Timing Reference Sources

WSTS 2018 TUTORIAL SESSION

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Consultant
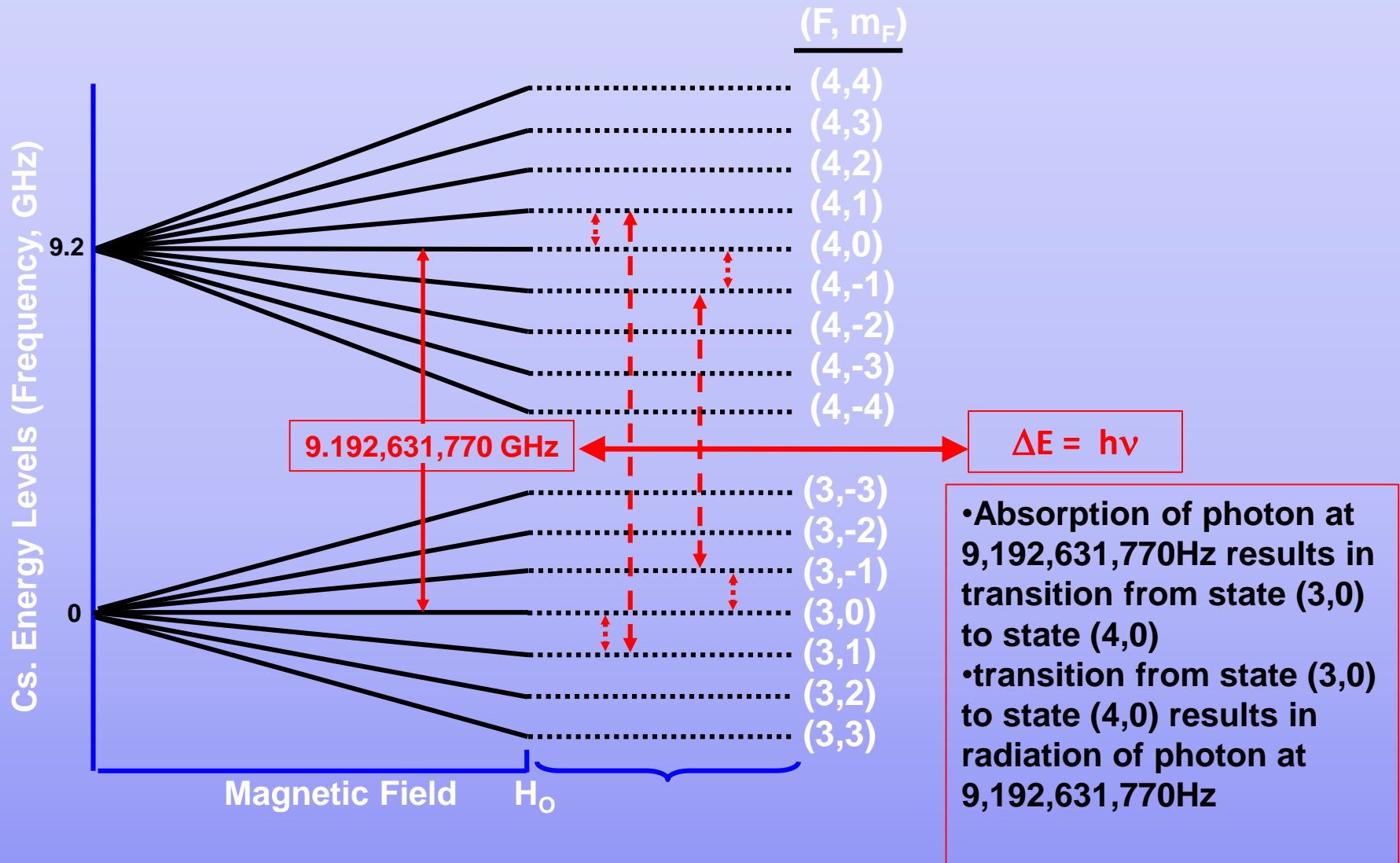Spirent
marcweissconsulting@gmail.com

Primary Sources
for Time and Frequency

- **Atomic Clocks**

- **Time and Frequency Transfer**

- **GNSS**

- **Conclusions**

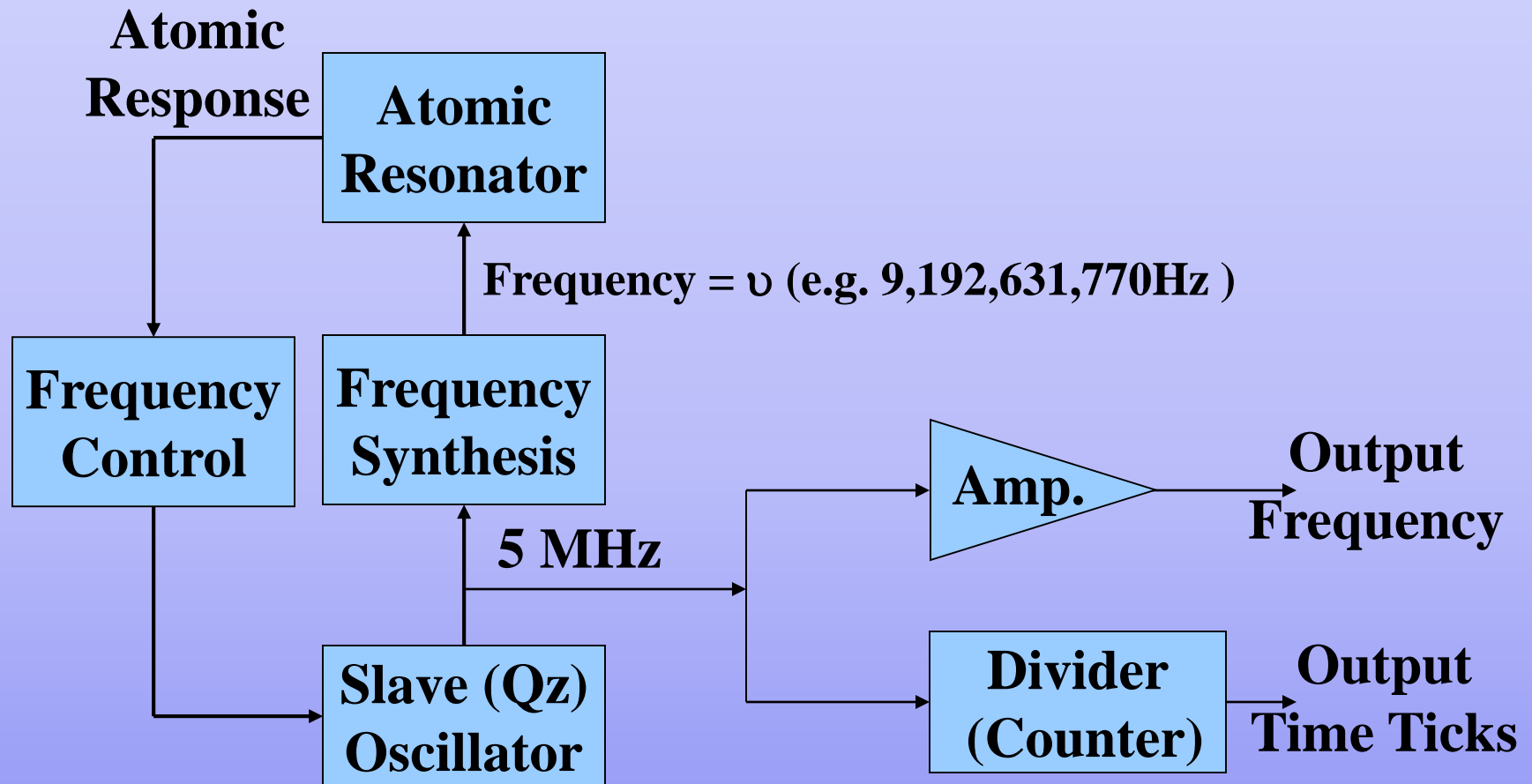- **Extra Slides**

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

Atomic Response

Atomic Resonator

Frequency = υ **(e.g. 9,192,631,770Hz)**

Frequency Control

Frequency Synthesis

5 MHz

Slave (Qz) Oscillator

Amp.

Output Frequency

Divider (Counter)

Output Time Ticks

Types of Commercial 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
- Note that new clocks are under development!

Holding a Microsecond after Loss of Sync (circa 2015)

	Temperature Controlled Crystal Oscillator (TCXO)	Oven Controlled Crystal Oscillator (OCXO)	Rb Oscillator (5E-12/mo. aging)
Range of times to hold a microsecond	10 minutes – 1 hour	1 – 8 hours	8 hours – 3 days
Cost Range	$5-50	$50-500	$500-1500

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.
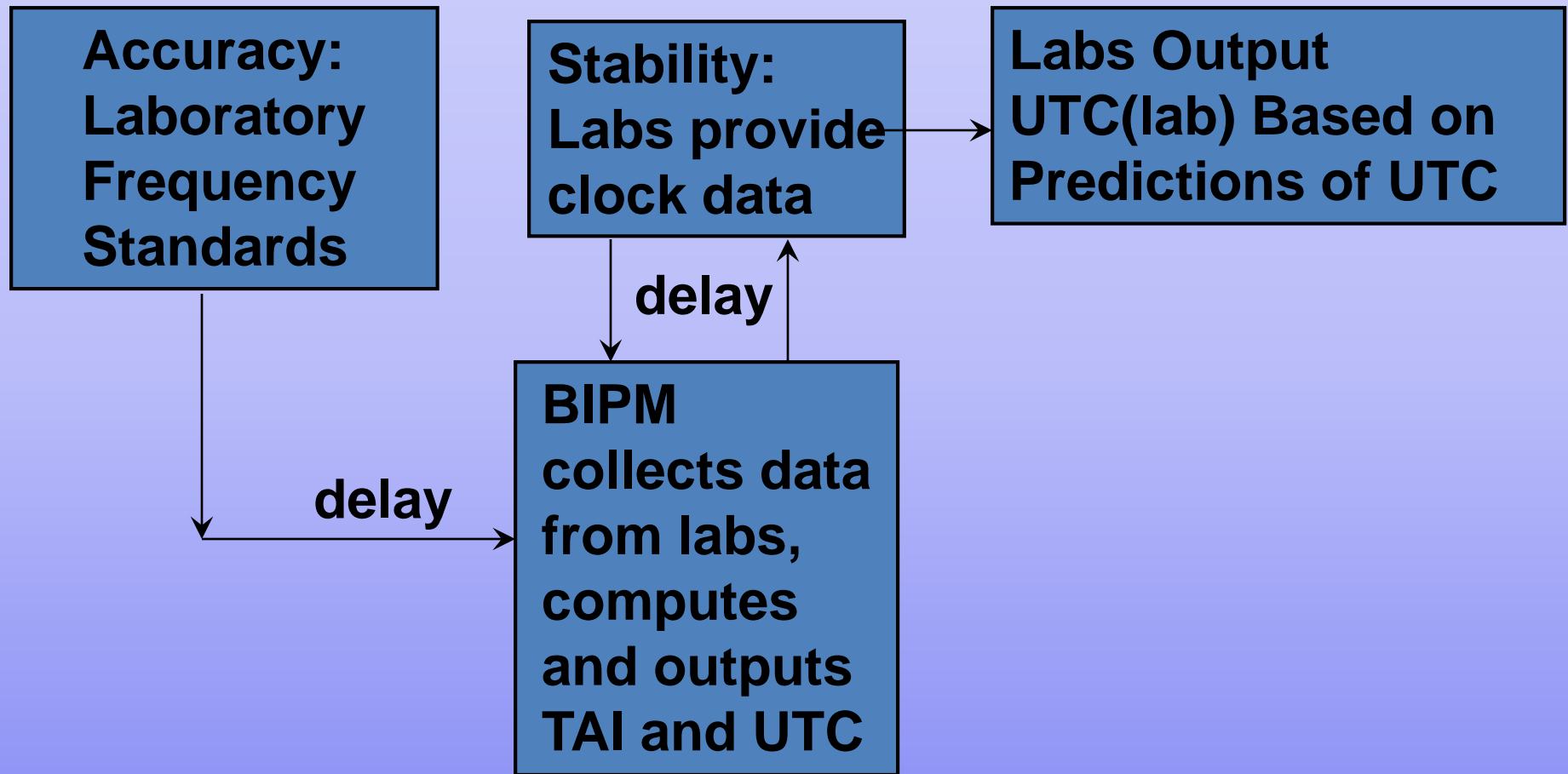
Frequency Accuracy:
History of NIST Primary Frequency Standards
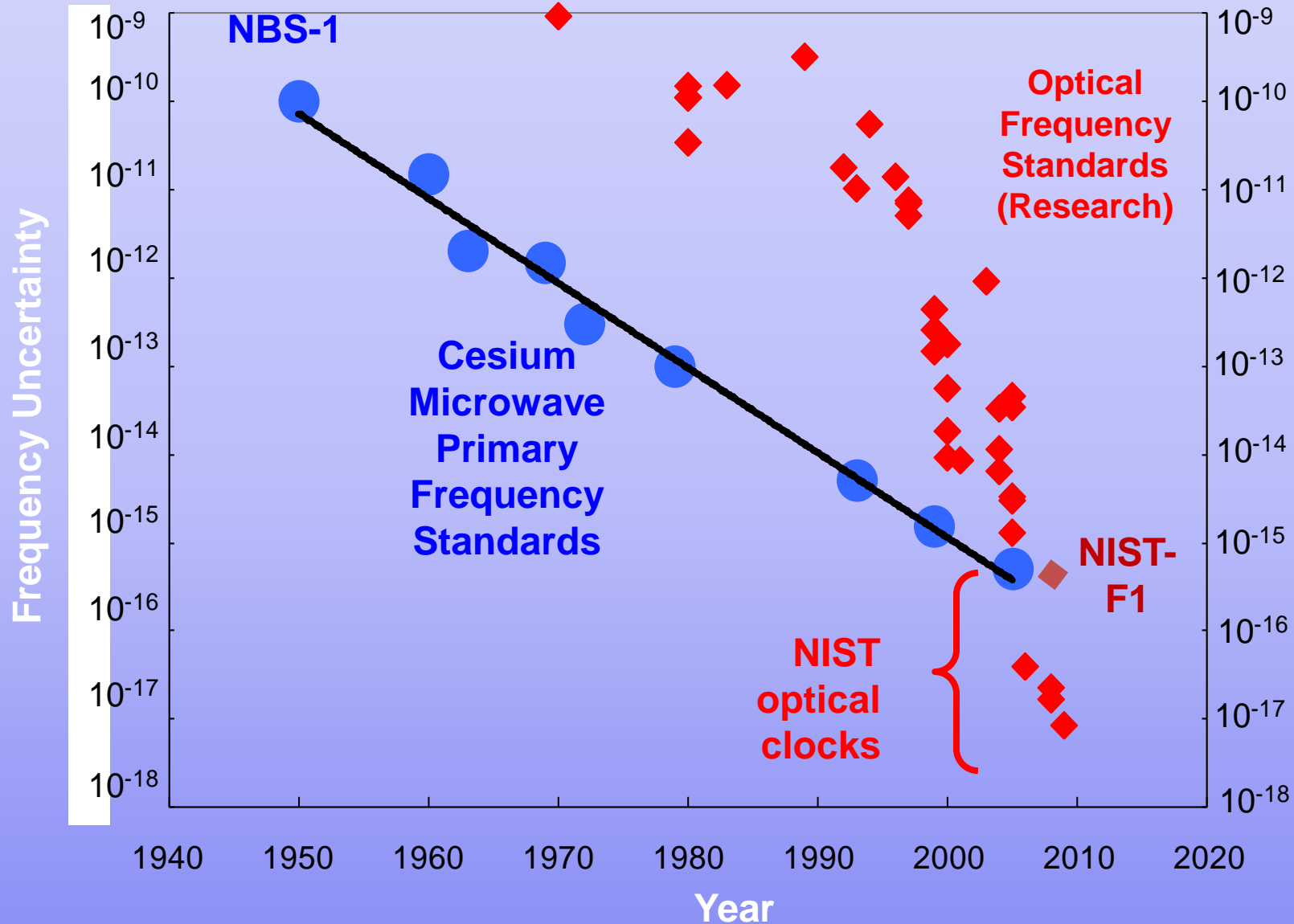
The Generation of UTC: Time Accuracy
Any Real Time UTC is only a Prediction, A PLL with a one-month delay

Accuracy: Laboratory Frequency Standards

Stability: Labs provide clock data

Labs Output UTC(lab) Based on Predictions of UTC

delay

BIPM collects data from labs, computes and outputs TAI and UTC

delay

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Time and Frequency Transfer:
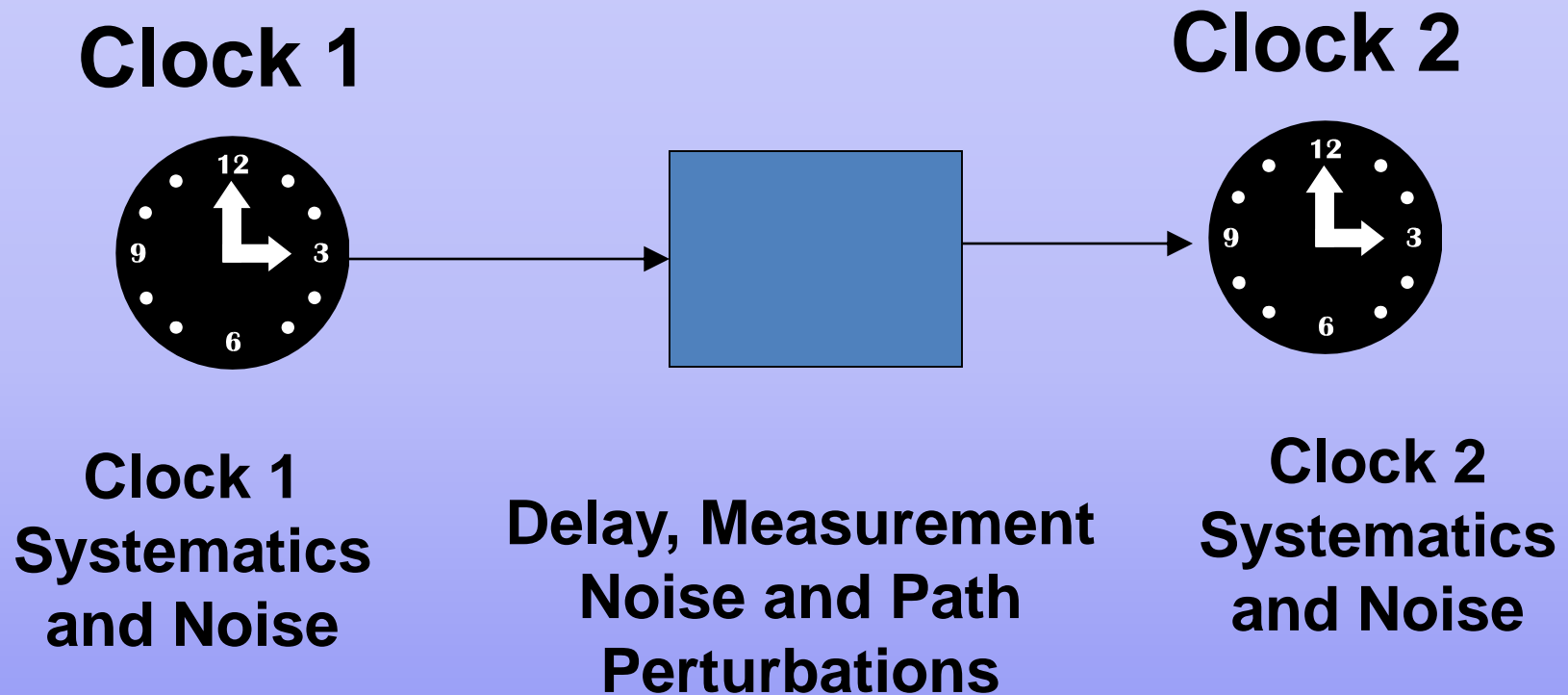# How to Deliver a Timing Reference

- 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
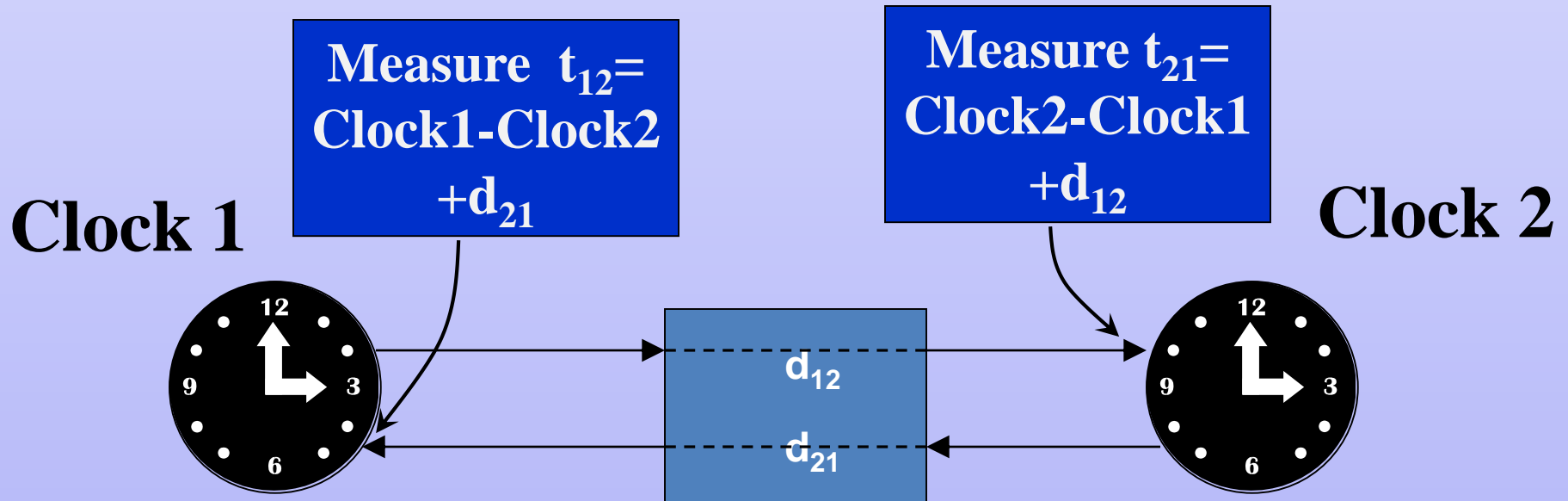 - Now suppose you timestamped when you sealed the letter and the receiving person timestamped when he got it…

- Time Stability = Frequency Accuracy

One-Way Dissemination or Comparison System

Clock 1

Clock 2

Clock 1 Systematics and Noise

Delay, Measurement Noise and Path Perturbations

Clock 2 Systematics and Noise

Two -Way Comparison System

(e.g. IEEE1588 – PTP)

Measure $t_{12}=$ Clock1-Clock2 $+d_{21}$

Measure $t_{21}=$ Clock2-Clock1 $+d_{12}$

Clock 1

Clock 2

d_{12}

d_{21}

Clock 1 Systematics and Noise

Measurement Noise and Path Perturbations
Largely Reciprocal:
$d_{21} = d_{12}$

Clock 2 Systematics and Noise

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The Family of Global Navigation Systems

GPS
US

Galileo
EU

GLONASS
Russia

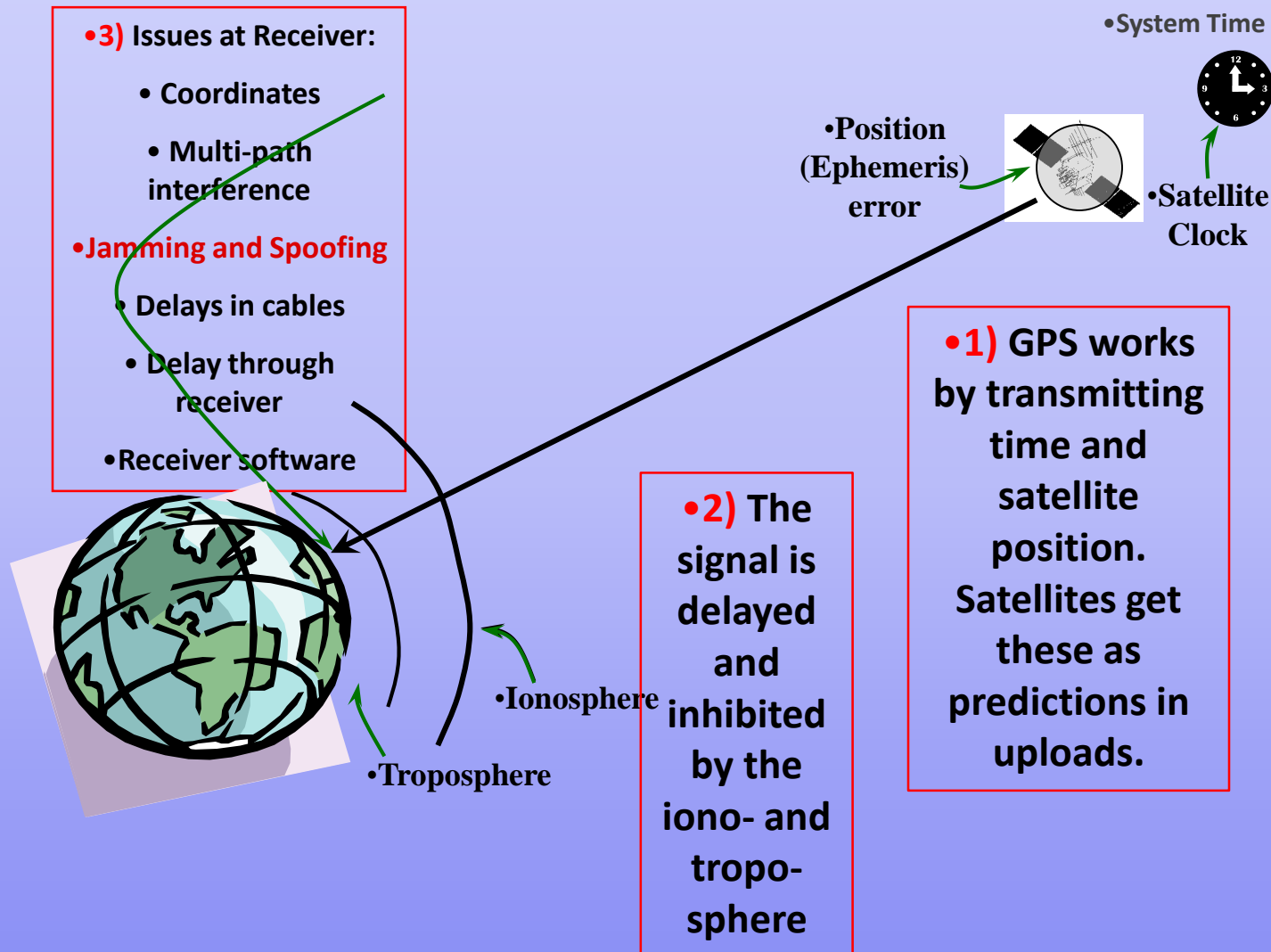**Beidou/Compass**
China

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 > $100B industry

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

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
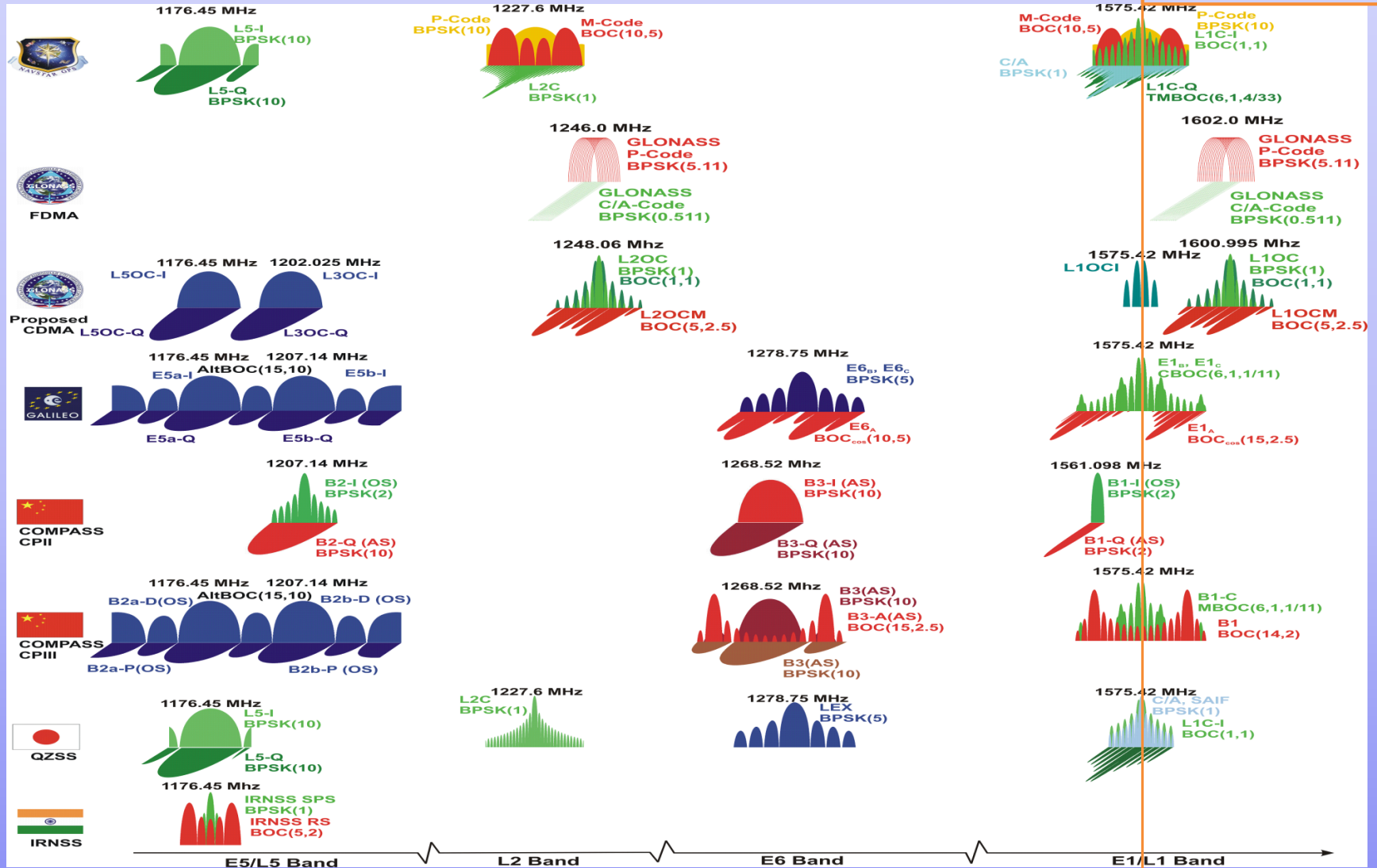 - But also makes it is relatively easy to jam GNSS and spoof

Time from GNSS:
Intentional and Unintentional Error Sources

•**System Time**

•**3) Issues at Receiver:**

• **Coordinates**

• **Multi-path interference**

•**Jamming and Spoofing**

• **Delays in cables**

• **Delay through receiver**

•**Receiver software**

•**Position (Ephemeris) error**

•**Satellite Clock**

•**1) GPS works by transmitting time and satellite position. Satellites get these as predictions in uploads.**

•**2) The signal is delayed and inhibited by the iono- and tropo-sphere**

•Ionosphere

•Troposphere

Spectra of GNSS's

GNSS Vulnerability

- GNSS best feature and worst problem: it is extremely reliable

- Jamming Power Required at GPS Antenna
  - On order of a Picowatt (10^{-12} watt)

- Many Jammer Models Exist
  - Watt to MWatt Output – Worldwide Militaries
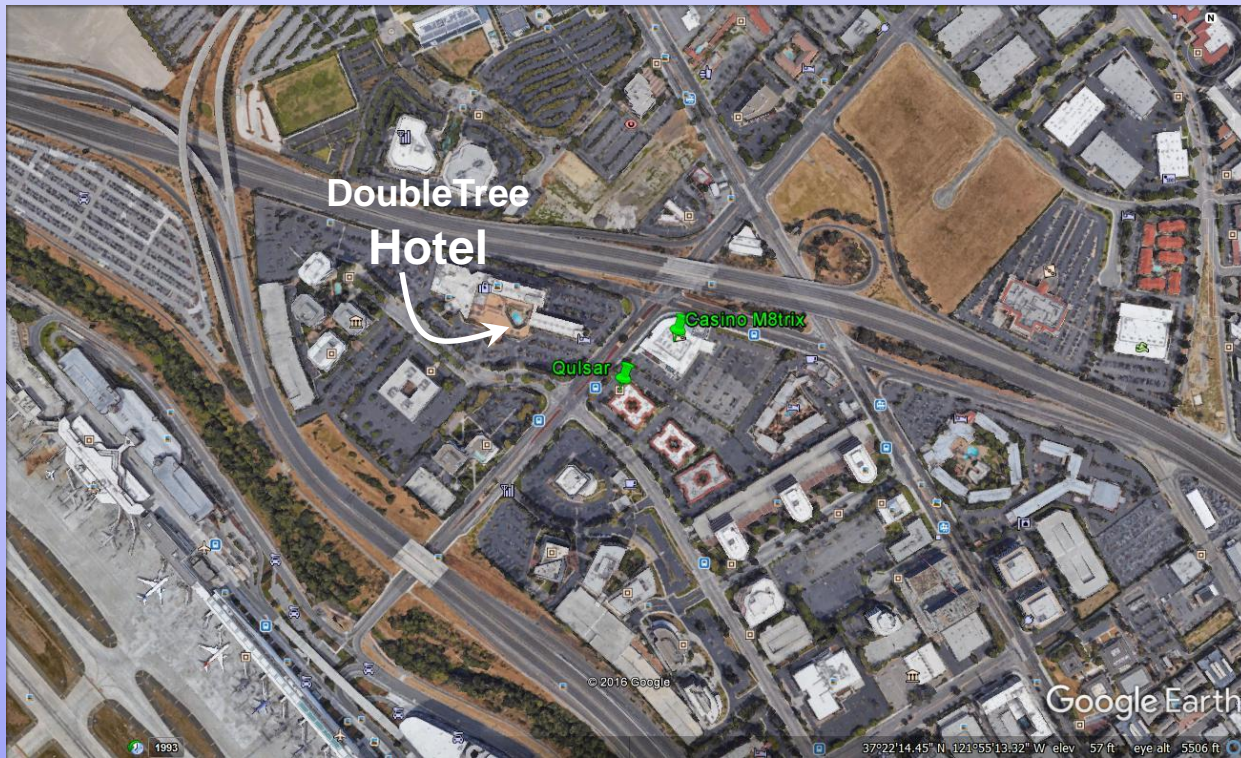 - Lower Power (<100 watts); "Hams" Can Make

- "Personal Privacy" Device

- Military Jammer

GPS Jammer

Jamming Detector, Qulsar, San Jose

Jamming Detector Courtesy of Prof. Charles Curry BEng, CEng, FIET, Managing Director, Chronos Technology Ltd, UK

Jamming Events, hour of day
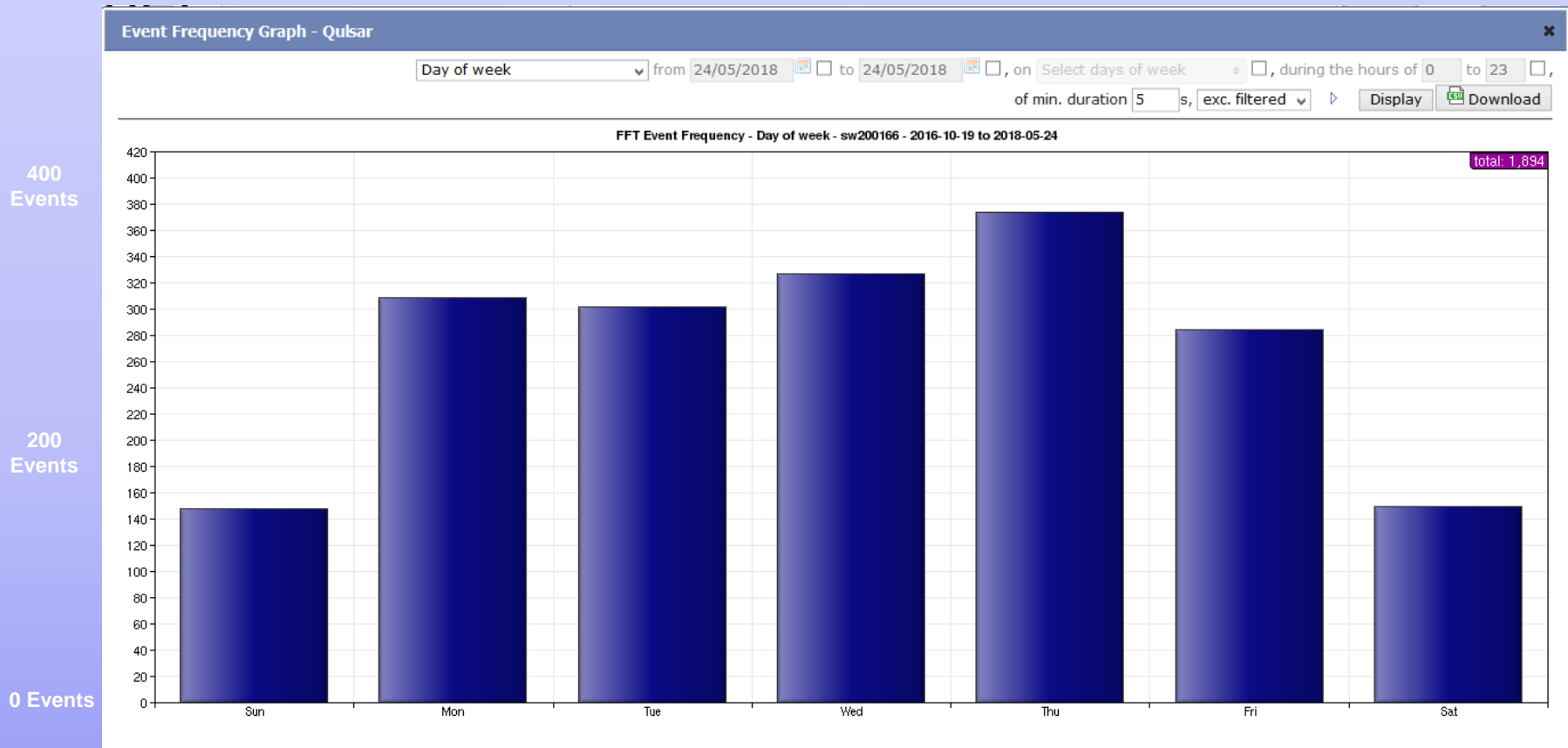# Number of Events out of 1894 Total
10/2016 to 05/2018
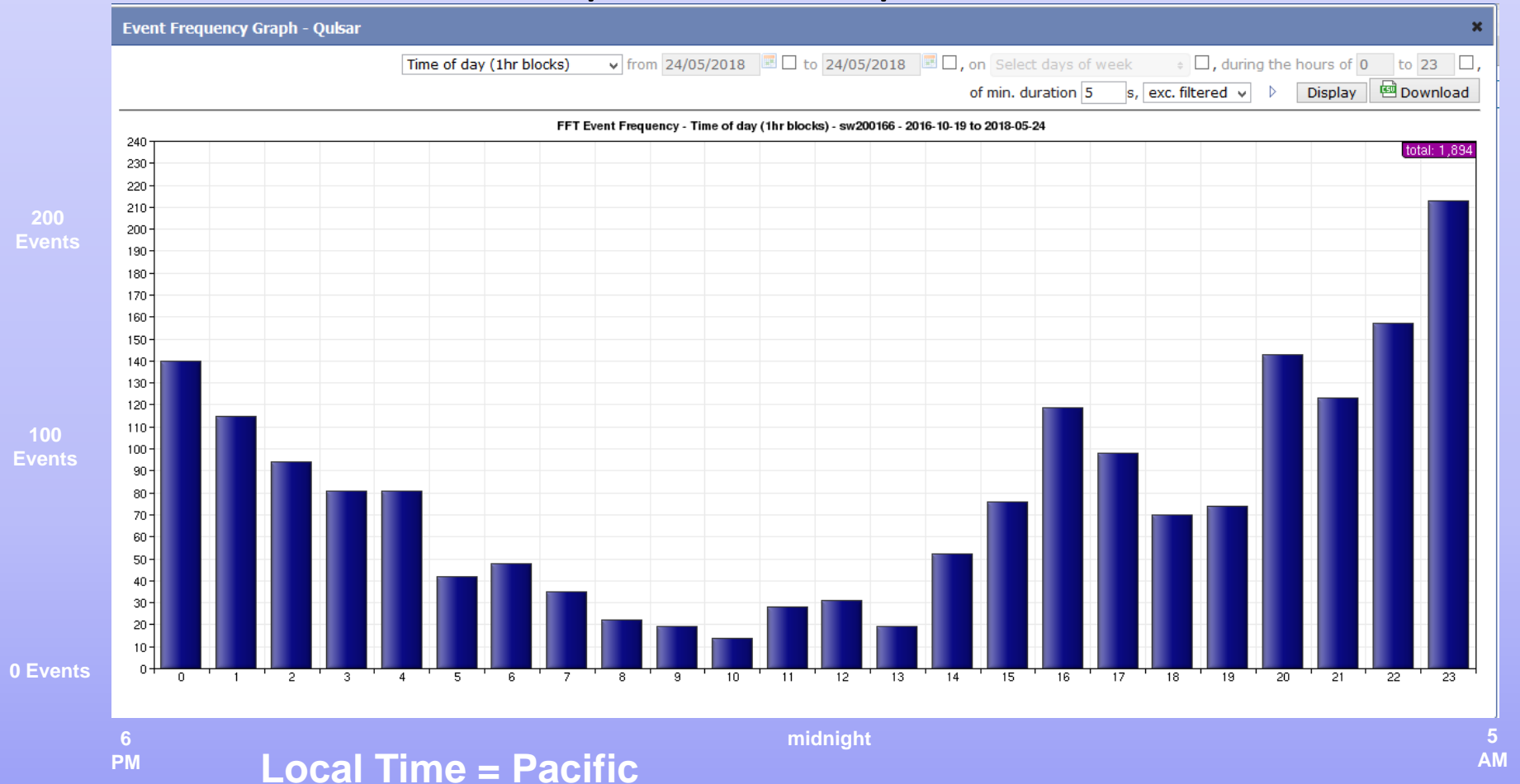
Local Time = Pacific

Jamming Detector Courtesy of Prof. Charles Curry BEng, CEng, FIET, Managing Director, Chronos Technology Ltd, UK

Jamming Events, day of week
Number of Events out of 1894 Total
10/2016 to 05/2018

Disruption Mechanisms - Spoofing/Meaconing

- Spoof – Counterfeit GNSS Signal
    - C/A Code Short and Well Known
    - Widely Available Signal Generators
- Meaconing – Delay & Rebroadcast
- Possible Effects
    - Long Range Jamming
    - Injection of Misleading PVT Information
- No "Off-the-Shelf" Mitigation

1. Match Real Code

3. Pull Off

Spoof Code
GPS S.V. Code

Successful Spoof
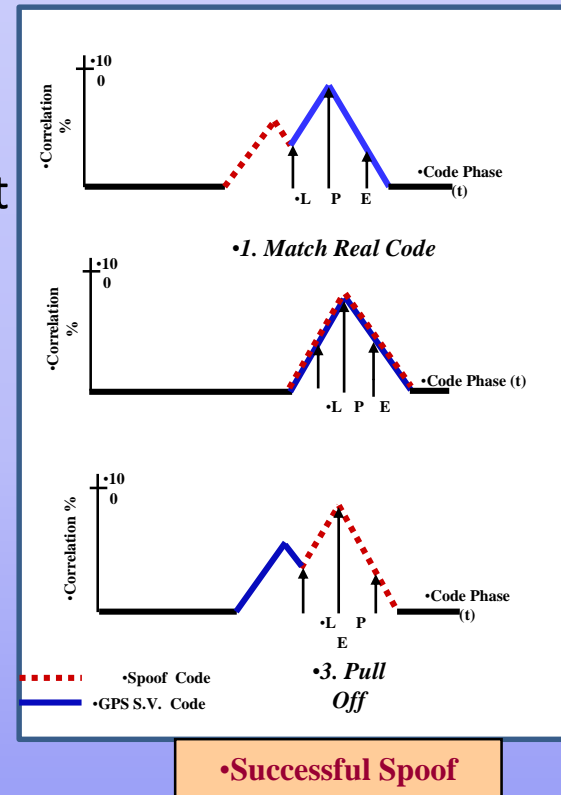
Civil GPS Spoofing Threat Continuum*

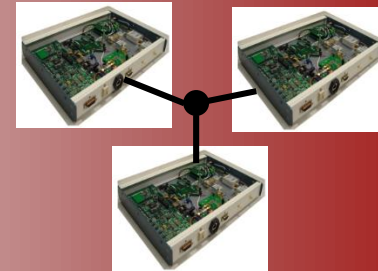*Simplistic*   *Intermediate*   *Sophisticated*

Commercial signal simulator   **Portable software radio**   **Coordinated attack by multiple phase-locked spoofers**

•* Courtesy of Coherent Navigation, Inc

SDR is making Spoofing Easy

Standard Engineering School classes teach techniques for signal generation that easily apply to spoofing

Primary Sources
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- **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

Thanks for your attention!

Extra slides follow

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Clock Stability

Clock (in)stability is given by:

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

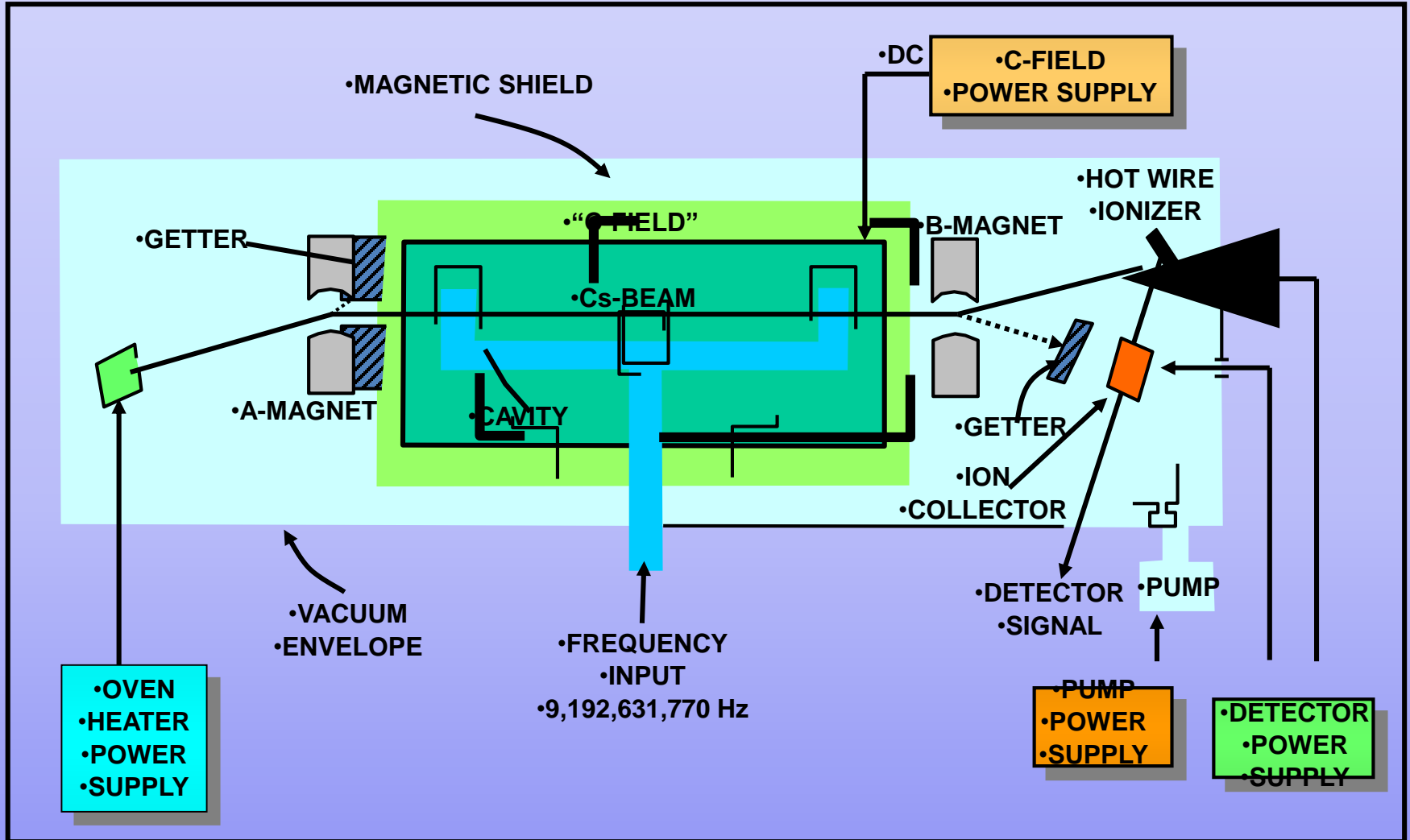**Atomic Line Q**   **Signal to Noise**
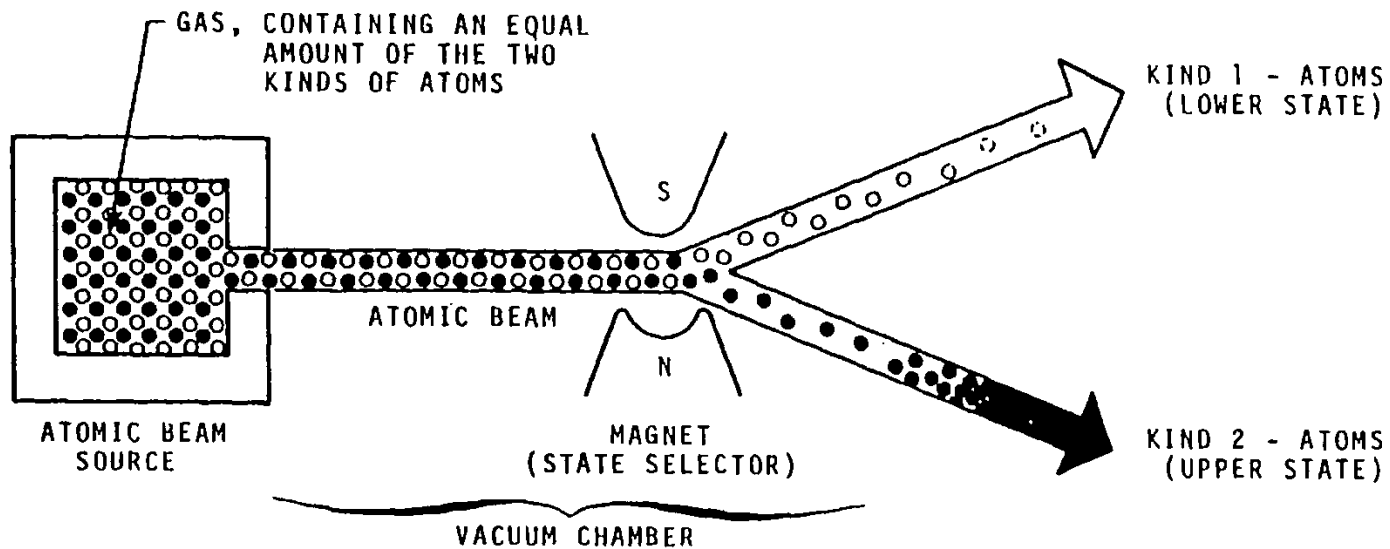
Clock stability can be improved by:

Increase Ramsey (observation) times (decrease $\Delta\omega = 1/T_{Ramsey}$)
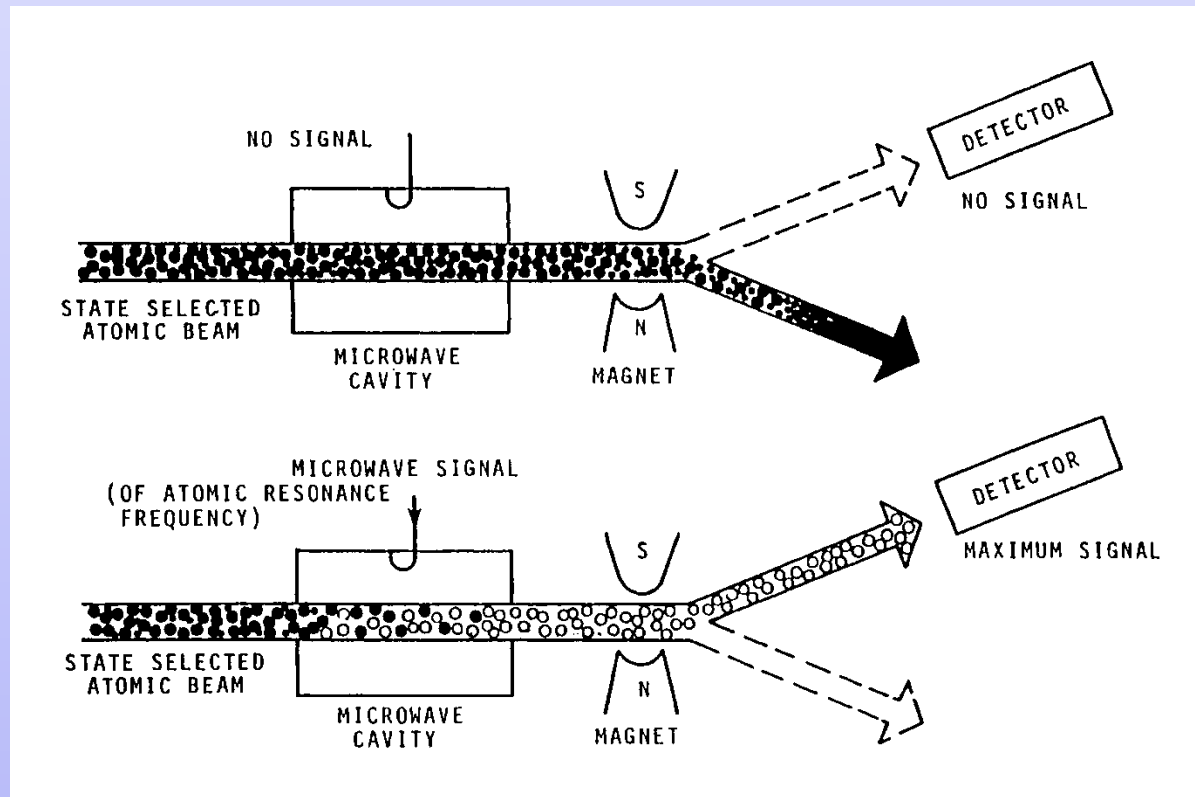
Improve the S/N (more atoms!)

Increase the frequency of the clock transition (optical?)

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 $\nu = 9.193$ GHz**

- **A second magnet selects atoms which have made the transition**

- **The number of detected atoms is used to tune the frequency**

Commercial Cesium Standards

•Telecom

•Laboratory/Timekeeping
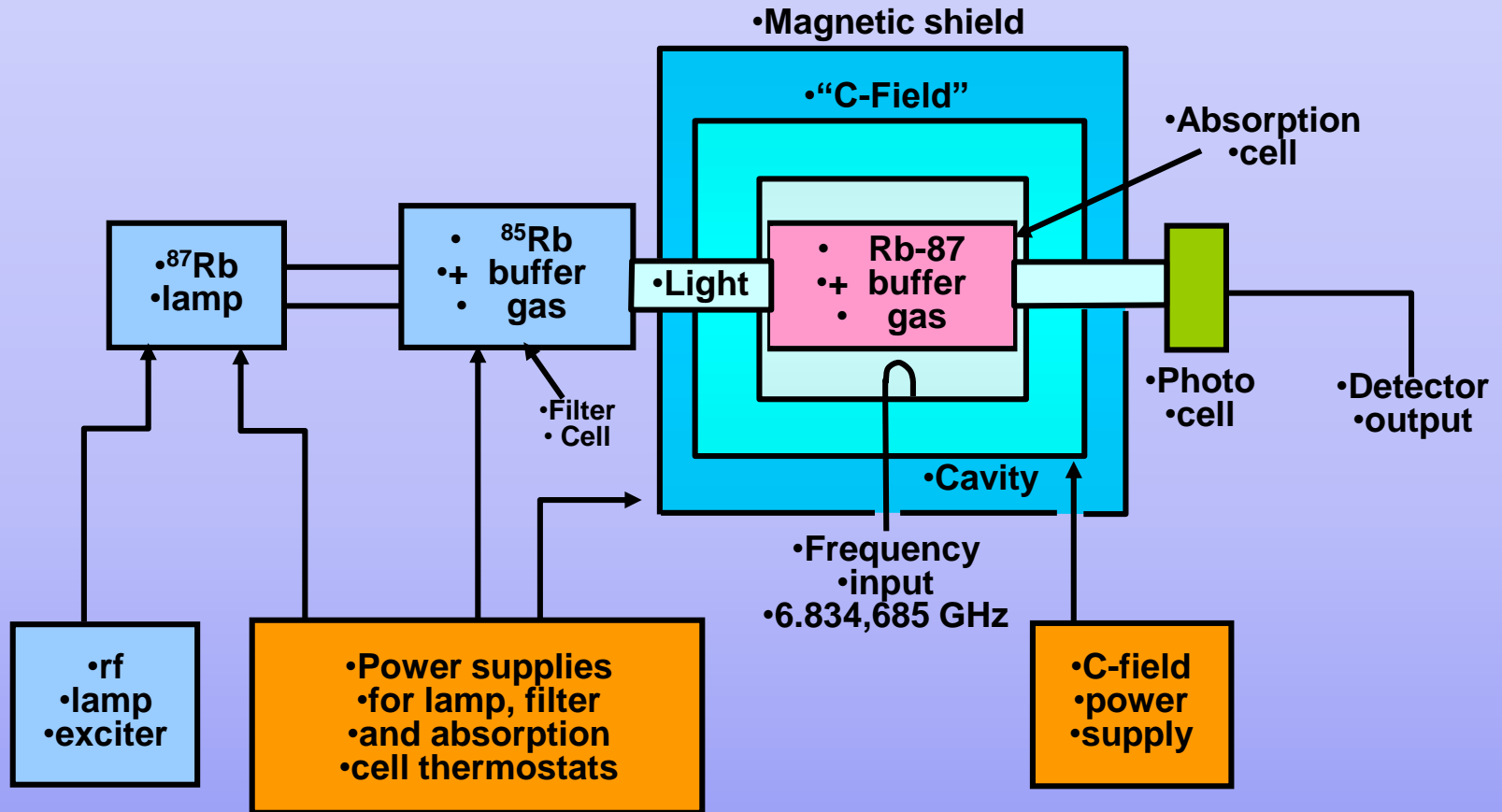

•Space/GPS

•Courtesy of Robert Lutwak, Symmetricom

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

Rubidium Standard

- **Magnetic shield**
- **"C-Field"**
- **Absorption cell**

^{87}Rb lamp

- **^{85}Rb + buffer gas**
- **Filter Cell**

- **Light**

- **Rb-87 + buffer gas**

- **Photo cell**
- **Detector output**

- **Cavity**

- **Frequency input 6.834,685 GHz**

- **rf lamp exciter**

- **Power supplies for lamp, filter and absorption cell thermostats**

- **C-field power supply**

- **Adapted from figure by John Vig**

Optical Microwave Double Resonance
Simplified Rb energy level diagram

•^{87} **Rb**

•**B**
•**A**

•6.835 GHz

•3.035 GHz

•780 nm

•^{85} **Rb**
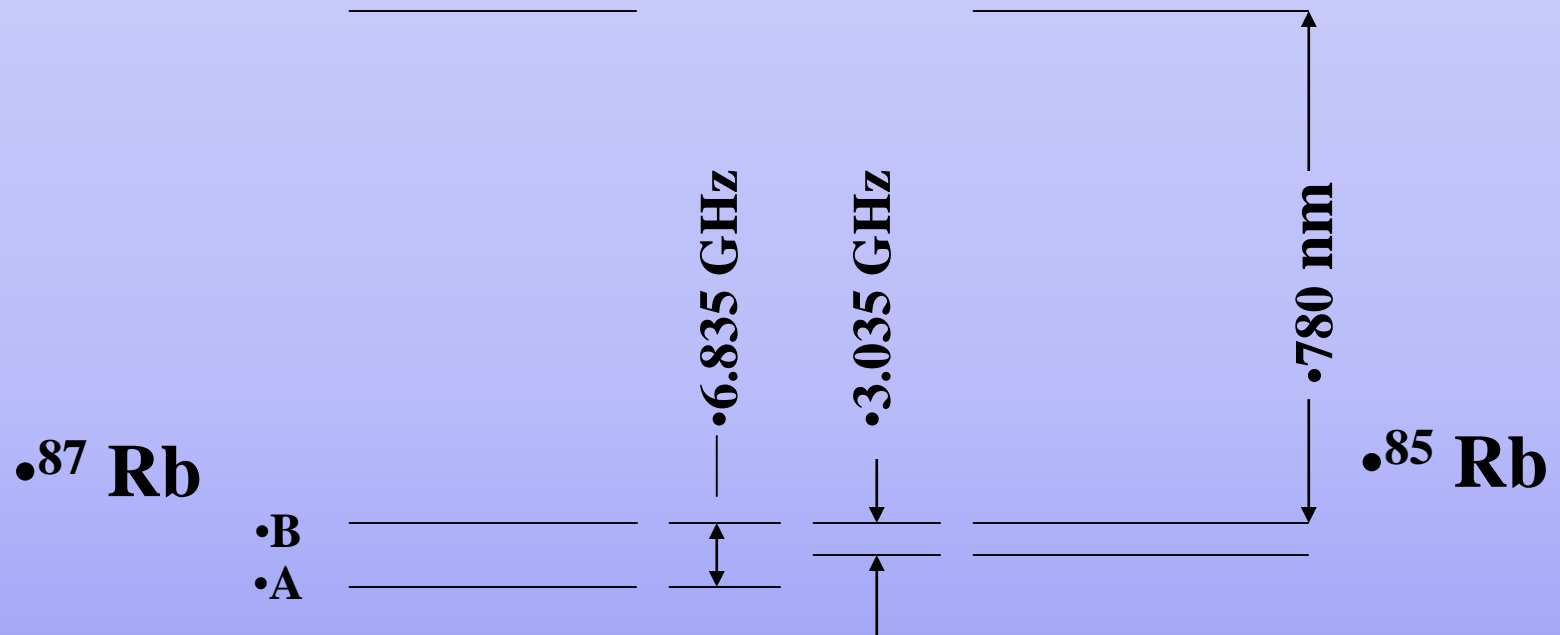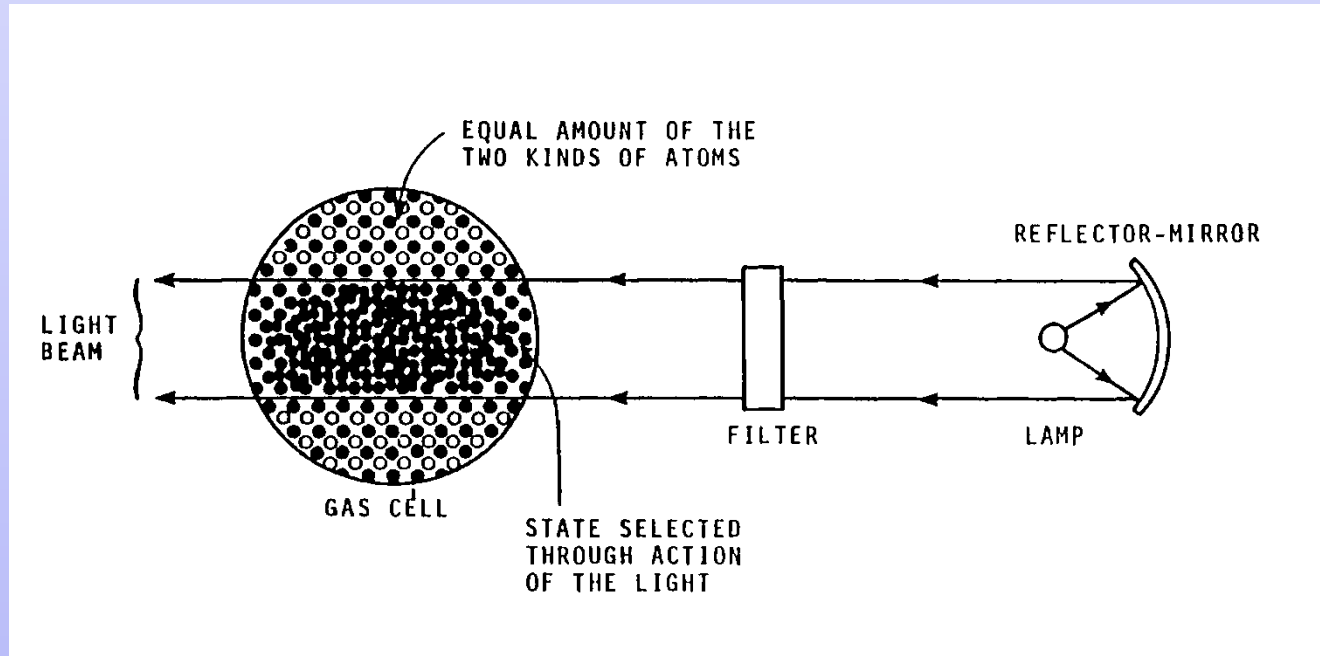
- **Optical pumping is used to deplete one hyper-fine level**

- **Light tuned to the transition frequency from "A" to the**
  - **unstable excited state puts all of the atoms in the**
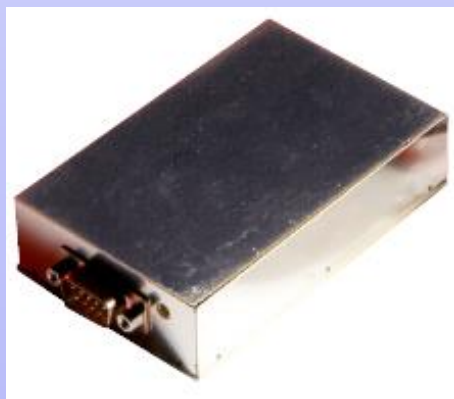   - **hyper-fine state "B"**
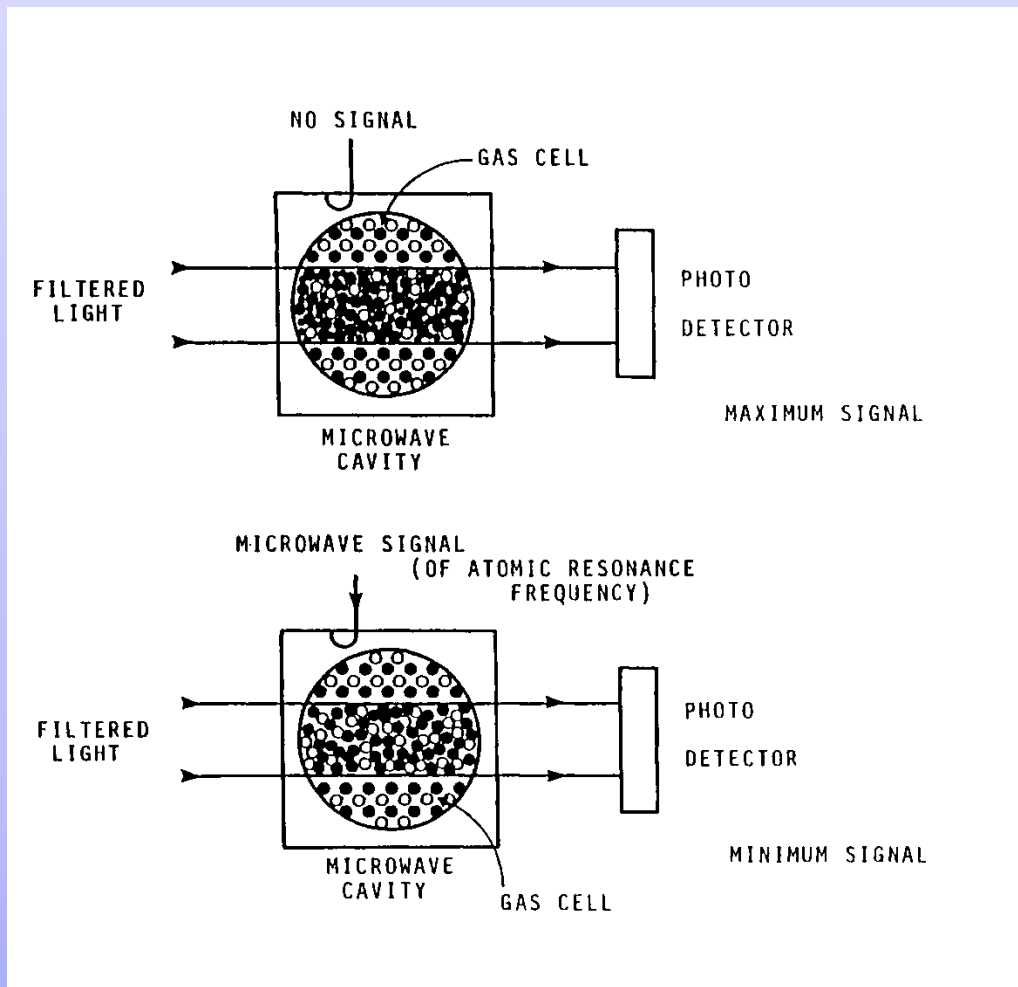
- Microwaves at $\nu = 6.835$ GHz stimulate the transition from "B" to "A"
- The absorption of light is measured
- The frequency ν is tuned to minimize the light coming through the ^{87} Rb cell

Frequency Stability of a Rubidium Standard
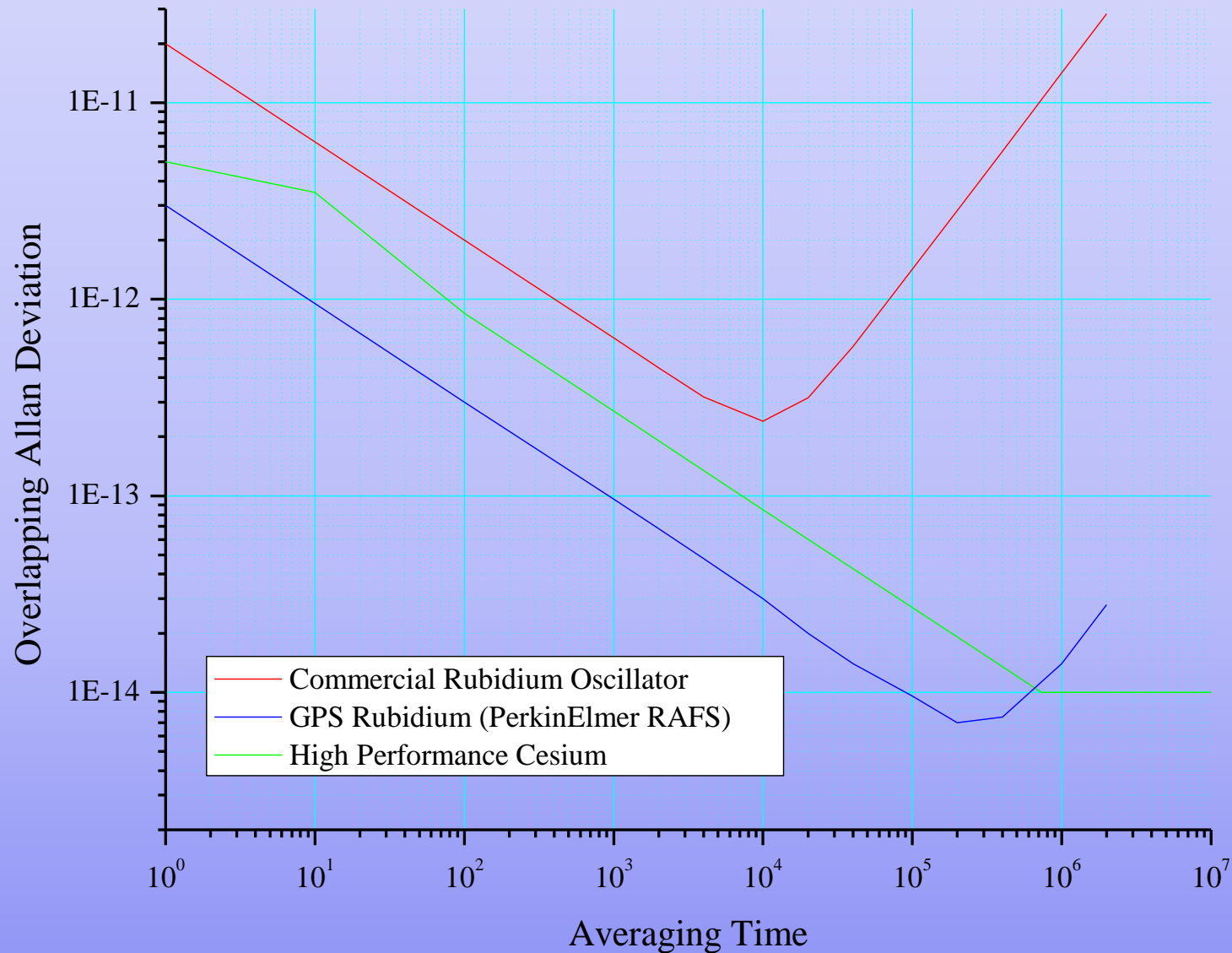
Commercial Rubidium Standards

•Stanford Research PRS10

•Frequency Electronics
• FE-5680A

•Quartzlock E10

•Temex SR100

•PerkinElmer GPS RAFS

•Symmetricom X72

•Accubeat AR-70A

•Courtesy of Robert Lutwak, Symmetricom

Hydrogen Maser
(Active Standard)

•Teflon coated
•storage bulb

•Microwave
•cavity

•Microwave
•output

•State selector
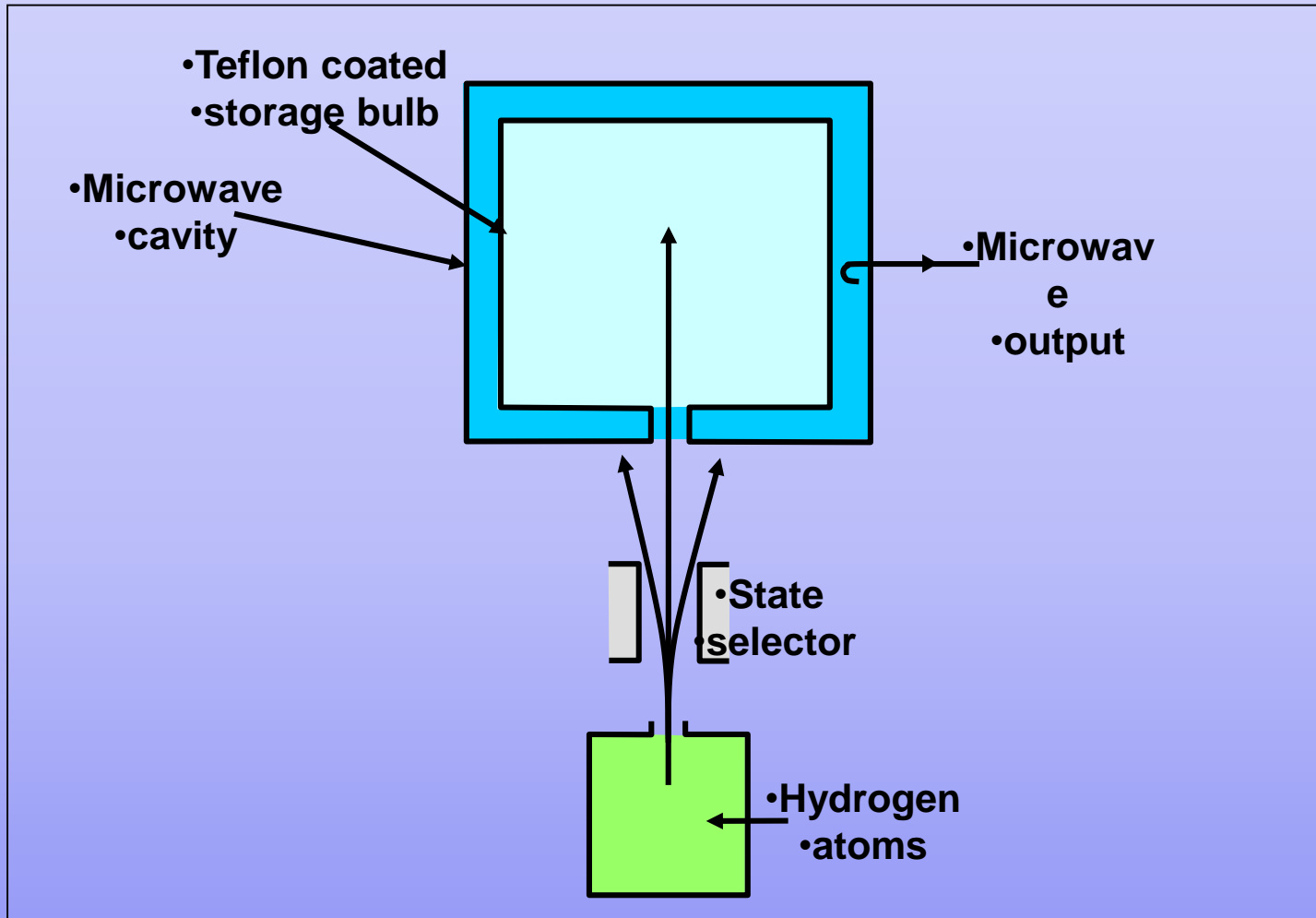
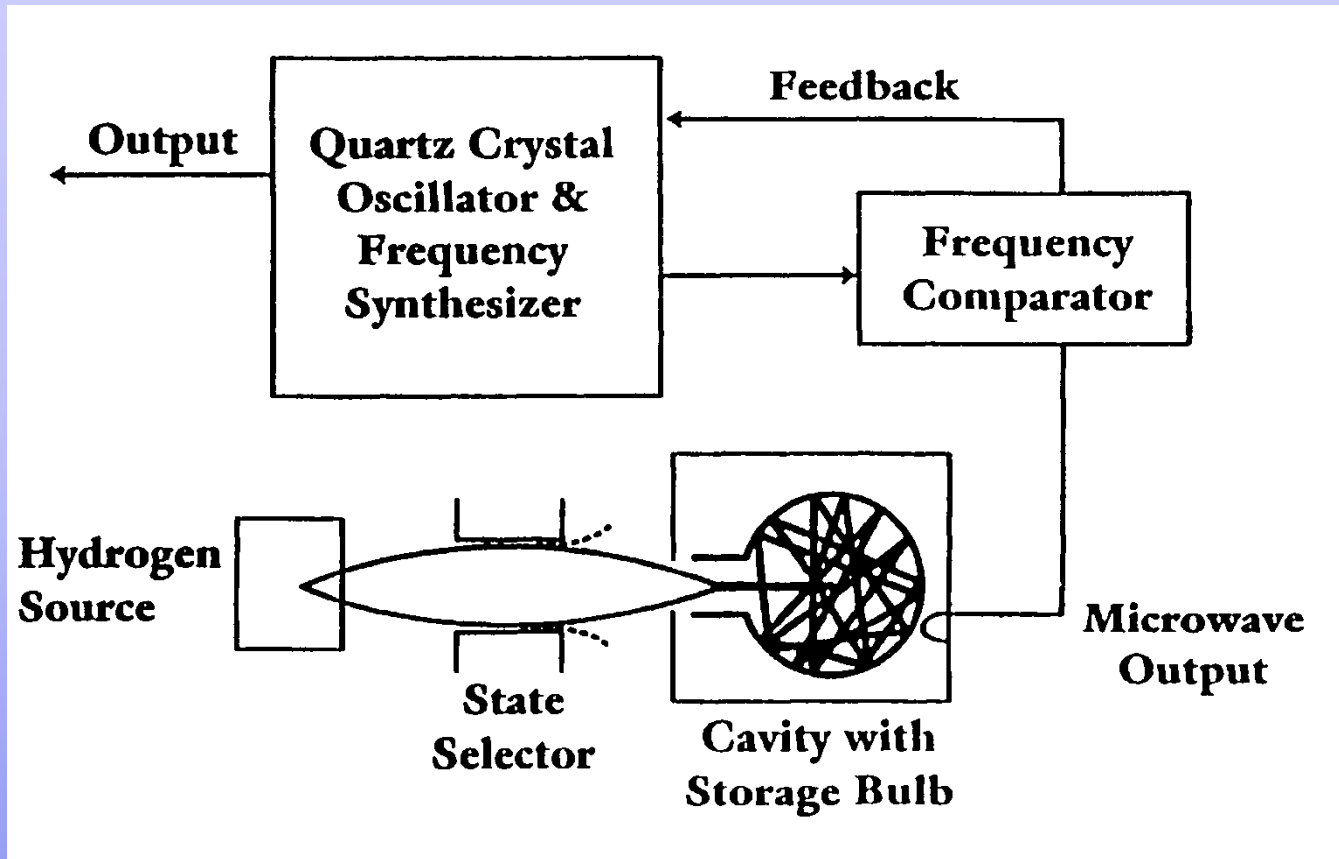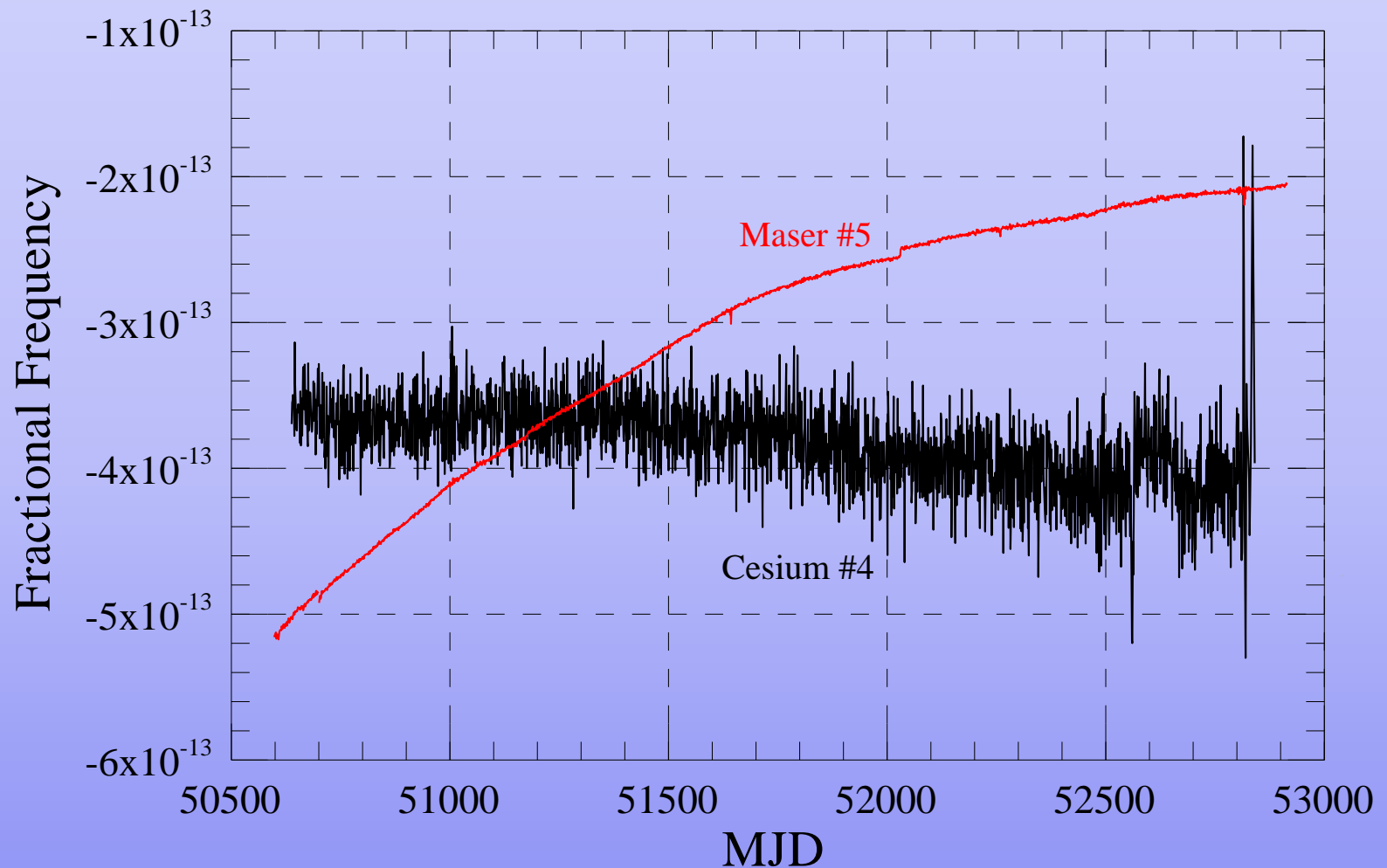•Hydrogen
•atoms

•Adapted from a figure by John Vig

Hydrogen Maser
(Active Standard)

Frequency Drift of a Commercial Cesium Standard and a Hydrogen Maser

Frequency Stability of a Cesium Standard
(No frequency drift removed)
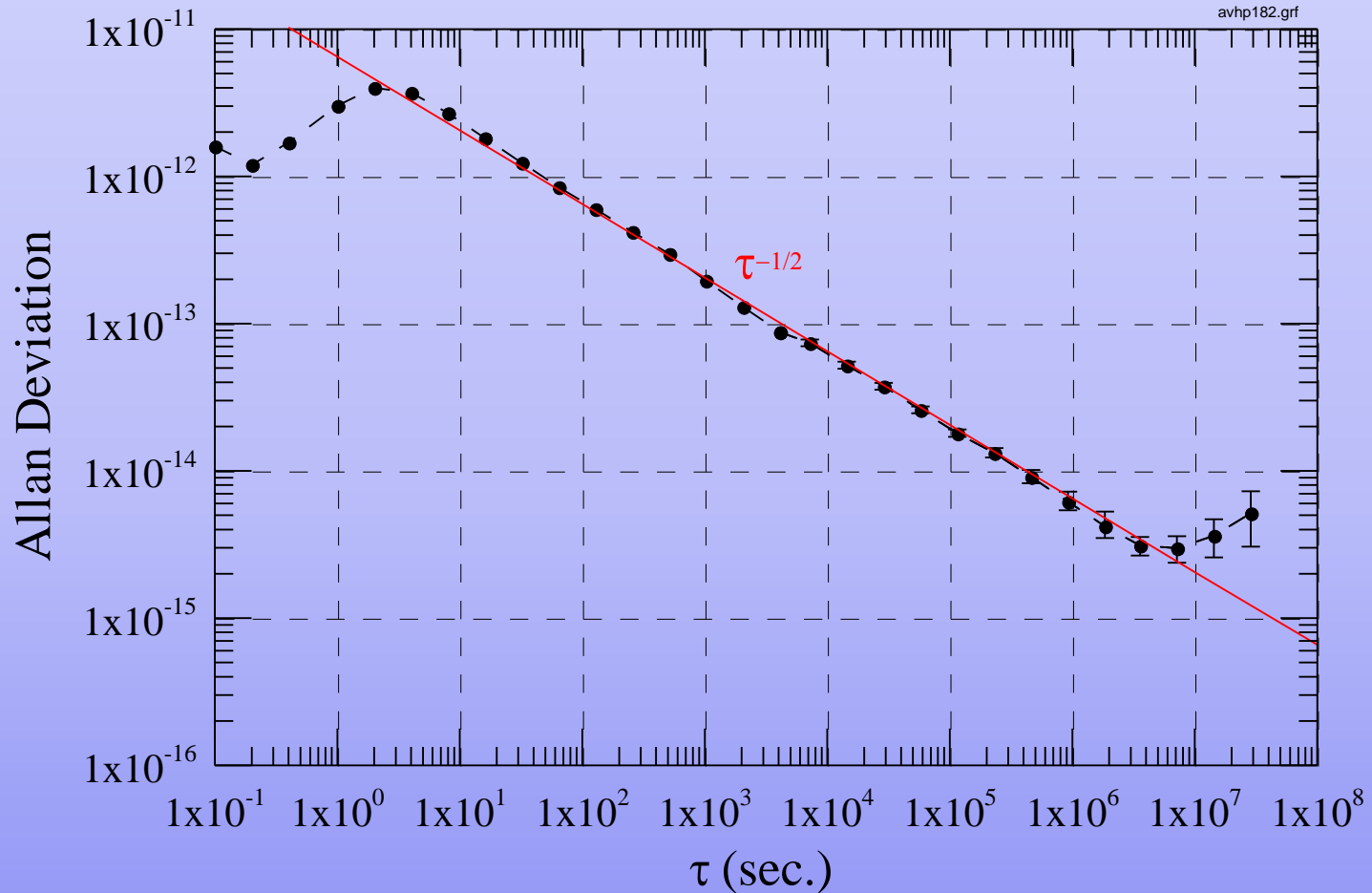
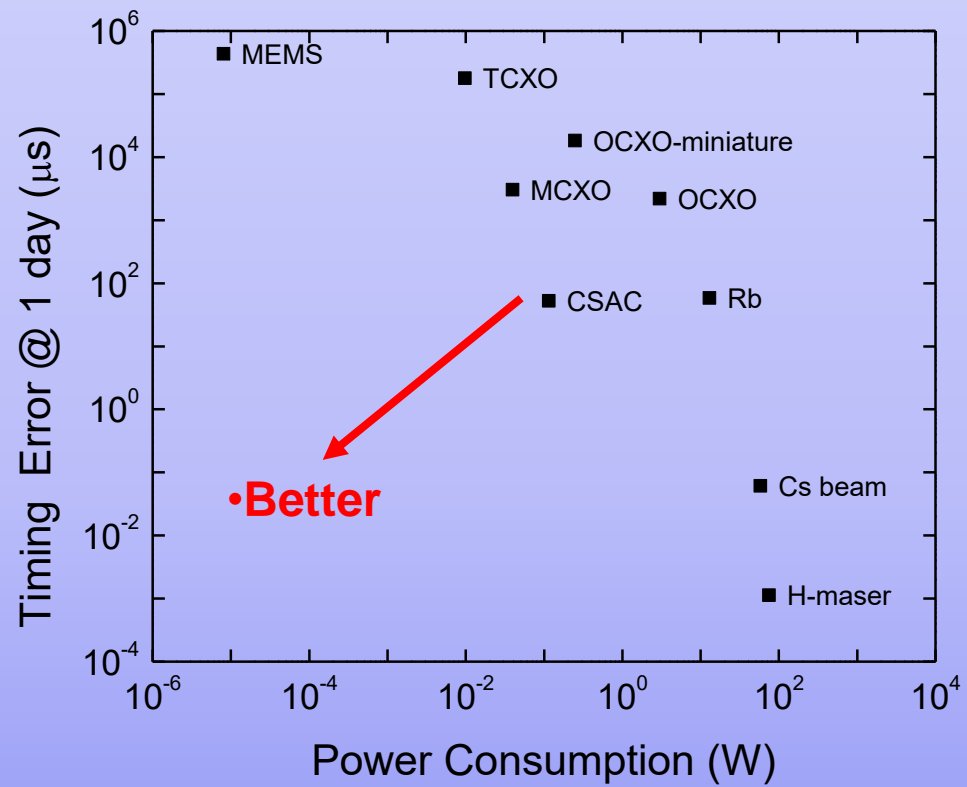# Commercial Active Hydrogen Maser

Frequency Stability of a Hydrogen Maser
(Frequency drift removed – $1x10^{-16}$/day typical)
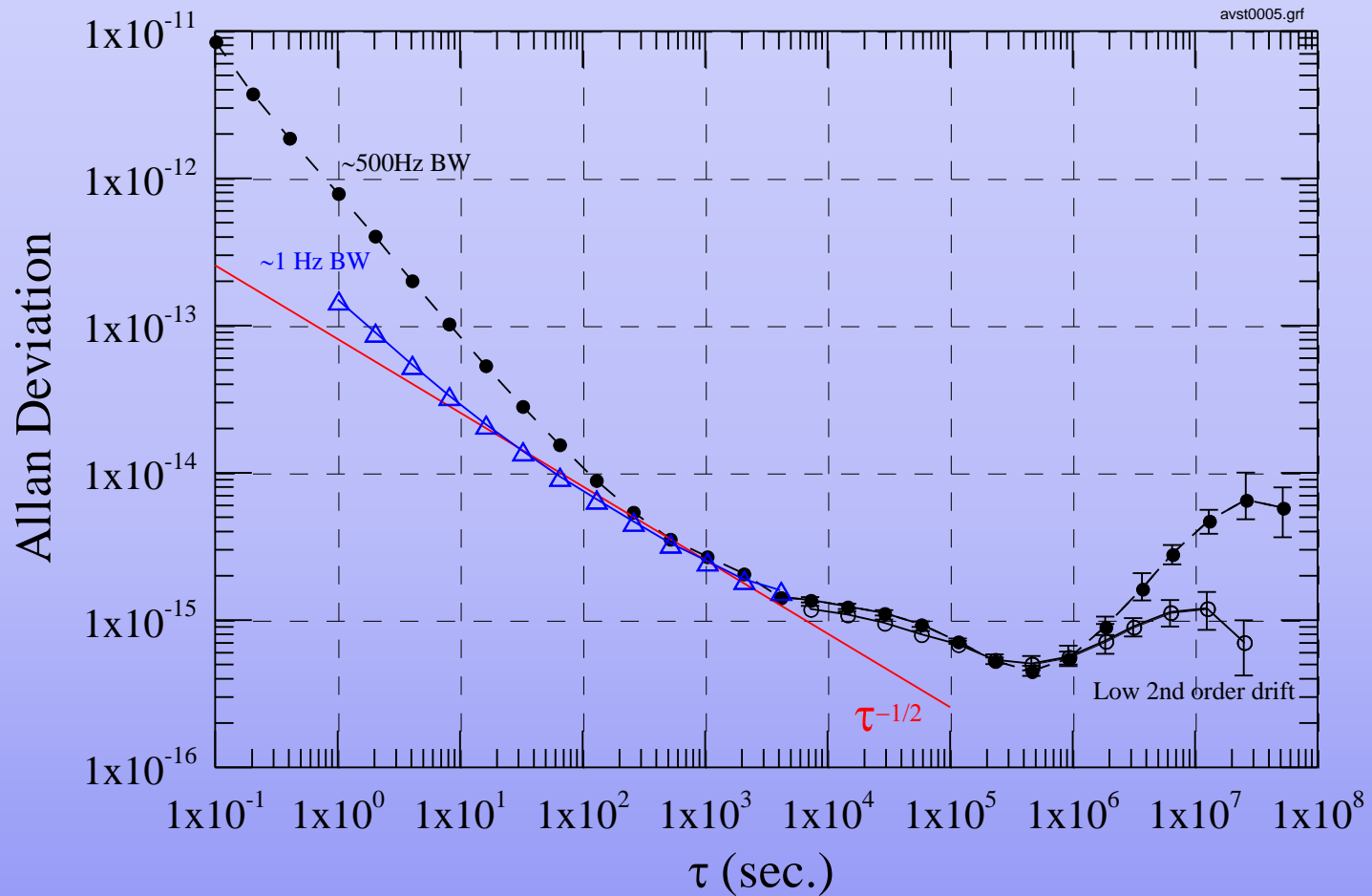
Something New!

- 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}	~10^{-11}	~10^{-11}	10^{-7} to 10^{-8}	Wristwatch, computer, cell phone, household clock/appliance,…
Hi-quality Quartz, OCXO	10^{-8}	~10^{-12}	~10^{-12}	10^{-9} to 10^{-11}	Network sync, test equipment, radar, comms, nav,…
Rb Oscillator	~10^{-9}	~10^{-11}	~10^{-13}	10^{-11} to 10^{-13}	Wireless comms infrastructure, lab equipment, GPS, …
Cesium Beam	~10^{-13}	~10^{-11}	~10^{-14}	nil	Timekeeping, Navigation, GPS, Science, Wireline comms infrastructure,…
Hydrogen Maser	~10^{-11}	~10^{-13}	~10^{-15}	10^{-15} to 10^{-16}	Timekeeping, Radio astronomy, Science,…

Oscillator Comparison (continued)

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

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- **GNSS**

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- **Extra Slides**

Time and Frequency Transfer

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

- Continuous vs Intermittent Measurements

Clock Hierarchies

Clock 1

Clock 2

Clock 1 Systematics and Noise

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

Clock 2 Systematics and Noise
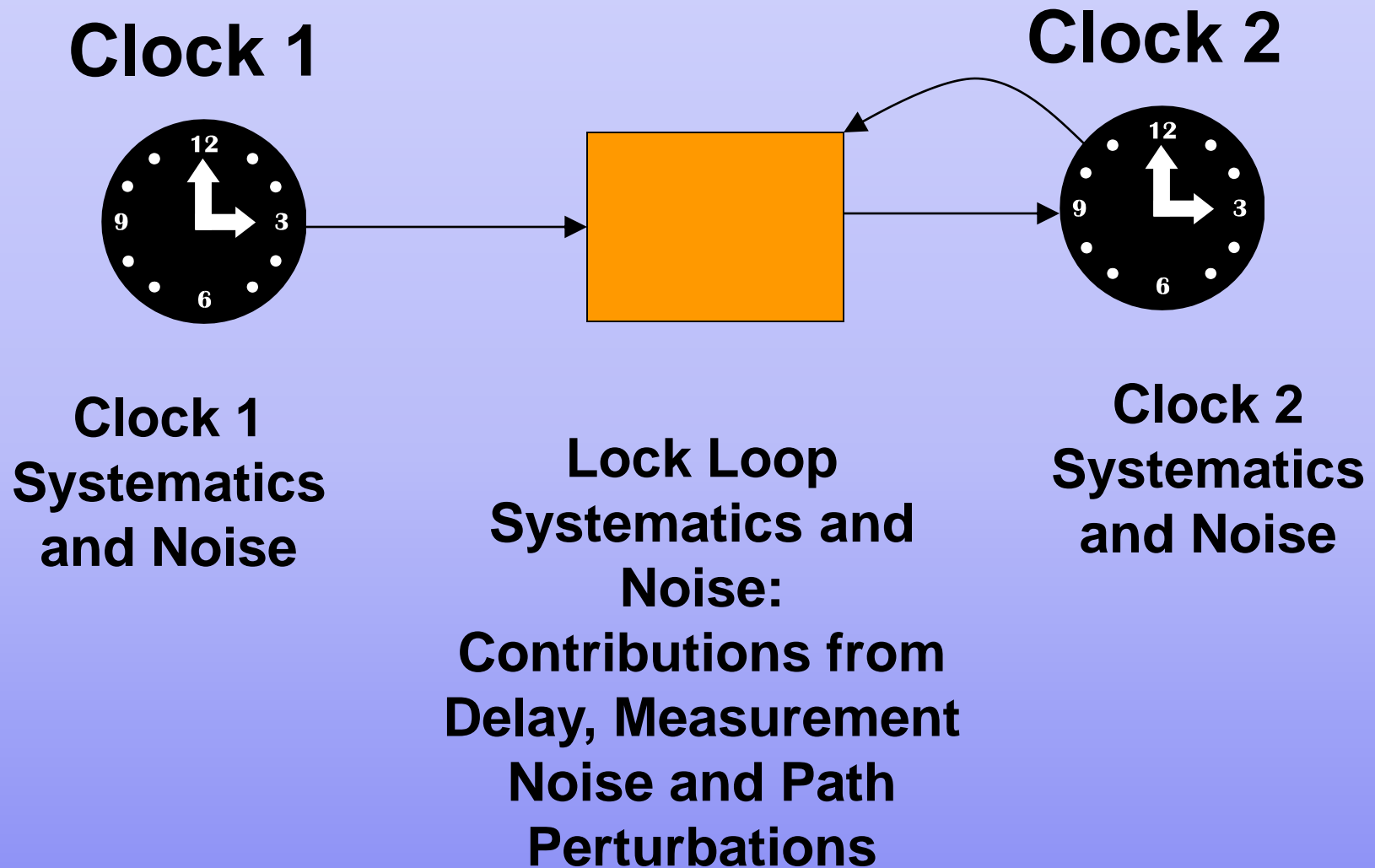
Two-Way has Four Time Stamps

•Clock1(t_k) = t_k

•Clock2(t_k) = t_k - Offset

•Ideal Two-Way

•t_1

•A

•t_2

•Clock Offset

•Pulse D

•t_3

•B

•Clock Offset

•t_4
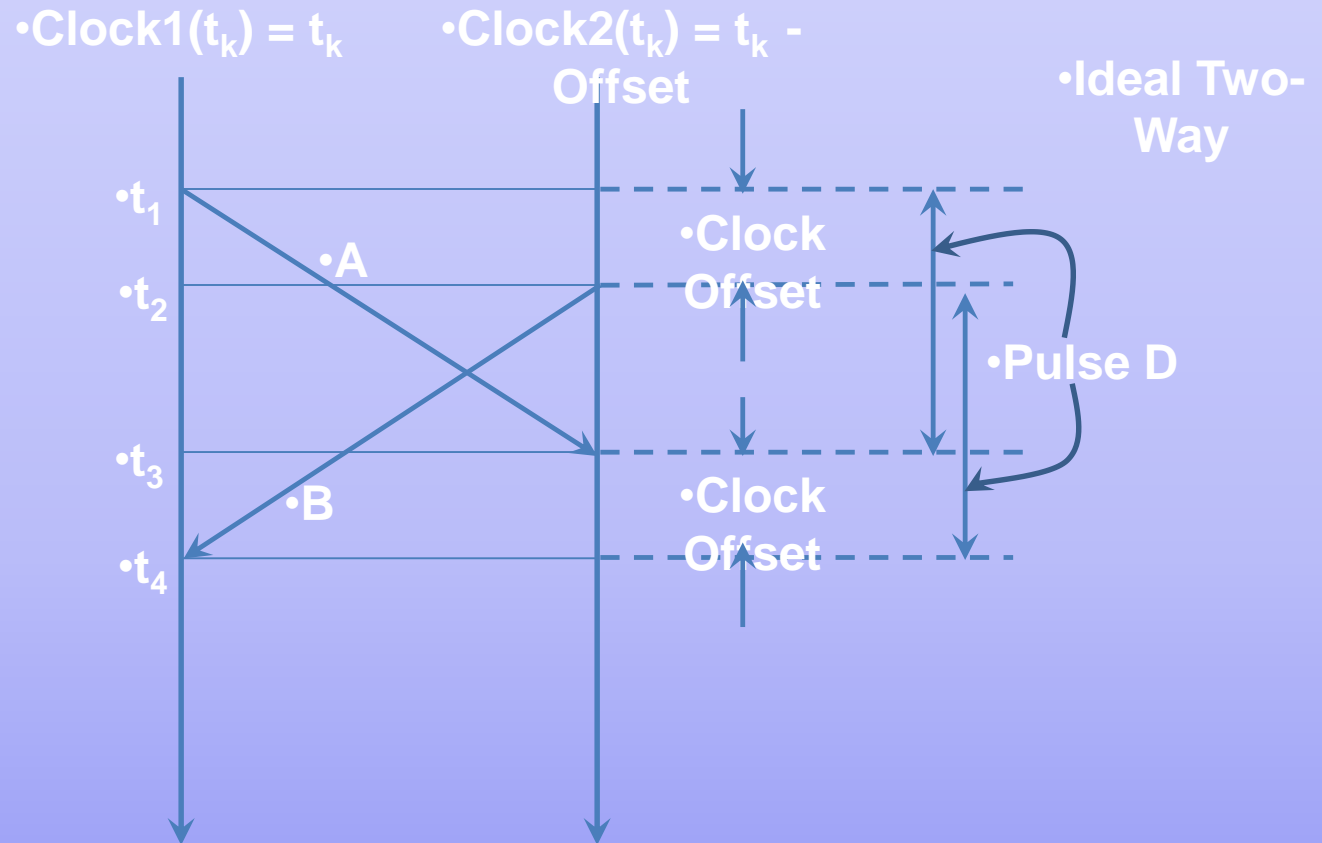
Ideal Two-Way Computation

- Signal A: $t_{31} = \text{Clock2}(t_3) - \text{Clock1}(t_1)$
- Signal B: $t_{42} = \text{Clock1}(t_4) - \text{Clock2}(t_2)$
- Assume Clock1 is correct, Clock2 has an offset or error E, and Delays, D, are reciprocal
  - $\text{Clock1}(t_j) = t_j$, $\text{Clock2}(t_j) = t_j - E$
  - Transmission times on local clocks: $\text{Clock2}(t_2) = \text{Clock1}(t_1)$, 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 $t_{31} = \text{Clock2}(t_3) - \text{Clock1}(t_1) = t_3 - E - t_1 = t_1 + D - E - t_1 = D - E$
- And $t_{42} = \text{Clock1}(t_4) - \text{Clock2}(t_2) = t_4 - (t_2 - E) = t_2 + D - (t_2 - E) = D + E$
- Therefore
  - $D = \tfrac{1}{2}(t_{42} + t_{31})$
  - $E = \tfrac{1}{2}(t_{42} - t_{31})$

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
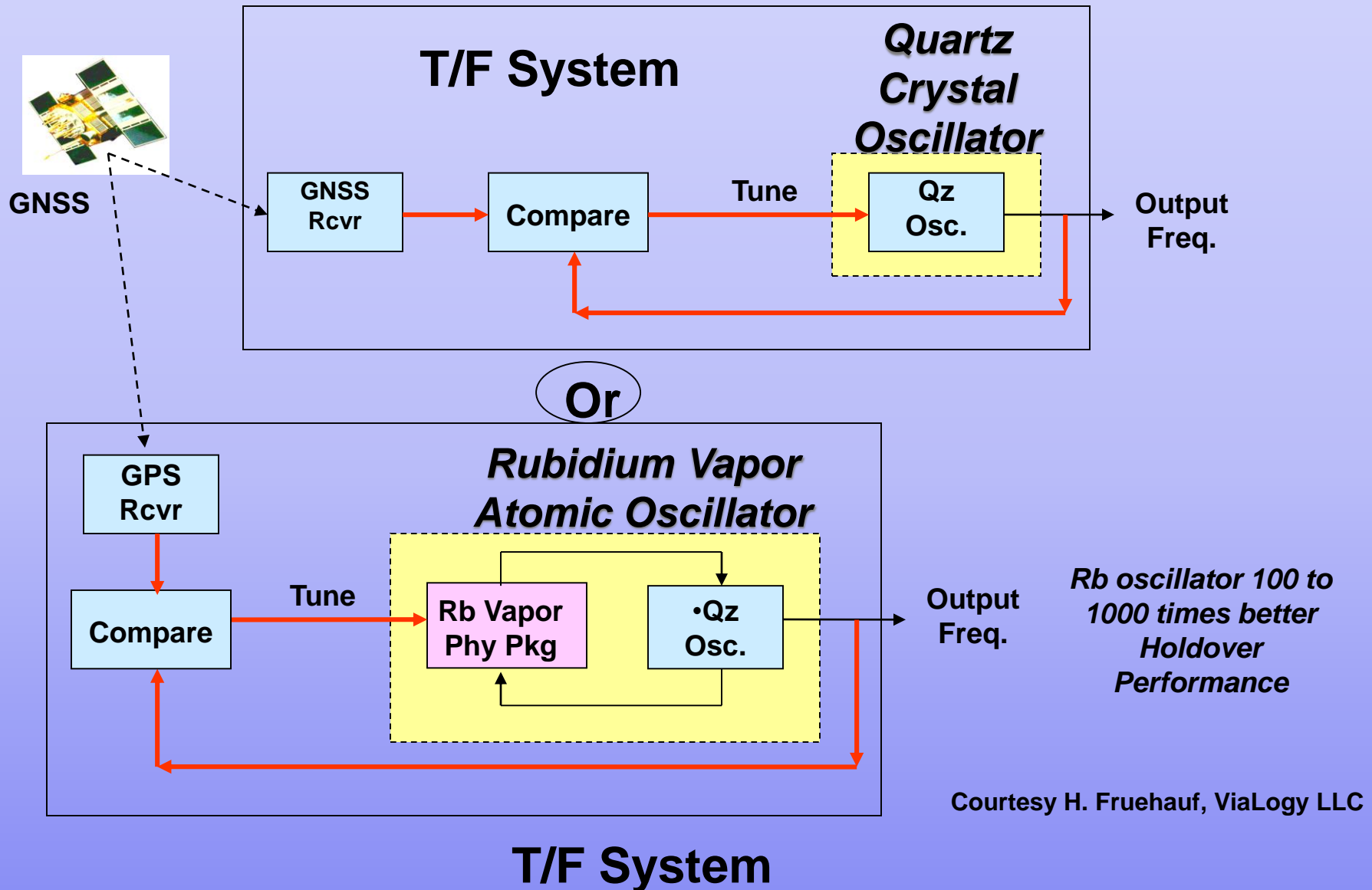
- Syntonization vs Synchronization

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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

GNSS-aided Time and Frequency Systems

GNSS

T/F System

Quartz Crystal Oscillator

GNSS Rcvr → Compare → Tune → Qz Osc. → Output Freq.

Or

Rubidium Vapor Atomic Oscillator

GPS Rcvr → Compare → Tune → Rb Vapor Phy Pkg / •Qz Osc. → Output Freq.

Rb oscillator 100 to 1000 times better Holdover Performance

Courtesy H. Fruehauf, ViaLogy LLC

T/F System

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/