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SYNC MASTERS

WSTS 2019 TUTORIAL SESSION
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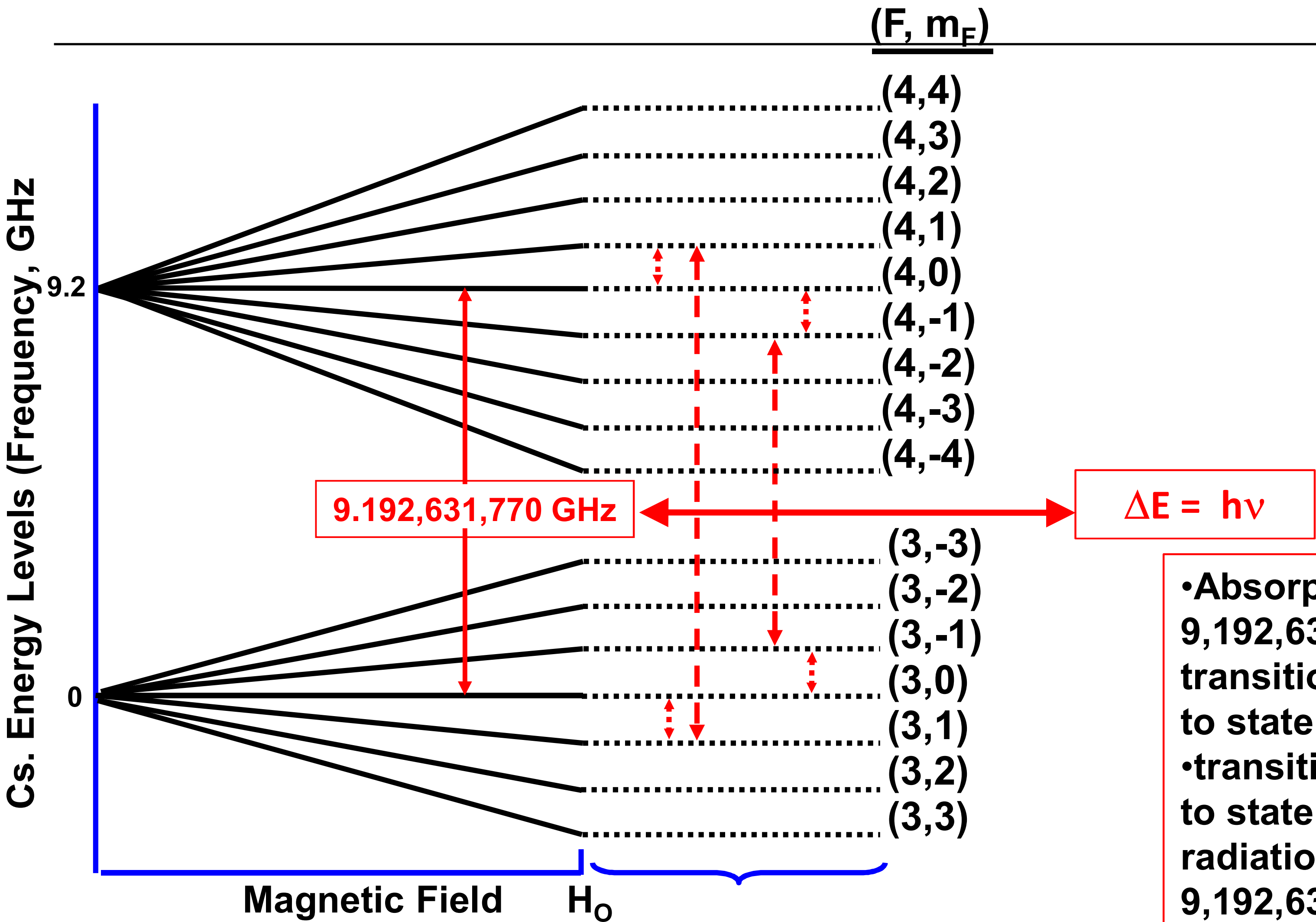
ITU-T STANDARDS

Application/ Technology	Accuracy	Specification
PRTC (Primary Reference Time Clock) (Source)	±100 ns with respect to UTC (PRTC-A) ±40 ns with respect to UTC (PRTC-B)	**[ITU-T G.8272]**
ePRTC (Enhanced Primary Reference Time Clock) (Source)	**±30 ns with respect to UTC**	**[ITU-T G.8272.1]**

PRIMARY SOURCES FOR TIME AND FREQUENCY

- **Atomic Clocks**
- GNSS
- Conclusions
- Extra Slides

ATOMIC FREQUENCY STANDARDS: PRODUCE FREQUENCY LOCKED TO AN ATOMIC TRANSITION



•Absorption of photon at 9,192,631,770Hz results in transition from state (3,0) to state (4,0)
•transition from state (3,0) to state (4,0) results in radiation of photon at 9,192,631,770Hz

BASIC PASSIVE ATOMIC CLOCK

1. Obtain atoms to measure

2. Depopulate one hyperfine level

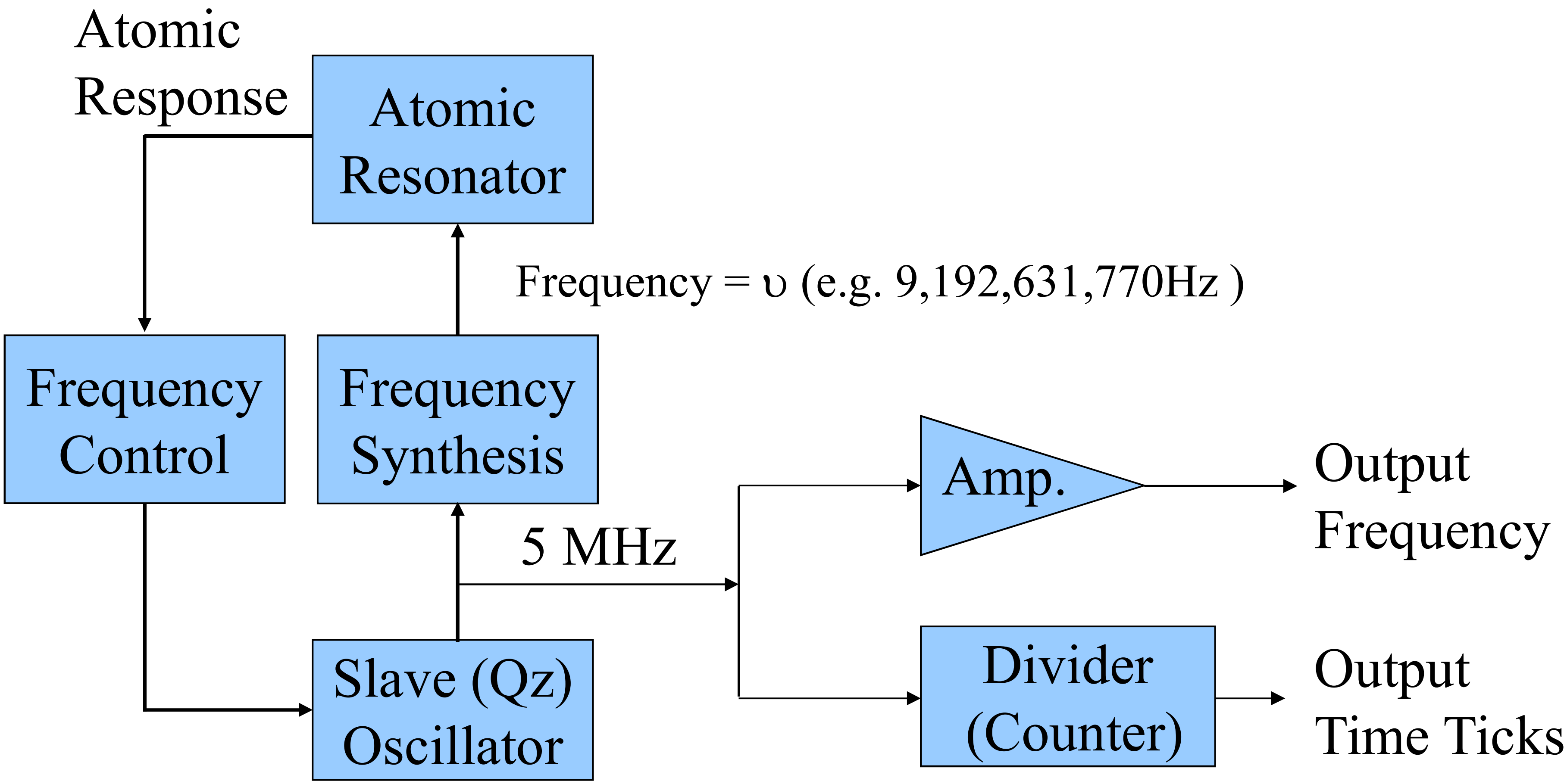
3. Radiate the state-selected sample with frequency ν

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 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)	Rubidium (RB) Cell Atomic Frequency Standard ($5*10^{-12}$/mo. aging)	Chip Scale Atomic Clock (CSAC)
Range of time intervals that can hold one microsecond	10 - 30 minutes	0.5 - 8 hours	8 hours – 3 days	1 – 2 days
Cost range	$5-25	$25-250	$250-1500	$1000-2000

CONCLUSIONS: ATOMIC STANDARDS

- Rubidium, cesium, and hydrogen atomic frequency standards share a common theme: the stabilization

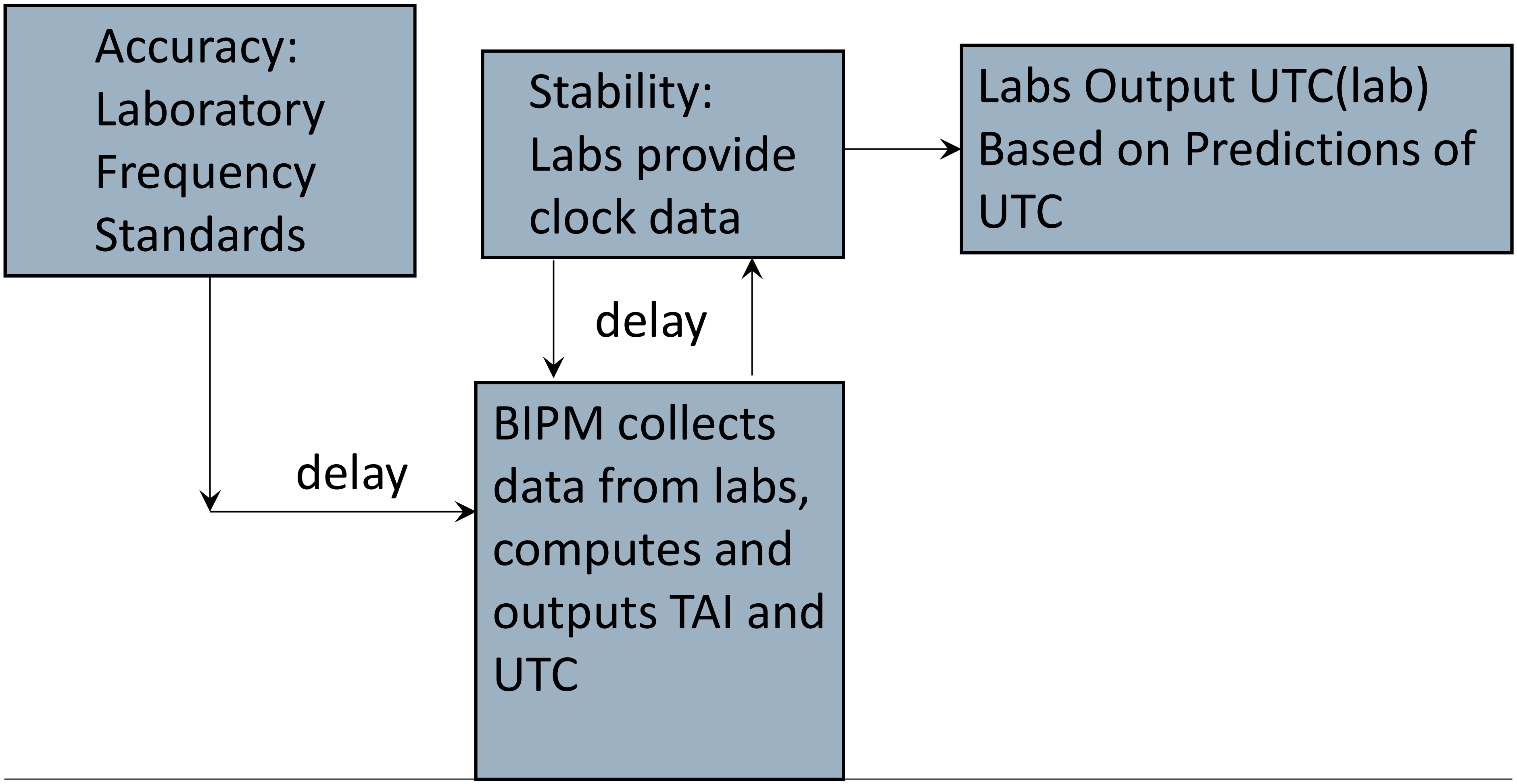
  of an electronic (quartz) oscillator with respect to an

  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.

THE GENERATION OF UTC: TIME ACCURACY

ANY REAL TIME UTC IS ONLY A PREDICTION, A PLL WITH A ONE-MONTH DELAY



PRIMARY SOURCES
FOR TIME AND FREQUENCY

- Atomic Clocks
- **GNSS**
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- Extra Slides

THE FAMILY OF GLOBAL NAVIGATION SATELLITE SYSTEMS

GPS	Galileo	GLONASS	Beidou/Compass
US	EU	Russia	China

Others are Regional Navigation Satellite Systems

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

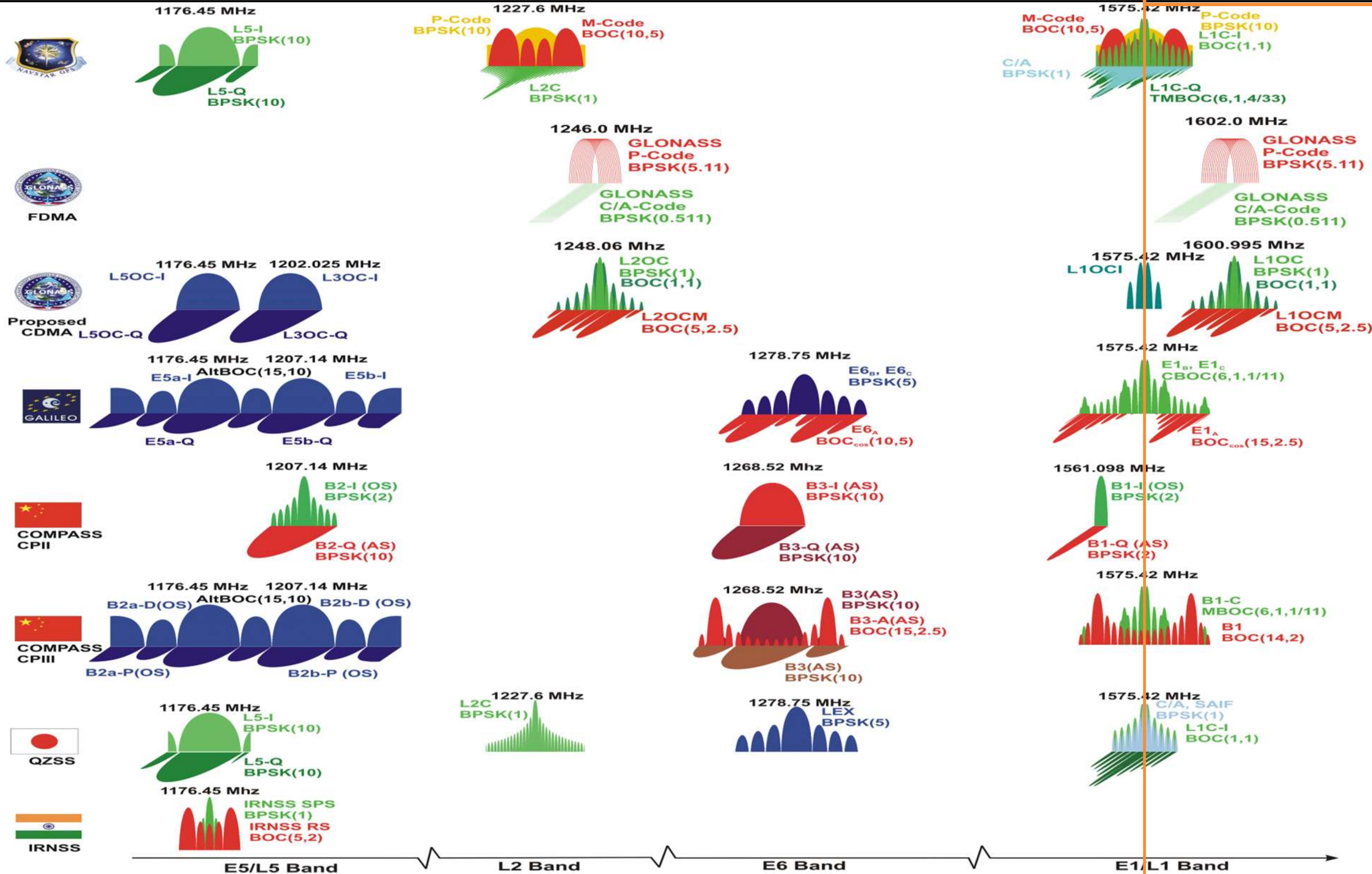
2. GNSS signals are dangerously vulnerable to both accidental and intentional interference

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

SPECTRA OF GNSS'S

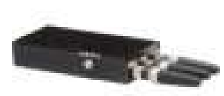
Primary Commercial Signal



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



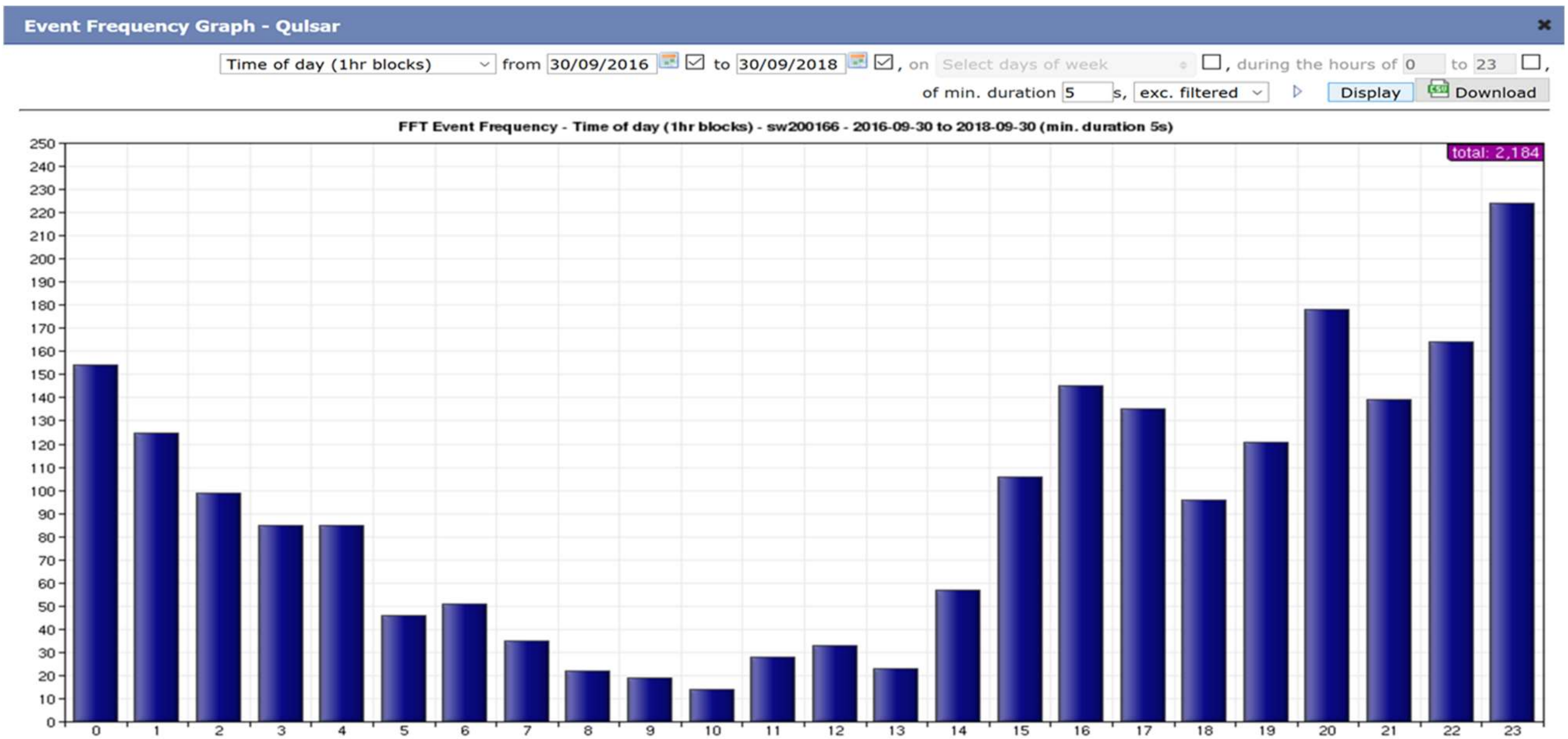
Military Jammer

JAMMING EVENTS, HOUR OF DAY
NUMBER OF EVENTS PER HOUR
10/2016 TO 10/2018

200 Events

100 Events

0 Events



6 PM midnight 5 AM

Local Time = Pacific

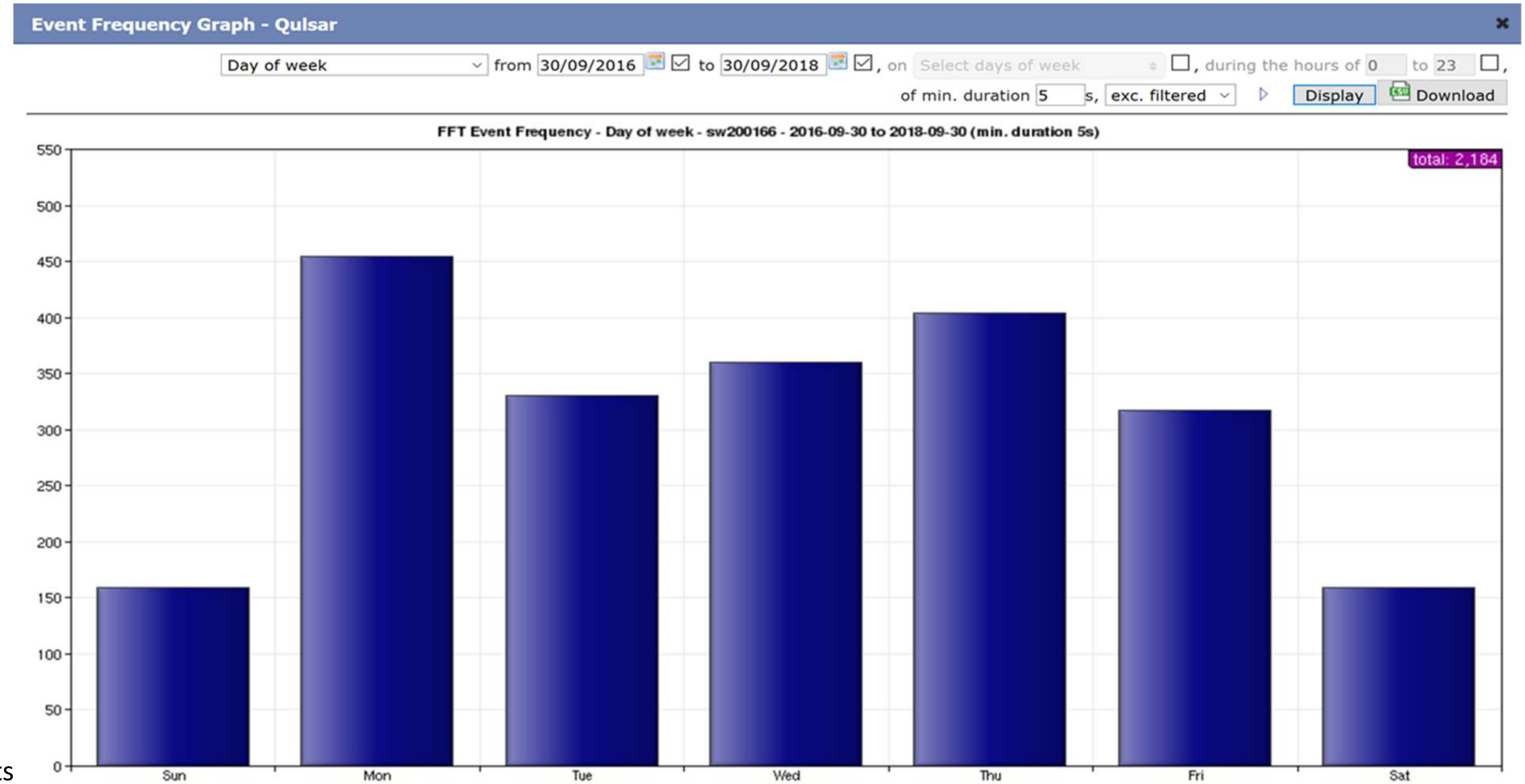
Jamming Detector at Qulsar, San Jose, CA, USA
Loan Courtesy of Prof. Charles Curry BEng, CEng, FIET,
Managing Director, Chronos Technology Ltd, UK

JAMMING EVENTS, DAY OF WEEK
NUMBER OF EVENTS PER DAY
10/2016 TO 10/2018

500 Events

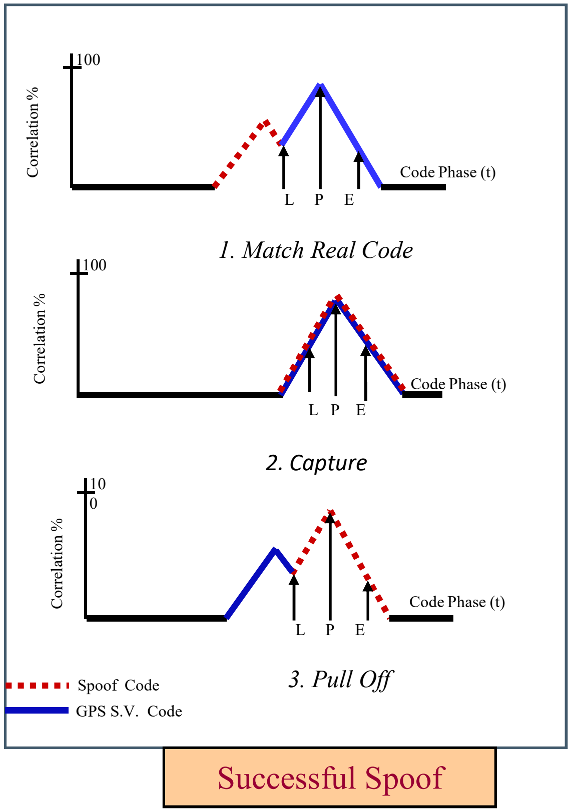
250 Events

0 Events

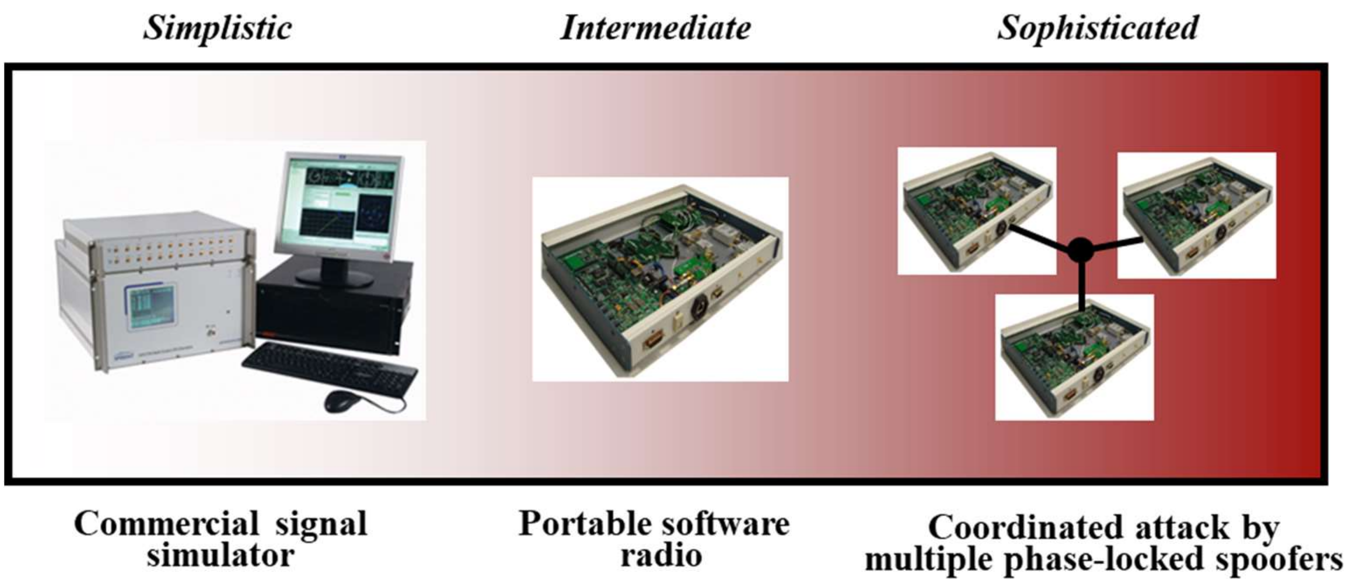


DISRUPTION MECHANISMS - SPOOFING/MEACONING

- 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



CIVIL GPS SPOOFING THREAT CONTINUUM*



*** 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 FOR TIME AND FREQUENCY

- Atomic Clocks
- 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

- 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

PRIMARY SOURCES FOR TIME AND FREQUENCY

- **Atomic Clocks**
- Time and Frequency Transfer
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- Conclusions
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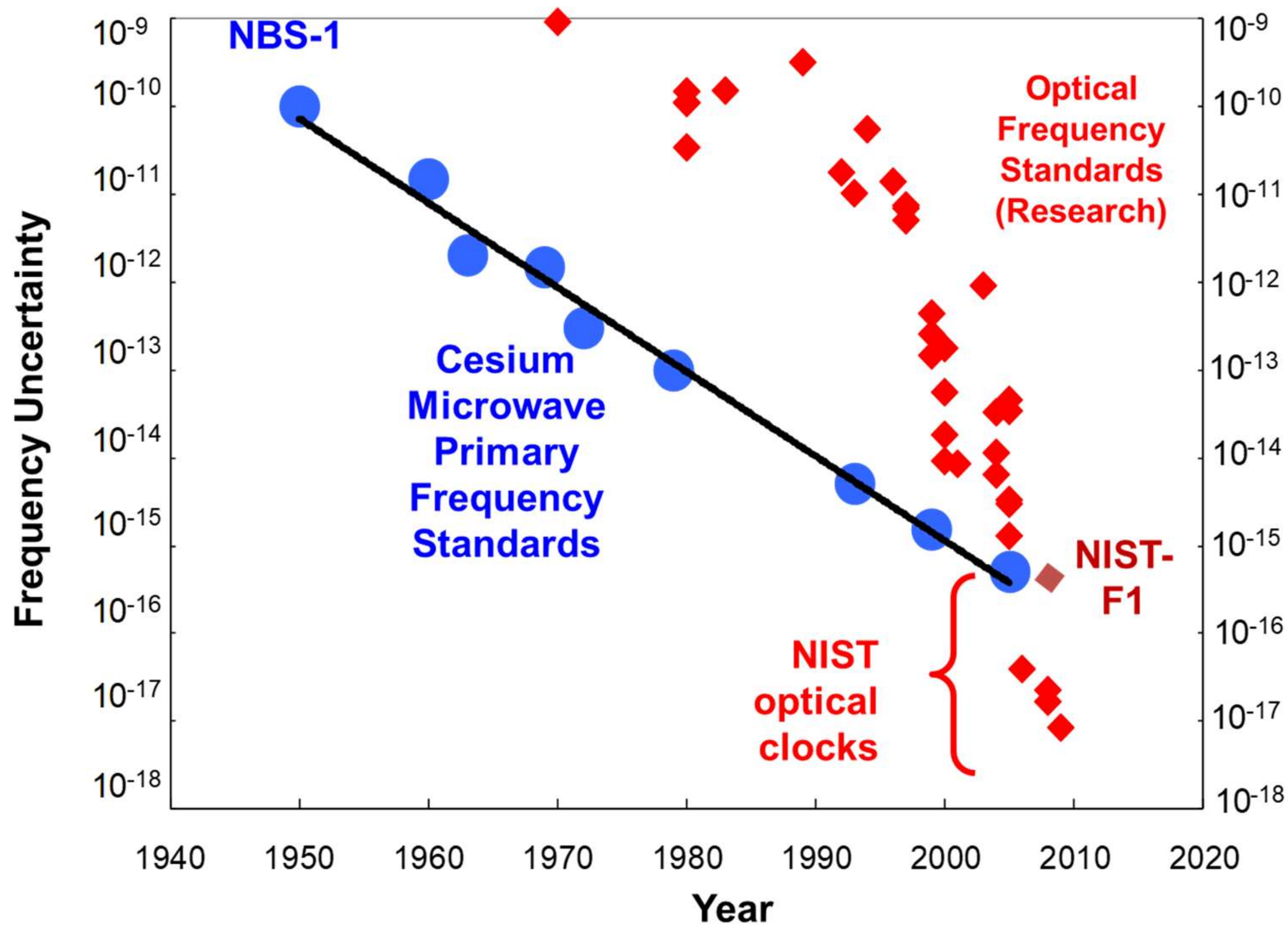
FREQUENCY ACCURACY:
HISTORY OF NIST PRIMARY FREQUENCY STANDARDS



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

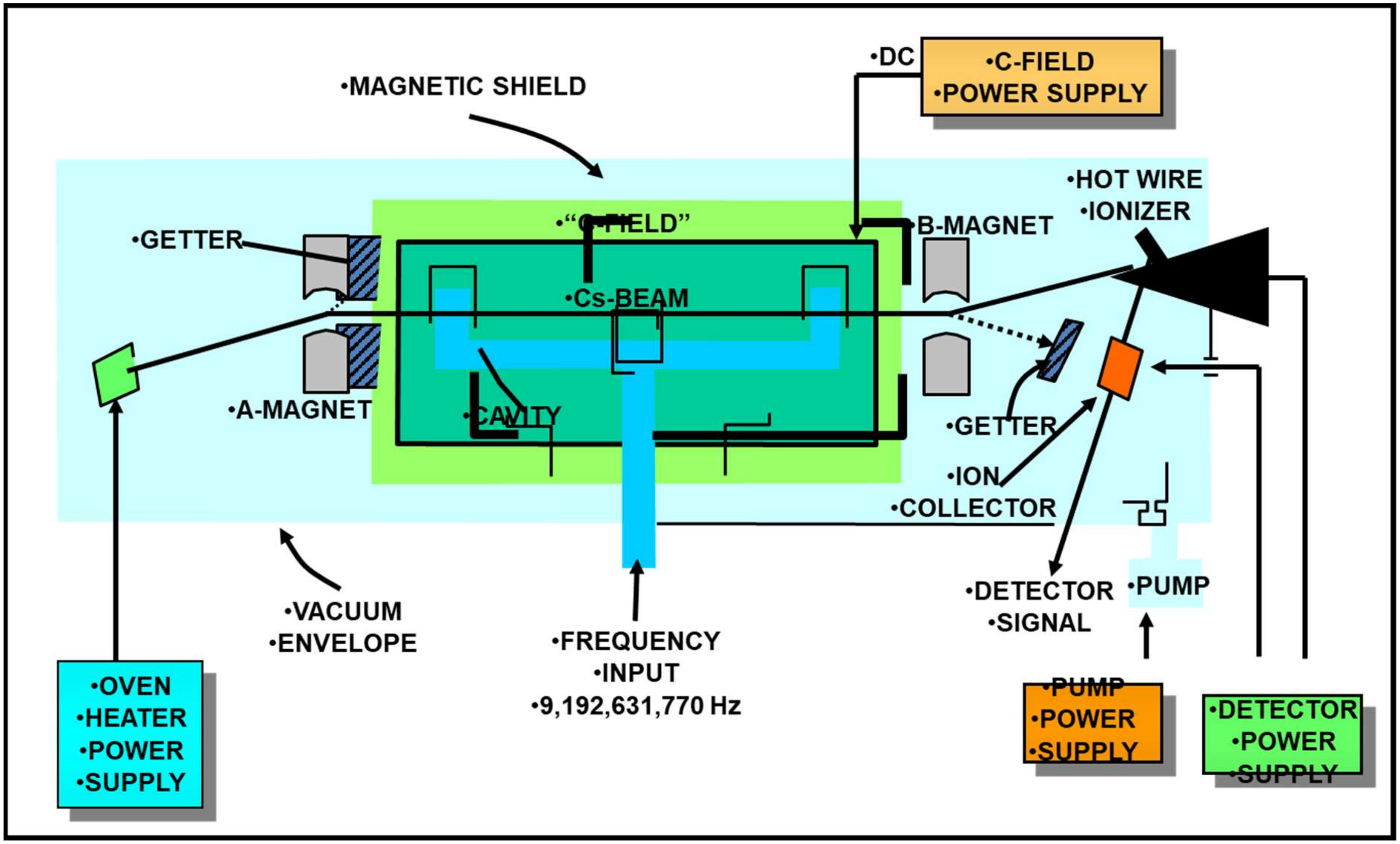
Clock stability can be improved by:

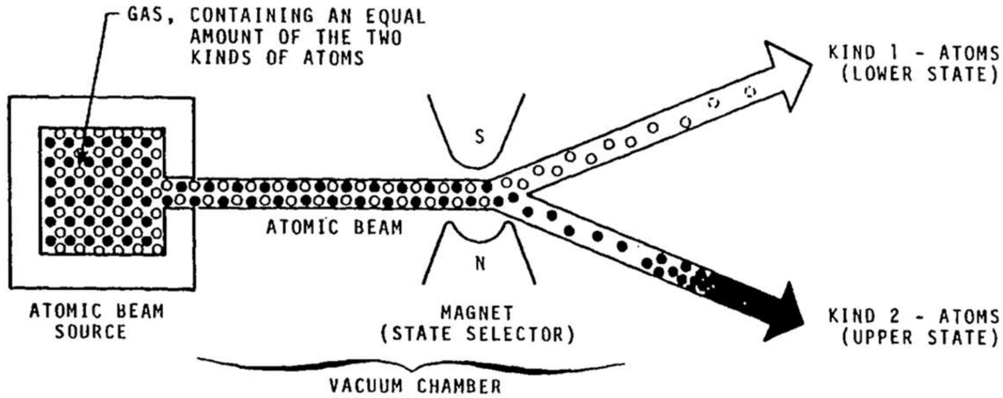
Increase Ramsey (observation) times (decrease $\Delta\omega = 1/T_{Ramsey}$)

Improve the S/N (more atoms!)

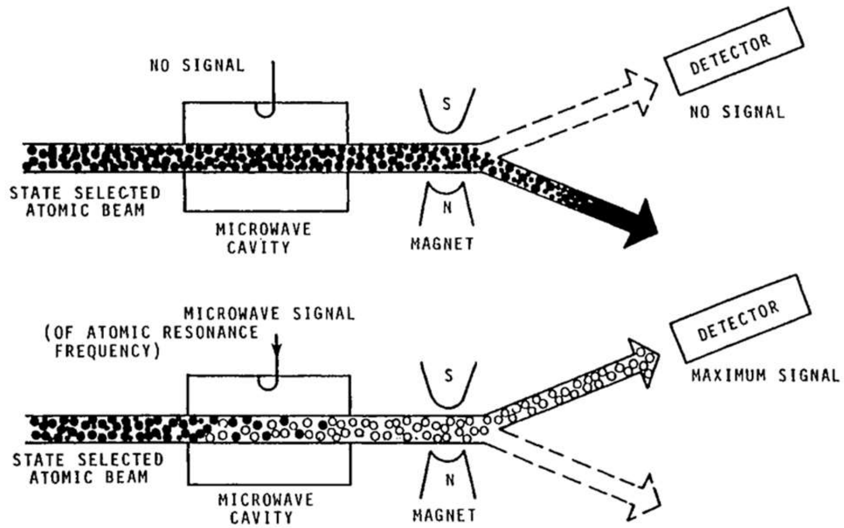
Increase the frequency of the clock transition (optical?)

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 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**

COMMERCIAL CESIUM STANDARDS

•Laboratory/Timekeeping

•Telecom

•Space/GPS

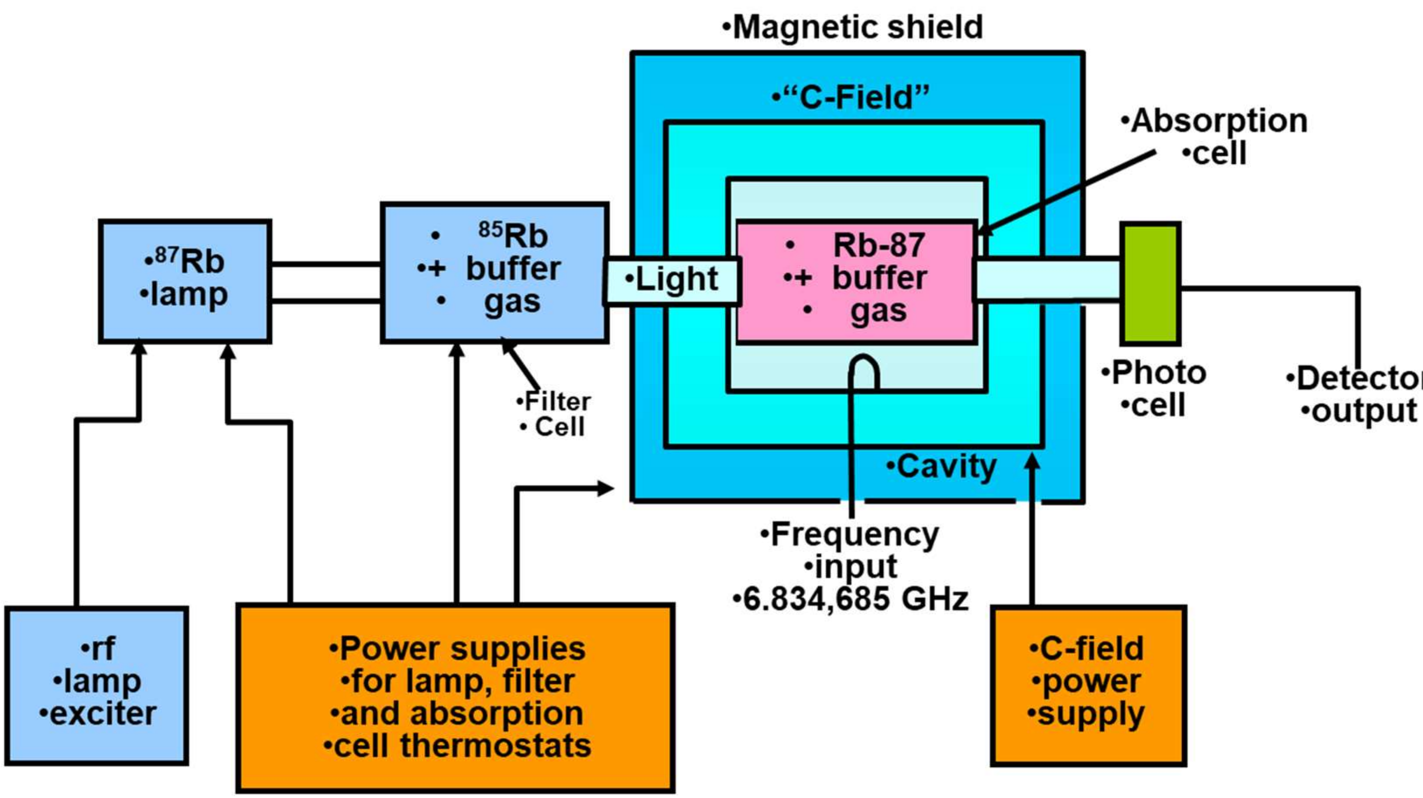
•Courtesy of Robert Lutwak, Symmetricom

RUBIDIUM STANDARD

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

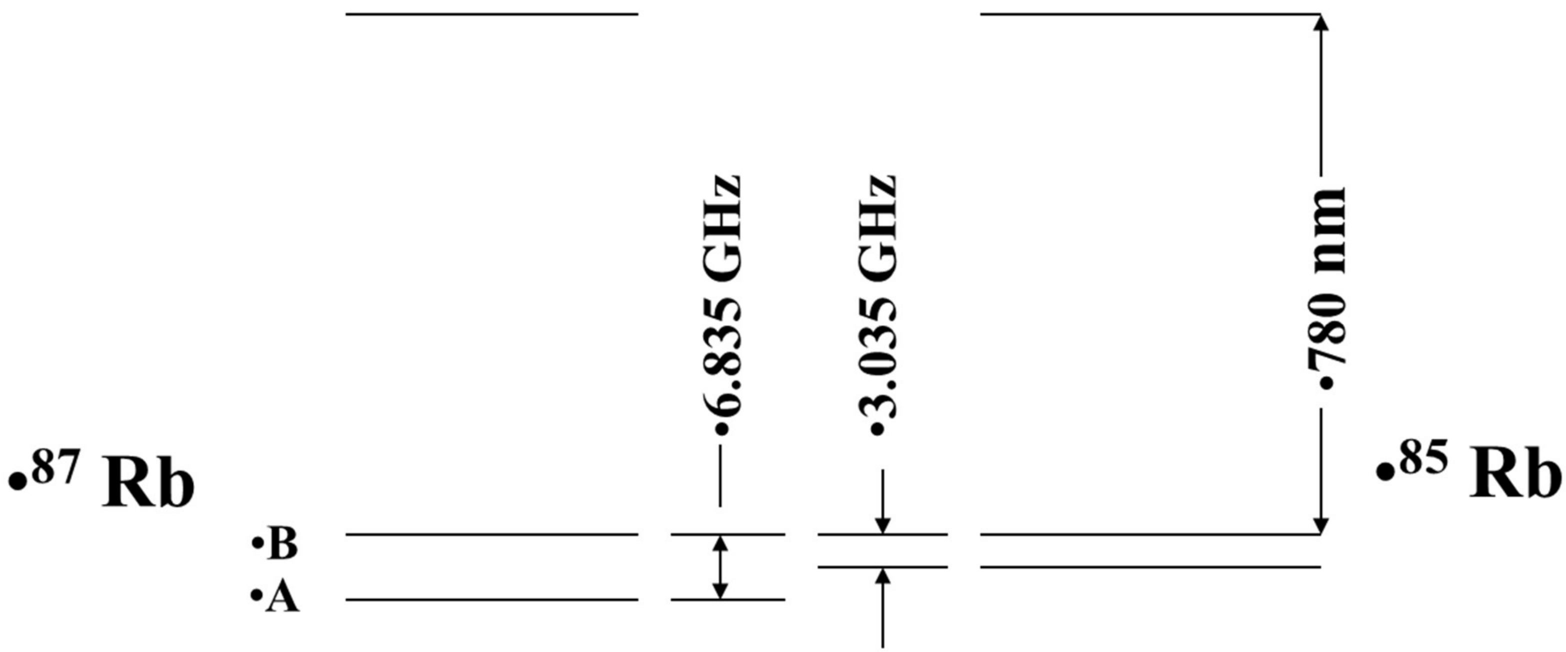
- Used where low cost and small size are important

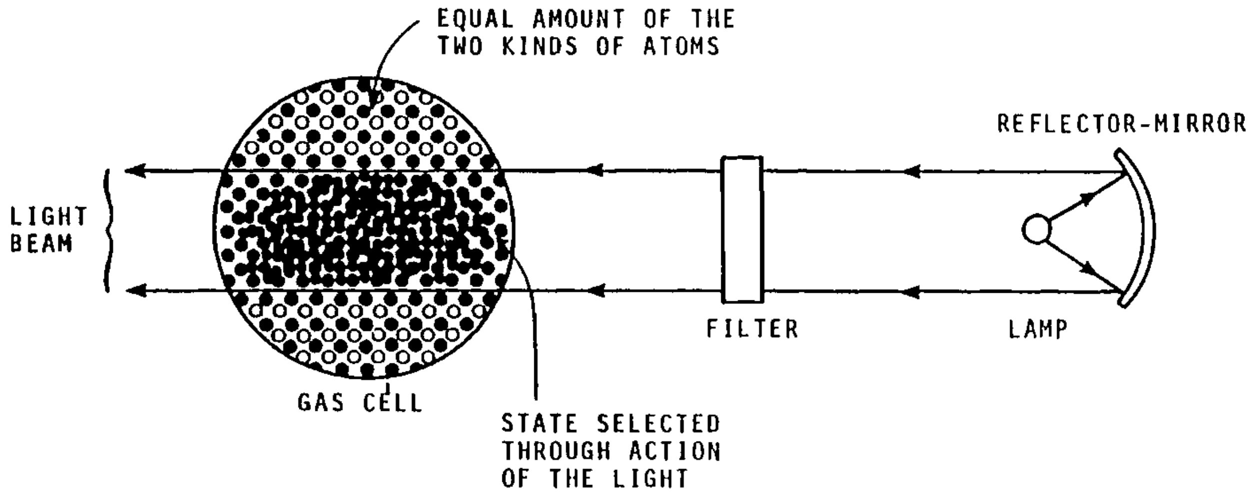
RUBIDIUM STANDARD



•Adapted from figure by John Vig

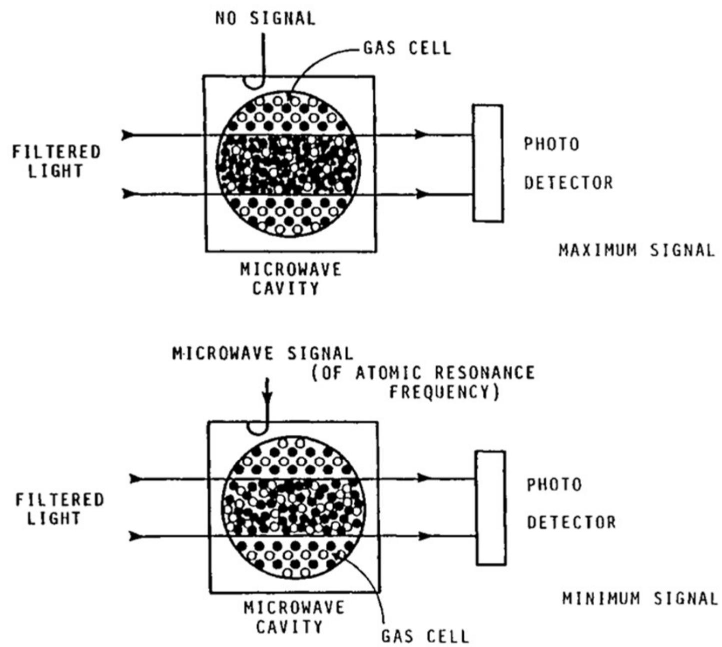
OPTICAL MICROWAVE DOUBLE RESONANCE
SIMPLIFIED RB ENERGY LEVEL DIAGRAM





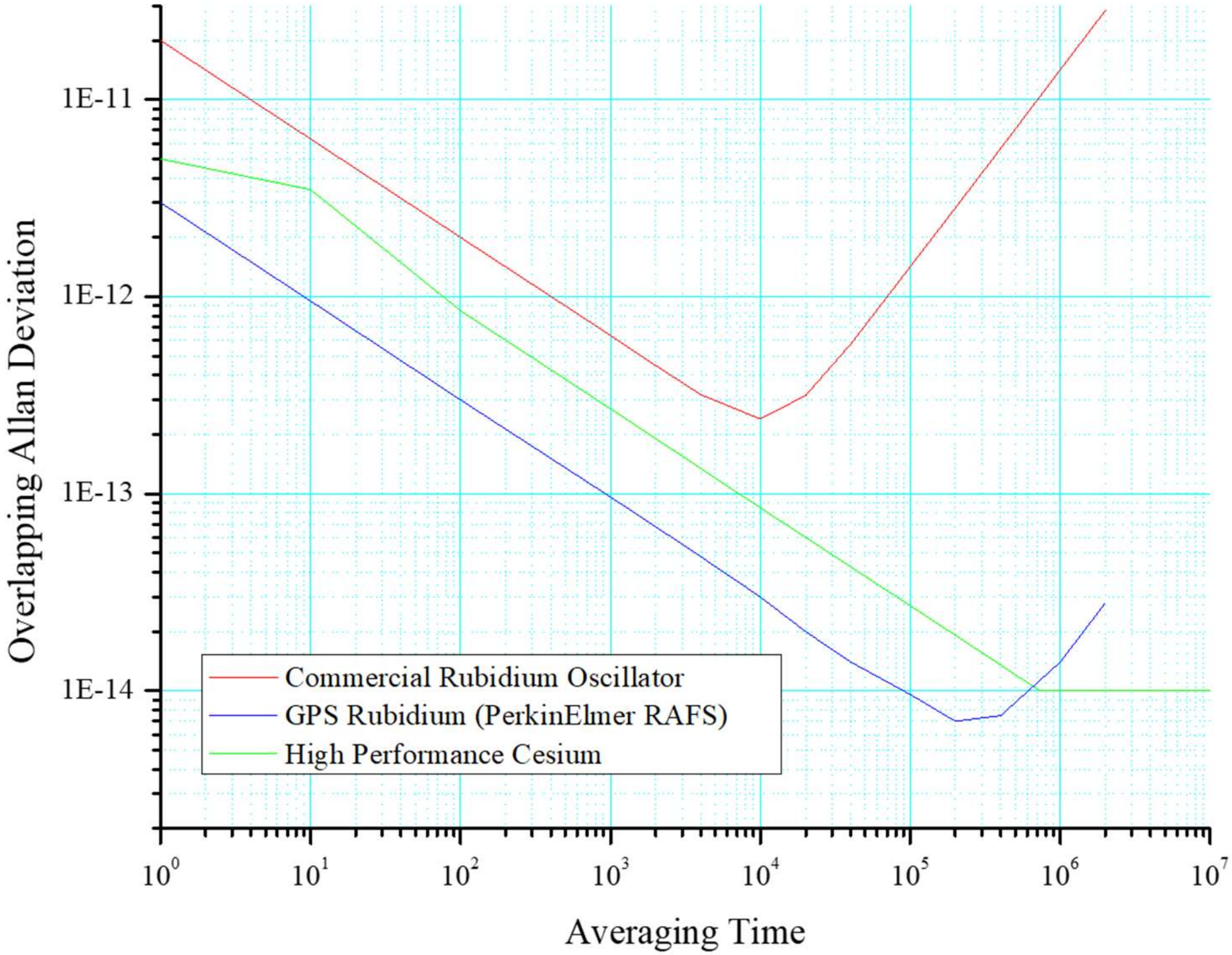
- Optical pumping is used to deplete one hyper-fine level

- 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

FREQUENCY STABILITY OF A RUBIDIUM STANDARD

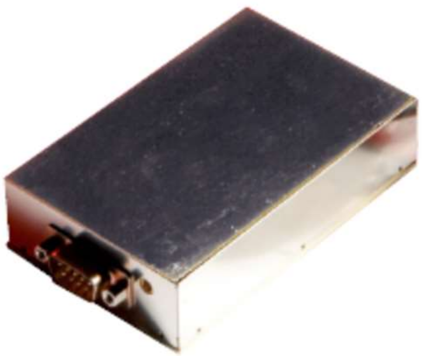


•**Courtesy of Robert Lutwak, Symmetricom**

COMMERCIAL RUBIDIUM STANDARDS

•Stanford Research PRS10

•Frequency Electronics
• FE-5680A



•Quartzlock E10

•Temex SR100

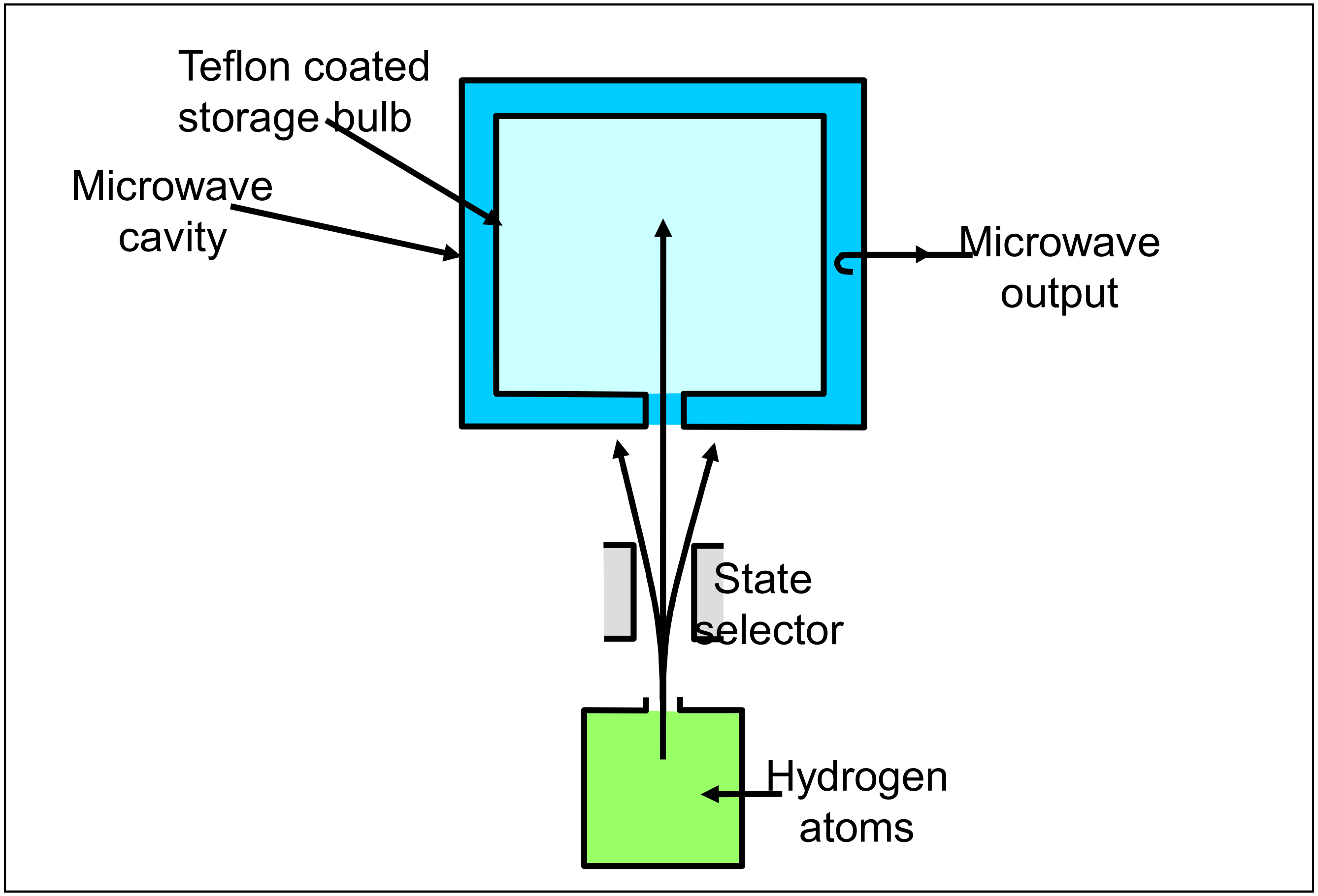
•PerkinElmer GPS RAFS

•Symmetricom X72

•Accubeat AR-70A

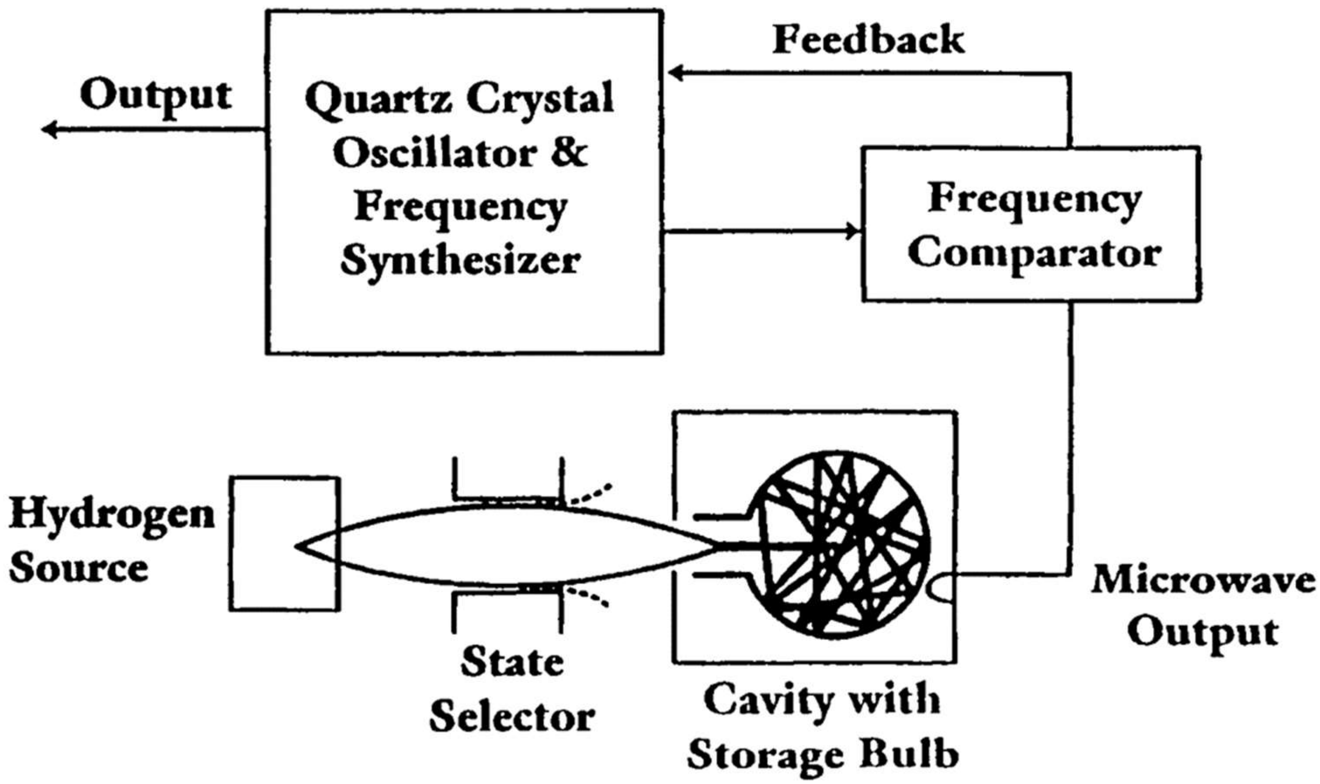
•Courtesy of Robert Lutwak, Symmetricom

HYDROGEN MASER
(ACTIVE STANDARD)

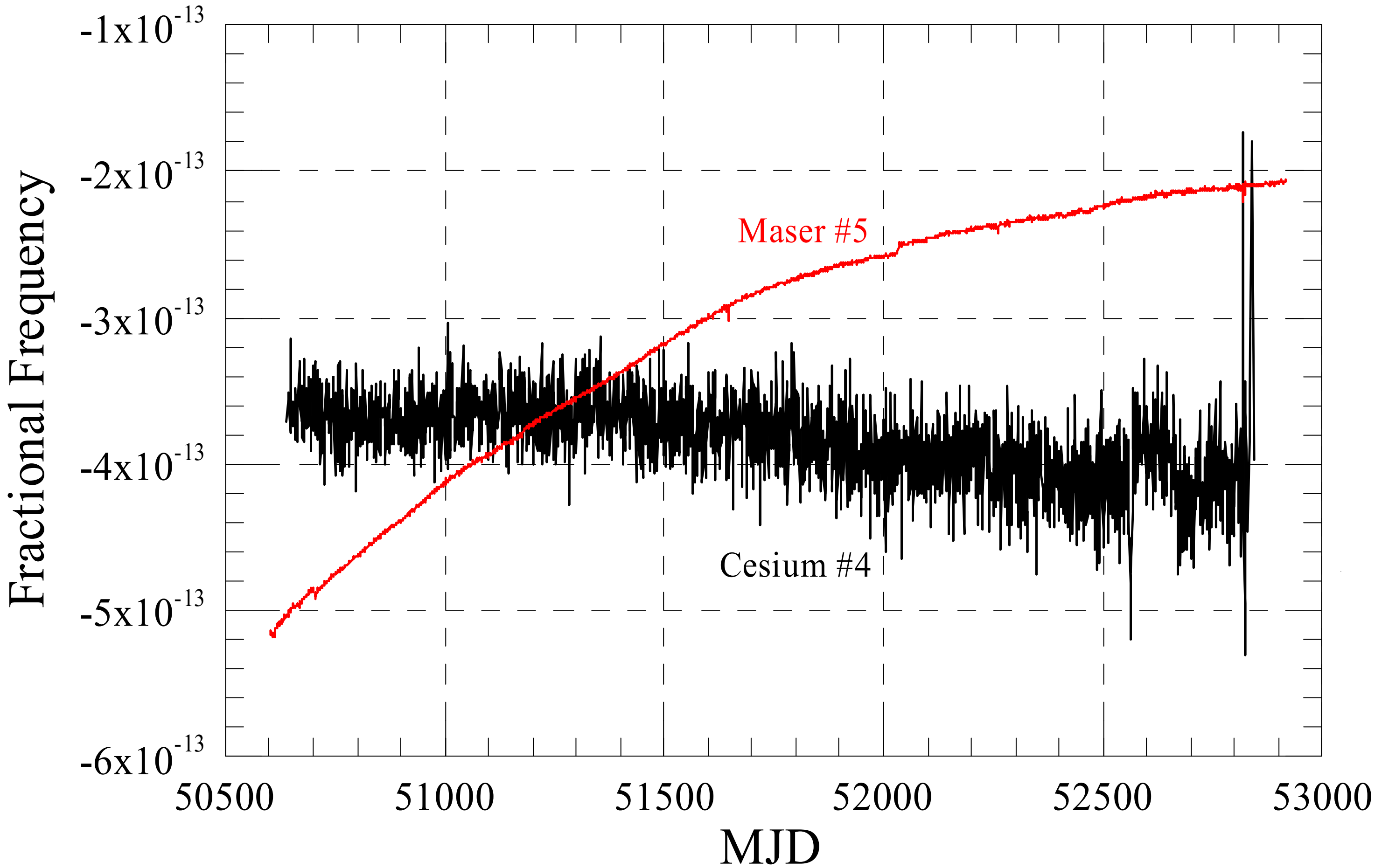


Adapted from a figure by John Vig

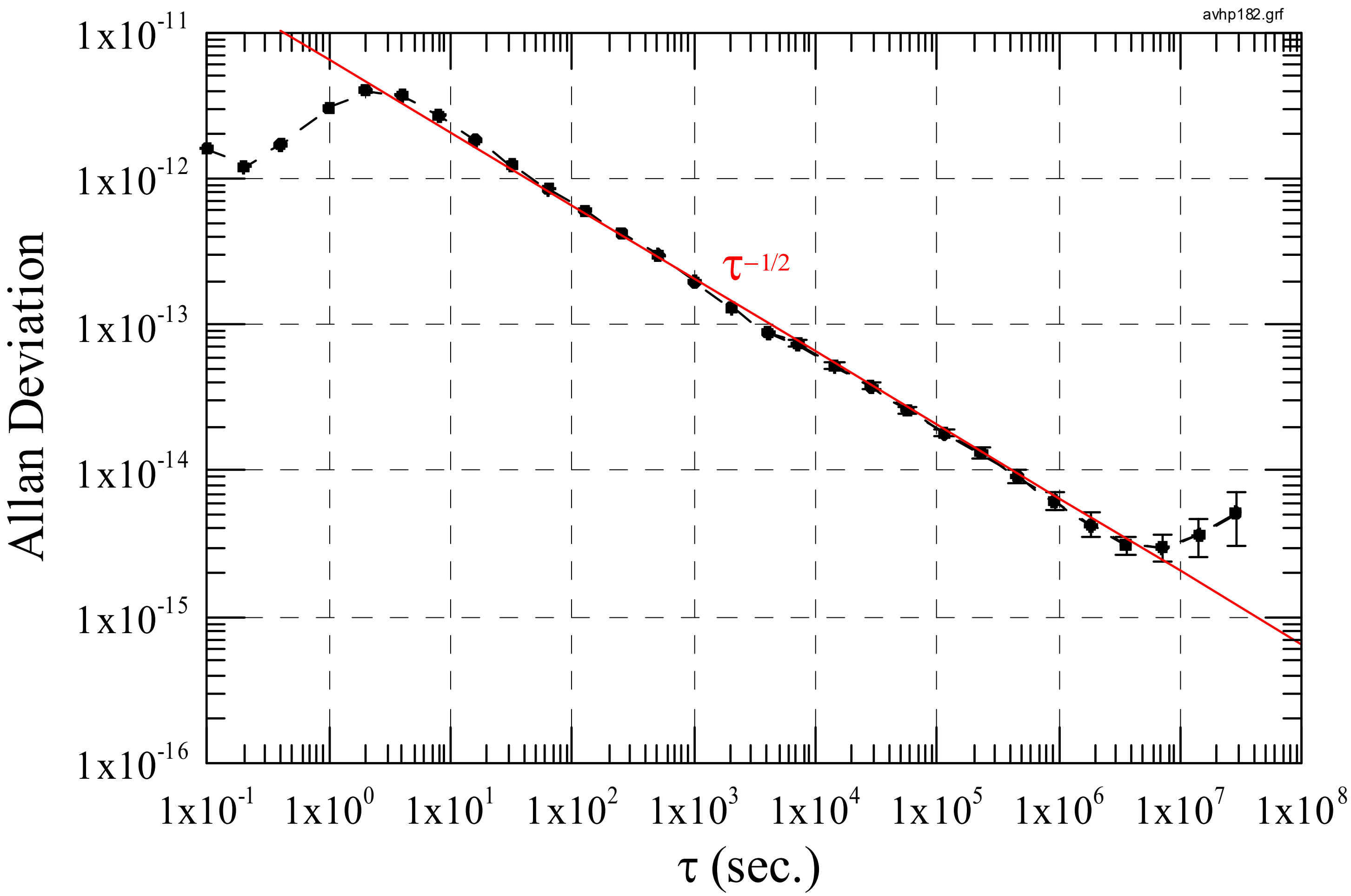
HYDROGEN MASER
(ACTIVE STANDARD)



FREQUENCY DRIFT OF A COMMERCIAL CESIUM STANDARD AND A HYDROGEN MASER



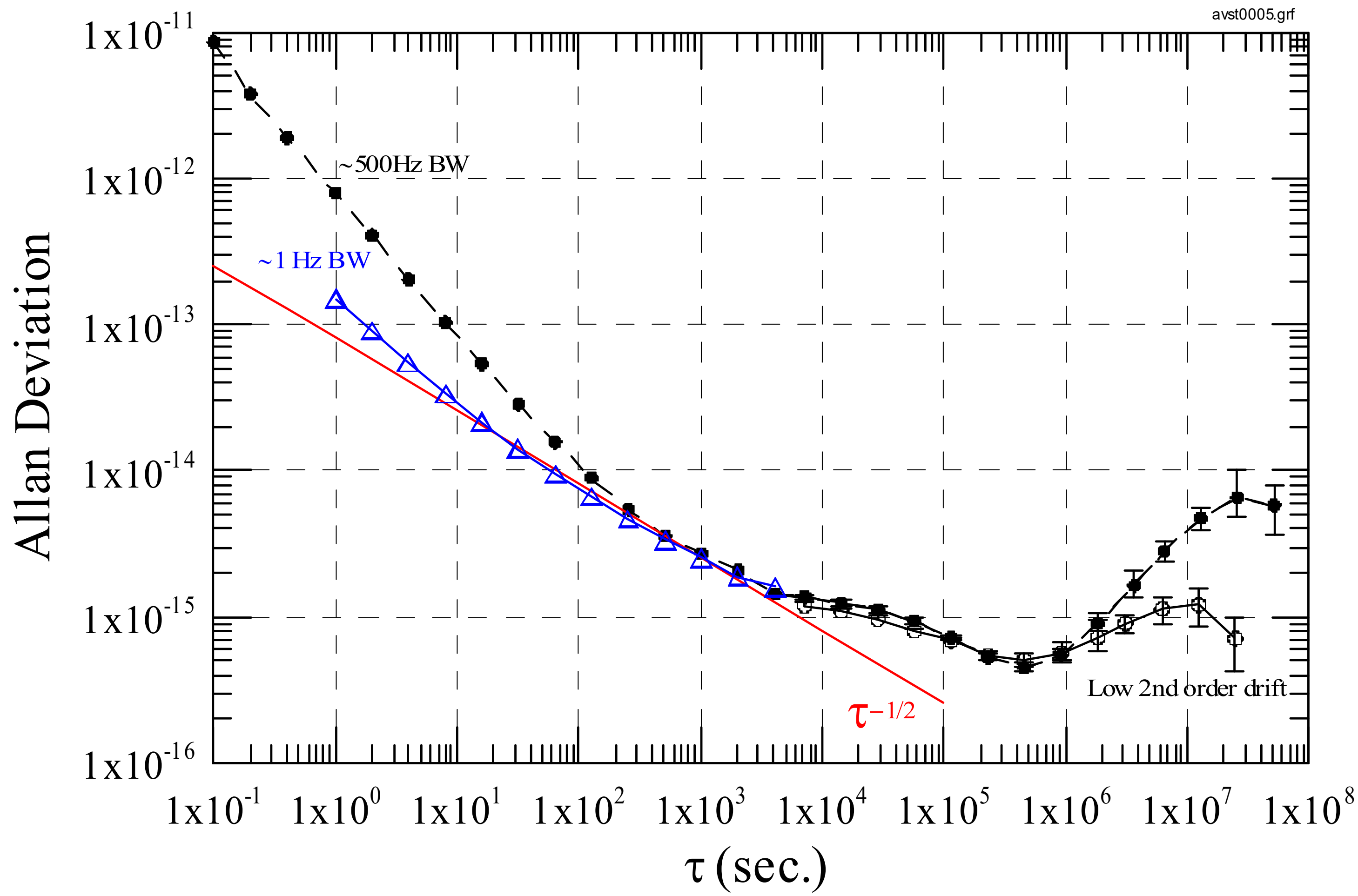
FREQUENCY STABILITY OF A CESIUM STANDARD
(NO FREQUENCY DRIFT REMOVED)



COMMERCIAL ACTIVE HYDROGEN MASER

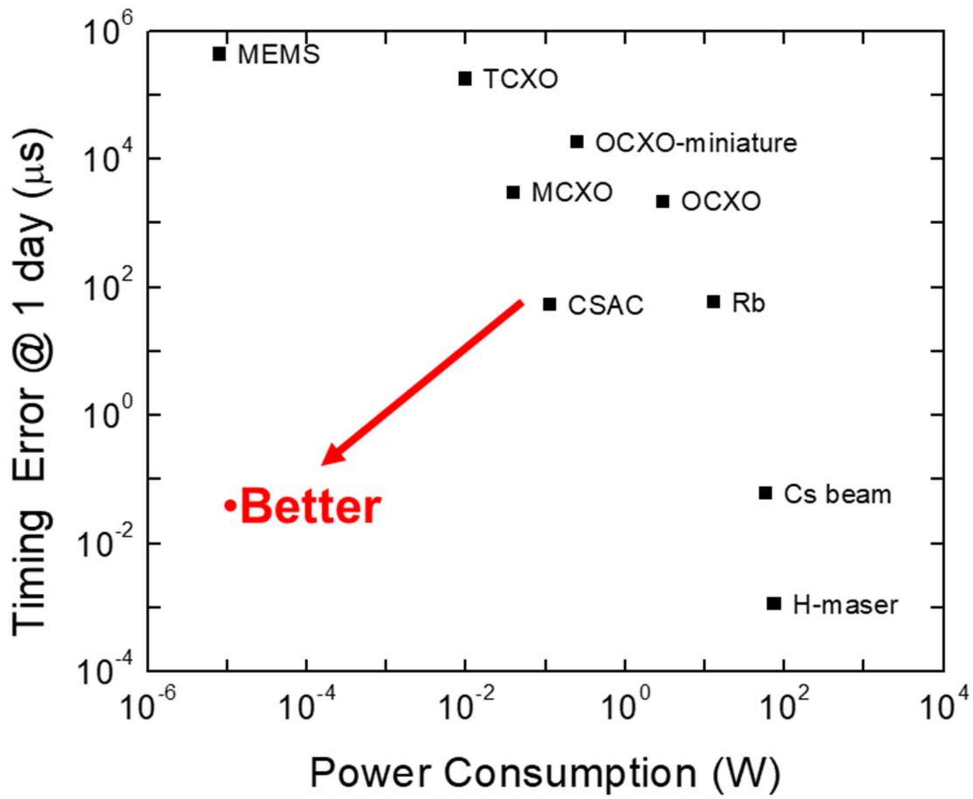
Courtesy of Robert Lutwak, Symmetricom

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



Timing Error @ 1 day (μs)
Power Consumption (W)
MEMS
TCXO
OCXO-miniature
MCXO
OCXO
CSAC
Rb
Cs beam
H-maser
•Better

OSCILLATOR COMPARISON

Technology	Intrinsic Accuracy	Stability (1s)	Stability (floor)	Aging (/day) initial to ultimate	Applications
Cheap Quartz, TCXO	10^{-6}	$\sim10^{-11}$	$\sim10^{-11}$	10^{-7} to 10^{-8}	Wristwatch, computer, cell phone, household clock/appliance,…
Hi-quality Quartz, OCXO	10^{-8}	$\sim10^{-12}$	$\sim10^{-12}$	10^{-9} to 10^{-11}	Network sync, test equipment, radar, comms, nav,…
Rb Oscillator	$\sim10^{-9}$	$\sim10^{-11}$	$\sim10^{-13}$	10^{-11} to 10^{-13}	Wireless comms infrastructure, lab equipment, GPS, …
Cesium Beam	$\sim10^{-13}$	$\sim10^{-11}$	$\sim10^{-14}$	nil	Timekeeping, Navigation, GPS, Science, Wireline comms infrastructure,…
Hydrogen Maser	$\sim10^{-11}$	$\sim10^{-13}$	$\sim10^{-15}$	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**

PRIMARY SOURCES FOR TIME AND FREQUENCY

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

TIME AND FREQUENCY TRANSFER

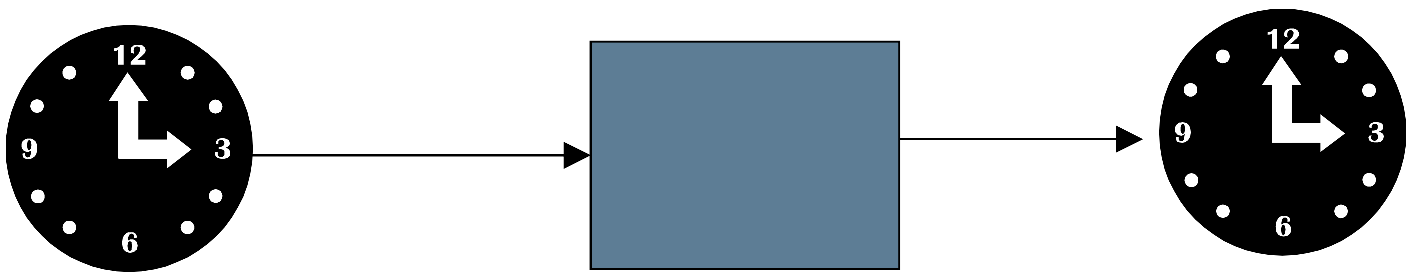
- Accuracy and Stability are the Concerns
  - Time Transfer Accuracy Requires Calibrating Delays
  - Time Stability = Frequency Accuracy

- Continuous vs Intermittent Measurements

One-Way Dissemination or Comparison System

Clock 1

Clock 2



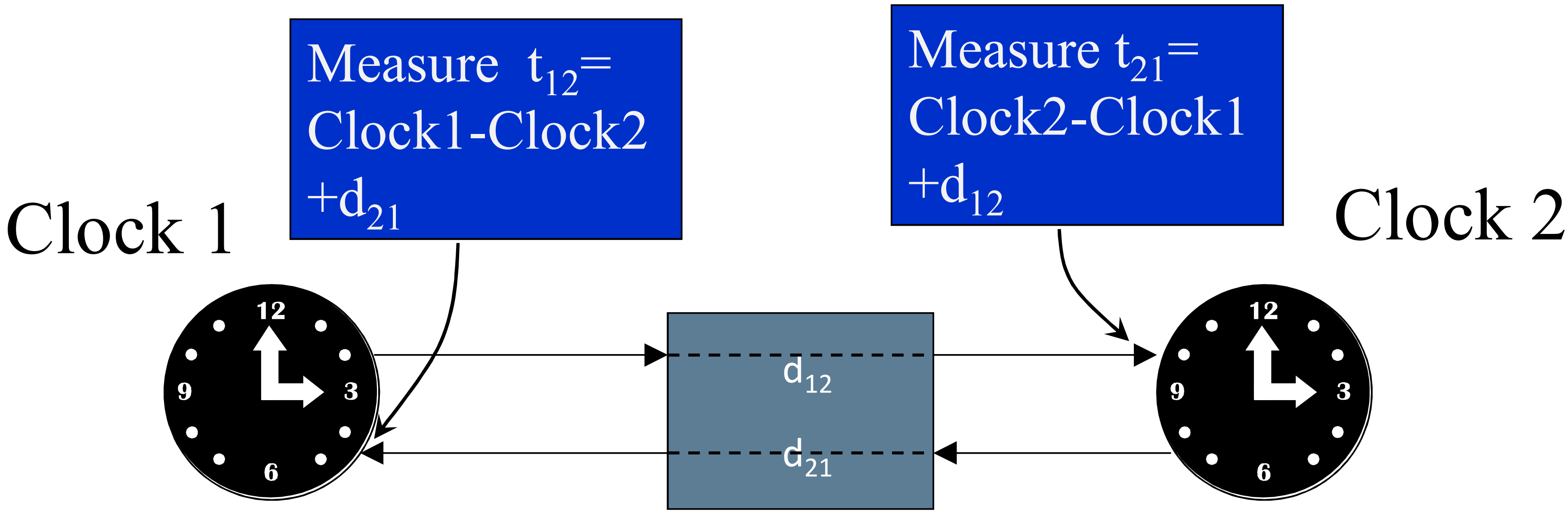
Clock 1 Systematics and Noise

Delay, Measurement Noise and Path Perturbations

Clock 2 Systematics and Noise

Two -Way Comparison System

(e.g. IEEE1588 – PTP)



Clock 1 Systematics and Noise

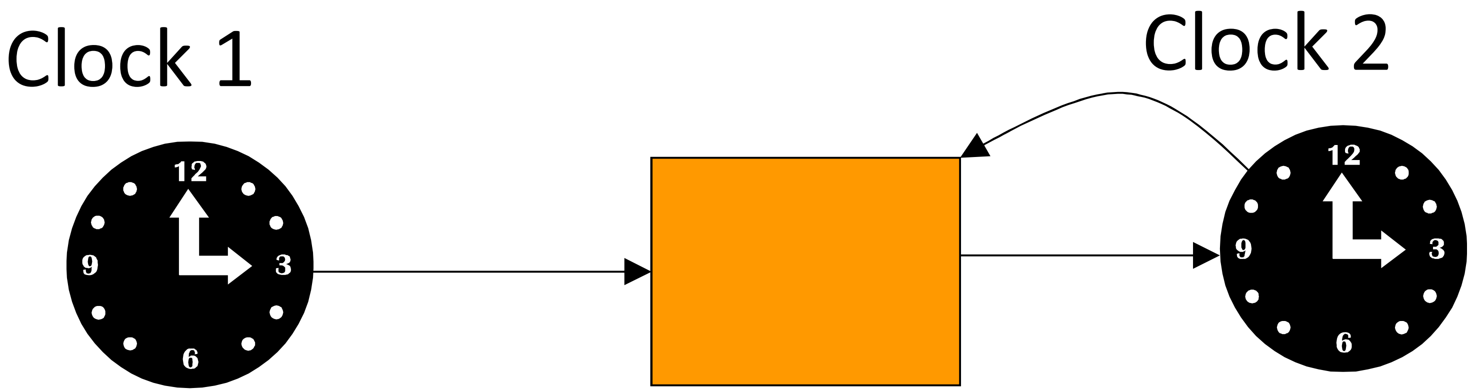
Measurement Noise and Path Perturbations

Largely Reciprocal:

$d_{21} = d_{12}$

Clock 2 Systematics and Noise

Clock Hierarchies

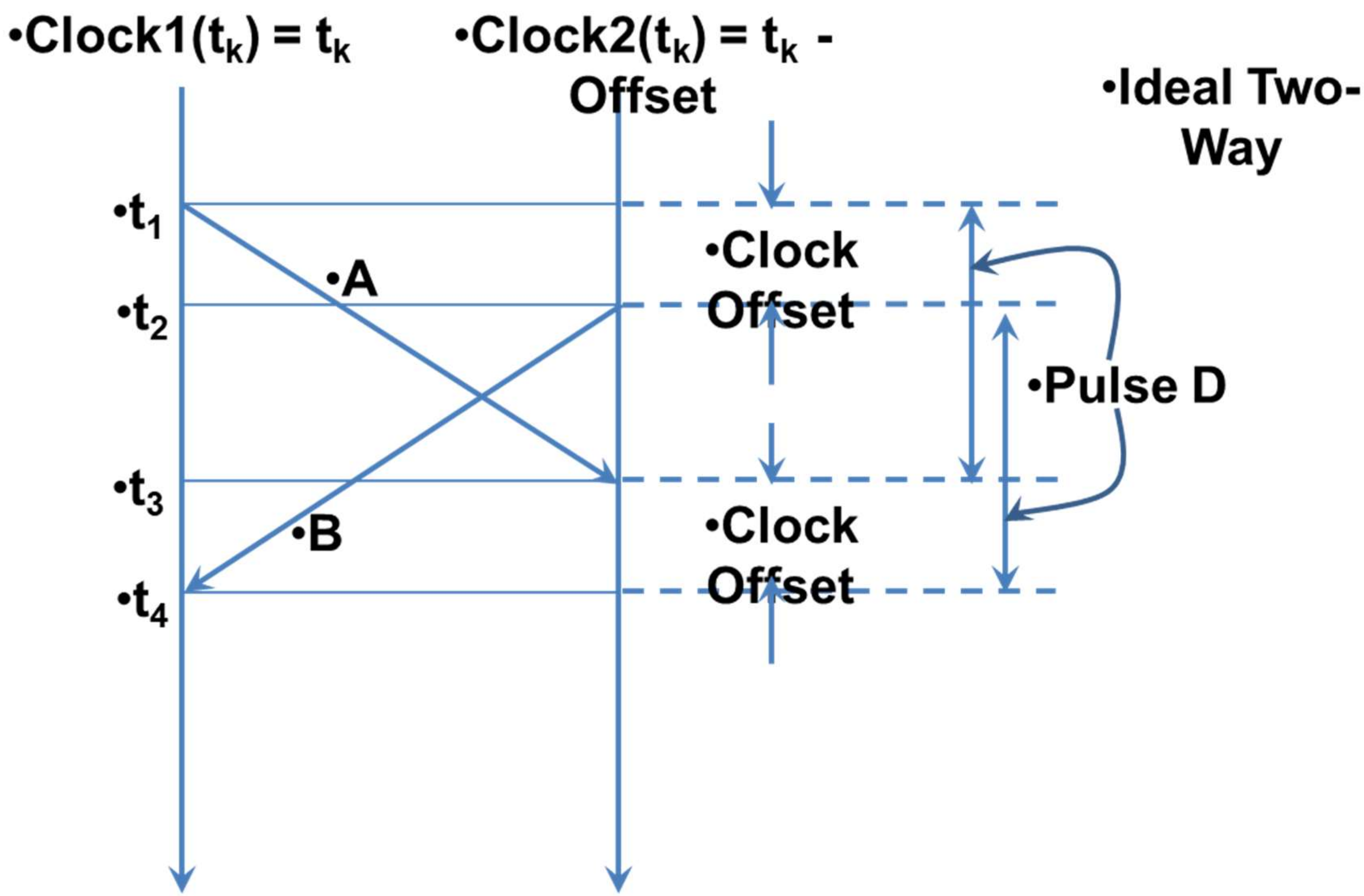


Clock 1
Systematics
and Noise

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

Clock 2
Systematics
and Noise

TWO-WAY HAS FOUR TIME STAMPS



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
  - $D = ½ (t_{42} + t_{31})$
  - $E = ½ (t_{42} - t_{31})$

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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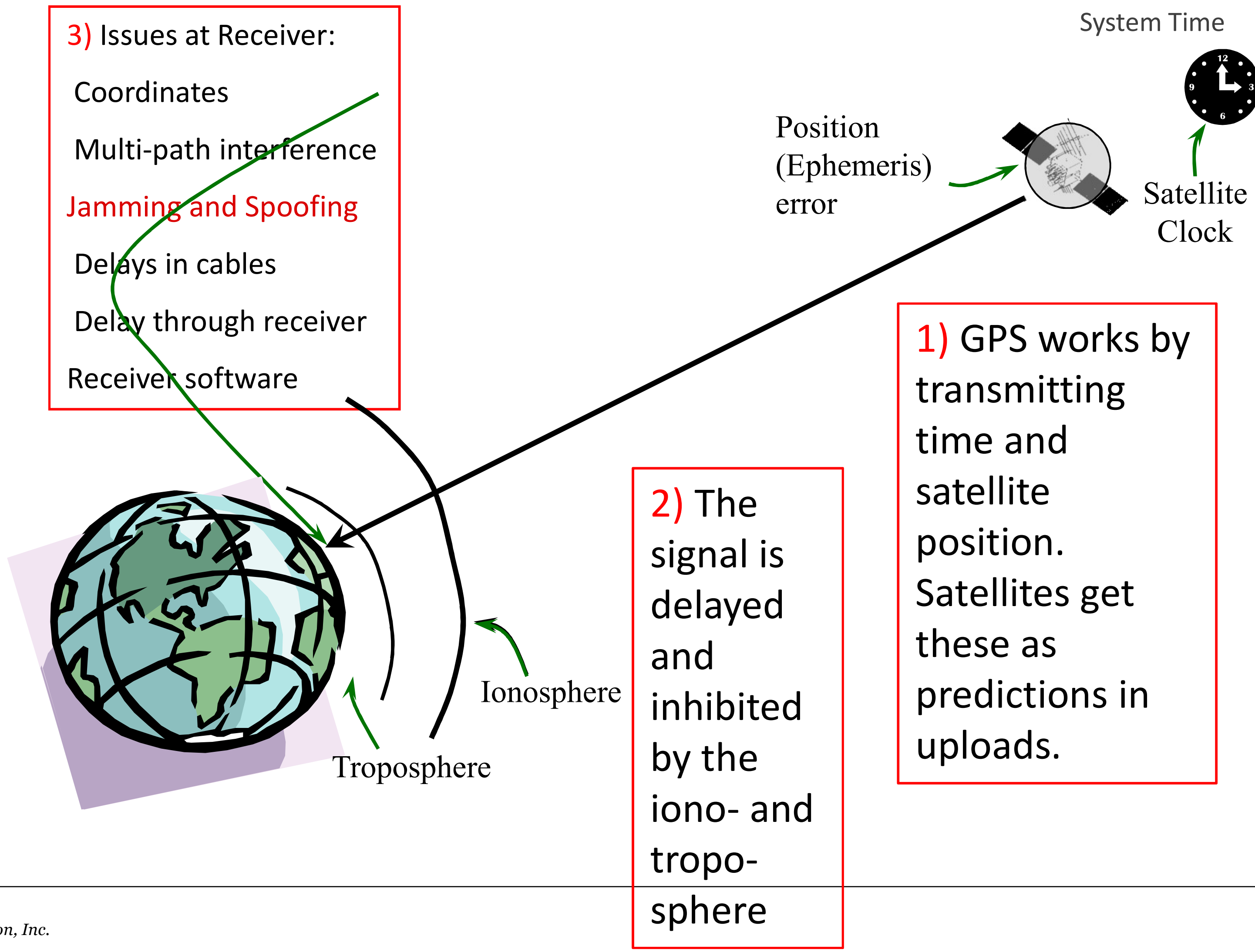
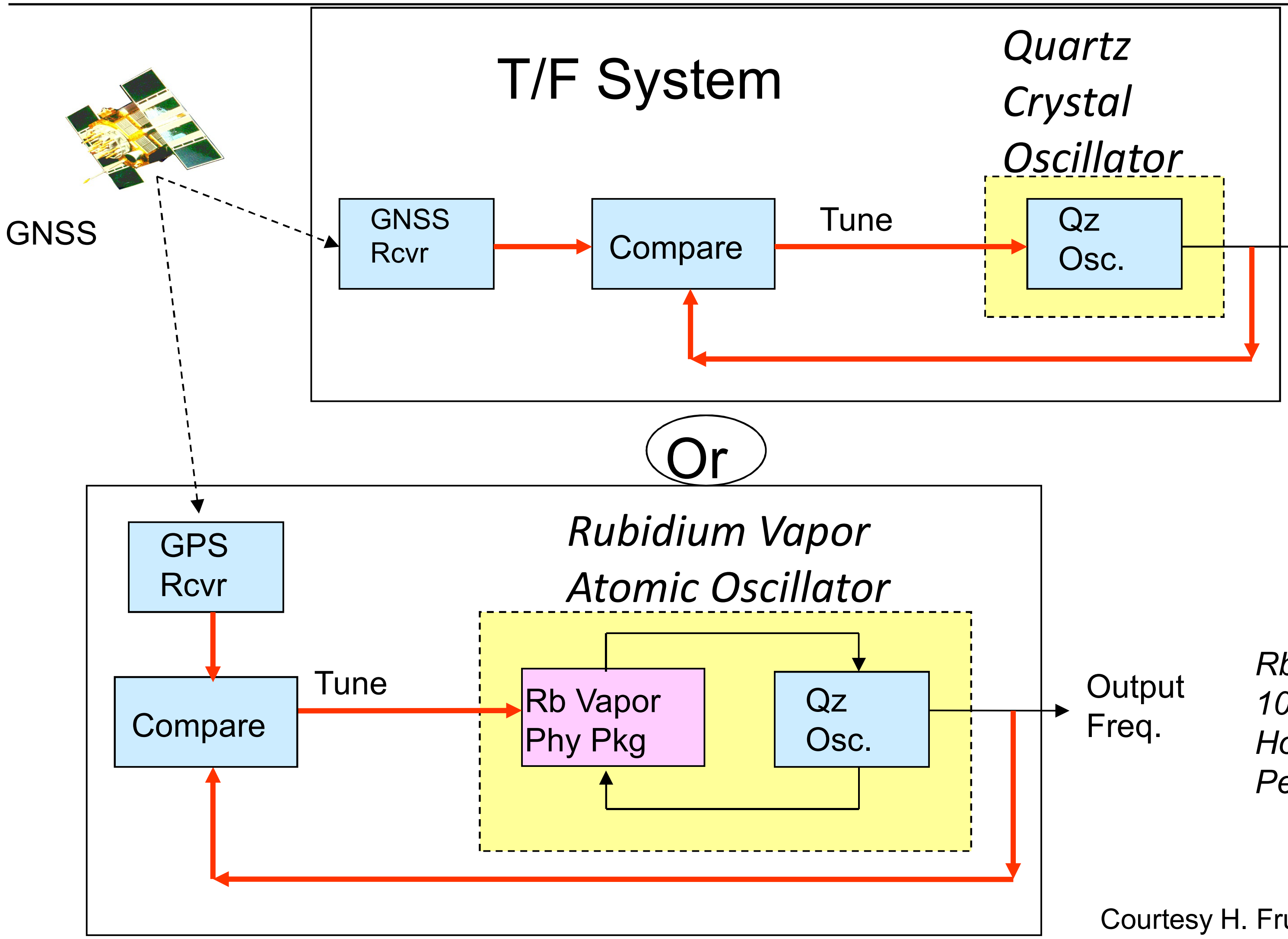
TIME FROM GNSS:
INTENTIONAL AND UNINTENTIONAL ERROR SOURCES



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

GNSS-aided Time and Frequency Systems



Rb oscillator 100 to 1000 times better Holdover Performance

Courtesy H. Fruehauf, ViaLogy LLC

T/F System

GNSS REFERENCES

- GPS
  - CGSIC 2018 https://www.gps.gov/cgsic/meetings/2018/
  - 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/