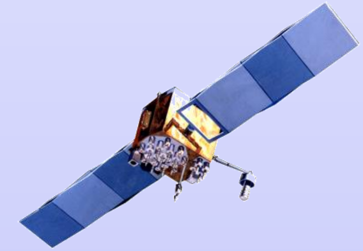

Timing Reference Sources

Tutorial June 9 ahead of WSTS, June 10-12, 2014

San Jose, CA

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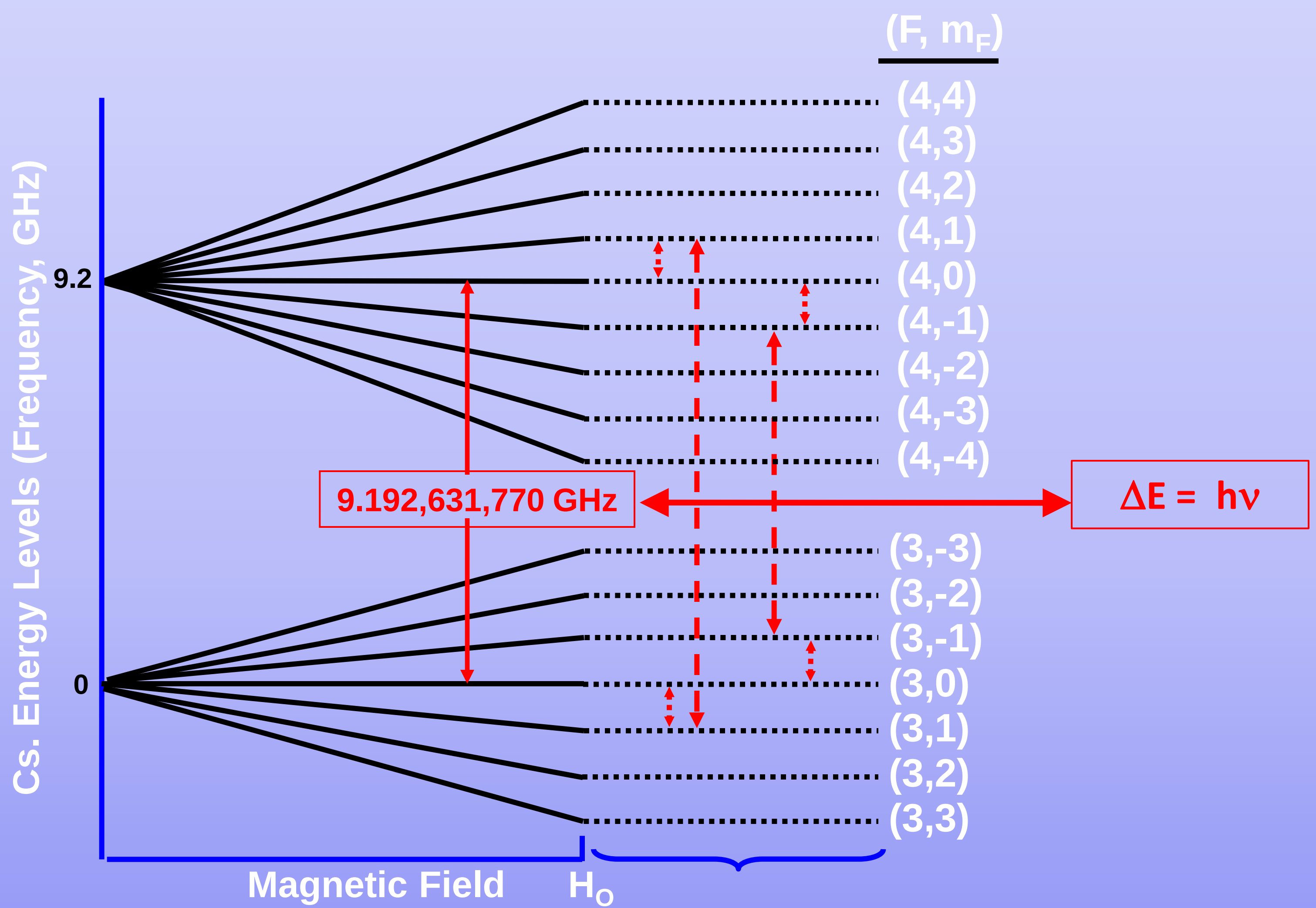
Primary Sources
for Time and Frequency

- **Atomic Clocks**
- **Time and Frequency Transfer**
- **GNSS**
- **Conclusions**
- **Extra Slides**

Atomic Frequency Standards:
Produce Frequency Locked to an Atomic Transition

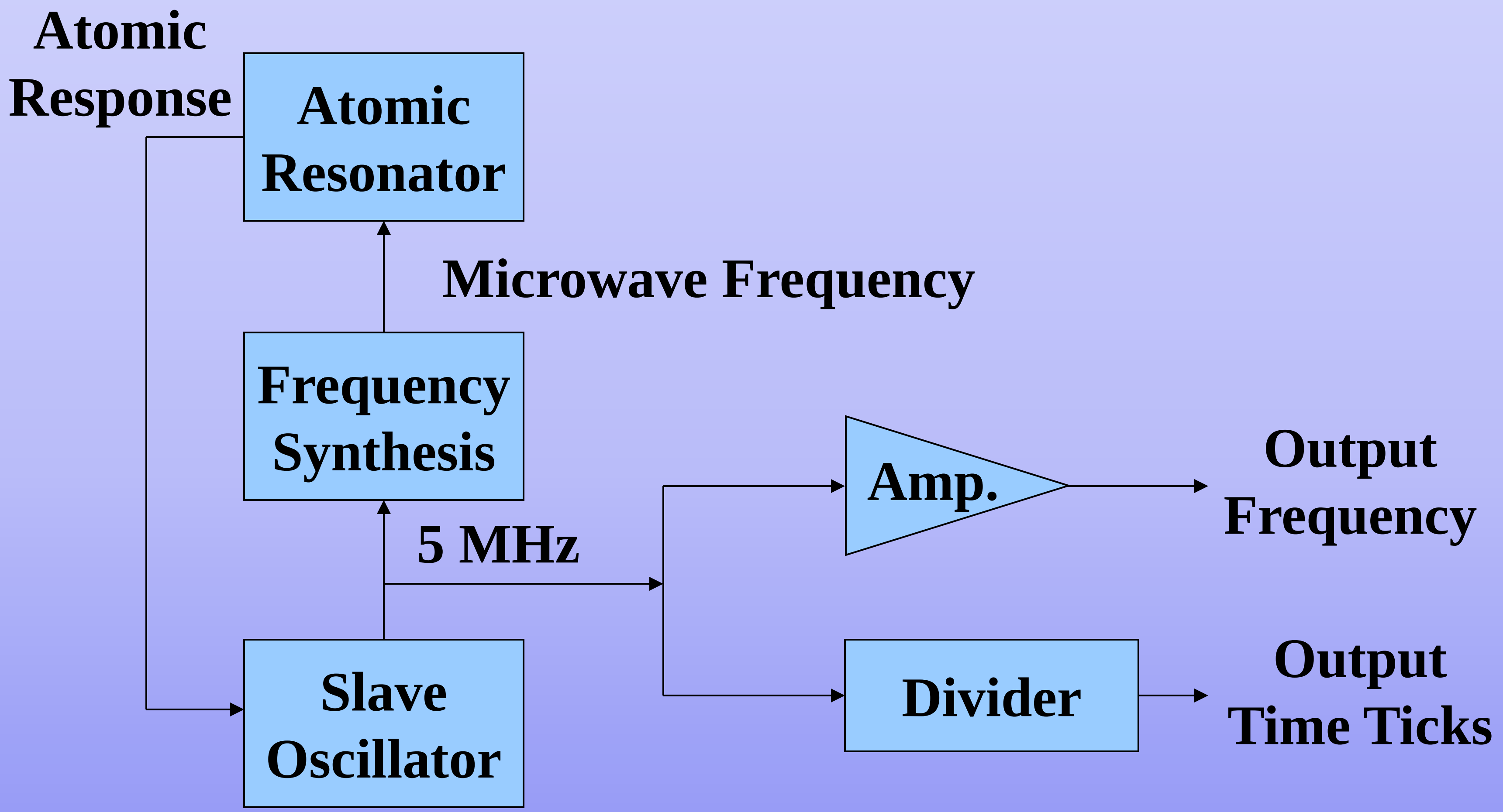


Basic Passive Atomic Clock

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

Block Diagram of Atomic Clock

Passive Standard



Types of Atomic Clocks

- Cesium thermal beam standard
  - Best long-term frequency stability
- Rubidium cell standard
  - Small size, low cost
- Hydrogen maser
  - Best stability at 1 to 10 days (short-term stability)
  - Expensive several $100K
- Chip Scale Atomic Clock (CSAC)
  - Very small size, low power

Clock Stability

Clock (in)stability is given by:

$$\sigma \approx \frac{\delta f}{f} \propto \frac{1}{Q(S/N)} = \frac{1}{(\omega/\Delta\omega)(S/N)}$$

Atomic Line Q **Signal to Noise**

Clock stability can be improved by:

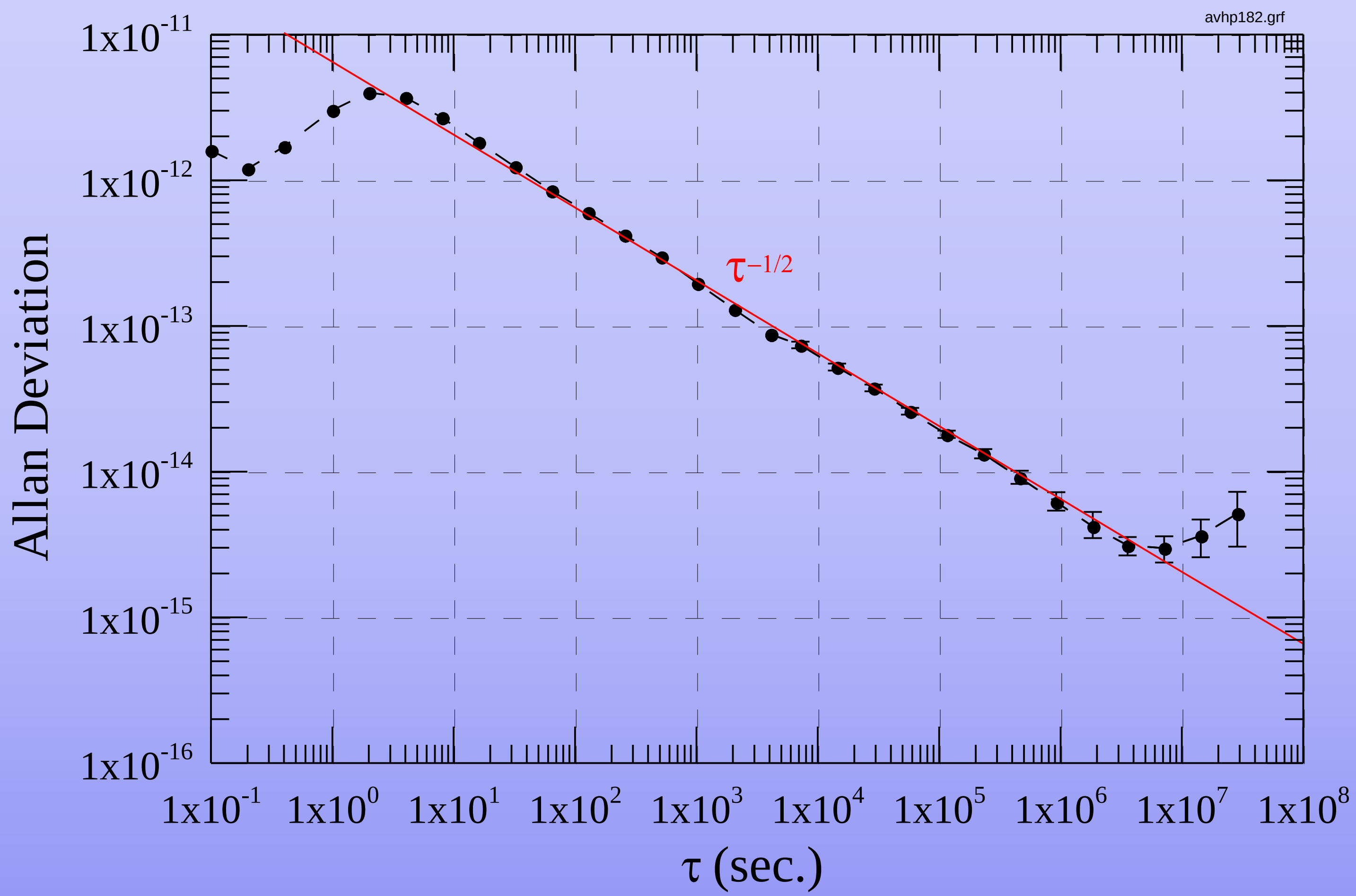
Increase Ramsey (observation) times (decrease $\Delta\omega = 1/T_{Ramsey}$)

Improve the S/N (more atoms!)

Increase the frequency of the clock transition (optical?)

Frequency Stability of a Cesium Standard

(No frequency drift removed)

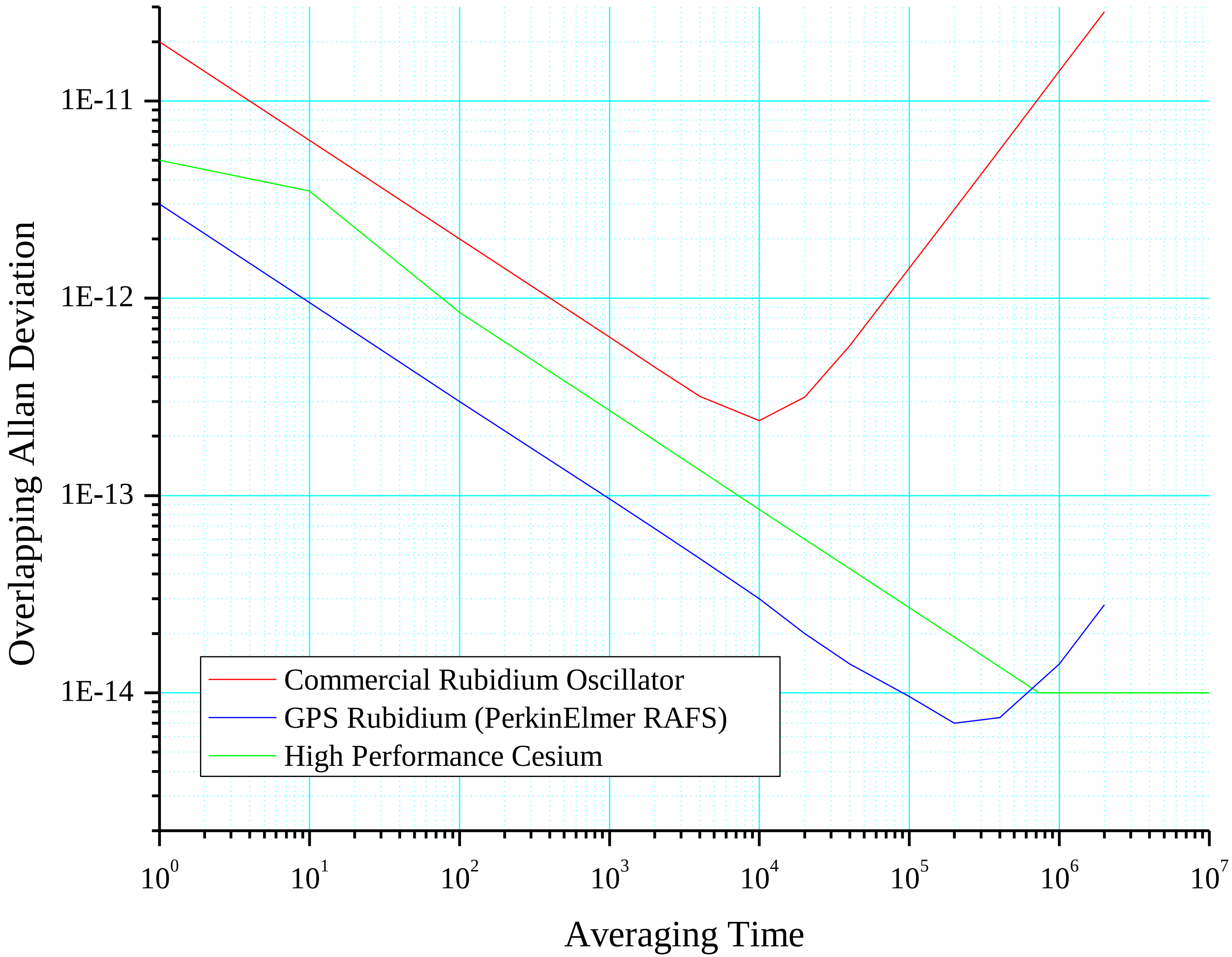


Rubidium Standard

- Two major differences from a cesium standard
  1. Cell standard (doesn’t use up rubidium)
  2. Optically pumped (no state selection magnets)

- Used where low cost and small size are important

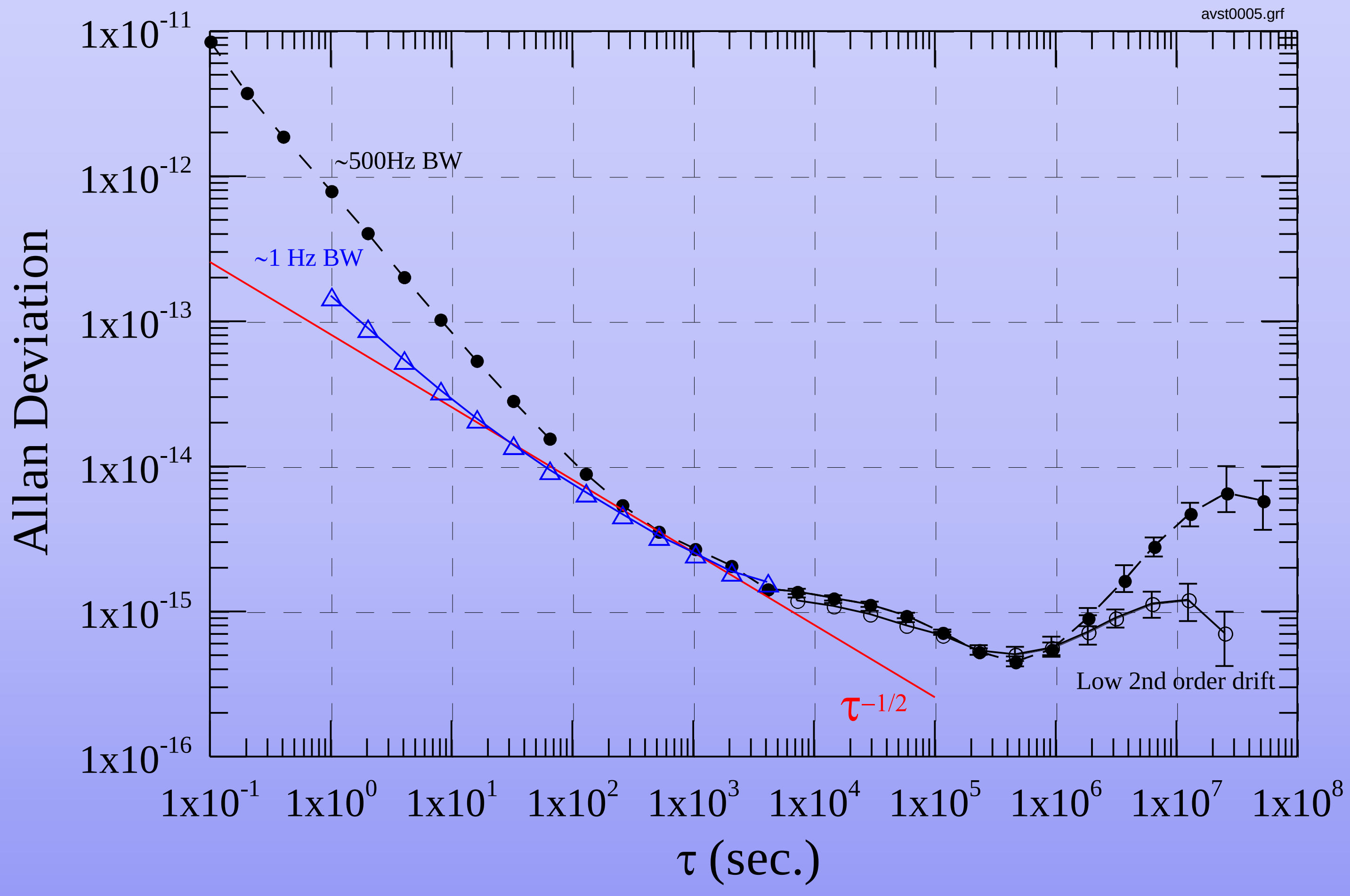
Frequency Stability of a Rubidium Standard



•**Courtesy of Robert Lutwak, Symmetricom**

Frequency Stability of a Hydrogen Maser

(Frequency drift removed – $1x10^{-16}$/day typical)



Something New!

- Chip Scale Atomic Clock (CSAC)
    1. Cesium cell standard
    2. Coherent Population Trapping (CPT)
- Very small size and low power consumption, but better performance than a quartz oscillator

Oscillator Comparison

Technology	Intrinsic Accuracy	Stability (1s)	Stability (floor)	Aging (/day) initial to ultimate	Applications
Cheap Quartz, TCXO	10^{-6}	$\sim 10^{-11}$	$\sim 10^{-11}$	10^{-7} to 10^{-8}	Wristwatch, computer, cell phone, household clock/appliance,…
Hi-quality Quartz, OCXO	10^{-8}	$\sim 10^{-12}$	$\sim 10^{-12}$	10^{-9} to 10^{-11}	Network sync, test equipment, radar, comms, nav,…
Rb Oscillator	$\sim 10^{-9}$	$\sim 10^{-11}$	$\sim 10^{-13}$	10^{-11} to 10^{-13}	Wireless comms infrastructure, lab equipment, GPS, …
Cesium Beam	$\sim 10^{-13}$	$\sim 10^{-11}$	$\sim 10^{-14}$	nil	Timekeeping, Navigation, GPS, Science, Wireline comms infrastructure,…
Hydrogen Maser	$\sim 10^{-11}$	$\sim 10^{-13}$	$\sim 10^{-15}$	10^{-15} to 10^{-16}	Timekeeping, Radio astronomy, Science,…

•**Courtesy of Robert Lutwak, Symmetricom**

Oscillator Comparison (continued)

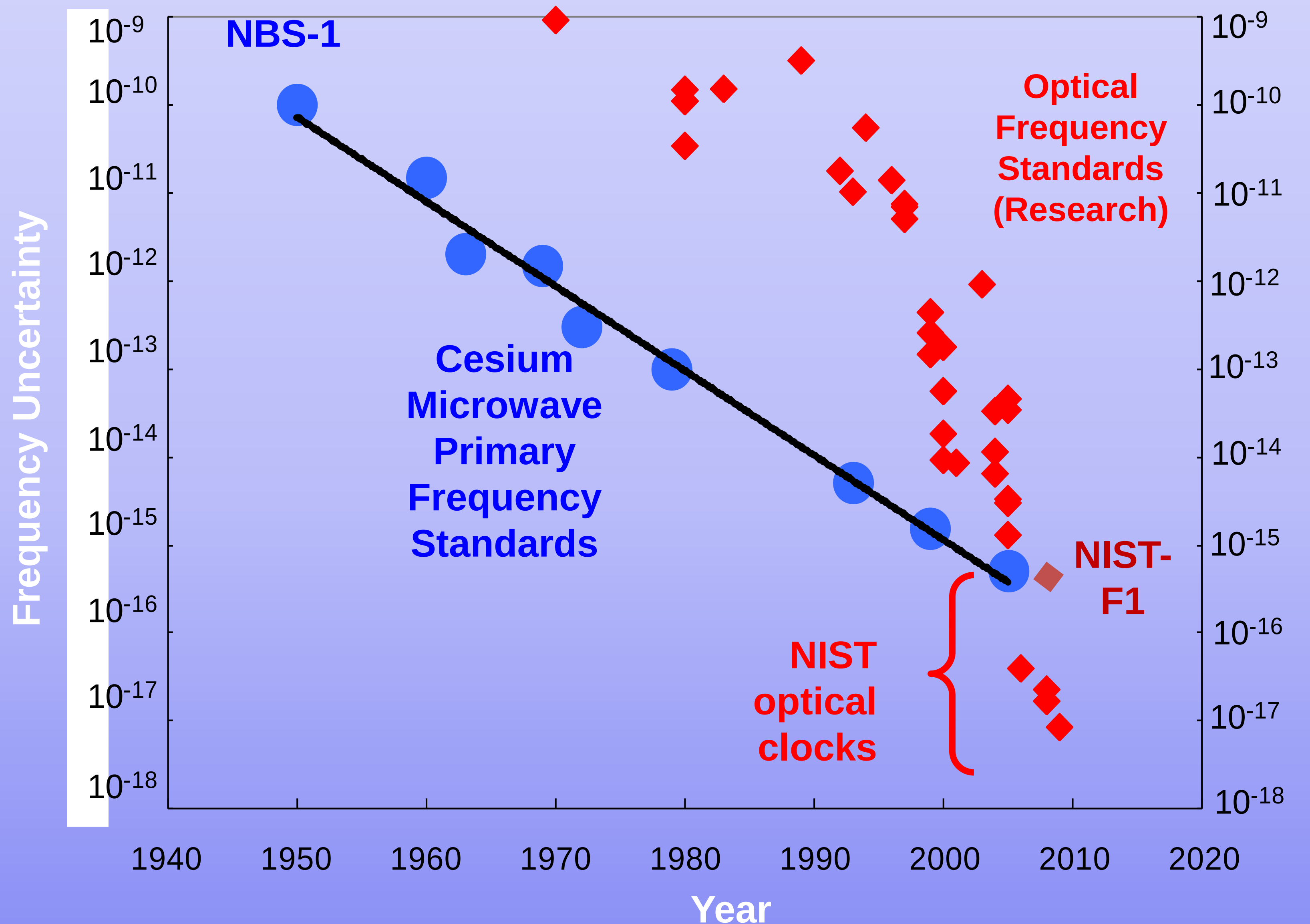
Technology	Size	Weight	Power	World Market	Cost
Cheap Quartz, TCXO	≈ 1 cm^3	≈ 10 g	≈ 10 mW	≈ 10^9s/year	≈ $1s
Hi-quality Quartz, OCXO	≈ 50 cm^3	≈ 500 g	≈ 10 W	≈ 10Ks/year	≈ $100s
Rb Oscillator	≈ 200 cm^3	≈ 500 g	≈ 10 W	≈ 10Ks/year	≈ $1000s
Cesium Beam	≈ 30,000 cm^3	≈ 20 kg	≈ 50 W	≈ 100s/year	≈ $10Ks
Hydrogen Maser	≈ 1 m^3	≈ 200 kg	≈ 100 W	≈ 10s/year	≈ $100Ks

- **Courtesy of Robert Lutwak, Symmetricom**

Conclusions: Atomic Standards

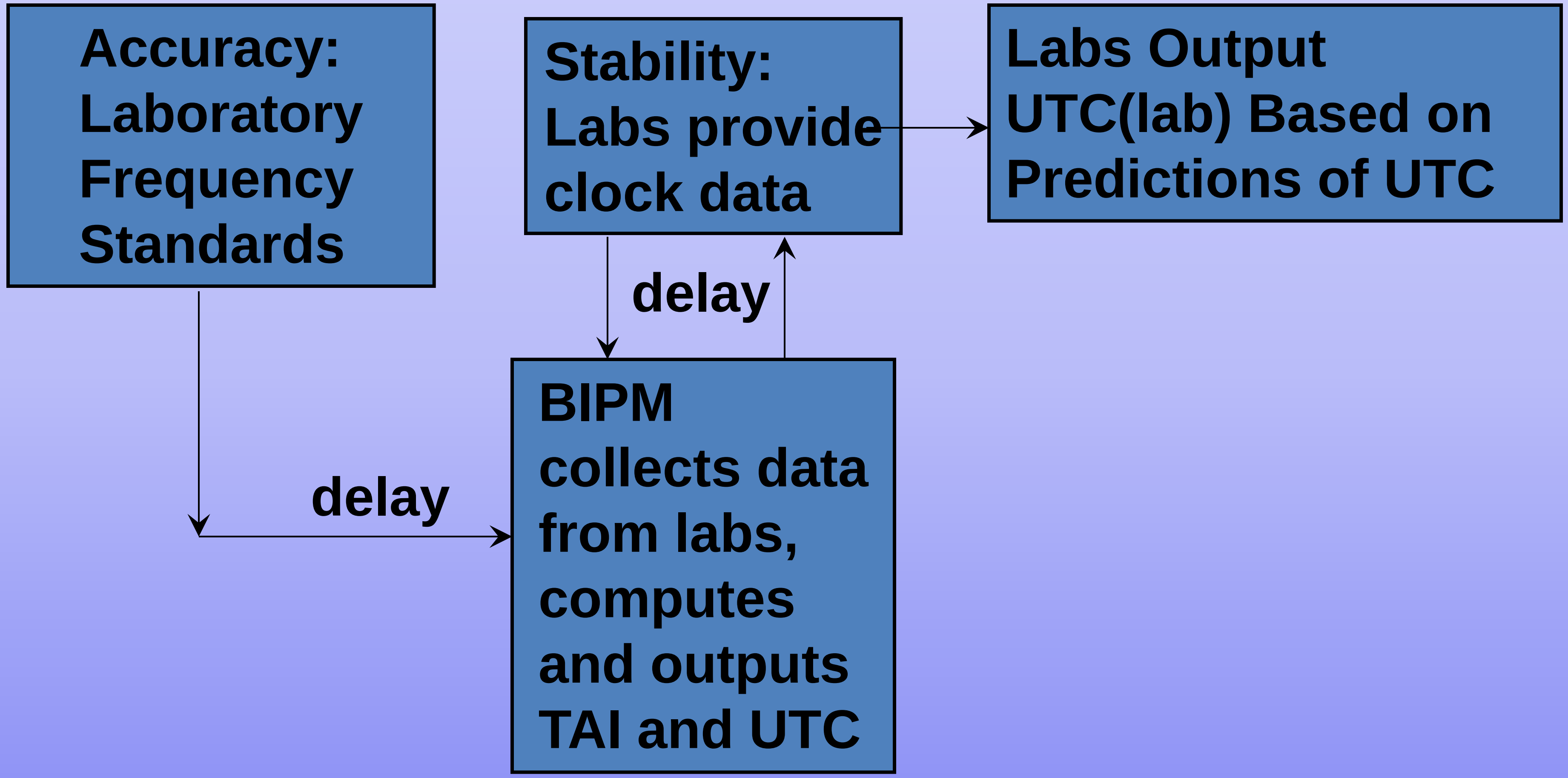
- **Rubidium, cesium, and hydrogen atomic frequency standards share a common theme: the stabilization of an electronic (quartz) oscillator with respect to an atomic resonance.**
- **Although the use of atoms brings with it new quantum mechanical problems, the resulting long-term stability is unmatched by traditional classical oscillators.**

Frequency Accuracy: History of NIST Primary Frequency Standards



The Generation of UTC: Time Accuracy

Any Real Time UTC is only a Prediction,
A PLL with a one-month delay



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Time and Frequency Transfer: How to Deliver a Timing Reference

- Time Transfer Accuracy Requires Calibrating Delays

- Imagine writing a letter: "It is now 2 PM– set your watch"
- Seal it in an envelope and drop it in a mail box
- Only useful if you know how long it took to get to you

- Time Stability = Frequency Accuracy

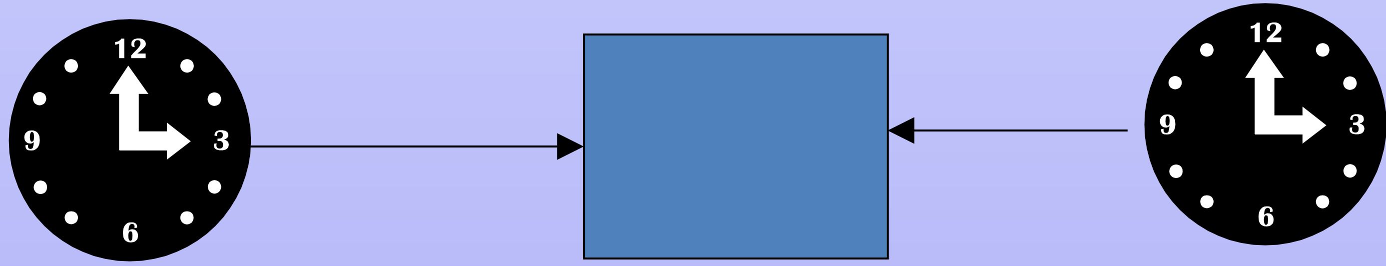
Time and Frequency Transfer

- Accuracy and Stability are the Concerns
  - Time Transfer Accuracy Requires Calibrating Delays
  - Time Stability = Frequency Accuracy

- Continuous vs Intermittent Measurements

Dissemination or Comparison System

Clock 1 **Clock 2**



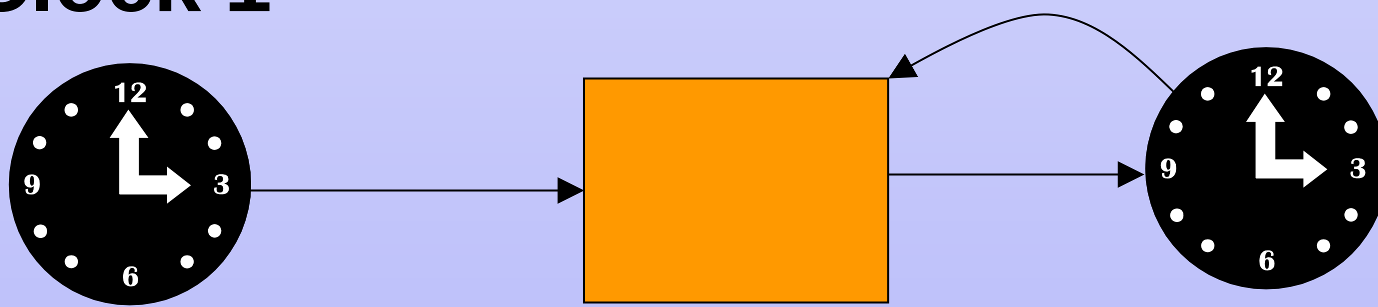
Clock 1 Systematics and Noise

Measurement Noise and Path Perturbations

Clock 2 Systematics and Noise

Clock Hierarchies

Clock 1 **Clock 2**



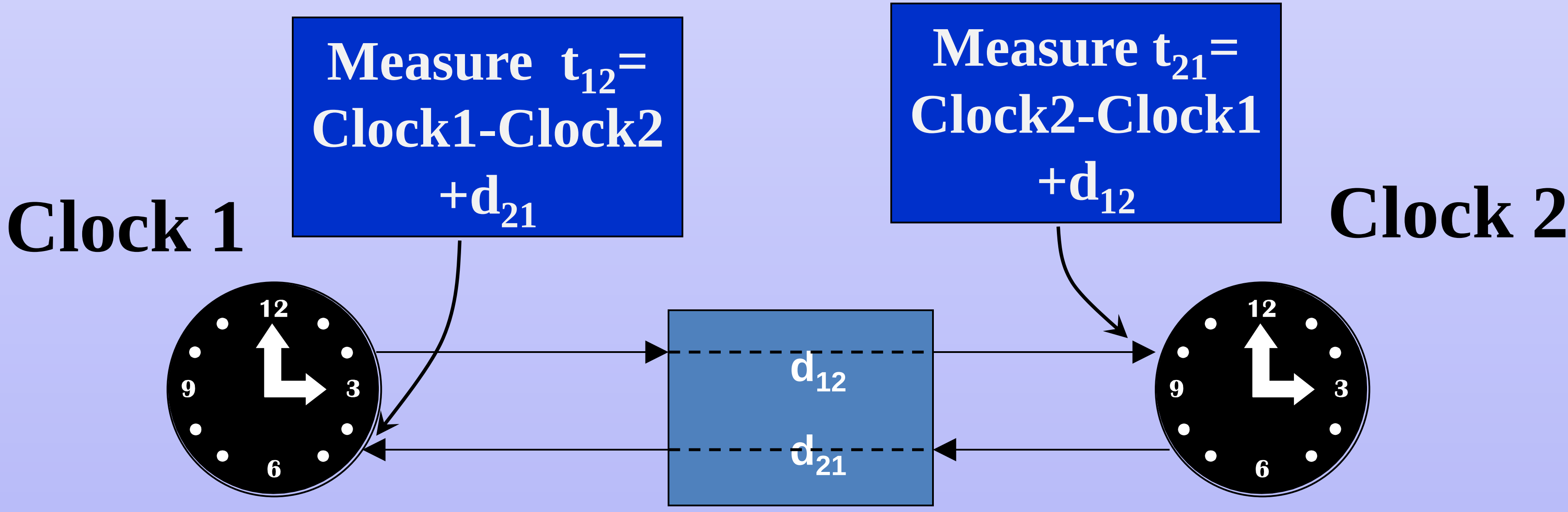
Clock 1 Systematics and Noise

Lock Loop Systematics and Noise: Contributions from Measurement Noise and Path Perturbations

Clock 2 Systematics and Noise

Two -Way Comparison System

(e.g. IEEE1588 – PTP)



Clock 1 Systematics and Noise

Measurement Noise and Path Perturbations

Largely Reciprocal:

$d_{21} = d_{12}$

Clock 2 Systematics and Noise

Synchronization vs Syntonization

Two Separate Concepts
Both called "Synchronization" in Telecom

Synchronization

- Same Time
- Same Phase
- Phase Lock

Syntonization

- Same Frequency
- Frequency Lock $\Rightarrow$ Phase Offset Unbounded

How to Characterize Attributes of Time and Frequency Transfer Systems

1. Time Transfer Accuracy
   1. Agreement with the “true” clock difference
   2. Evaluate with a more accurate transfer system
   3. Never better than stability

2. Time Transfer Stability -- Plot x(t)
   1. TDEV, $\sigma_x(\tau)$
   2. Spectrum, $S_x(f)$

3. Frequency Transfer Accuracy
   1. Directly related to time transfer stability
   2. A function of averaging time, τ, and processing

4. Frequency Transfer Stability-- Plot y(t)
   1. ADEV, $\sigma_y(\tau)$
   2. Spectrum, $S_y(f)$
   3. Estimate Drift

Summary:
Time and Frequency Transfer Systems

- Time: Calibrate the Delay
- Stability: Keep the delay constant
- Issues
  - Accuracy
  - Stability
  - Uncertainty
  - Systematic vs Random Deviations
- Syntonization vs Synchronization

Primary Sources for Time and Frequency

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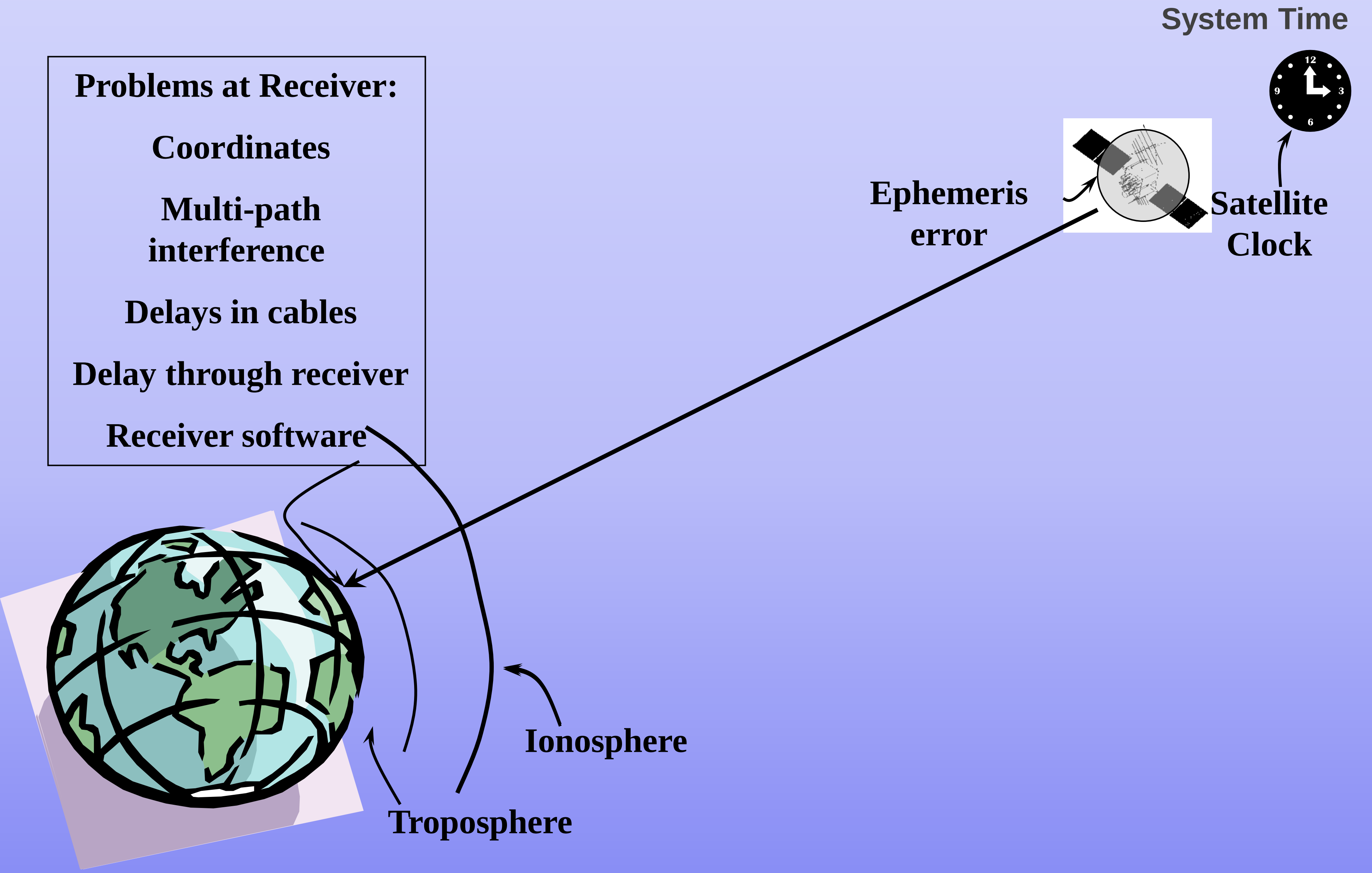
- **GNSS**
- **Conclusions**
- **Extra Slides**

Two Messages About GNSS

1. GNSS are extremely useful
   1. Constellations are growing
   2. Provide reliable, extremely accurate real-time UTC time and frequency for mostly free
   3. Excellent navigation
   4. A global > $10B industry

2. GNSS signals are dangerously vulnerable to both accidental and intentional interference

Time from GNSS: Noise Sources



Time From GNSS

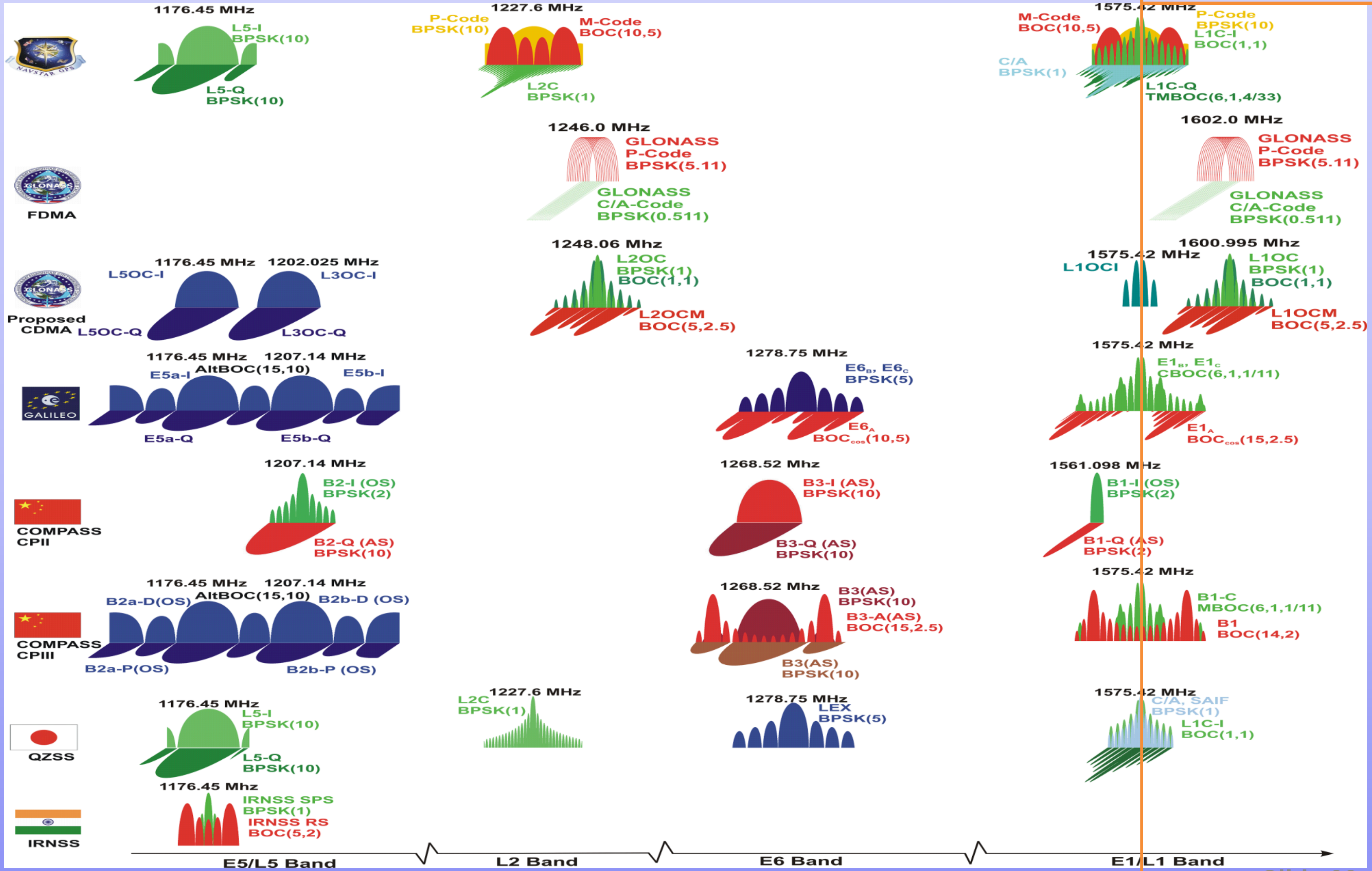
- Clocks on Satellite Vehicles (SVs) are free-running
  - Data provides the offset in Time and Frequency
  - System time is offset from UTC
- The positions of the satellite and receiver are needed for the delay
- SV Clocks and positions are ***predicted*** and uploaded, for GPS about once per day

The Family of Global Navigation Systems

GPS	Galileo	GLONASS	Beidou/Compass
US	EU	Russia	China
(24+, Now 30)	(27, Now 4 IOV)	(24, Now 29)	(35, Now 15)

Spectra of GNSS's

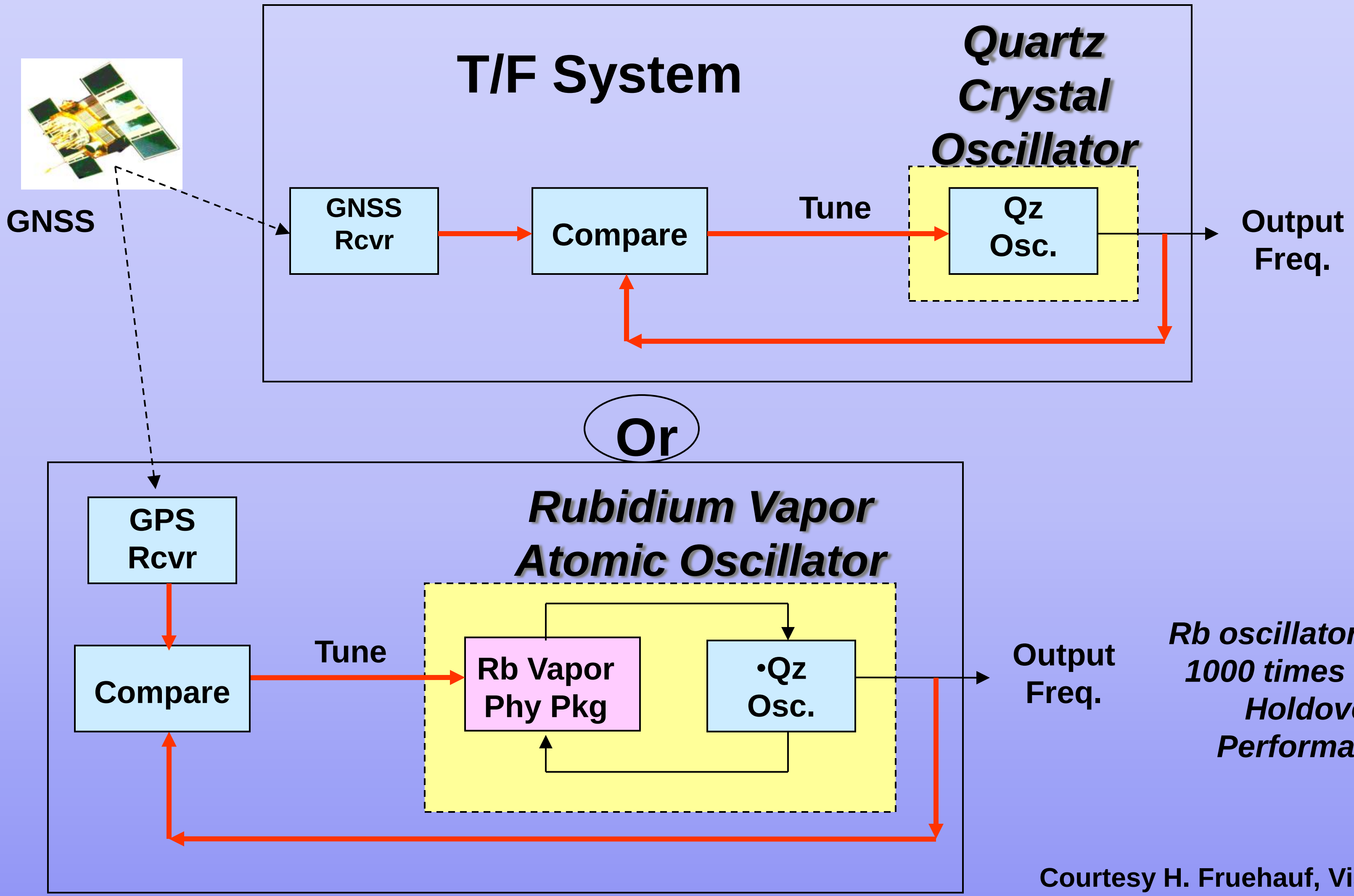
Primary Commercial Signal



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
- All signals are weak and clustered in the spectrum
  - Allows interoperability
  - But also makes it is relatively easy to jam GNSS and spoof

GNSS-aided Time and Frequency Systems



Rb oscillator 100 to 1000 times better Holdover Performance

Courtesy H. Fruehauf, ViaLogy LLC

T/F System

Primary Sources
for Time and Frequency

- **Atomic Clocks**
- **Time and Frequency Transfer**
- **GNSS**
- **Conclusions**
- **Extra Slides**

Conclusions

- Atomic clocks are accurate and/or stable by design
  - Cs. can be a primary frequency standard
  - Others can be very stable
- Time transfer requires calibration of the delay
  - Two-way cancels the delay if it is symmetric
  - GNSS measures the delay
  - Frequency transfer only requires stable delay
- GNSSs are very accurate both for time and frequency, many signals free for use, and are very reliable
  - Perhaps their greatest advantage and disadvantage!
  - Signals are subject to interference

Extra Slides

Primary Sources
for Time and Frequency

- **Atomic Clocks**
- **Time and Frequency Transfer**
- **GNSS**
- **Conclusions**
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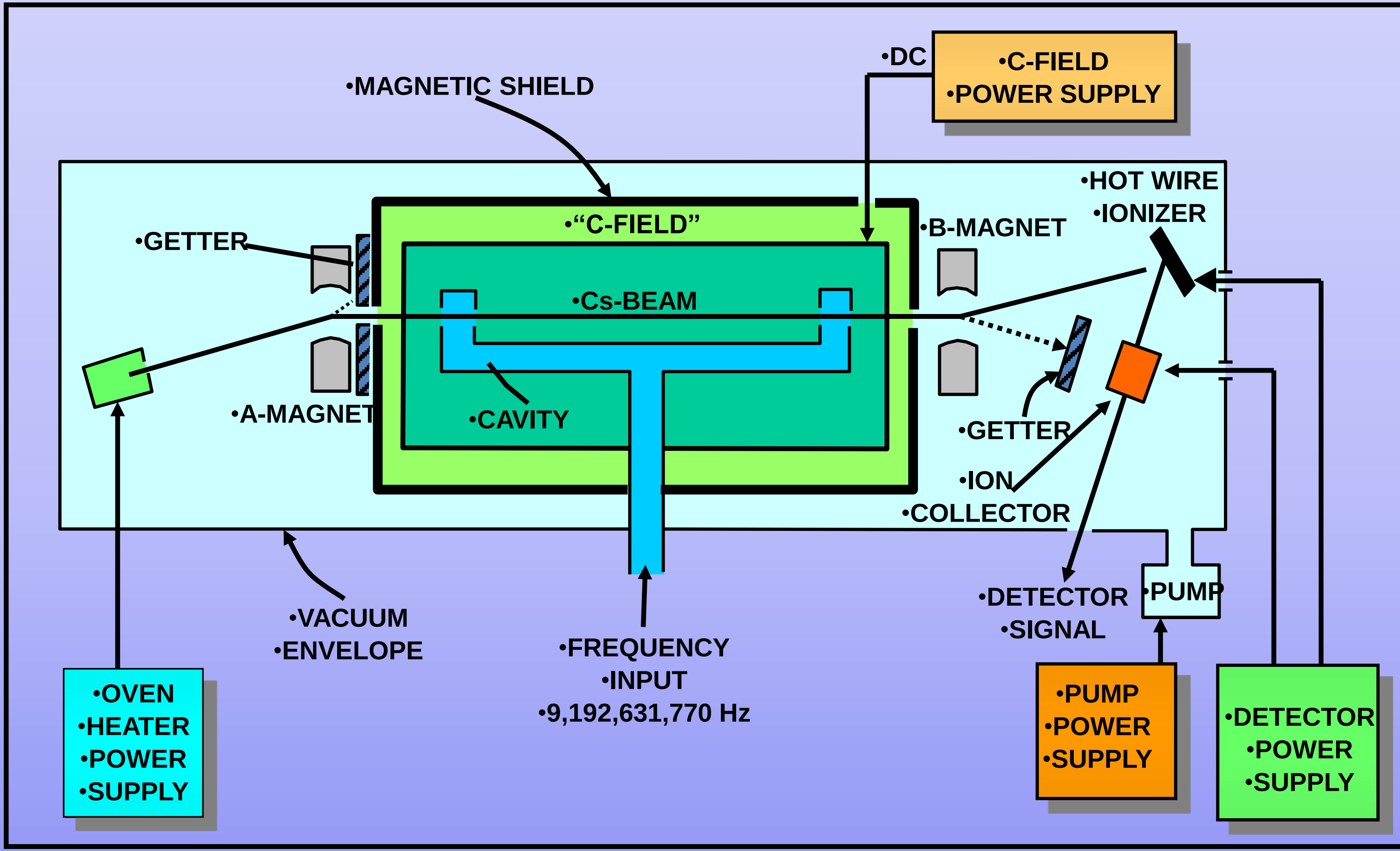
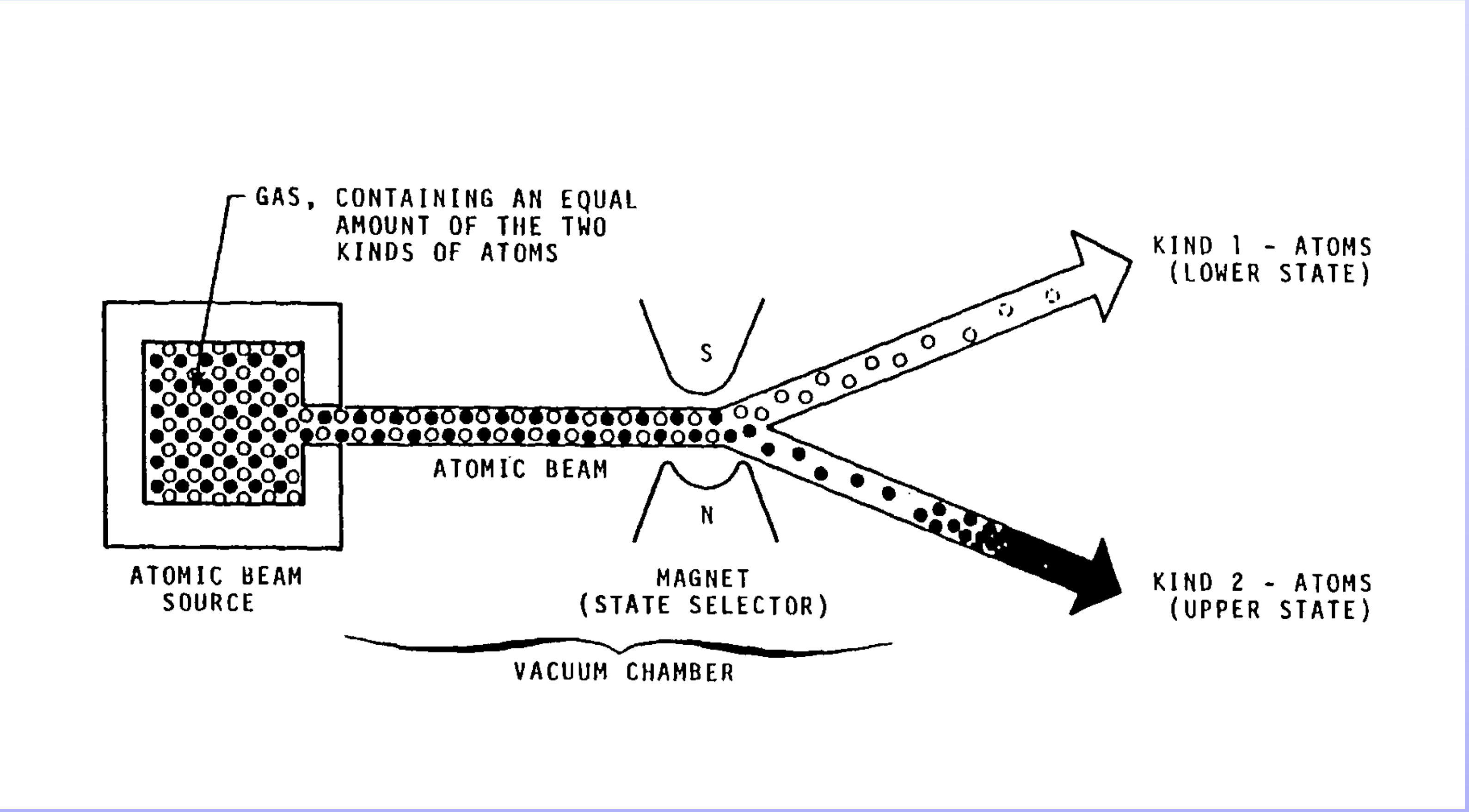
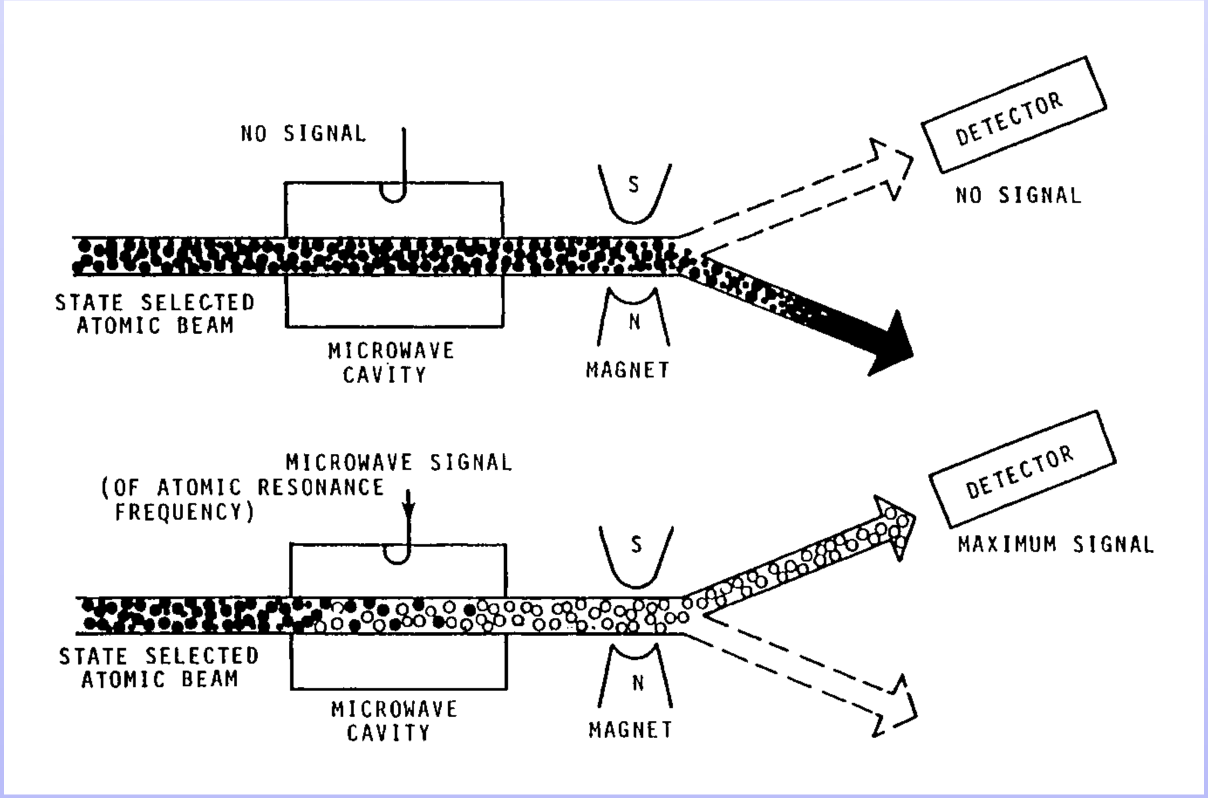
Cesium Standard



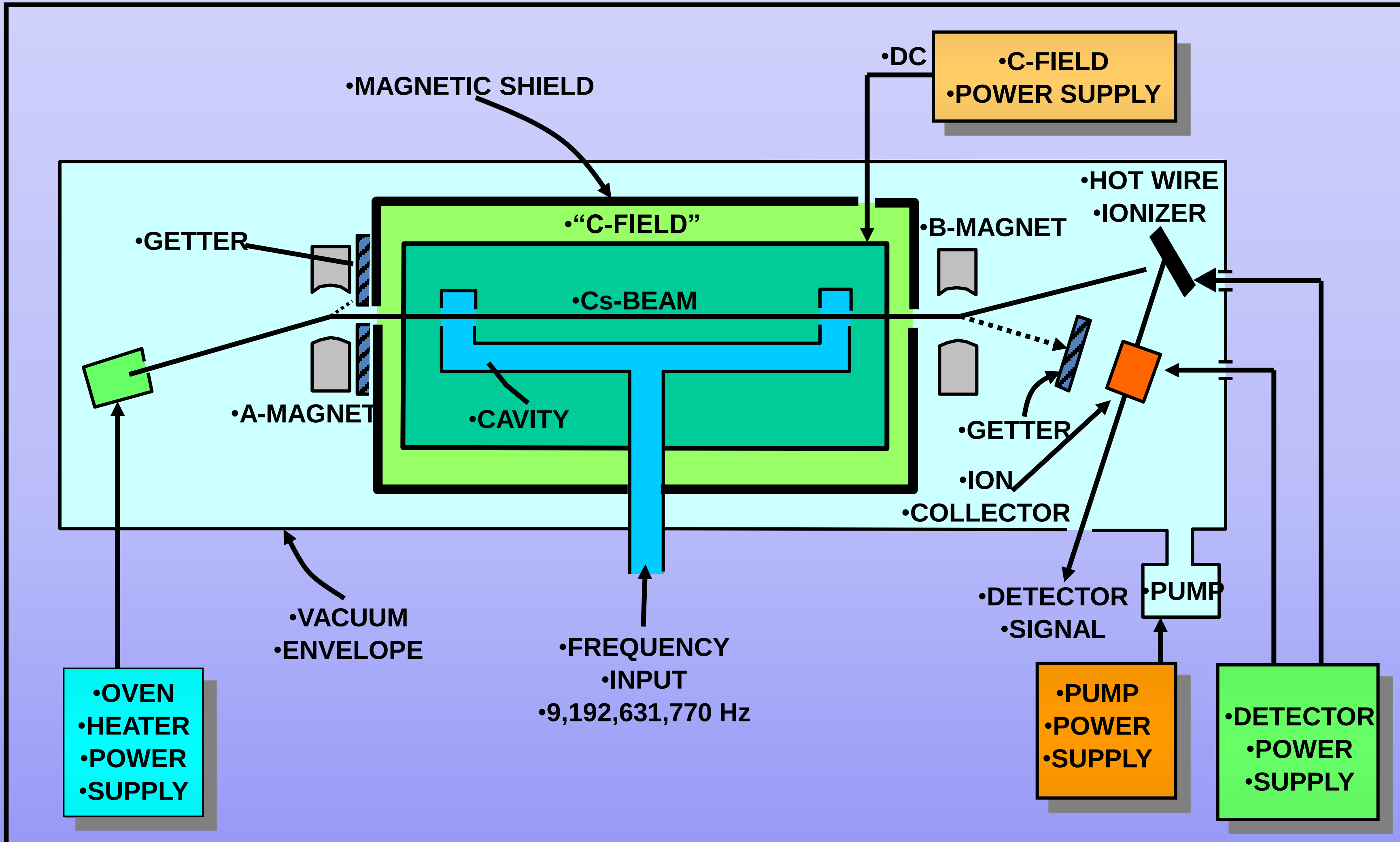


- Atoms come from an oven in a beam
-
- A magnet is used to deflect the atoms in different
- hyper-fine states



- **Atoms pass through a Ramsey cavity in a magnetic field to be exposed to microwaves at frequency ν = 9.193 GHz**
- **A second magnet selects atoms which have made the transition**
- **The number of detected atoms is used to tune the frequency**

Cesium Standard



Commercial Cesium Standards

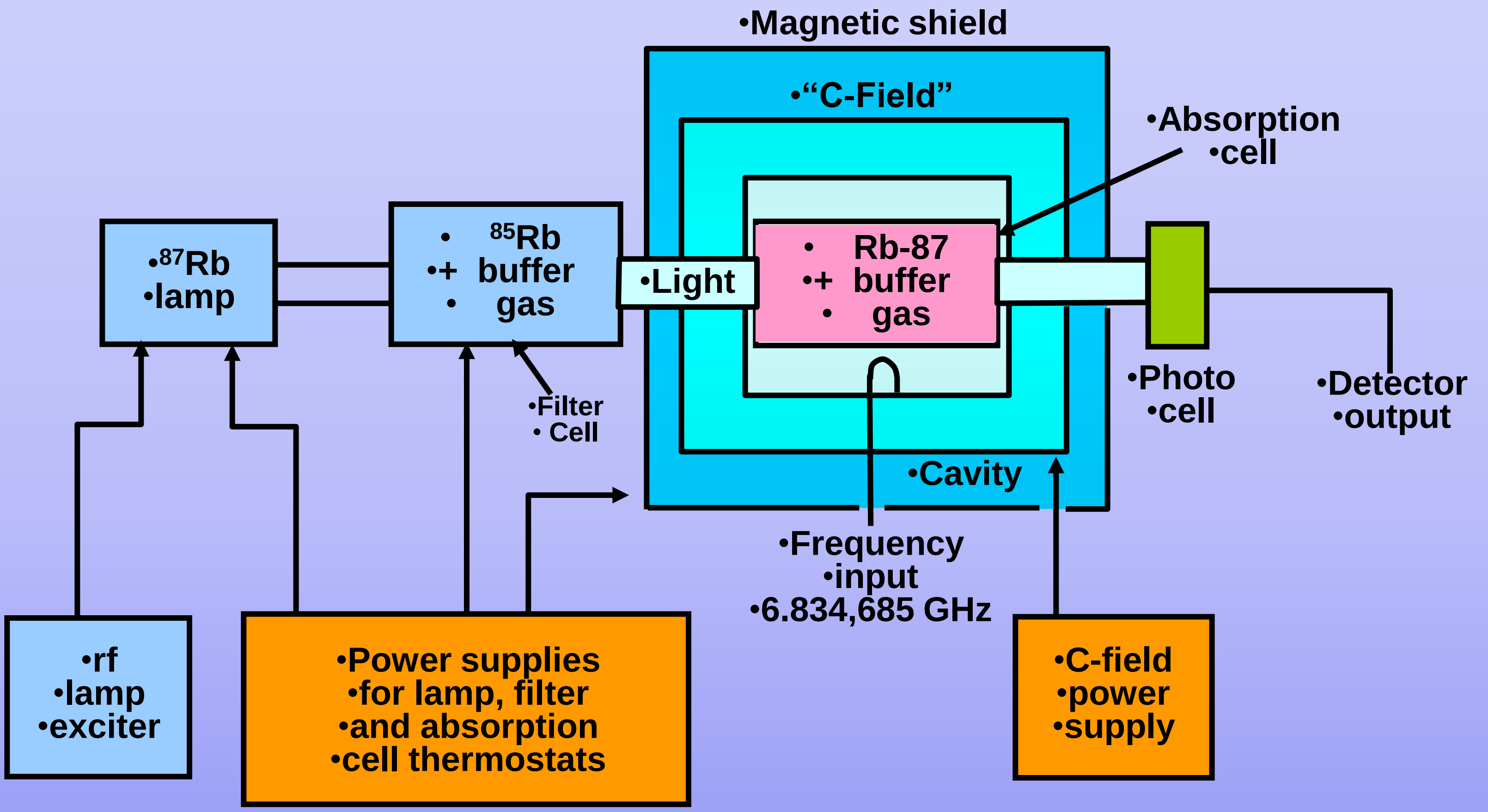
•Telecom

•Laboratory/Timekeeping

•Space/GPS

•Courtesy of Robert Lutwak, Symmetricom

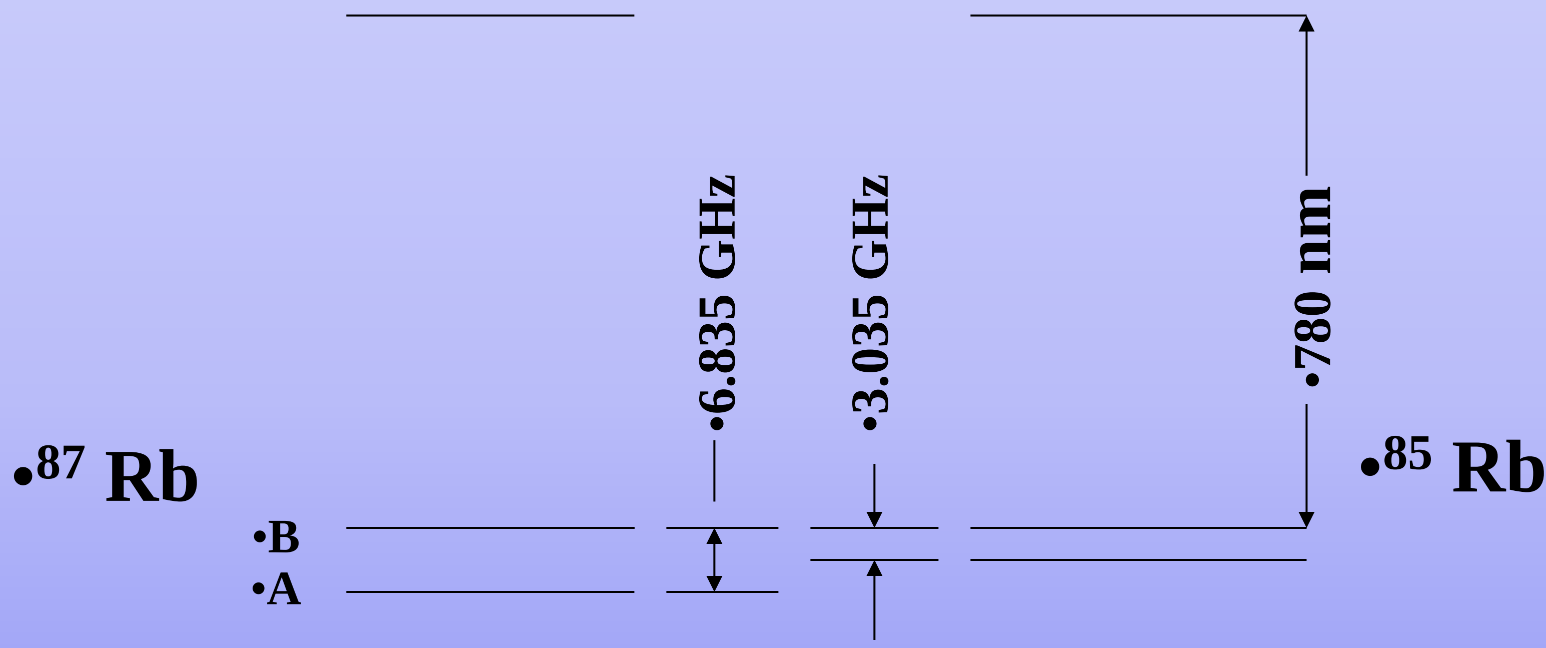
Rubidium Standard

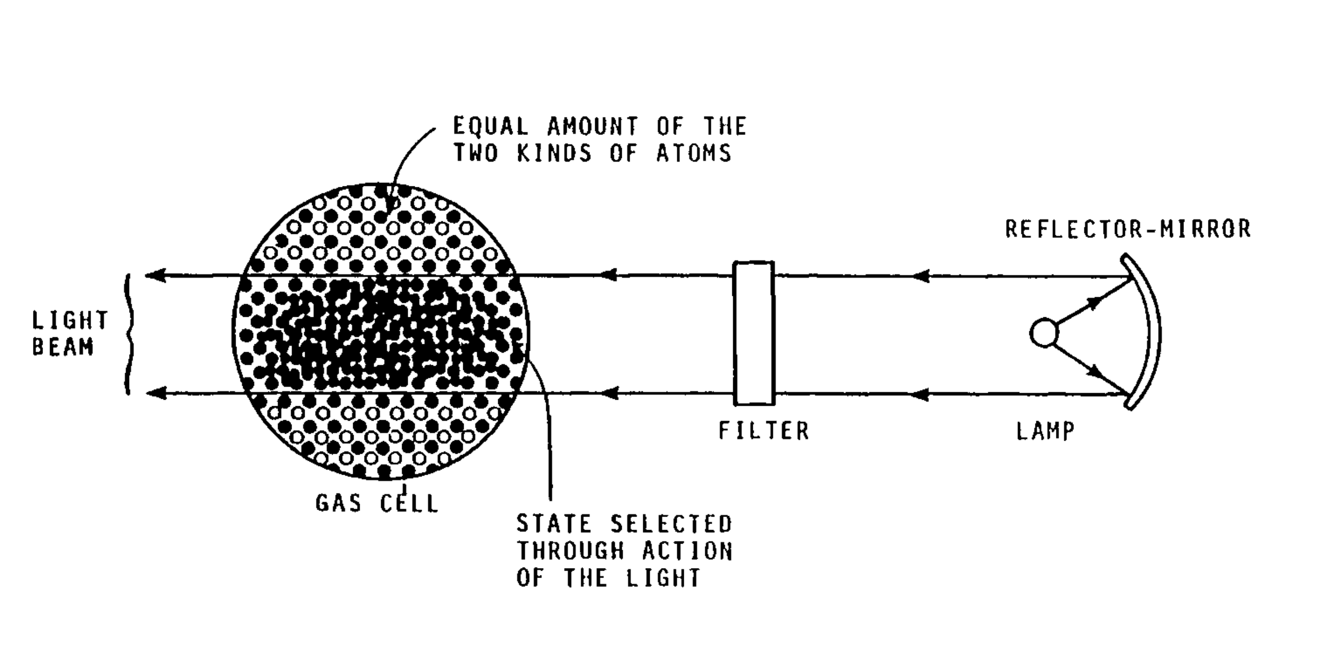


•Adapted from figure by John Vig

Optical Microwave Double Resonance

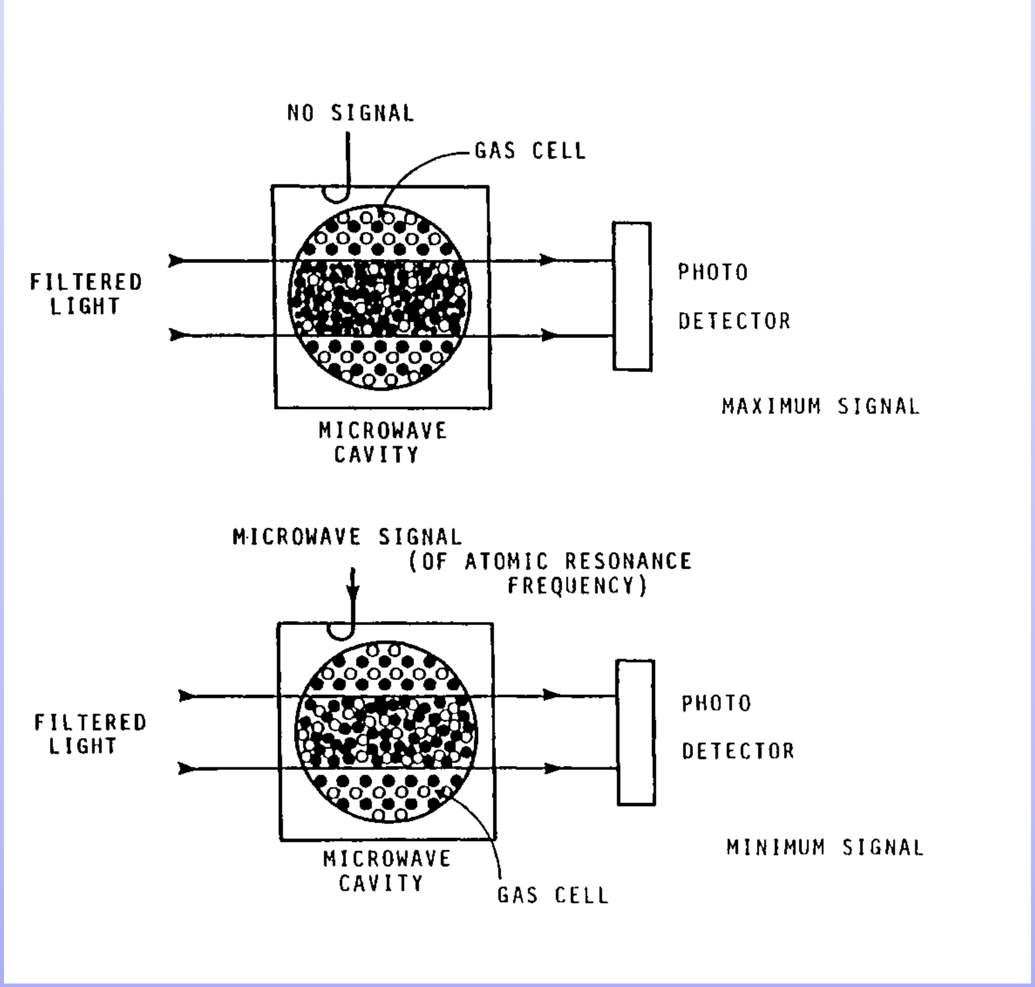
Simplified Rb energy level diagram





- Optical pumping is used to deplete one hyper-fine level

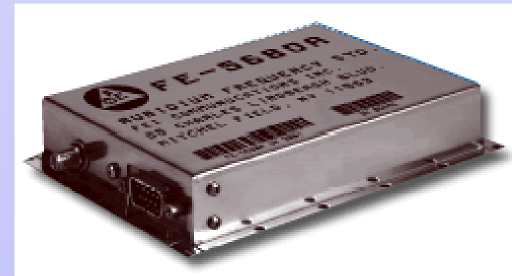
- Light tuned to the transition frequency from "A" to the
- unstable excited state puts all of the atoms in the
- hyper-fine state "B"



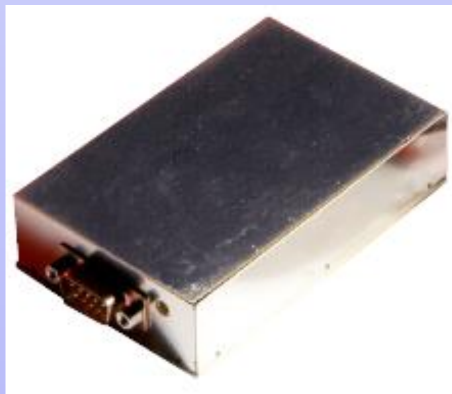
- Microwaves at ν = 6.835 GHz stimulate the transition from “B” to “A”
- The absorption of light is measured
- The frequency ν is tuned to minimize the light coming through the ^{87}Rb cell

Commercial Rubidium Standards

•Stanford Research PRS10



•Frequency Electronics
• FE-5680A



•Quartzlock E10

•Temex SR100

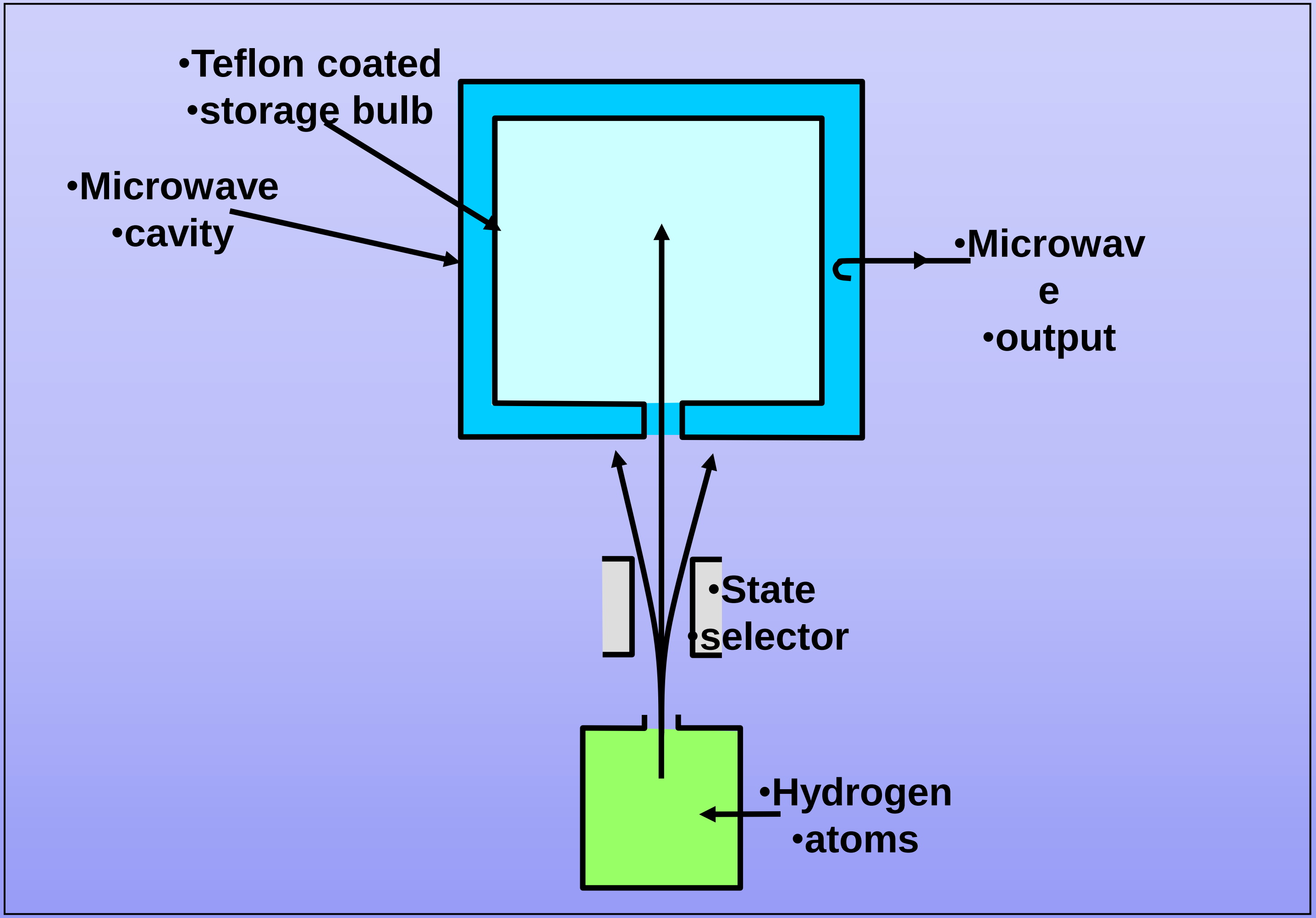
•Accubeat AR-70A

•PerkinElmer GPS RAFS

•Symmetricom X72

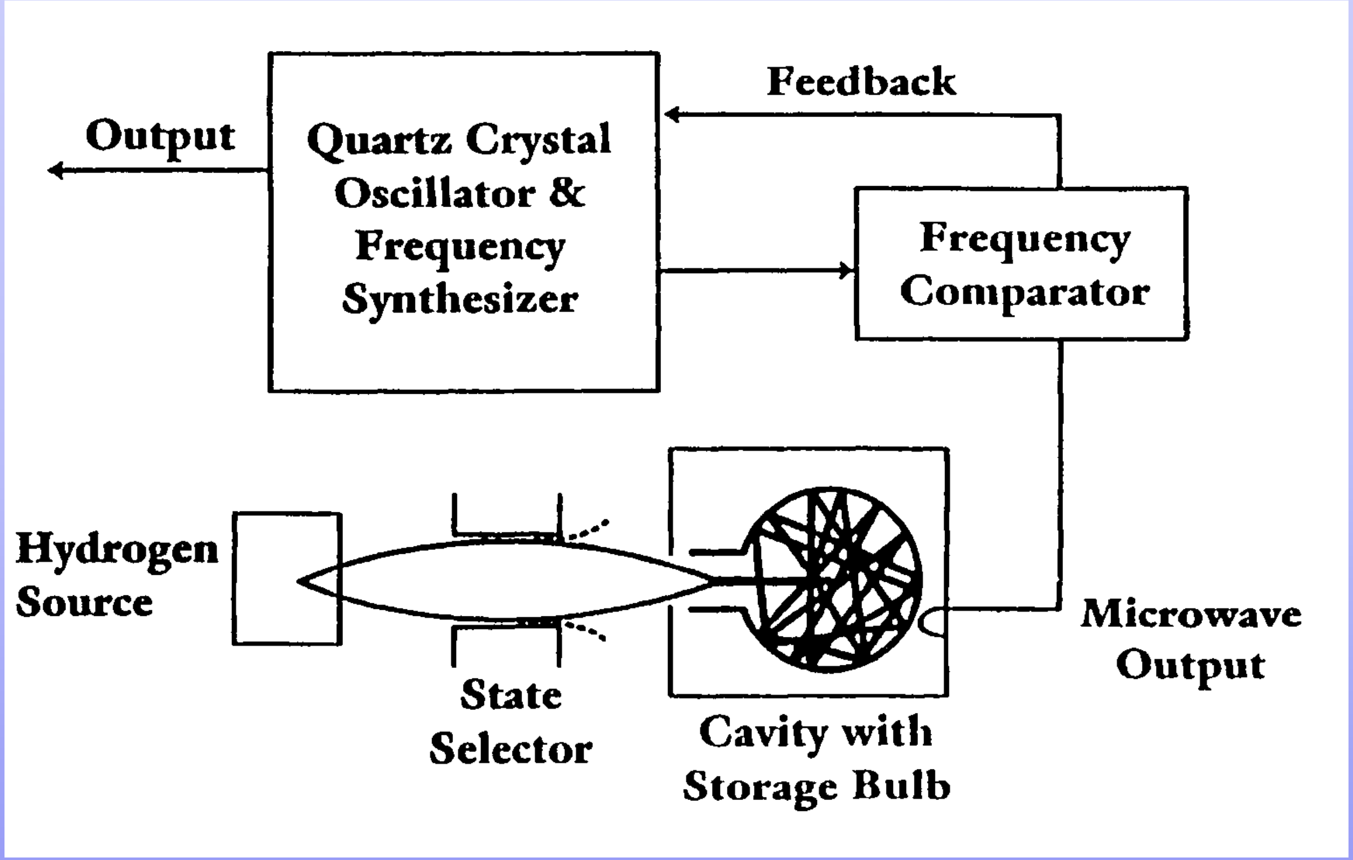
•Courtesy of Robert Lutwak, Symmetricom

Hydrogen Maser
(Active Standard)

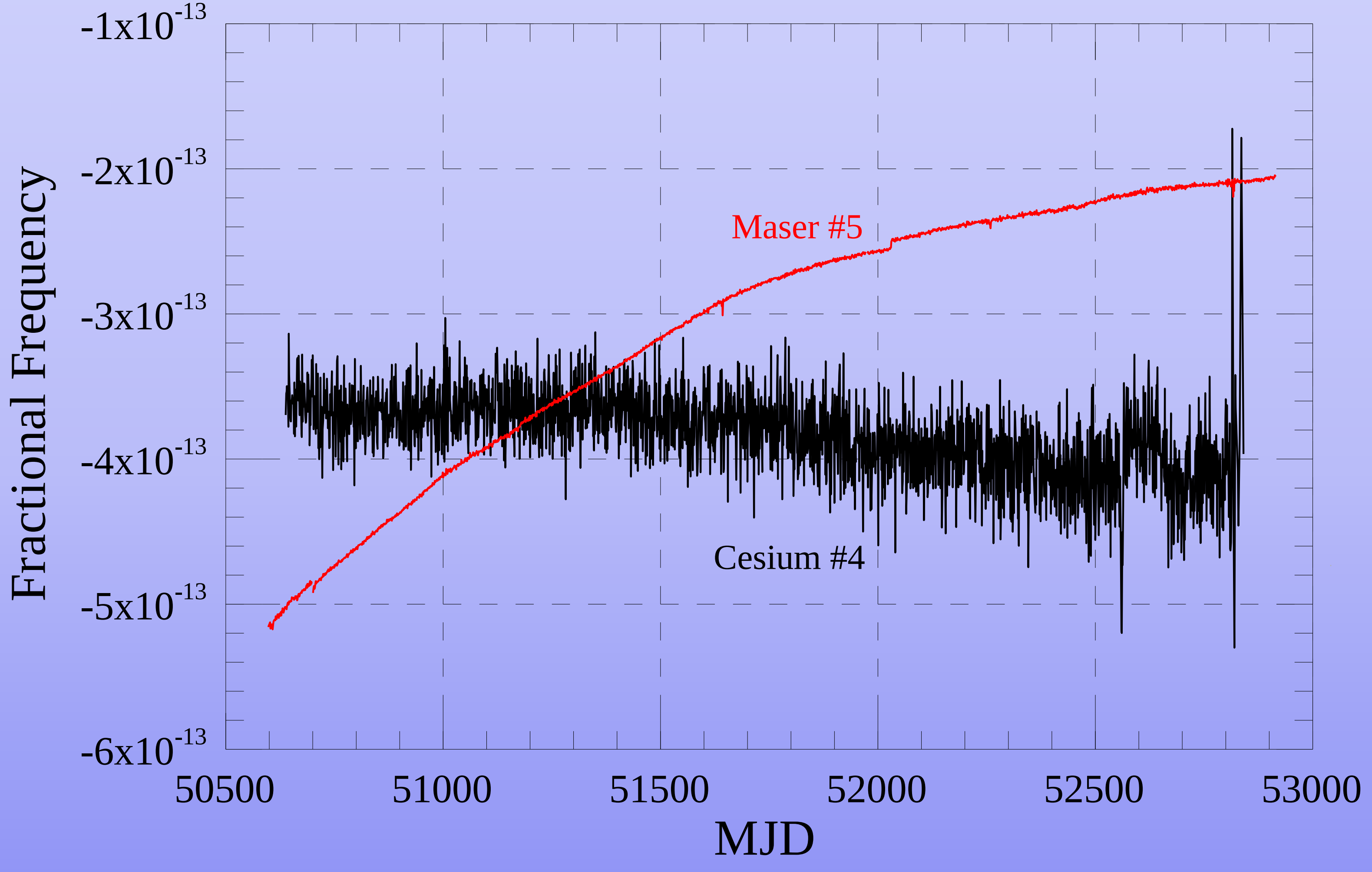


•Adapted from a figure by John Vig

Hydrogen Maser
(Active Standard)



Frequency Drift of a Commercial Cesium Standard and a Hydrogen Maser



Commercial Active Hydrogen Maser

•**Courtesy of Robert Lutwak, Symmetricom**

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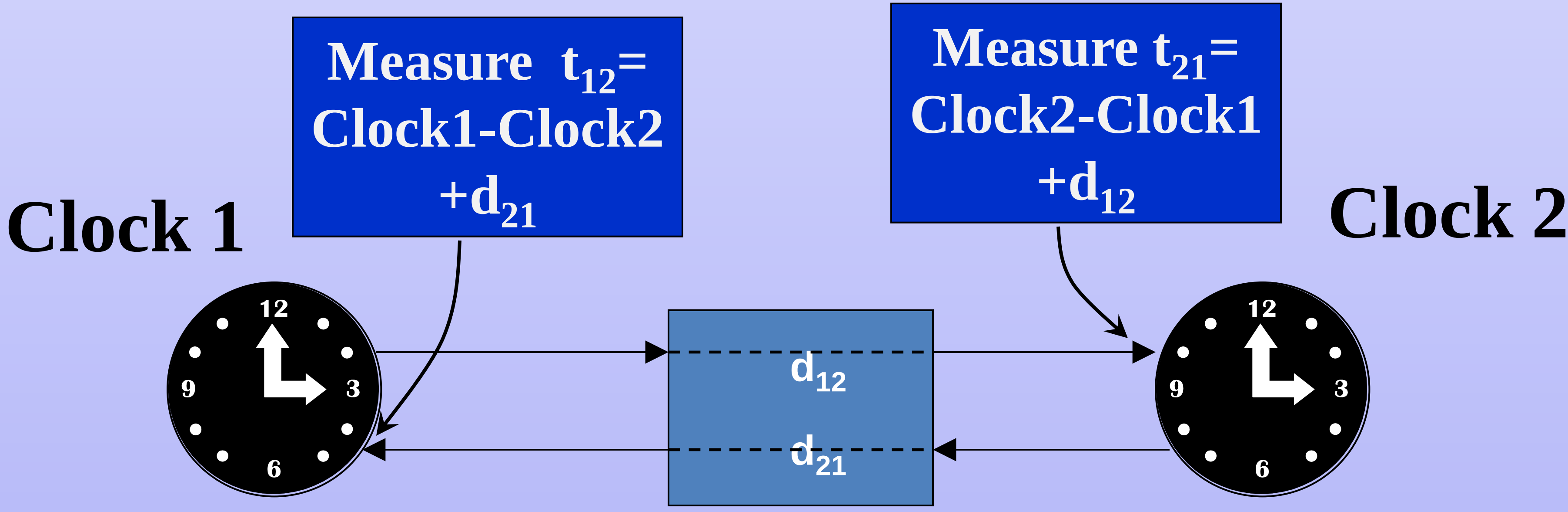
Two -Way Comparison System

(e.g. IEEE1588 – PTP)



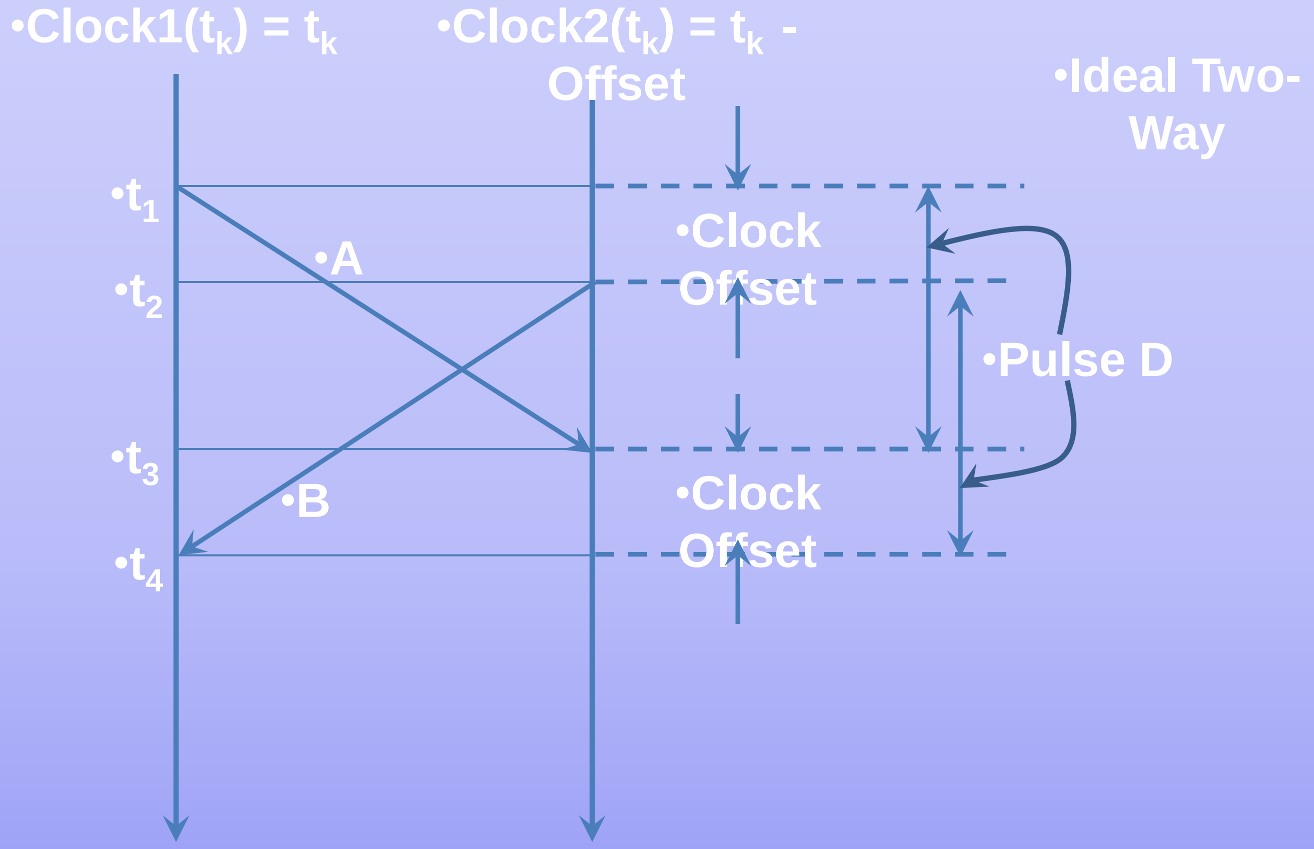
Clock 1 Systematics and Noise

Measurement Noise and Path Perturbations Largely Reciprocal:

$d_{21} = d_{12}$

Clock 2 Systematics and Noise

Two-Way has Four Time Stamps



Ideal Two-Way Computation

- Signal A: t_{31}= Clock2(t_3) - Clock1(t_1)
- Signal B: t_{42}= Clock1(t_4) – Clock2(t_2)
- Assume Clock1 is correct, Clock2 has an offset or error *E*, and Delays, *D*, are reciprocal
  - Clock1(t_j) = t_j, Clock2(t_j) = $t_j - E$
  - Transmission times on local clocks: Clock2(t_2)= Clock1(t_1), i.e. $t_2 = t_1 + E$
  - Reciprocal Delays: $d_{12} = d_{21} = D$
- Then $t_2 = t_1 + E$, $t_3 = t_1 + D$, $t_4 = t_2 + D$
- Then t_{31} = Clock2(t_3) - Clock1(t_1) = $t_3 - E - t_1 = t_1 + D - E - t_1 = D - E$
- And t_{42}= Clock1(t_4) – Clock2(t_2) = $t_4 - (t_2 - E) = t_2 + D - (t_2 - E) = D + E$
- Therefore
  - $D = ½ (t_{42} + t_{31})$
  - $E = ½ (t_{42} - t_{31})$

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GNSS References

- GPS
  - CGSIC 2013 http://www.gps.gov/cgsic/meetings/2013/
  - Coast Guard Nav Center http://www.navcen.uscg.gov/
- Galileo http://www.gsc-europa.eu/system-status/Constellation-Information
- Glonass http://www.sdcm.ru/smglo/grupglo?version=eng&site=extern
- Beidou:
  - IGS page http://igs.org/mgex/Status_BDS.htm

- General
  - GPS World http://gpsworld.com/
  - Inside GNSS http://www.insidegnss.com/