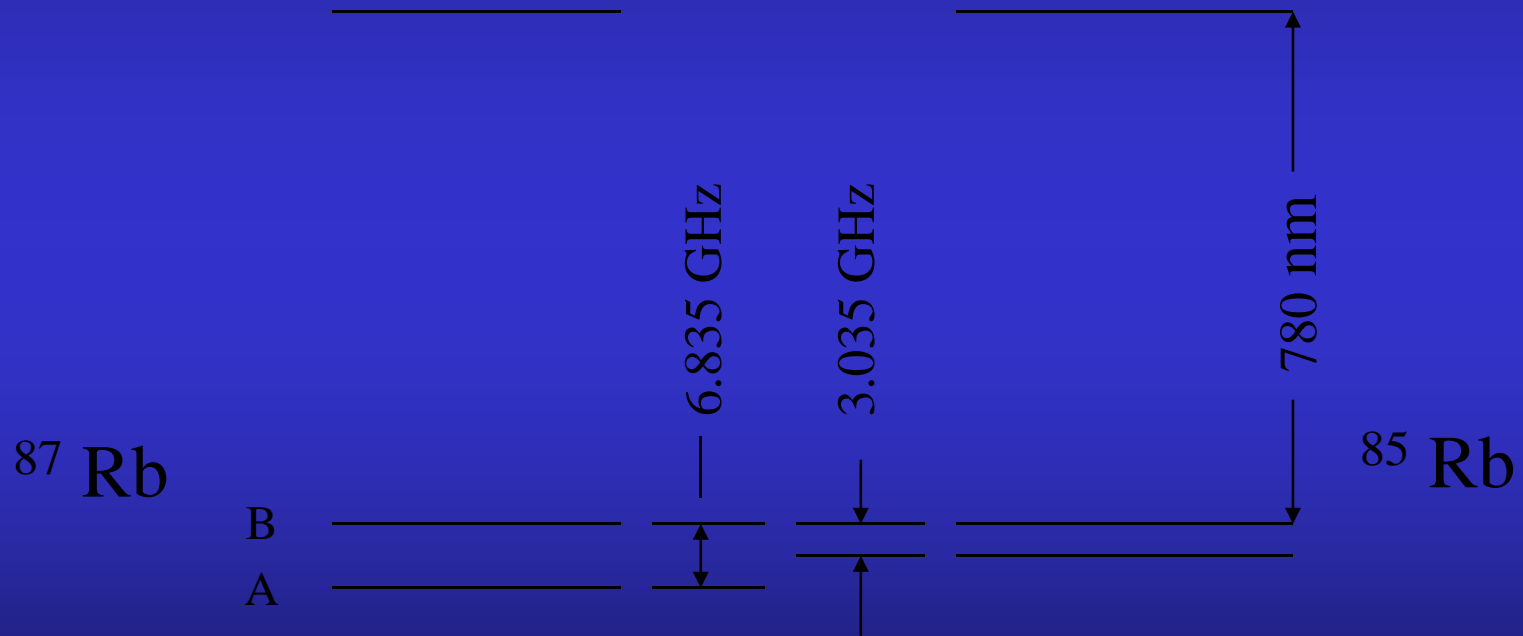


Frequency Stability of a Cesium Standard (No frequency drift removed)

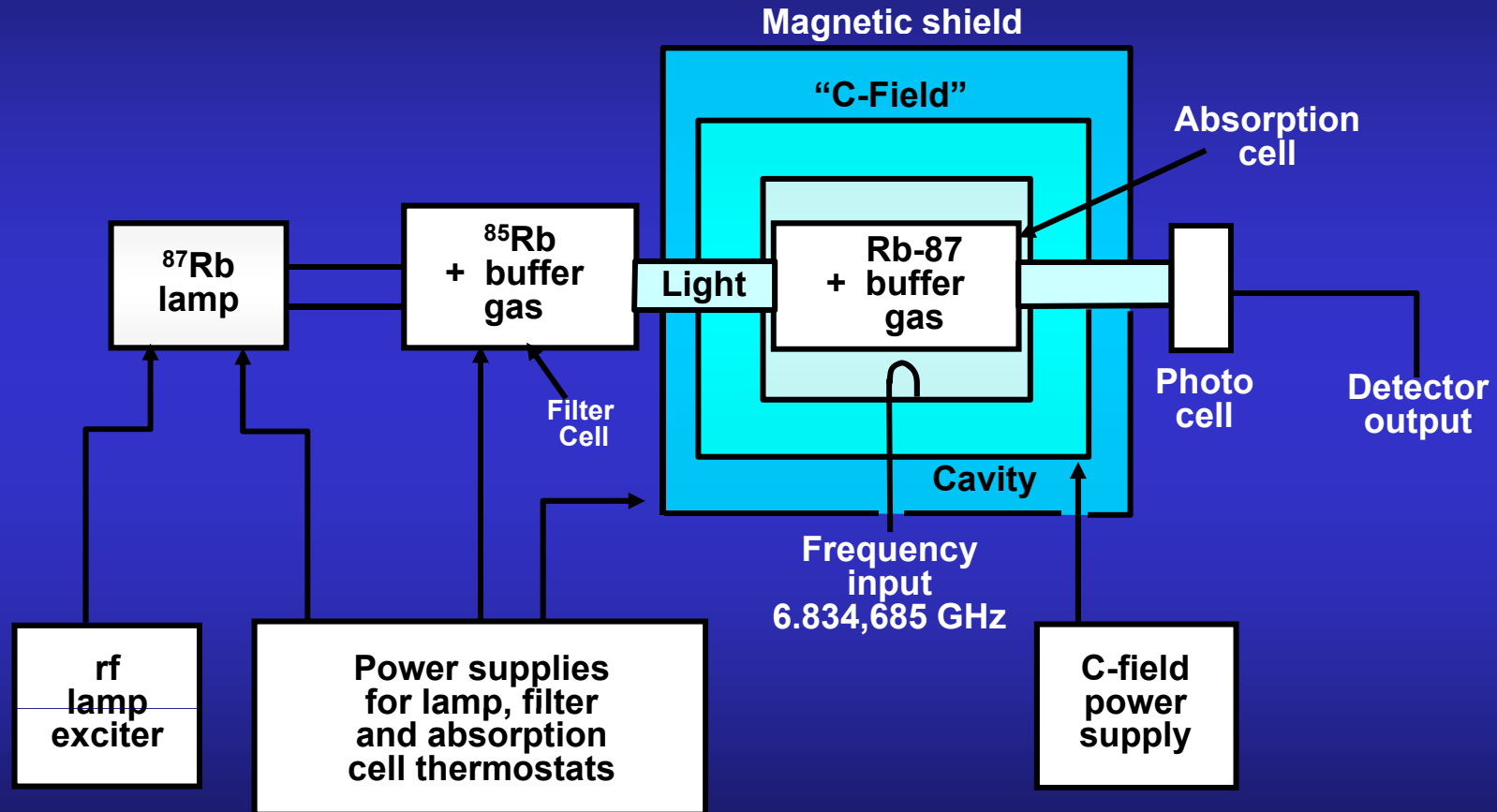


Optical Microwave Double Resonance

Simplified Rb energy level diagram

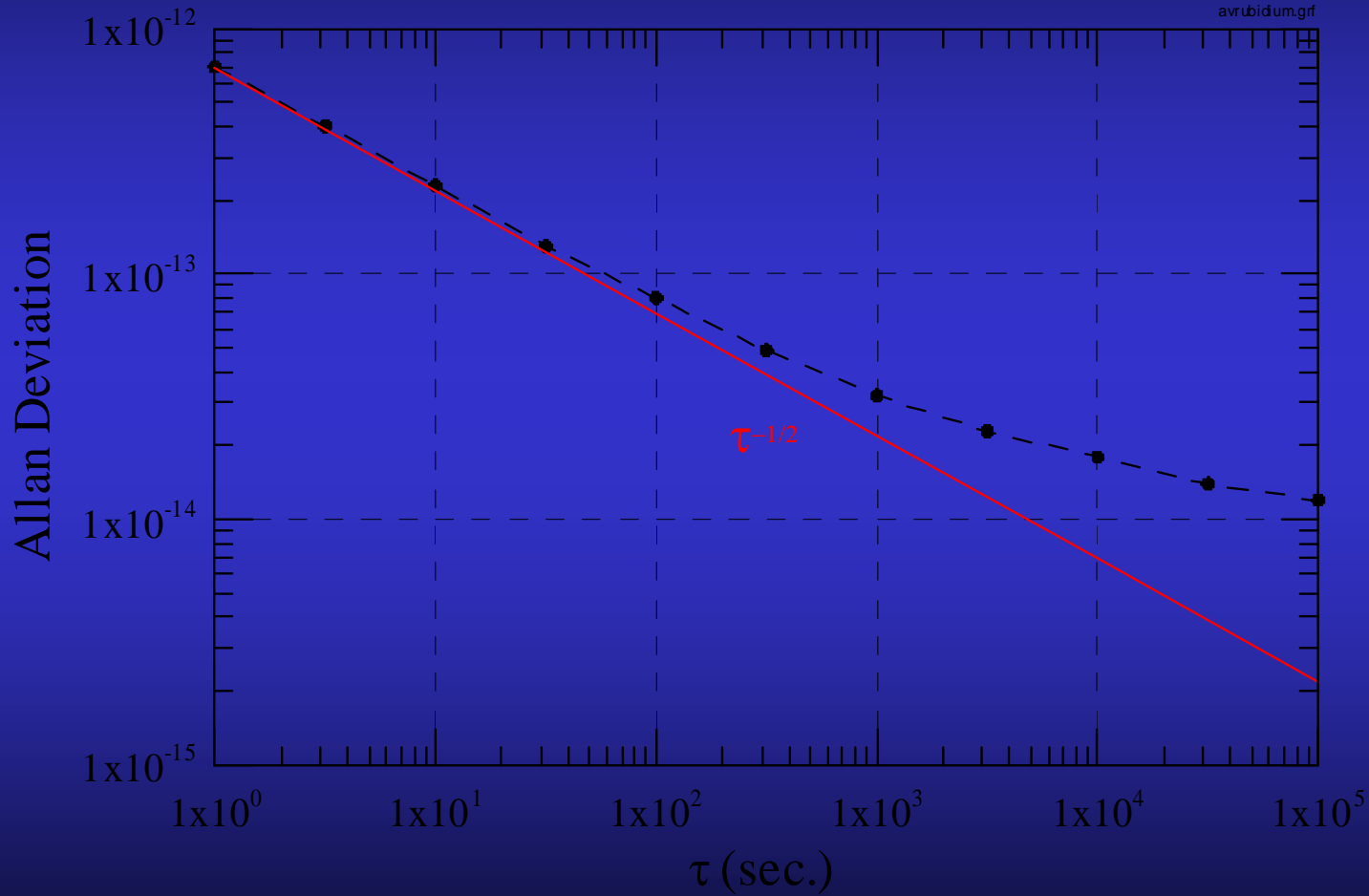


Rubidium Standard (Gas Cell)



Adapted from figure by John Vig

Frequency Stability of a Rubidium Standard (Frequency drift removed – 3×10^{-13} /day typical)



Courtesy of Bill Riley

Primary & 'Almost' Primary Reference Sources

Parameters (benign environment; $\pm 5^{\circ}\text{C}$)	Cs Beam Frequency Std.	GPS disciplined* Rb T/F System	Passive Hydrogen Maser (Russia) ($\sim 1\text{E}-15/\text{day}$ aging)	Hi Performance Rb Oscillator ($5\text{E}-12/\text{mo.}$ aging)
Frequency Accuracy Free-run 30 Days Free-run 100 Days	$\pm 1\text{E}-12$ for Life $\pm 1\text{E}-12$ $\pm 1\text{E}-12$	$< \pm 1\text{E}-12$ $< \pm 1\text{E}-11$ $\sim \pm 1\text{E}-11$	$\sim \pm 5\text{E}-14$ after Cal $< \pm 5\text{E}-14$ $\pm 1\text{E}-13$	$\pm 1\text{E}-12$ after Cal $< \pm 1\text{E}-11$ $< \pm 2\text{E}-11$
Time Accuracy Free-run 30 Days Free-run 100 Days	Only after Calib'n $\sim \pm 3$ us $\sim \pm 10$ us	50 ns peak of UTC < 20 us < 50 us	Only after Calib'n < 1 us < 2 us	Only after Calib'n < 50 us < 100 us
Stability at 10^5 s GPS C/A signal GPS P(Y) Signal No GPS Signal	$\sim 1\text{E}-14$ N/A N/A N/A	- $< 2\text{E}-13$ $< 2\text{E}-14$ $\sim 1\text{E}-13$	$< 5\text{E}-15$ N/A N/A N/A	$\sim 1\text{E}-13$ N/A N/A N/A
Reliability	$\sim 5\%$ Return/Yr.	$\sim 0.5\%$ Return/Yr.	$< 10\%$ Return/Yr. ?	$< 0.5\%$ Return/Yr.
Lifetime Expectancy	7 to 10 yrs, then Cs Tube Replacement	25 years	4 to 6 yrs.?, then Getter & H_2 Supply Replacement	25 years +
Size	19" Rack, 3 to 5U	19" Rack, 1U & $<$	19" Rack, $\sim 5\text{U}$	20 in ³
Portability & Weight	No / < 40 lbs.	Yes / < 15 lbs.	No / < 50 lbs.	Very / < 4 lbs.
Cost Range	\$25K to \$50K	\$8K to \$12K	\$20K to \$30K	\$3K to \$5K

Courtesy H. Fruehauf, ViaLogy LLC

*Optimized GPS disciplining and Rb Osc. modeling algorithm

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Conclusions

- **GNSS Now**
 - Global GPS civil service performance commitment met/exceeded continuously since Dec 93
 - Glonass operational, committed to replenish
 - Galileo, Compass with experimental satellites
- **GNSS Future**
 - GPS: new signals, more accuracy, yet backward compatible, more integrity information
 - New/other systems: Glonass, Galileo, Compass, QZSS
- **GPS/GNSS failure modes:** they exist and there are precautions
- **Atomic Frequency Standards**
 - Cs. provides stratum 1 frequency, needs time calibration
 - Rb. Provides excellent hold-over

- **Resources are available:** see next slide

GNSS Resources

- U.S. Coast Guard Navigation Information Center
 - Voice Announcement ++1-703-313-5907
 - Resource Person ++1-703-313-5900
 - Web Page <http://www.navcen.uscg.gov/>
 - Civil GPS Service Interface Committee (CGSIC) – GNSS status and other info:
http://www.navcen.uscg.gov/cgsic/meetings/48thMeeting/48th_CGSIC_agenda_final.htm
- U.S. Space-Based Positioning, Navigation, and Timing Policy: <http://pnt.gov/policy/>
- International GNSS Service (IGS)
 - <http://igscb.jpl.nasa.gov/>
- US Timing Labs
 - NIST info: <http://www.boulder.nist.gov/timefreq/index.html>
 - U.S. Naval Observatory: <http://tycho.usno.navy.mil/gpstt.html>
- GPS World: www.gpsworld.com
- Inside GNSS: www.insidegnss.com
- Institute of Navigation www.ion.org