Sync Sources: GNSS and Atomic Clocks

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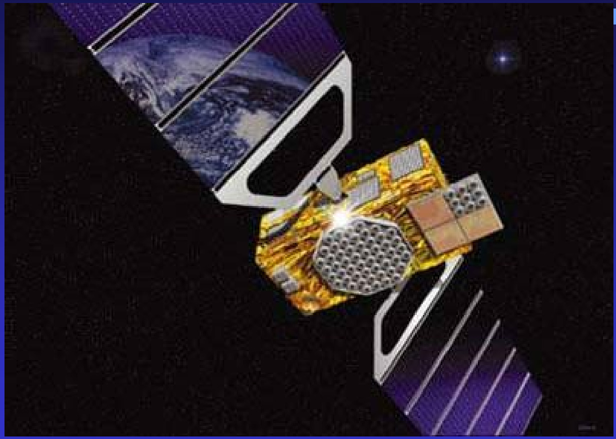
Sync Sources: GNSS and Atomic Clocks

- **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

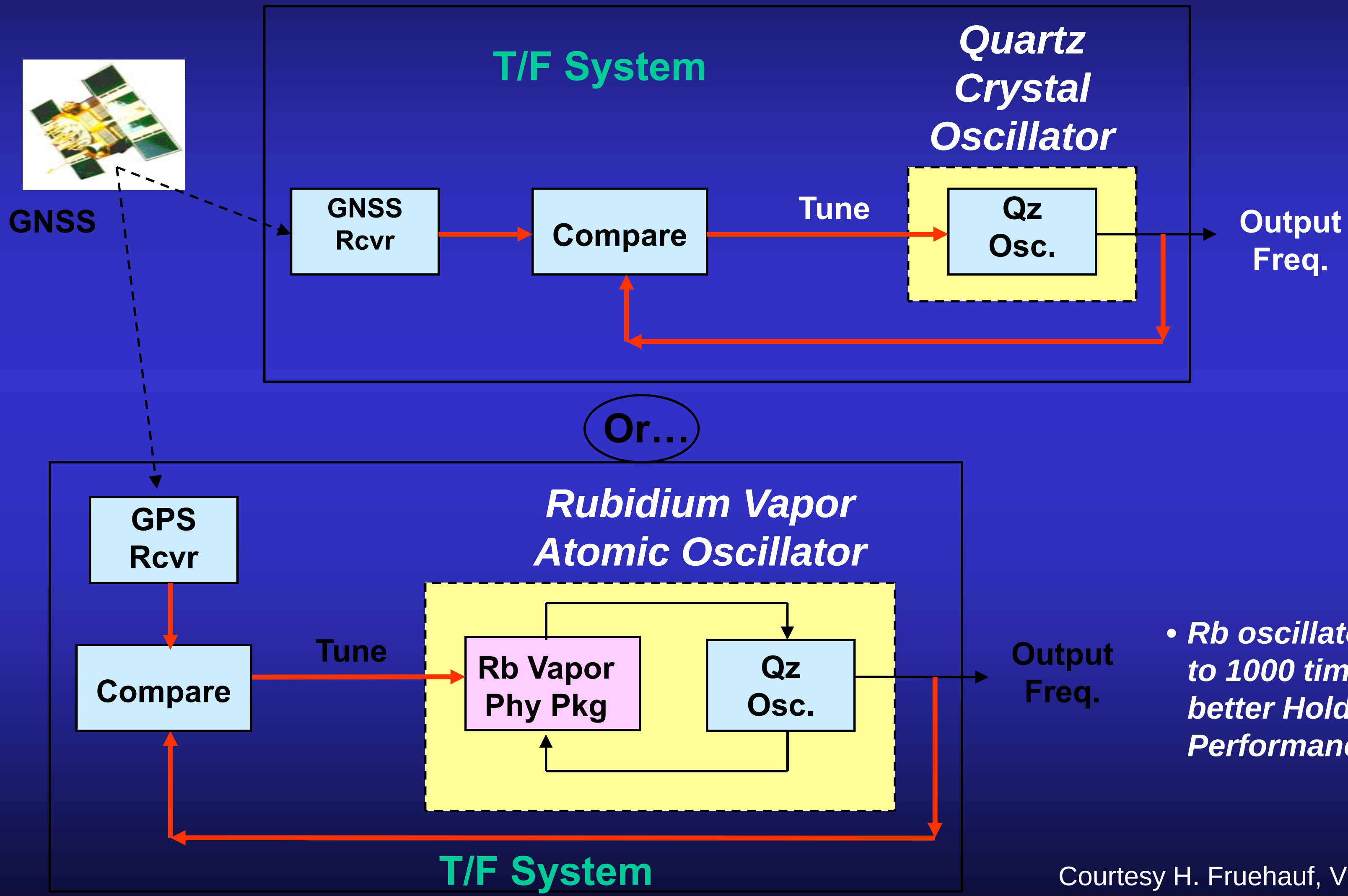
China/India - GAGAN

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



- ***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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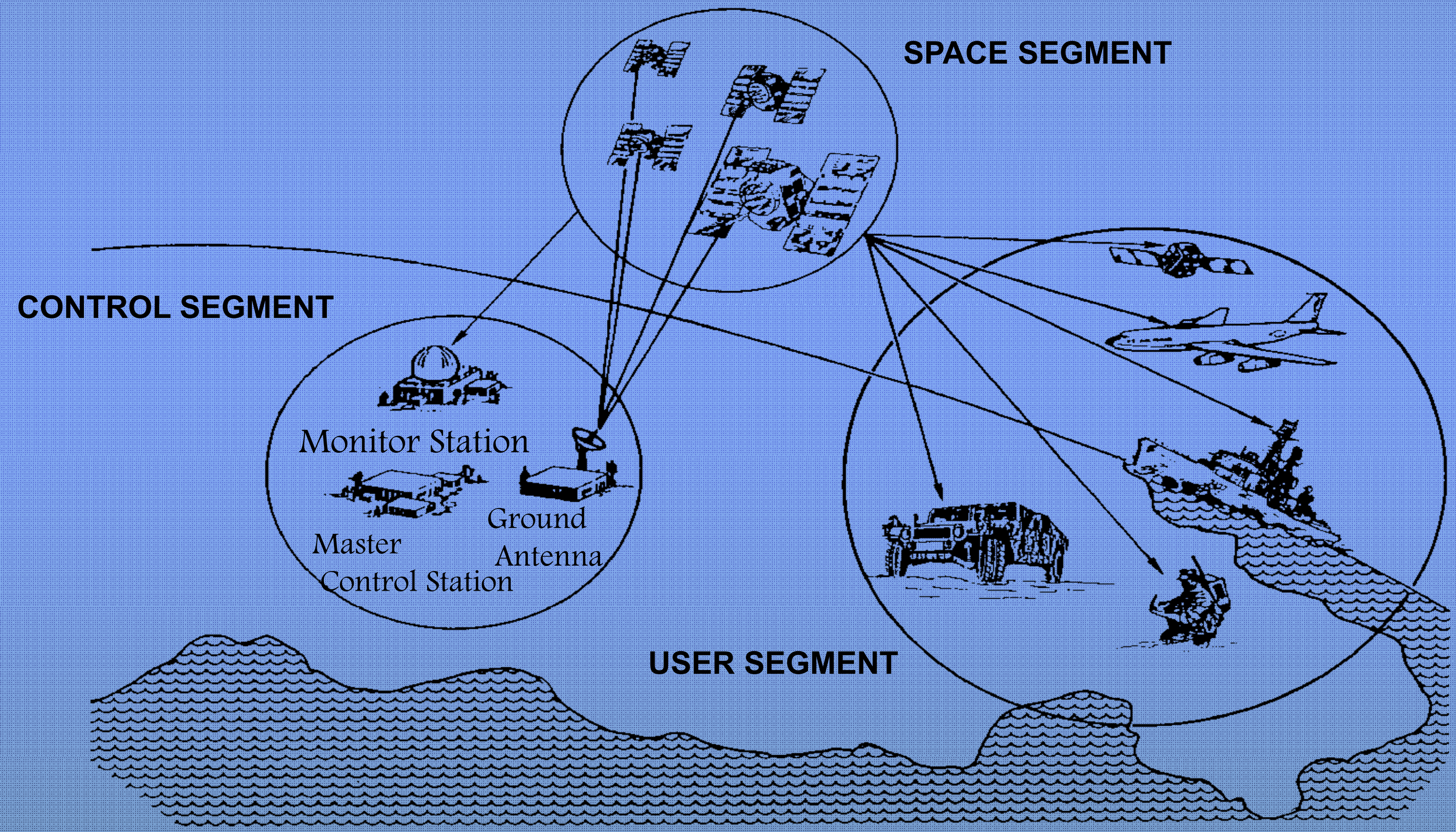
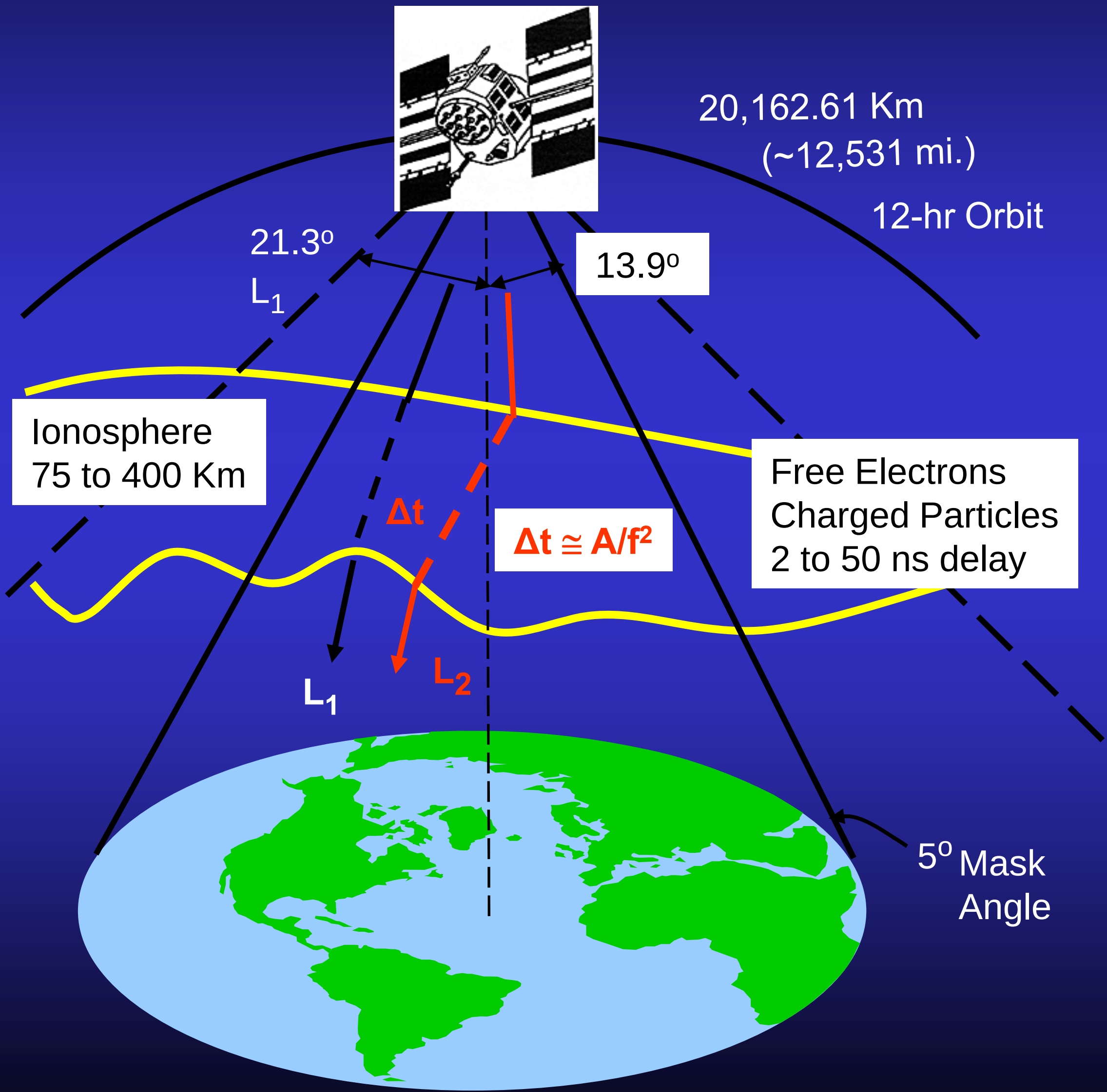
GPS (GNSS) System Configuration - Three Major Segments



GPS Satellite Signals



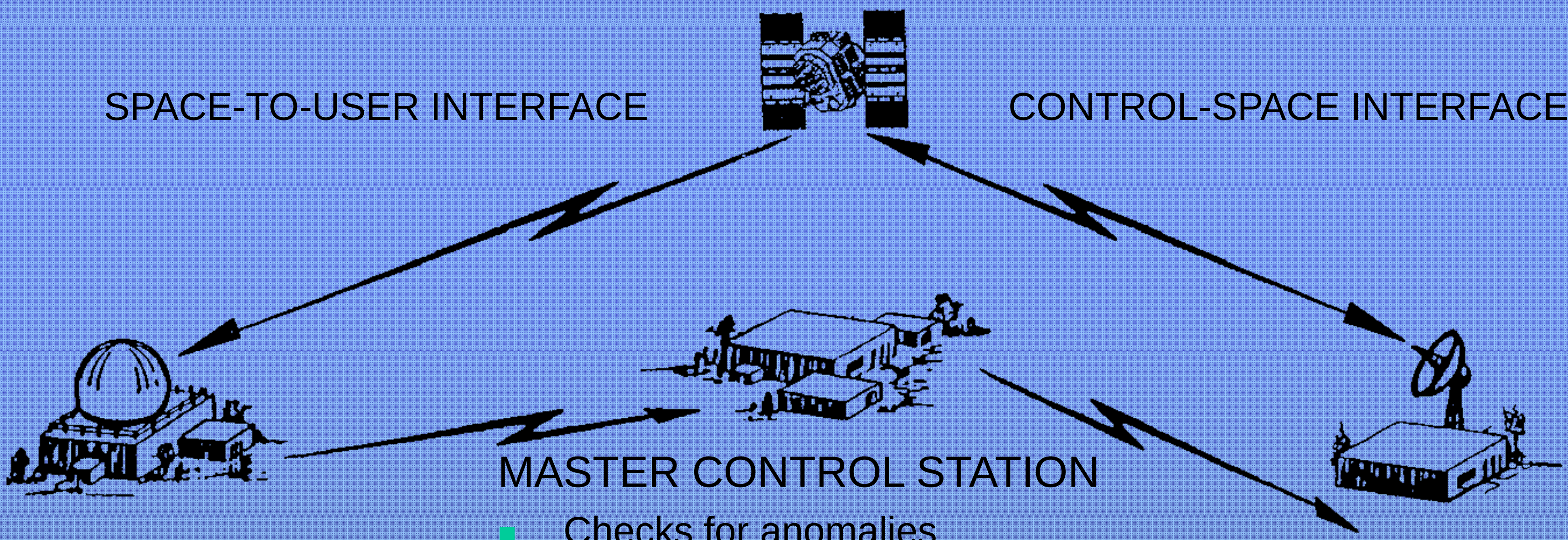
- L_1 1575.42 MHz
  C/A-Code 1.023 Mcps,
  P-Code 10.23 Mcps
  Data 50 bps
- L_2 1227.6 MHz
  P-Code 10.23 Mcps
  Data 50 bps
- **Four Satellites needed for 3-D navigation**
- **Maximum Doppler Shift between Satellites ~ ± 6KHz**

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



MONITOR STATION

- Sends raw observations to MCS

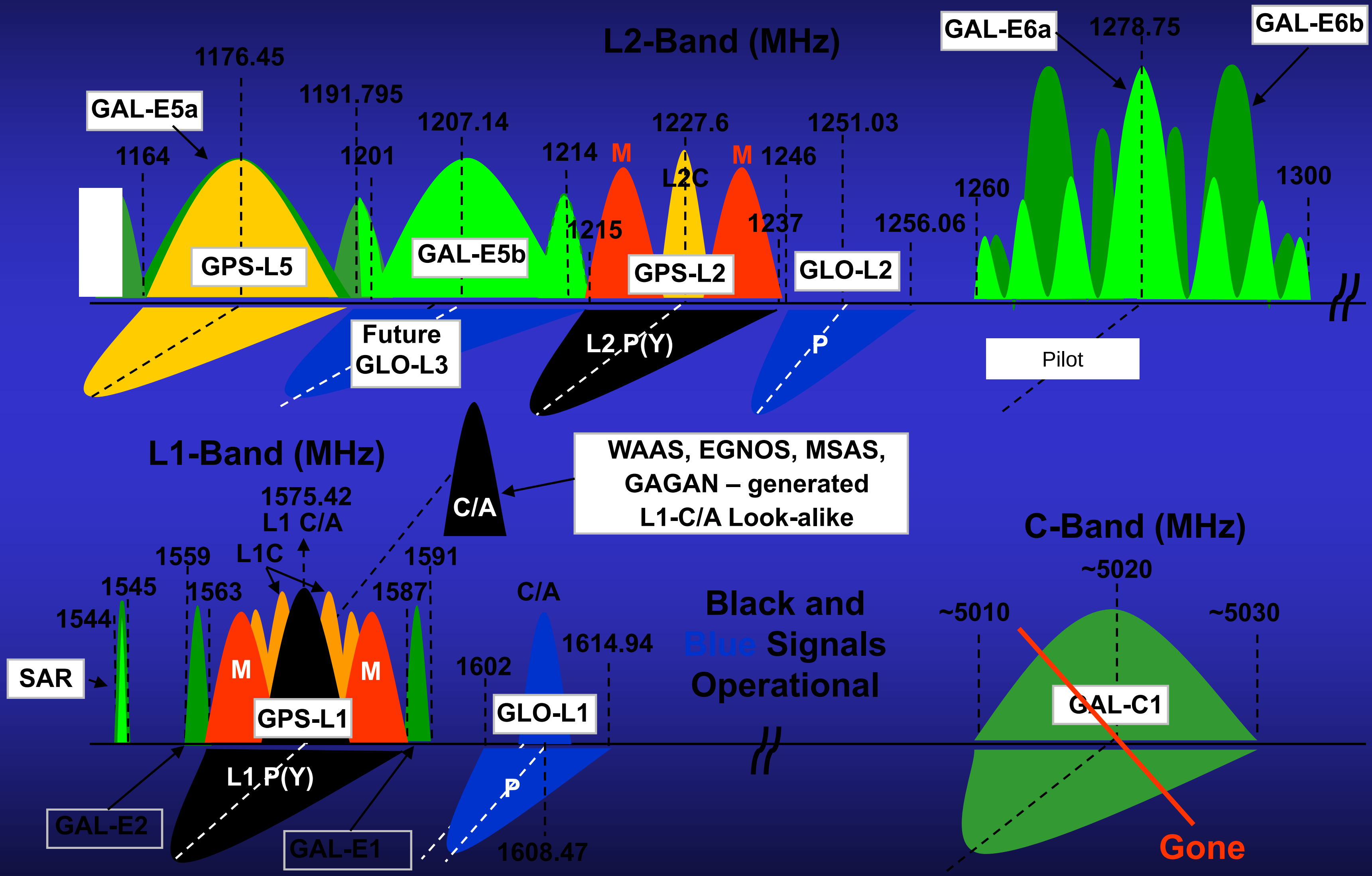
MASTER CONTROL STATION

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

GROUND ANTENNA

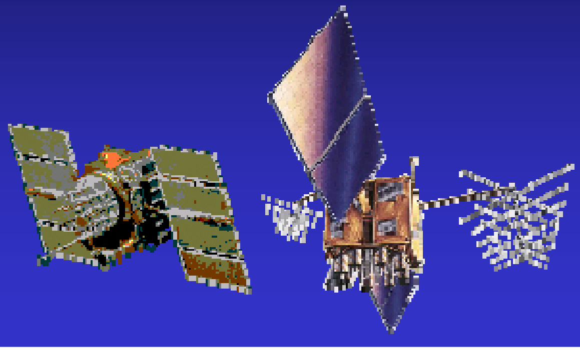
- Sends new upload to SV

Present & Upcoming GPS, Glonass & Galileo Signals

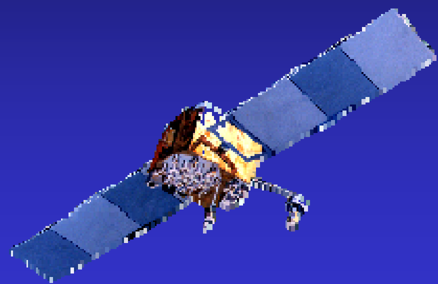


GPS Modernization Plan

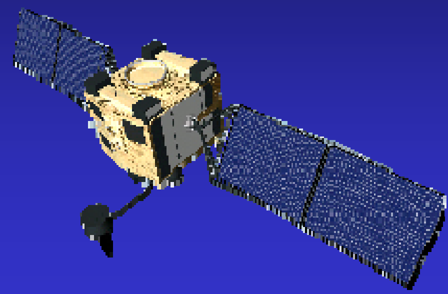
Block IIA/IIR



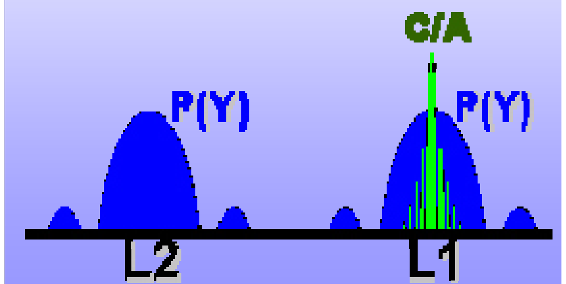
Block IIR-M, IIF



Block III



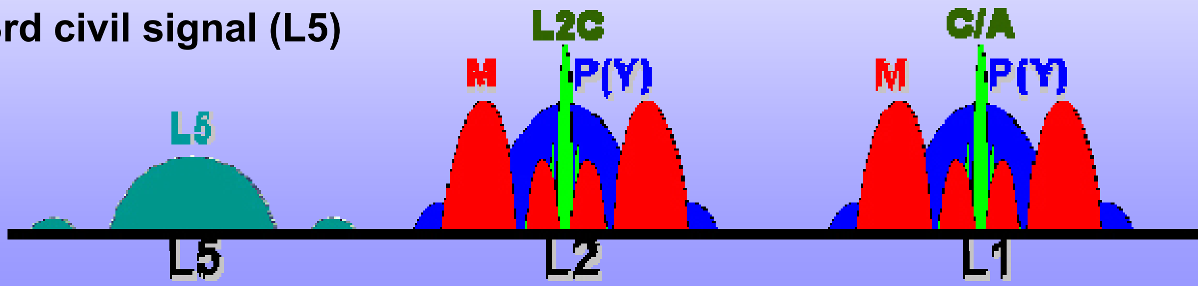
IIA / IIR: Basic GPS
- C/A civil signal (L1C/A)
- Std Service, 16-24m SEP
- Precise Service, 16m SEP
  - L1 & L2 P(Y) nav



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

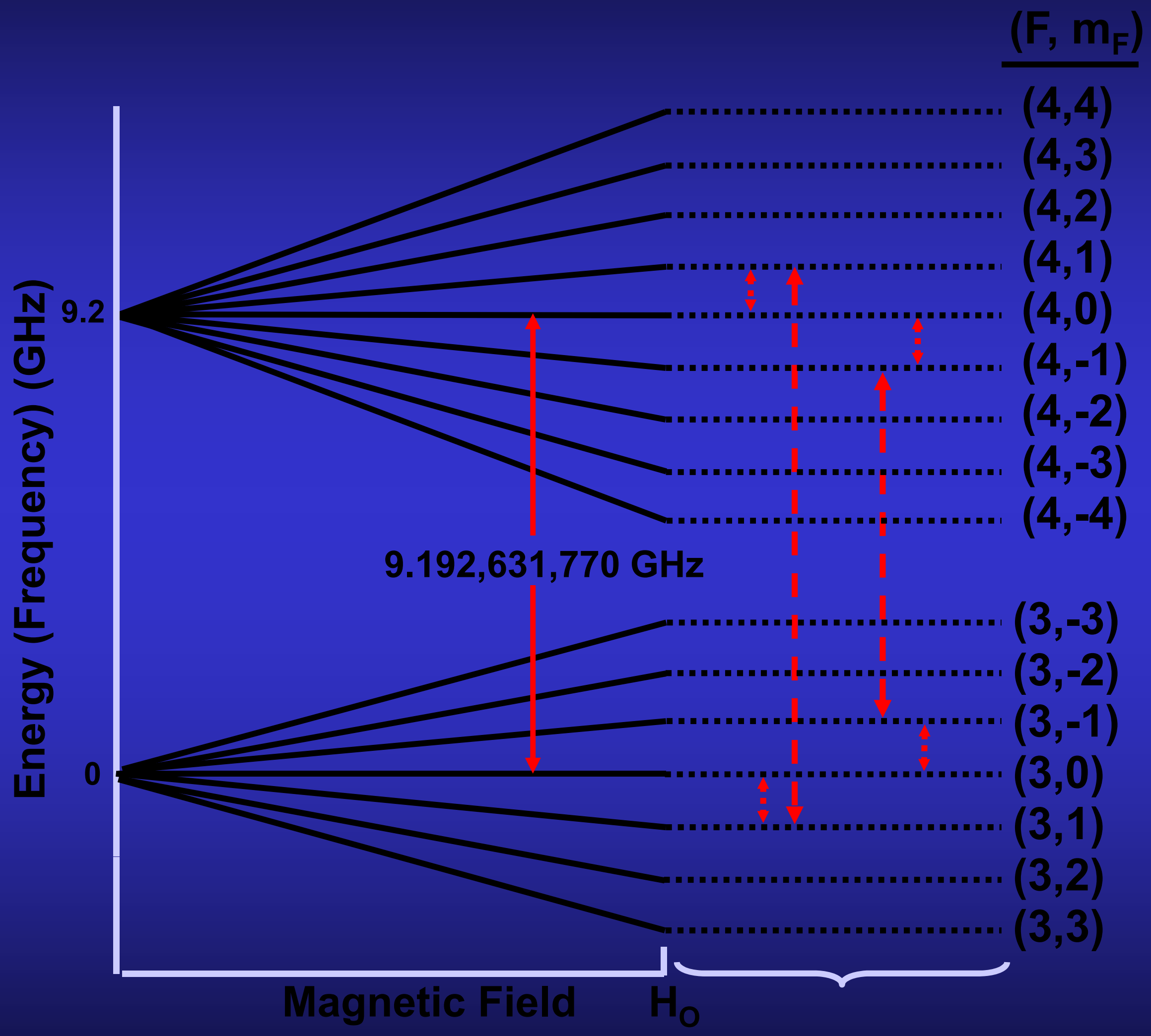
1. Atoms have discrete energy levels

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

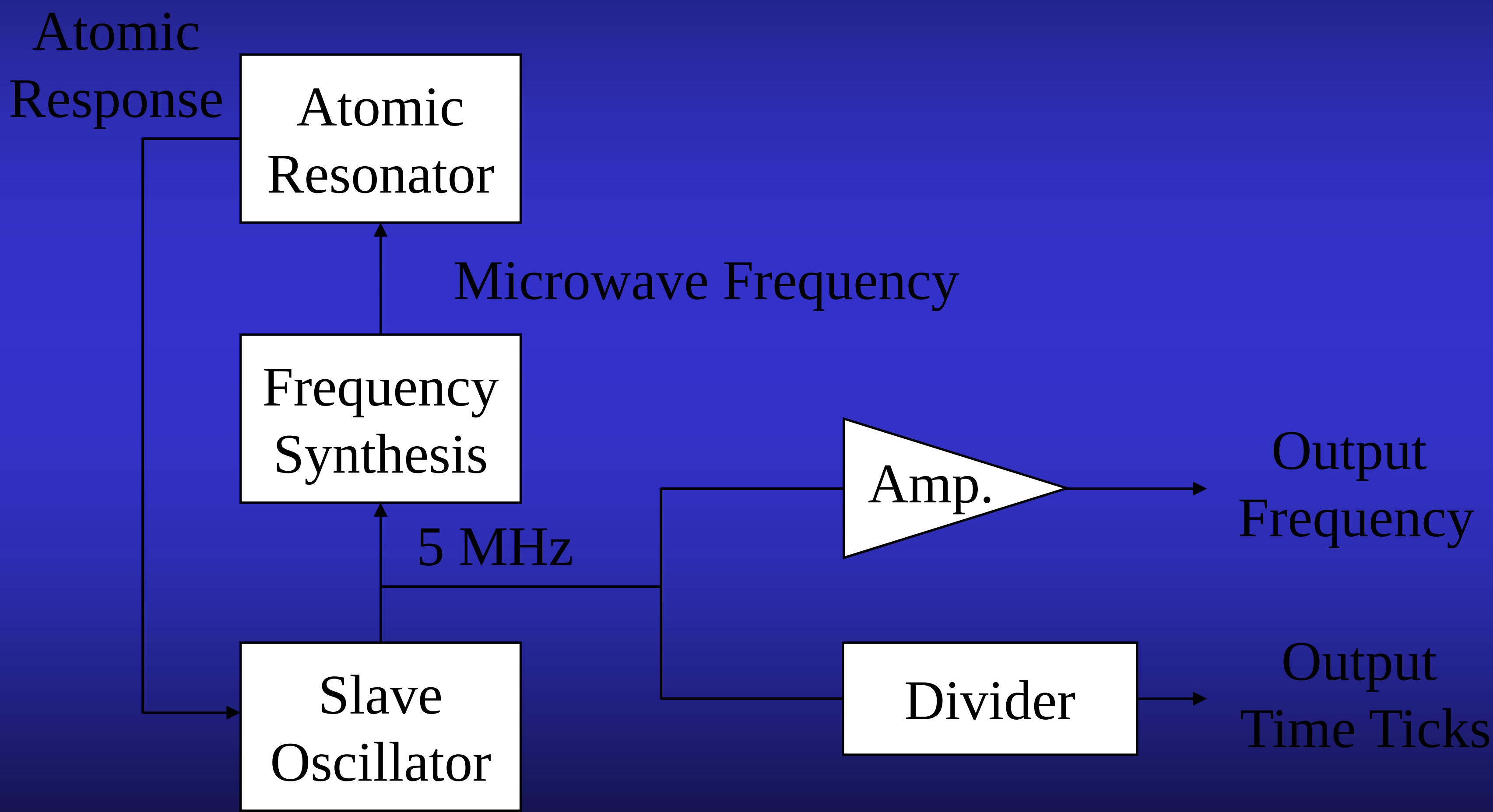


Basic Passive Atomic Clock

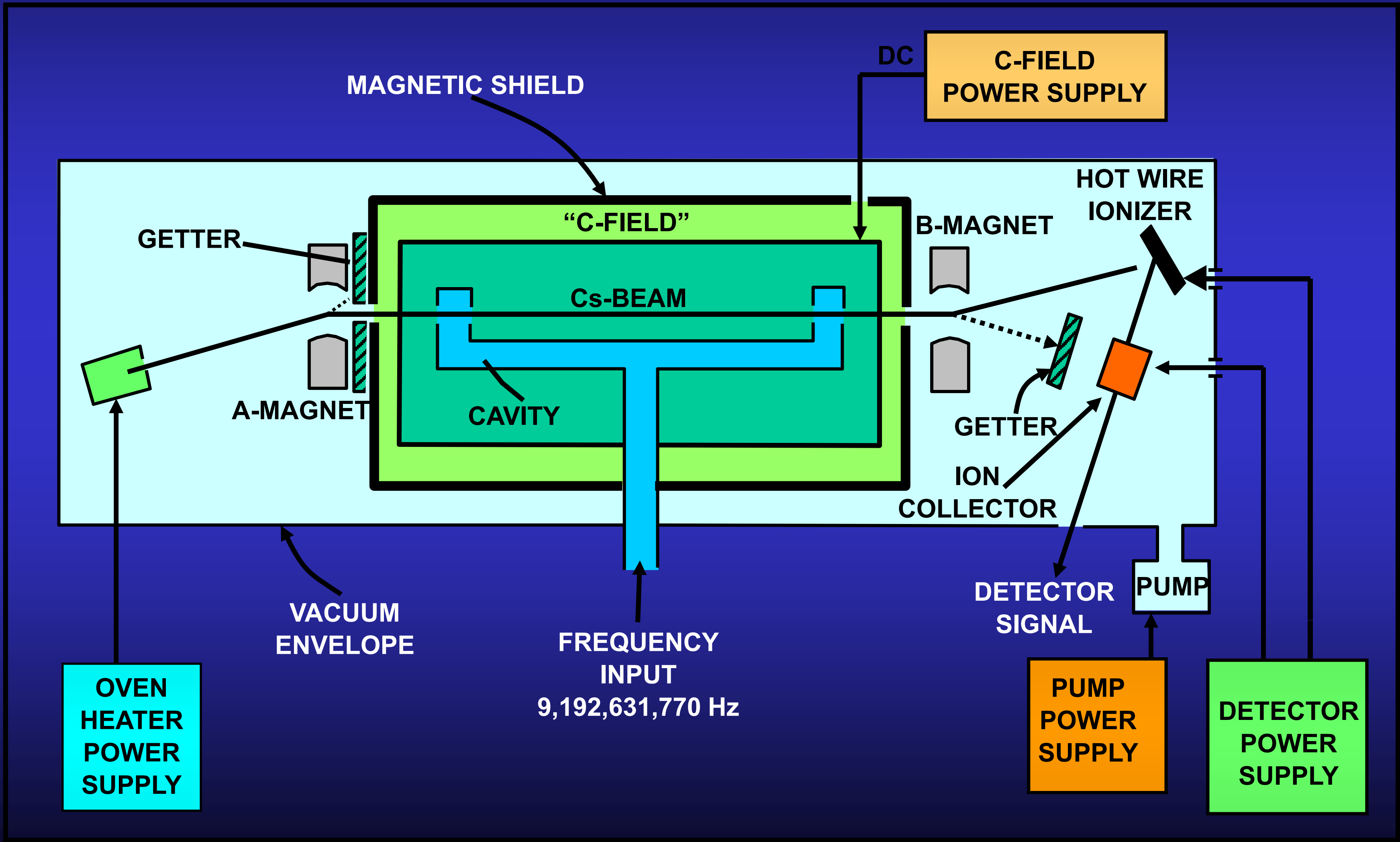
- Obtain atoms to measure
- Depopulate one hyperfine level
- Radiate the state-selected sample with frequency ν
- Measure how many atoms change state
- Correct ν to maximize measured atoms in changed state

Block Diagram of Atomic Clock

Passive Standard

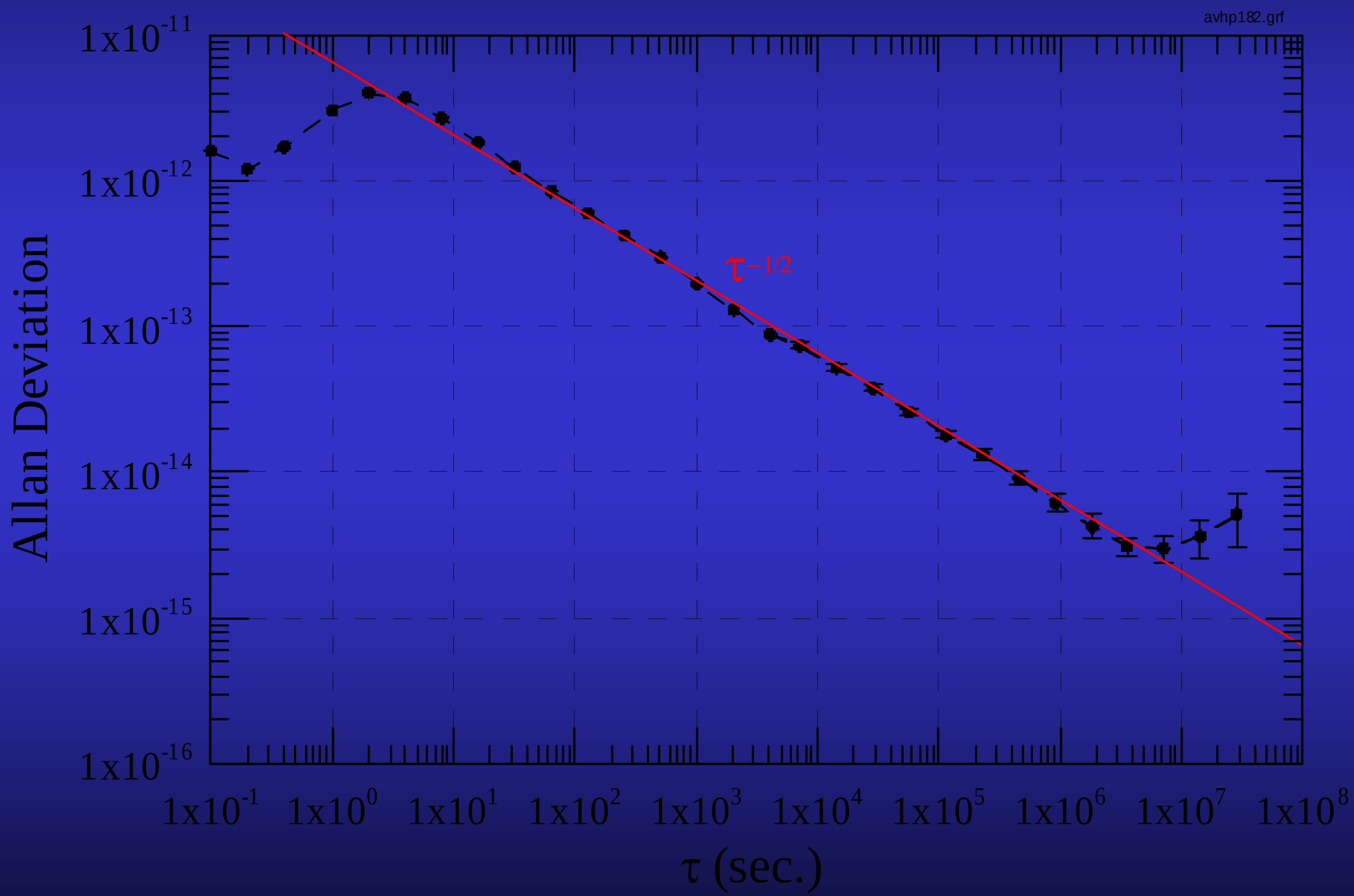


Cesium Standard
(Thermal Beam)

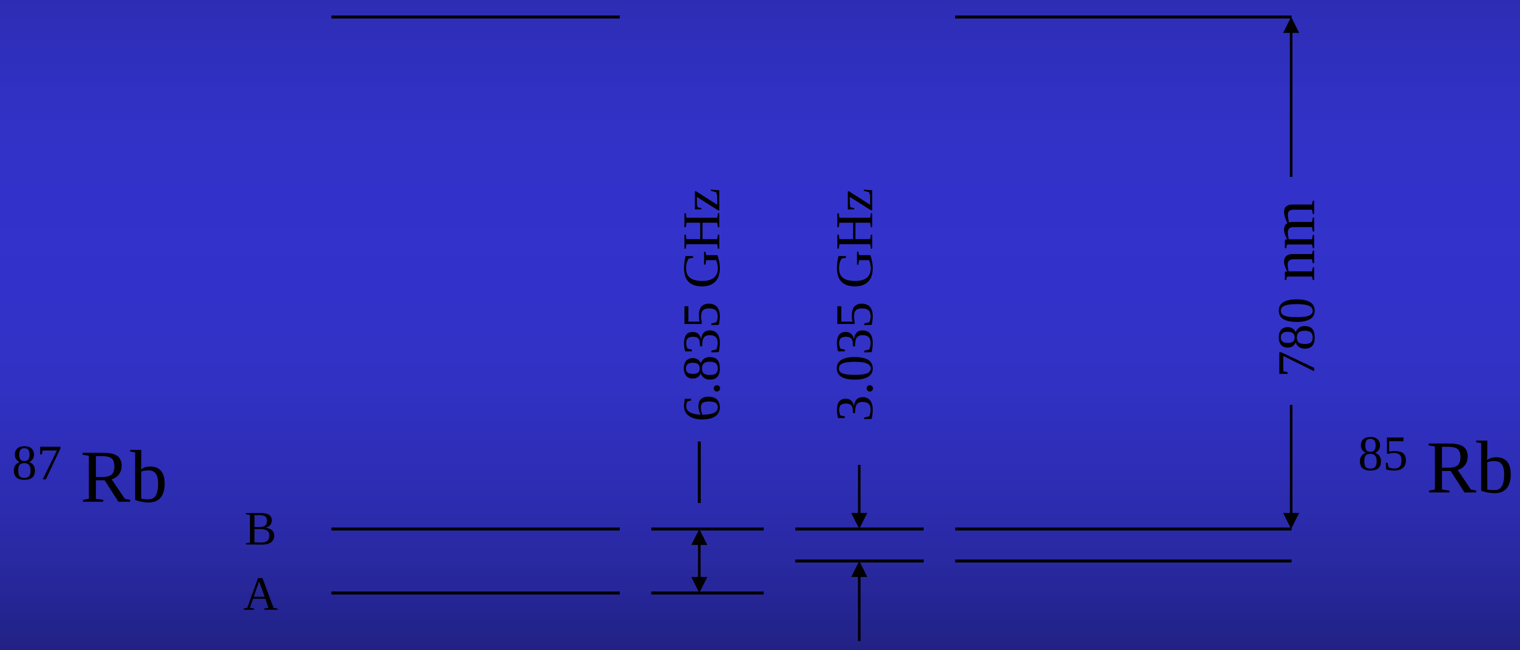


Frequency Stability of a Cesium Standard

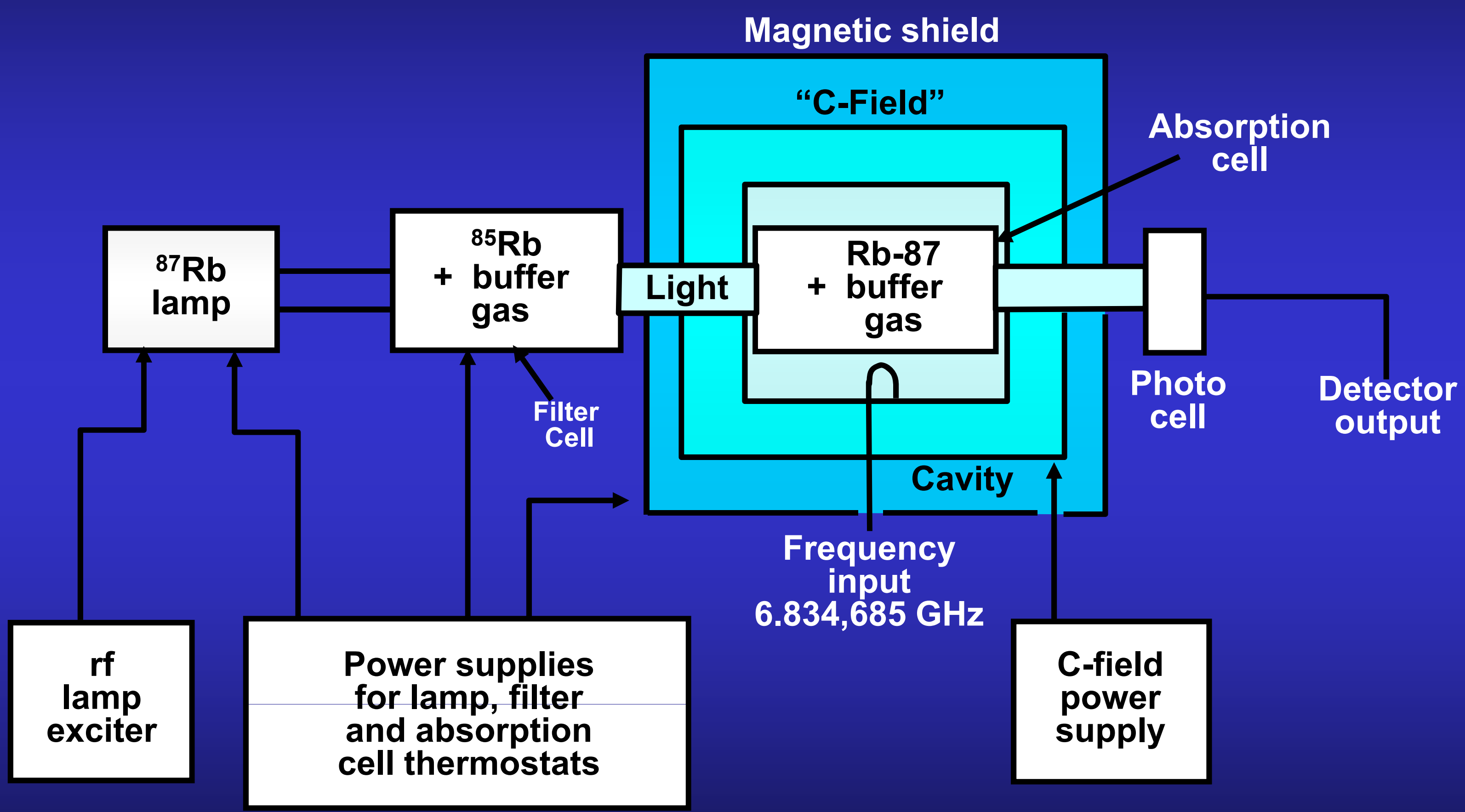
(No frequency drift removed)



Optical Microwave Double Resonance
Simplified Rb energy level diagram



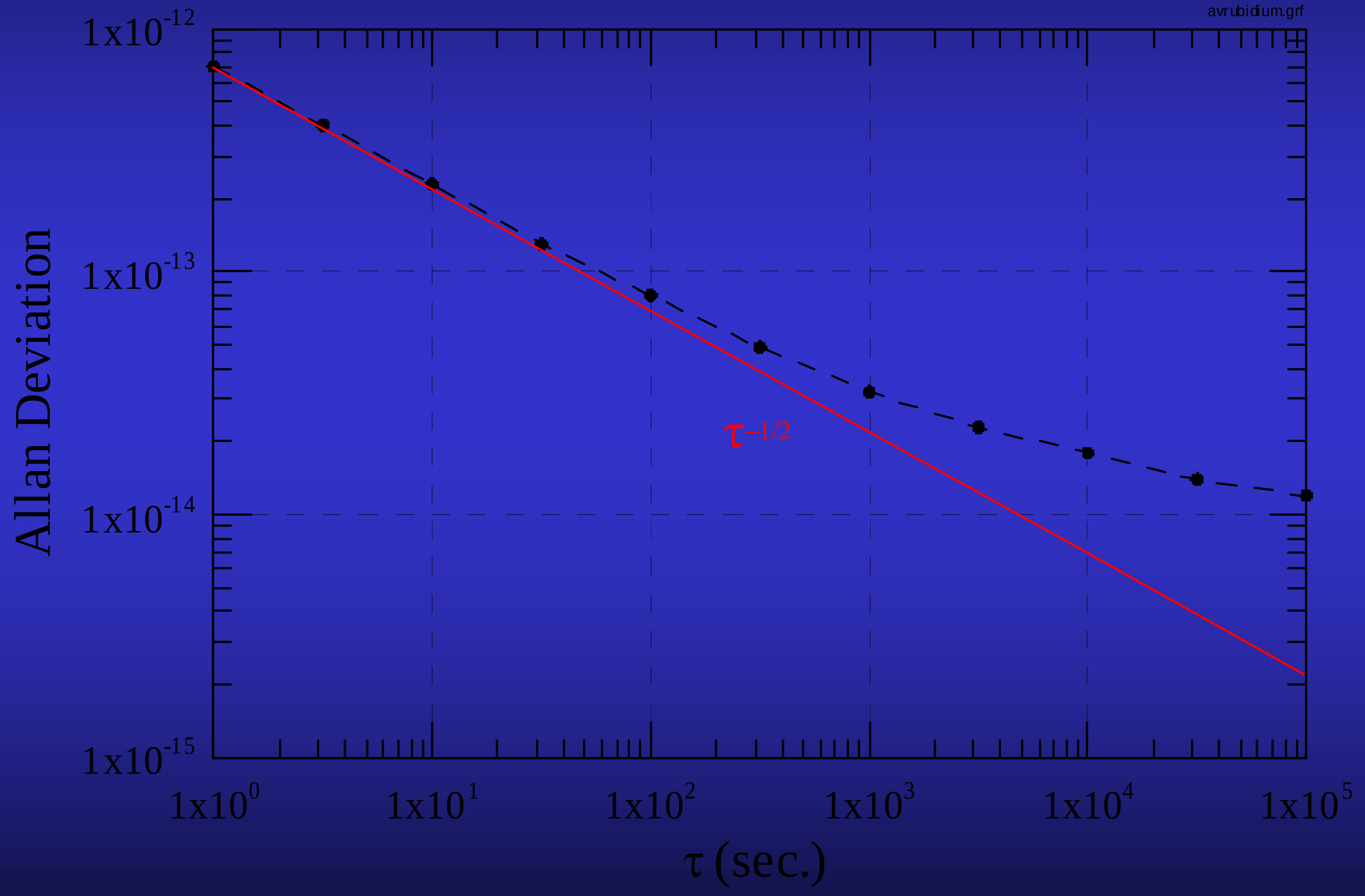
Rubidium Standard (Gas Cell)



Adapted from figure by John Vig

Frequency Stability of a Rubidium Standard

(Frequency drift removed – 3x10^{-13}/day typical)



Courtesy of Bill Riley

Primary & 'Almost' Primary Reference Sources

Parameters (benign environment; ±5°C)	**Cs Beam Frequency Std.**	**GPS disciplined* Rb T/F System**	**Passive Hydrogen Maser (Russia)** (~1E-15/day aging)	**Hi Performance Rb Oscillator** (5E-12/mo. aging)
Frequency Accuracy	±1E-12 for Life	< ±1E-12	~ ±5E-14 after Cal	±1E-12 after Cal
Free-run 30 Days	±1E-12	< ±1E-11	< ±5E-14	< ±1E-11
Free-run 100 Days	±1E-12	~ ±1E-11	±1E-13	< ±2E-11
Time Accuracy	Only after Calib'n	50 ns peak of UTC	Only after Calib'n	Only after Calib'n
Free-run 30 Days	~ ±3 us	< 20 us	< 1 us	< 50 us
Free-run 100 Days	~ ±10 us	< 50 us	< 2 us	< 100 us
Stability at 10^5 s	~1E-14	-	< 5E-15	~ 1E-13
GPS C/A signal	N/A	< 2E-13	N/A	N/A
GPS P(Y) Signal	N/A	< 2E-14	N/A	N/A
No GPS Signal	N/A	~ 1E-13	N/A	N/A
Reliability	~ 5% Return/Yr.	~ 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, ~5U	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