The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2135-4

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6 - 23 April 2010

Introduction to Clocks, GPS time, Precise Time Applications contd.

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Washington
USA

Time and Time Transfer

Legal Note

These viewgraphs are intended to cover technical aspects of the timekeeping art, but to specifically exclude legalities and/or government policy. If by accident any public timekeeping policy is alluded to, such allusions should be considered the personal opinions of Dr. Matsakis and not a representation of current or future policies of the U.S. Naval Observatory, Department of Defense, or U.S. government.

Course Outline

A. What is Time?

B. Pictorial Representation of Timekeeping Math

- Characterizing Clocks
  - Noise types
  - Stability measures
- Generation of timescales, including UTC
- Steering Clocks

C. Time Transfer

- Telephones, modems
- Internet: NTP
- GPS
- Two Way Satellite Time Transfer

D. Timing in the Future

Appendix 1: Parade of Clocks

Appendix 2: Philosophy of Time, including Relativity

Appendix 3: Statistical Details

Appendix 4: Timescale Details

Appendix 5: Control Theory

Appendix 6: Time Transfer Details

What Is Time?

According to Webster's New Collegiate Dictionary:

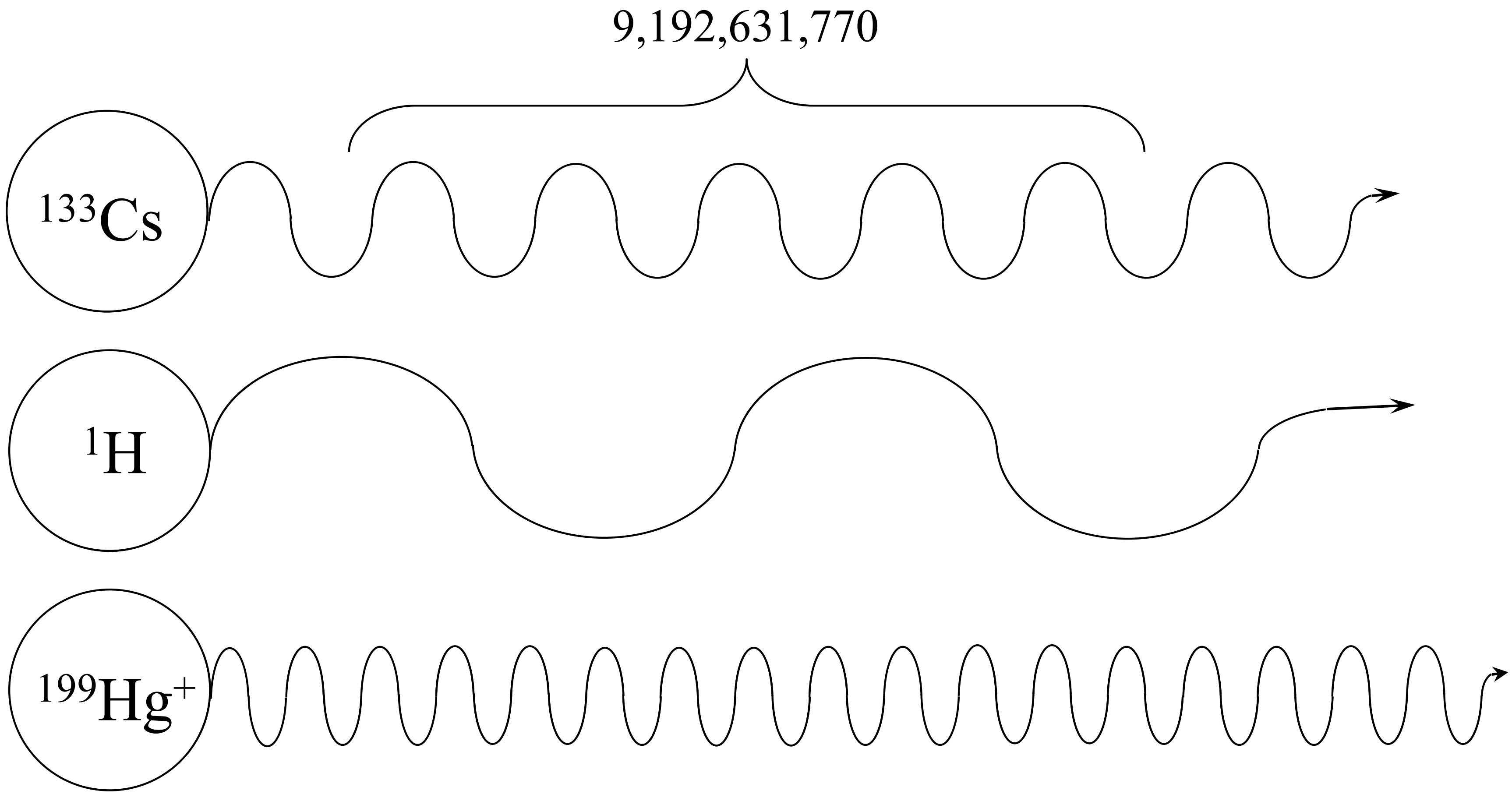
"The measured or measurable period during which an action, process, or condition exists"

According to Demetrios Matsakis:

"That coordinate which can be most simply related to the evolution of closed systems"

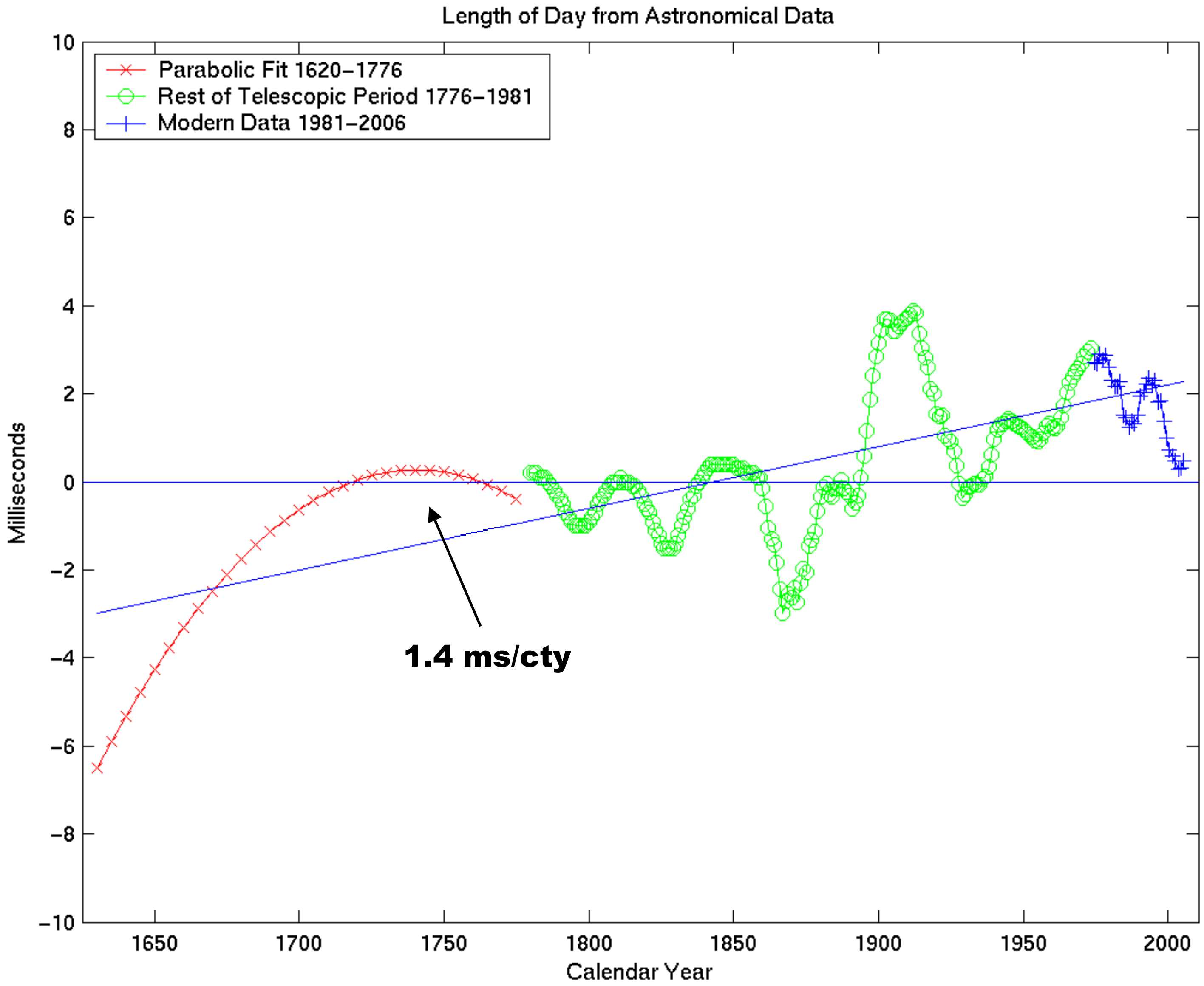
Time as Defined by Measurement

"The second is the duration of 9,192,631,770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of the undisturbed cesium-133 atom" Time is the phase of this radiation.



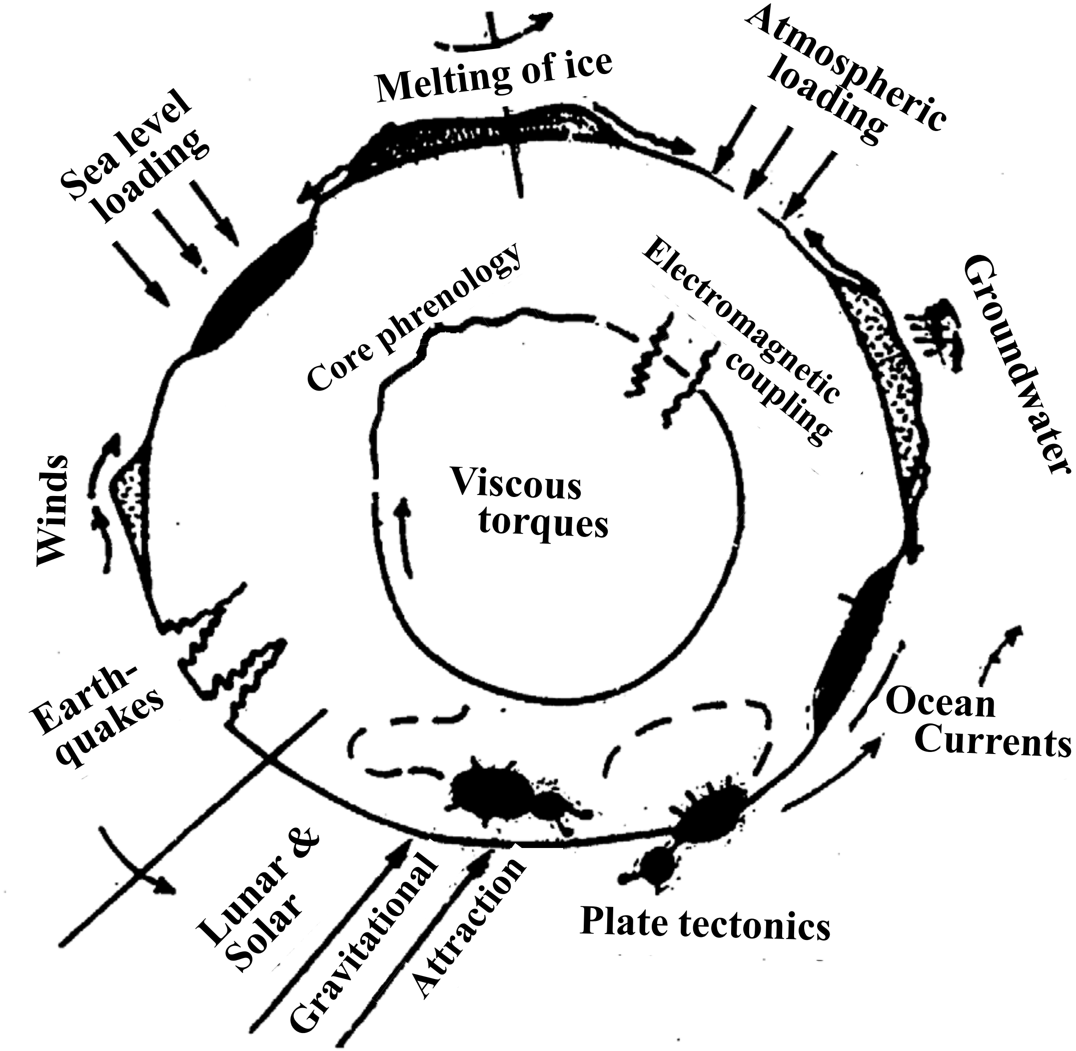
Why not just use the Earth's rotation?

Length of Day (LOD) 1620-2006



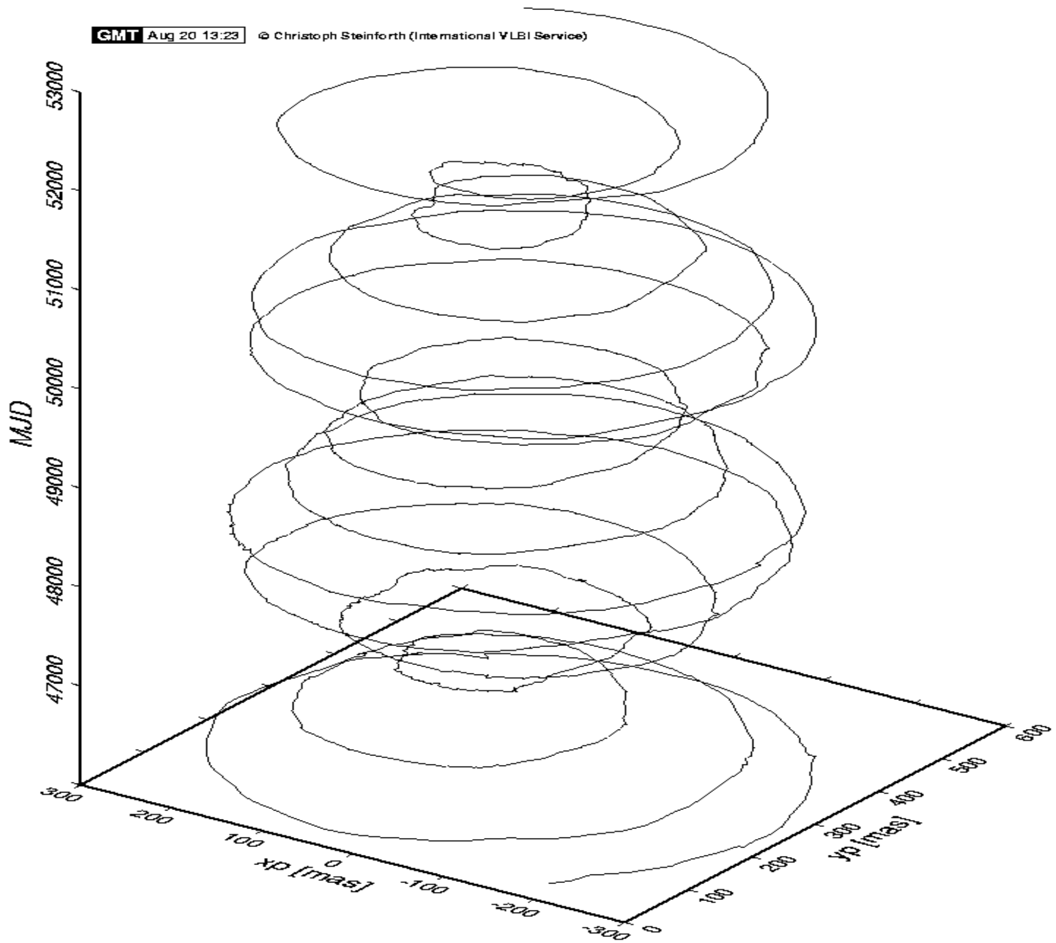
Sources: F.R. Stephenson and L.V. Morrison, *Phil. Trans. R. Soc. London* **A313**, 47 – 70 (1984), http://maia.usno.navy.mil, and ftp://maia.usno.navy.mil/ser7/finals.all

Schematic Illustration Of The Forces That Perturb The Earth's Rotation



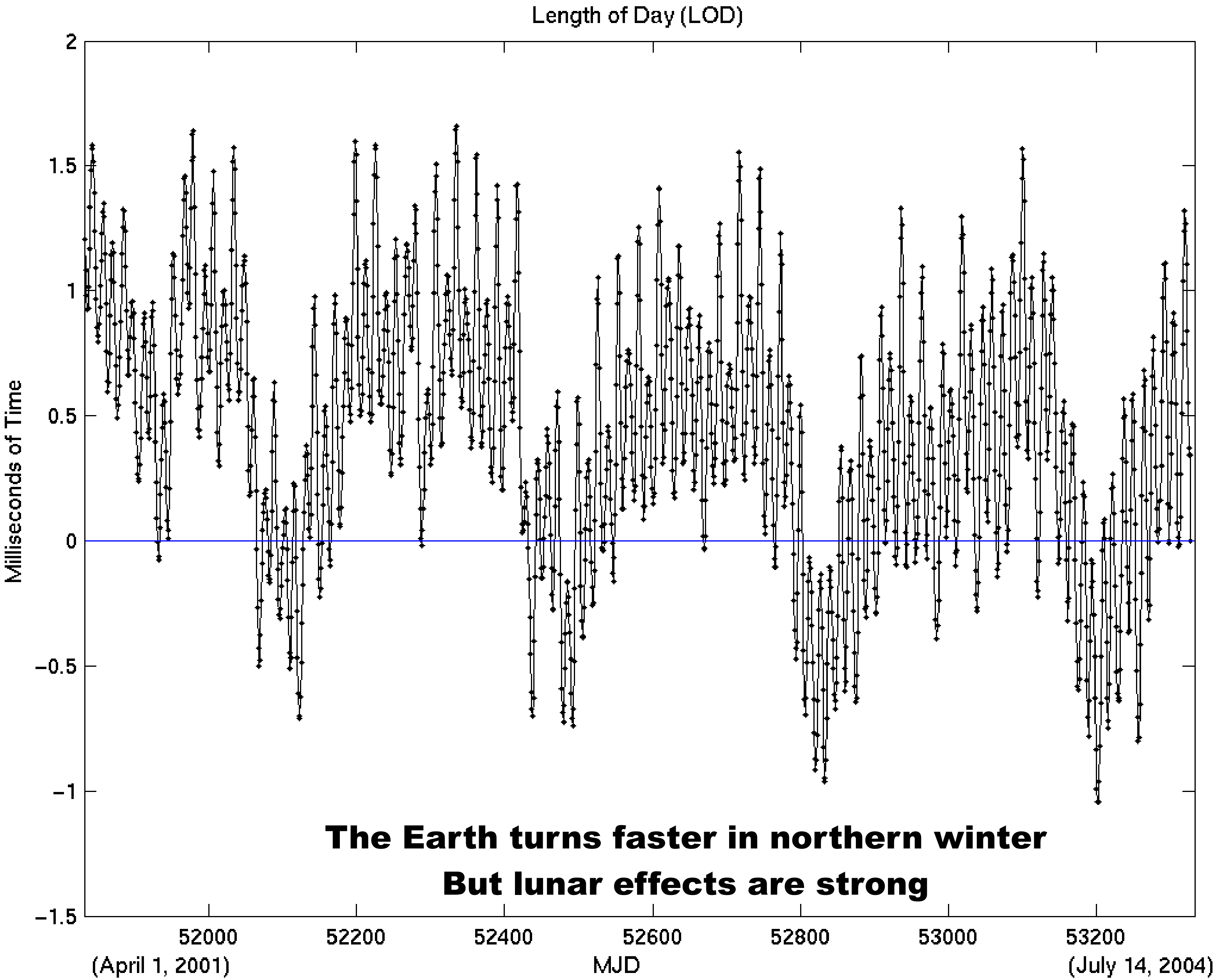
Source: Thomas Gold, *Nature*

Polar Motion (1984-2002)



Source: http://giub.geod.uni-bonn.de/vlbi/IVS-AC/combi-all/start.html

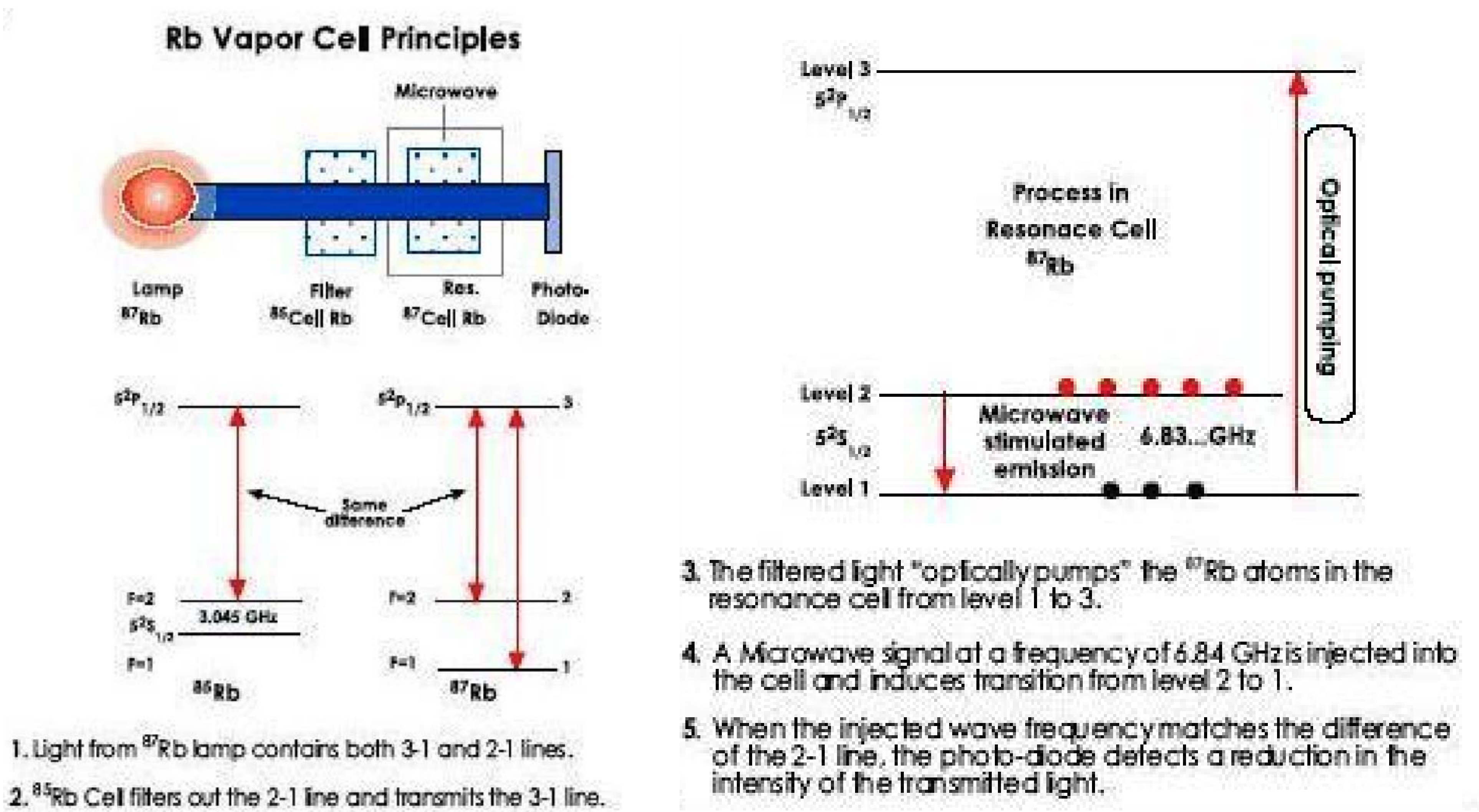
Variations in Length of Day



Modern Life has LONGER days

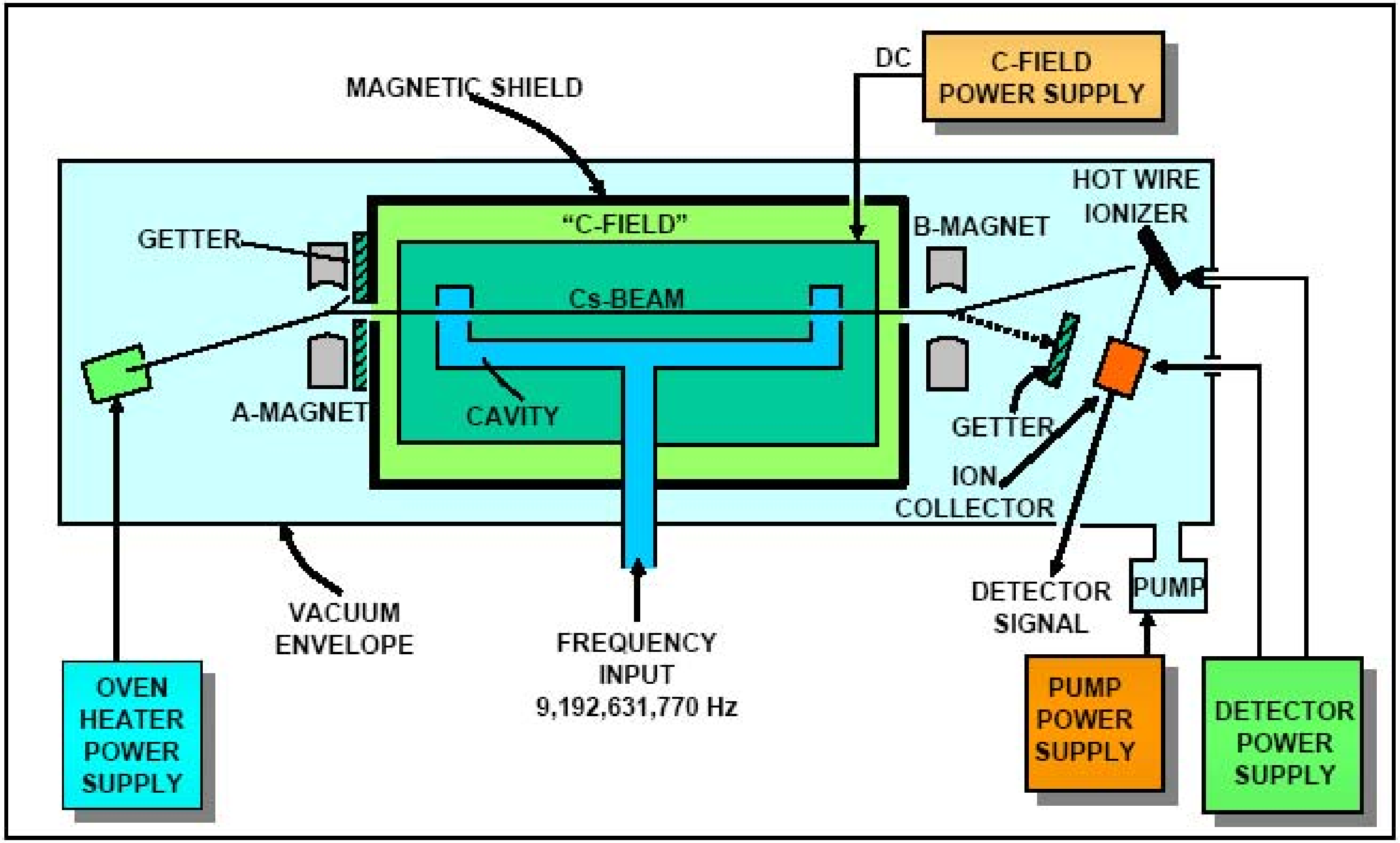
- Tides are oceans following moon
  - "Crashing" into coastline and seafloor
- Tides slow down the rotating Earth
  - Days get longer, 1 day approaches 1 month
  - Moon's orbit gets further away
  - Sun and other bodies also have effects
- Earth has lost 14 hours since 1815 BC
  - From Chinese solar-eclipse records
- ~100 million years ago, day lasted only 20 hours
  - From fossilized nematodes

Even the cheapest atomic clock is more precise than the Earth



Source: www.accubeat.com

Cesium Standard



Source: John Vig

Hydrogen Maser Frequency Standard

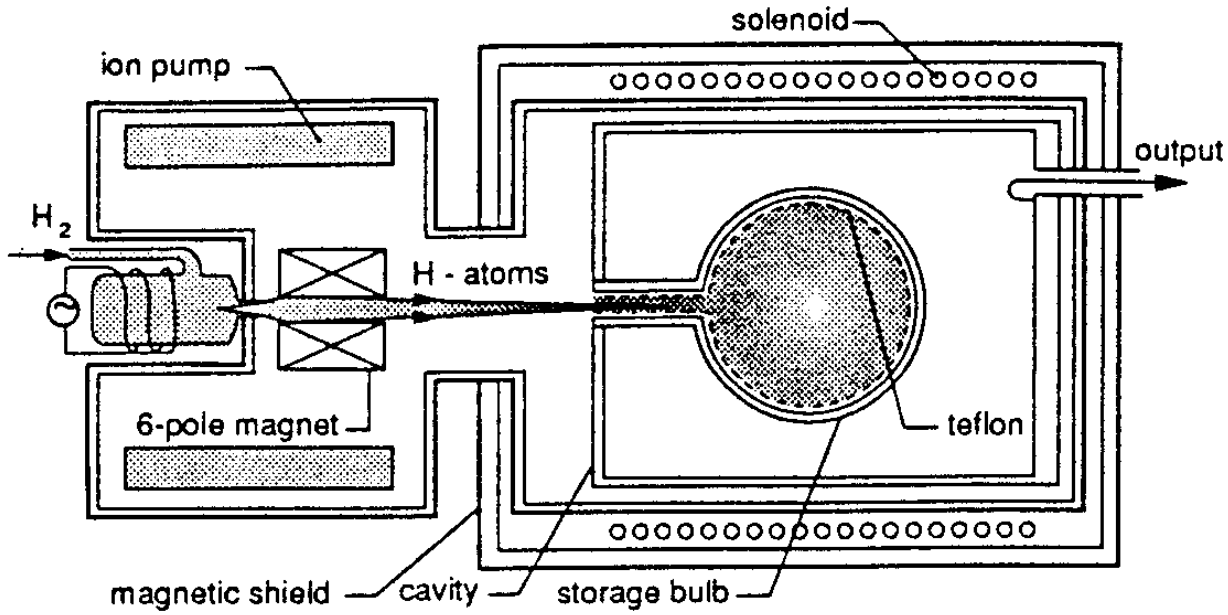


Figure 11.2 The basic elements of a hydrogen maser

F.G. Major Springer, “The Quantum Beat”, 1998

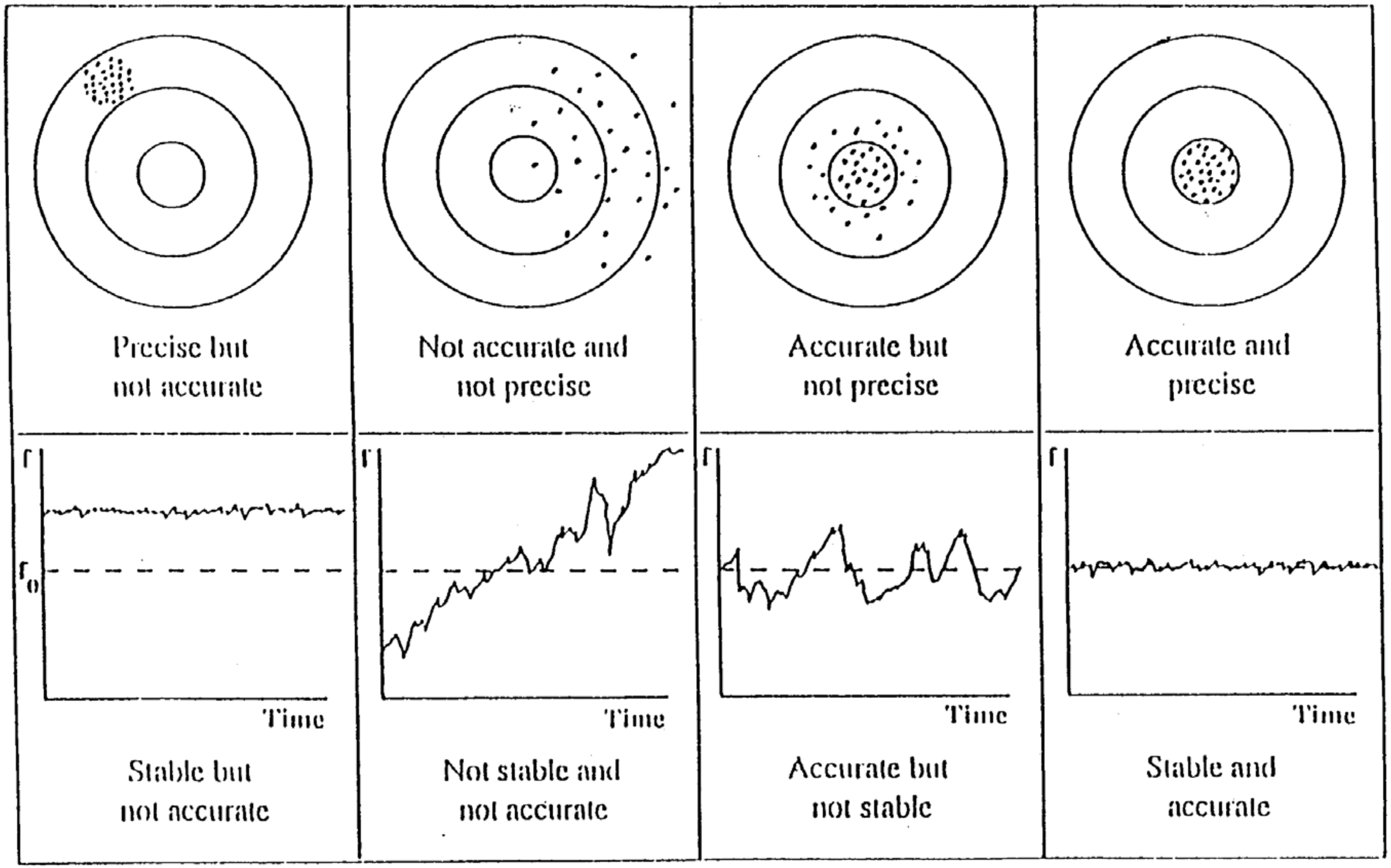
Time & Frequency Units

TIME				FREQUENCY $f=(t_b-t_a)/\Delta T$	
Second	1.0 s	s	10^0 s	1 s/day	1.16 10^{-5}
Millisecond	.001 s	ms	10^{-3} s	1 ms/day	1.16 10^{-8}
Microsecond	.000001 s	us	10^{-6} s	1 us/day	1.16 10^{-11}
Nanosecond	.000000001 s	ns	10^{-9} s	1 ns/day	1.16 10^{-14}
Picosecond	.000000000001 s	ps	10^{-12} s	1 ps/day	1.16 10^{-17}
Femtosecond	.000000000000001s	fs	10^{-15} s	1 fs/day	1.16 10^{-20}

Modified Julian Day (MJD)

- Julian Day = JD = days since 4713 BC
  - Invented by Joseph Scalinger, circa 1600
  - JD increments at noon
  - Better for astronomers who observe at night
- Modified Julian Day = MJD = JD-2400000.5
  - Days since 1858.8, November 18, 1858
  - Increments at midnight
  - Better for most people

Precision vs. Accuracy



Source: John Vig's Tutorial

Three Complementary Ways To Characterize Clock Time Series

I. Inspection

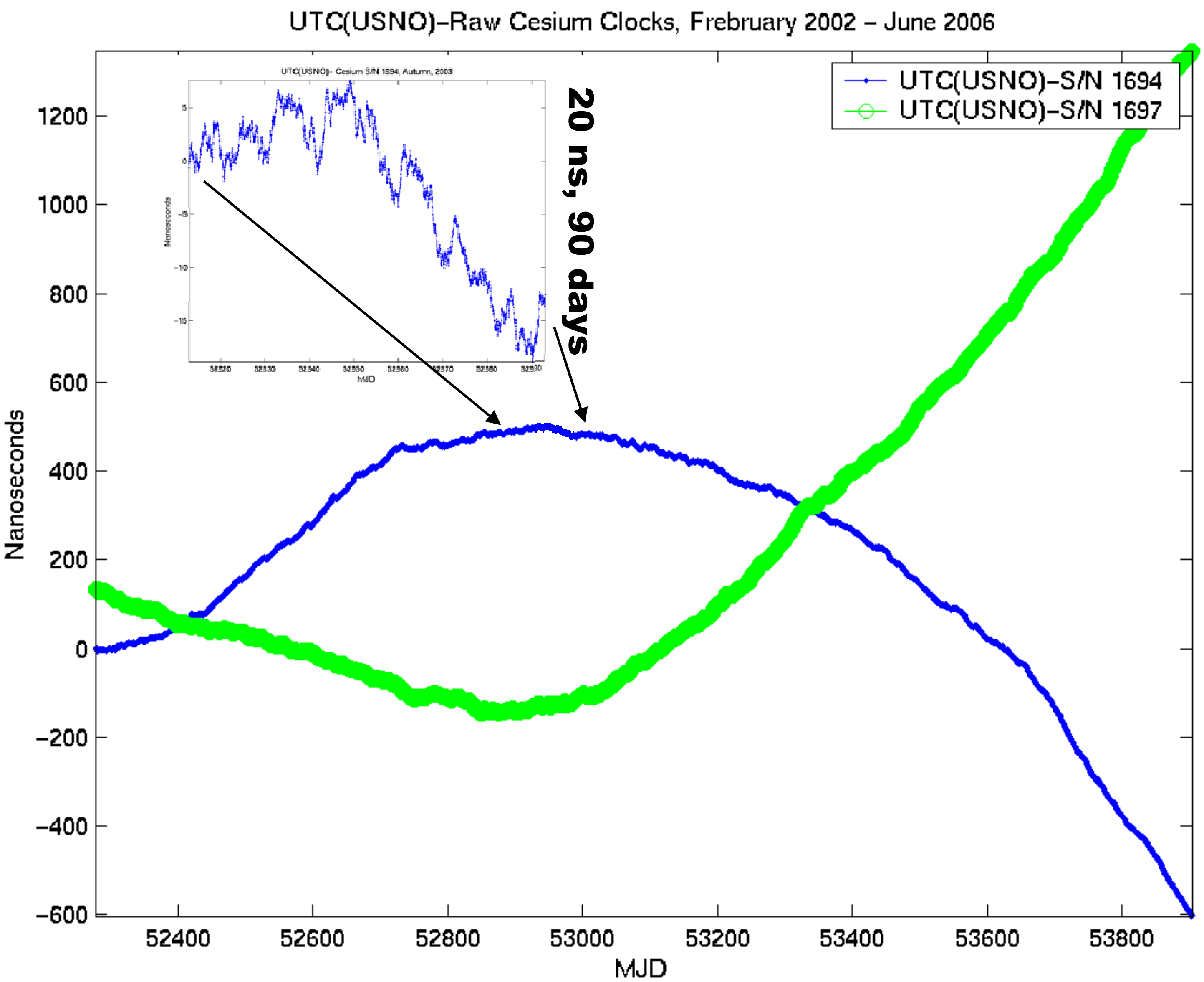
II. Fourier Transform

III. Variances of Differences:

AVAR, TVAR, MVAR,

HADAMARD, TOTDEV, etc.

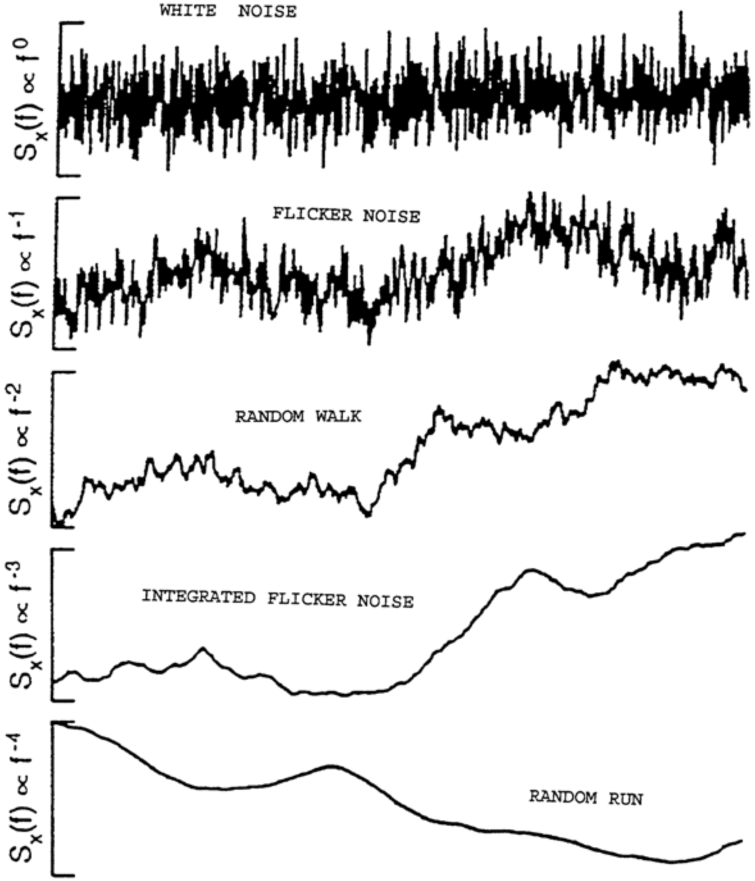
Illustrative Clock Data



Five Fundamental Noise Types

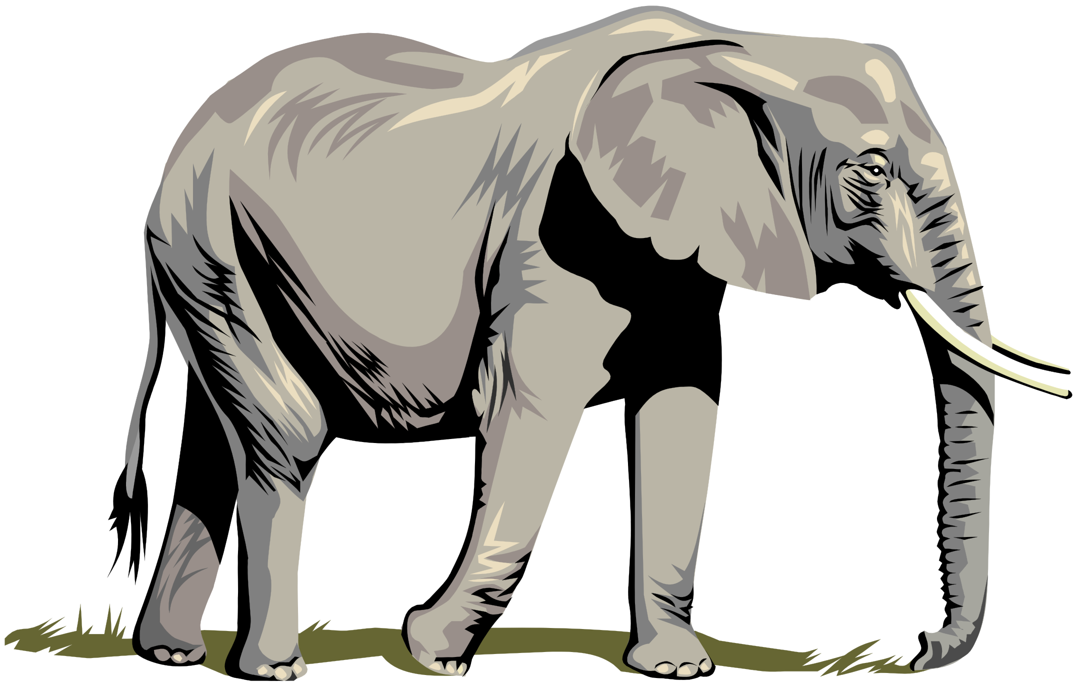
Combined, they can model clock noise

Source: Dave Allan



Noise in clock phase (time) also termed phase modulation (PM)

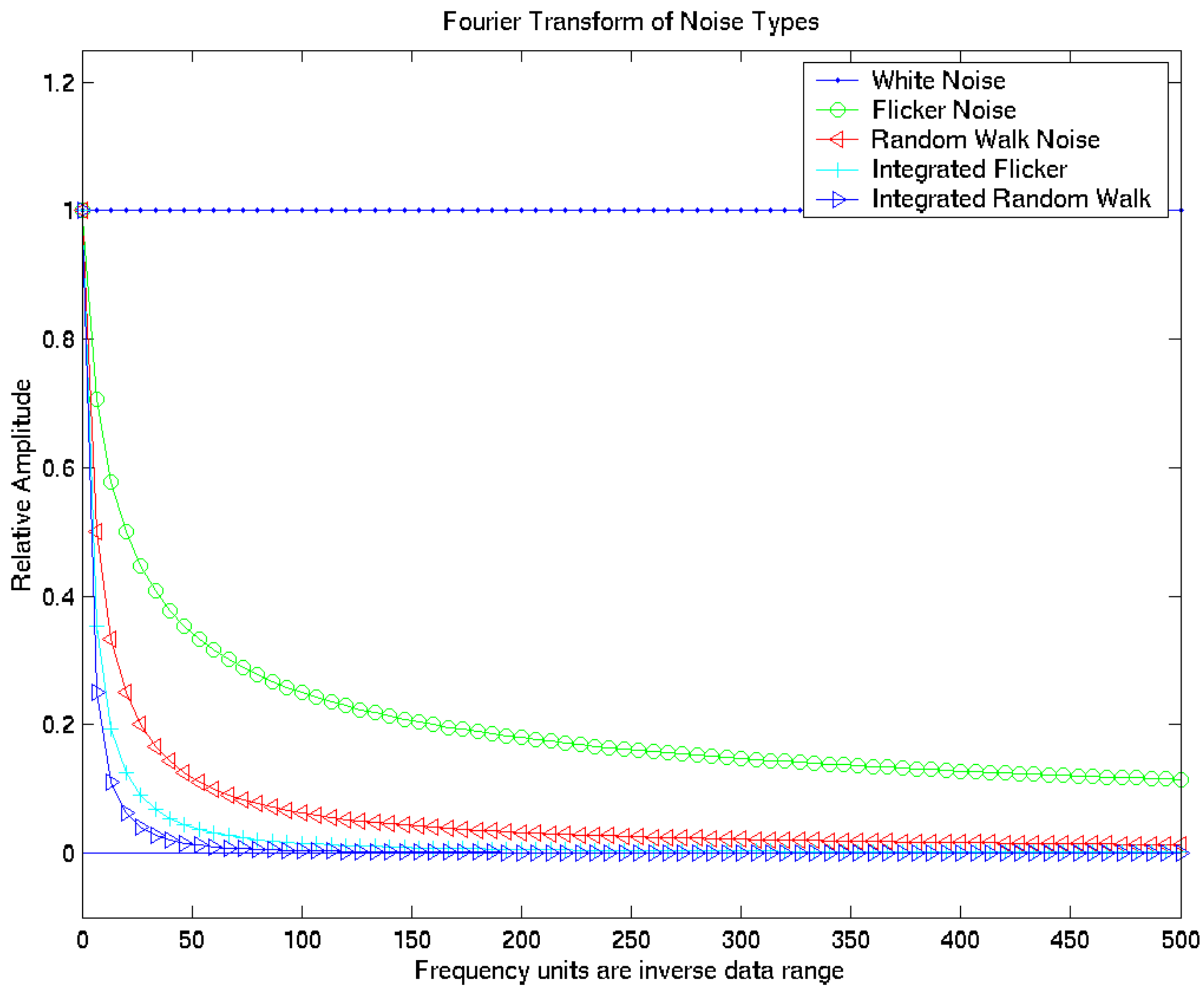
Noise in clock frequency also termed frequency modulation (FM)



"With five parameters I can fit an elephant."
- Enrico Fermi

Fourier Transform of Noise Models

Power Spectral Density is square of plotted amplitude (technique works better for periodic variations)



How to Quantitatively Measure a Clock's Time/Frequency Accuracy/Precision?

It could be measured by the data’s Root Mean Square (RMS), which is also the square root of the variance (VAR).

Unfortunately, if a clock changes frequency systematically over its life, its time and frequency RMS and VAR are unbounded.

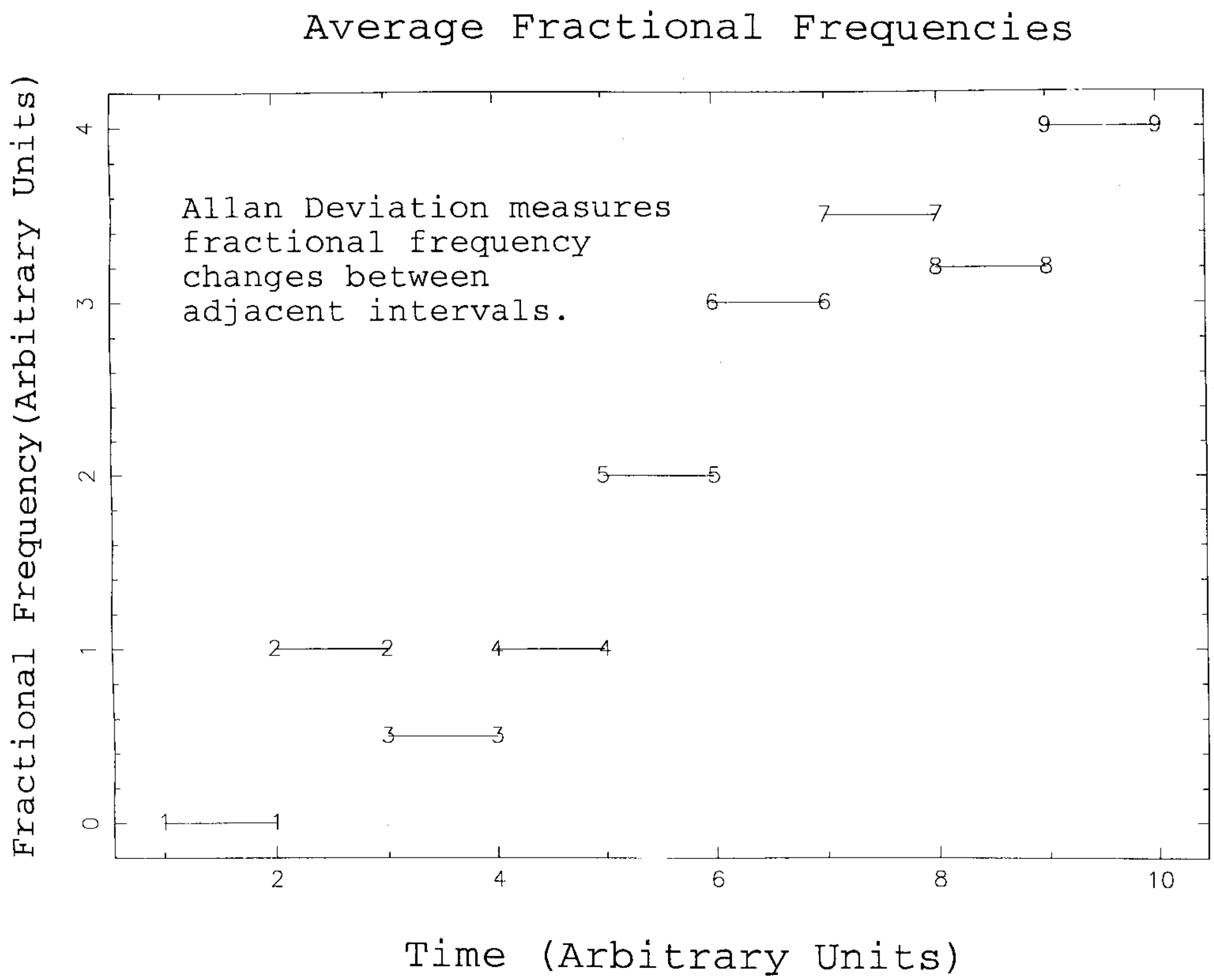
Every clock we know of does this.

Rephrase The Question

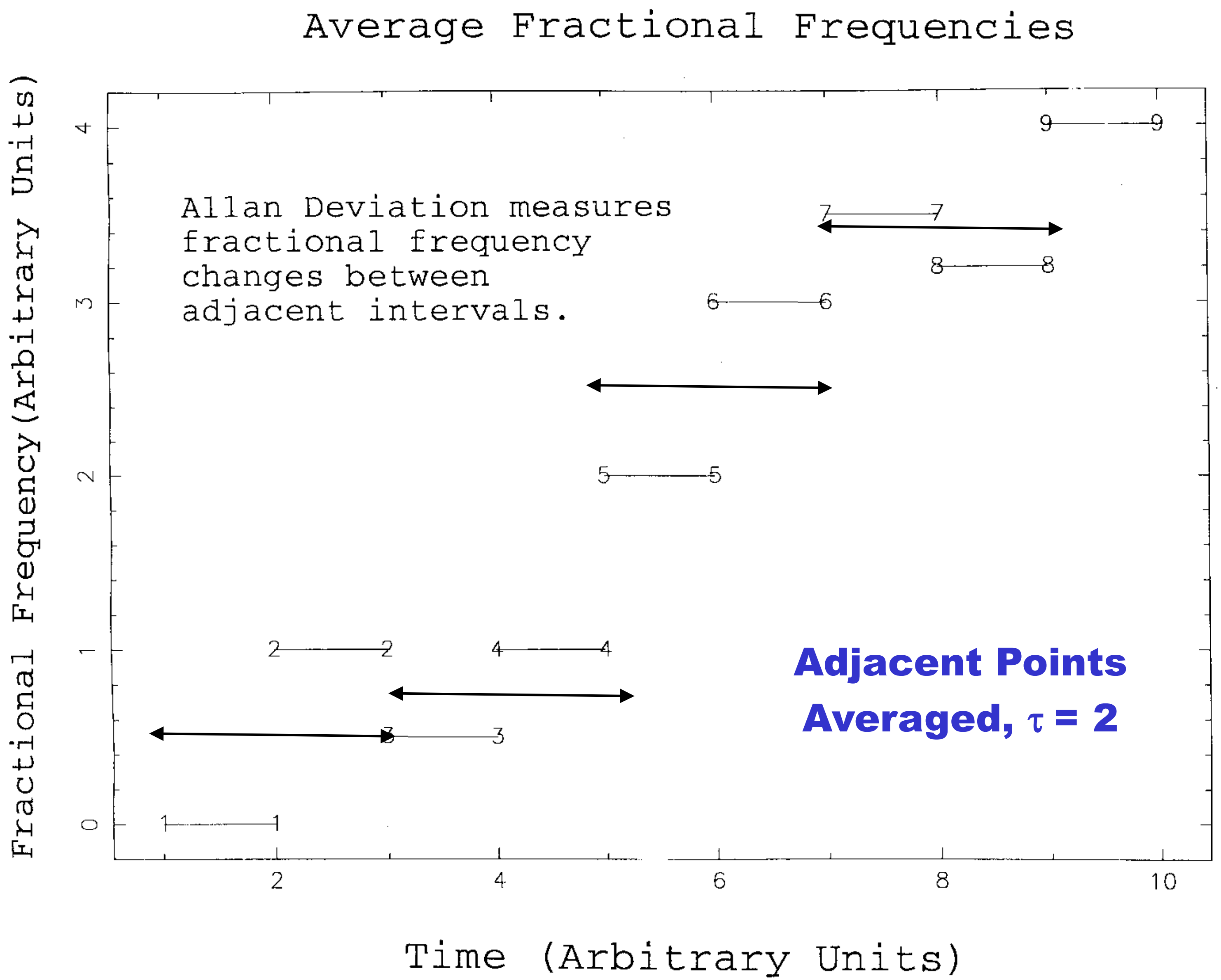
How much does the frequency vary from one interval, of duration τ, to the next interval?

- That's the Allan Deviation (ADEV)
- ADEV=square root of the Allan Variance (AVAR)
- ADEV is also written $\sigma_y(\tau)$
- AVAR is also written $\sigma^2_y(\tau)$)

Example: Clock Whose Frequency Increases



Example: Averaging Adjacent Frequency Bins



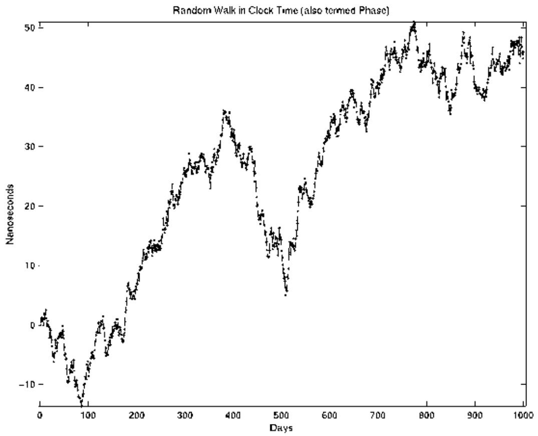
How does the Allan Deviation

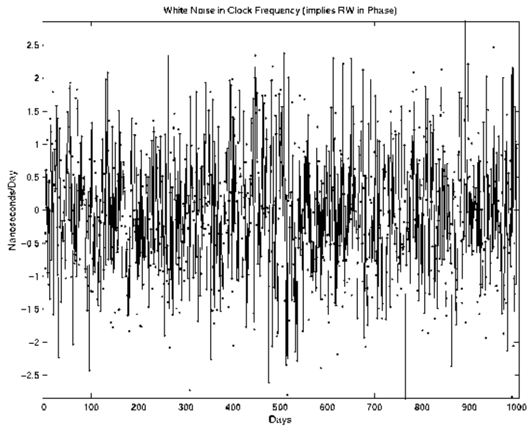
(ADEV, or $\sigma_y(\tau)$), depend upon

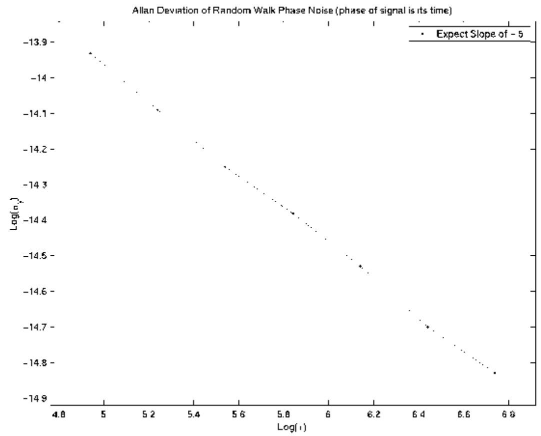
the kind of noise in the time series?

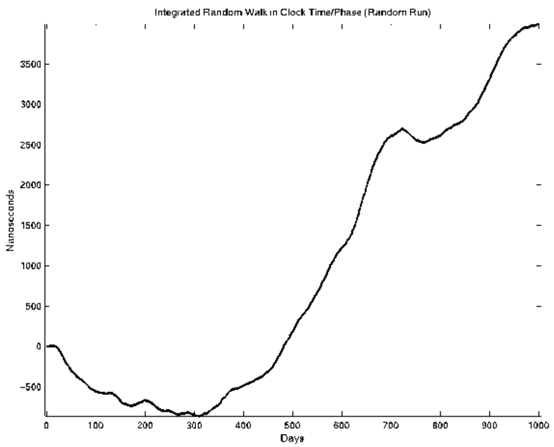
Allan Deviation of Random Walk and Random Run

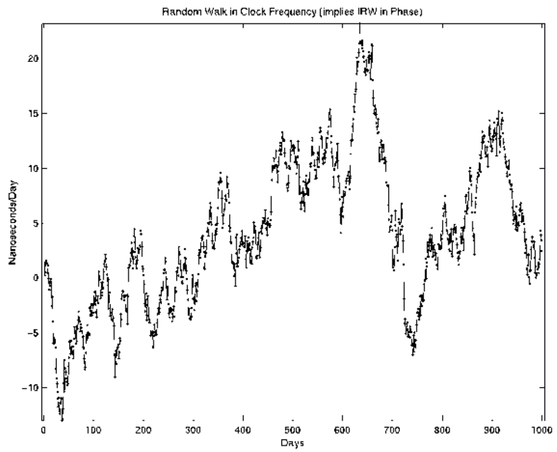
Clock Phase (=time) | Clock Freq. | Allan Deviation

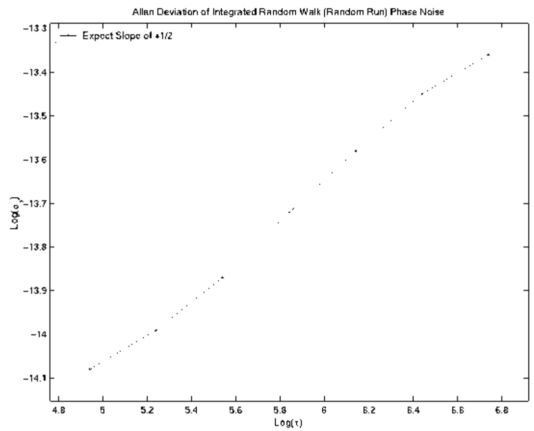






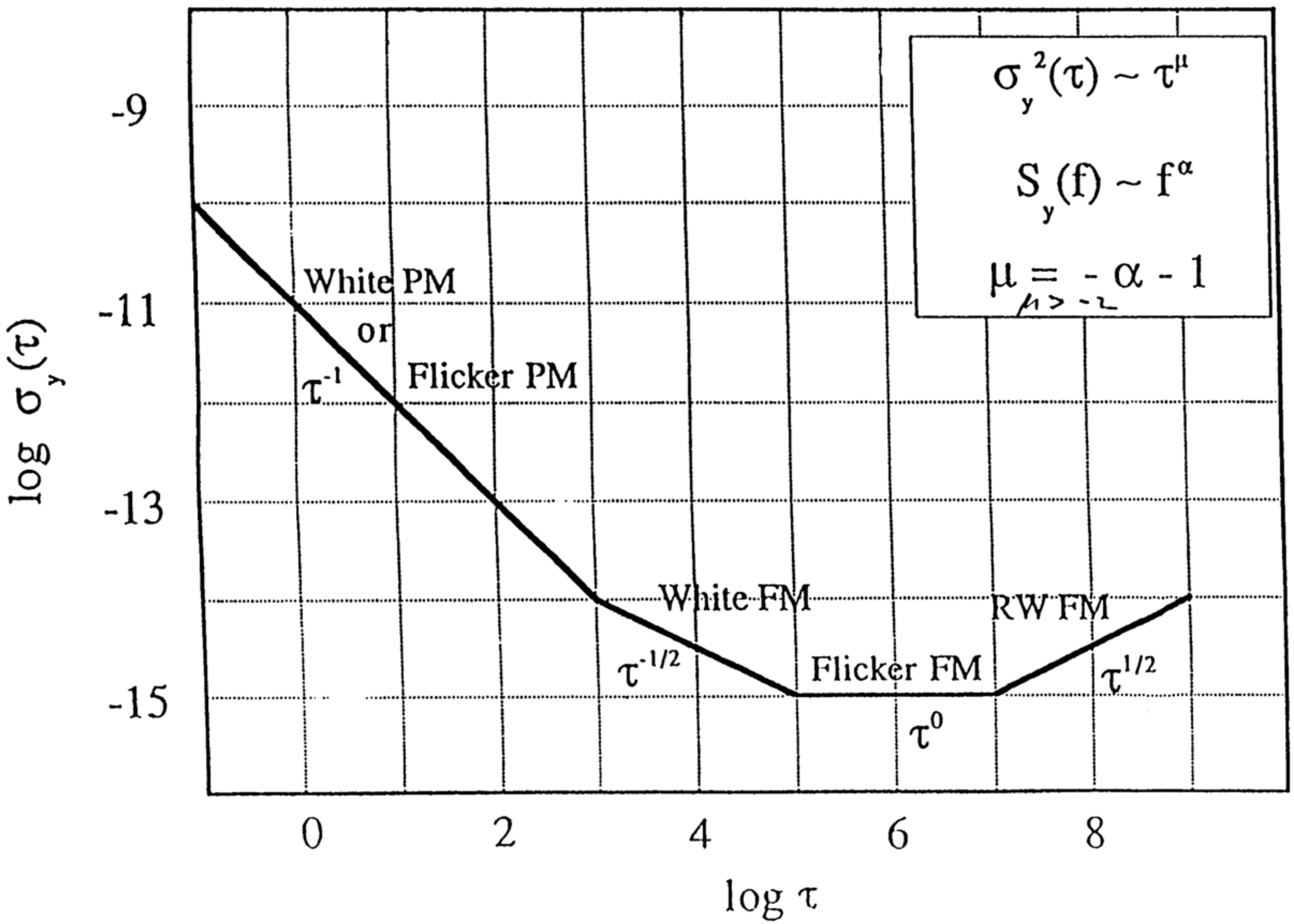






Typical Maser Sigma-Tau Pattern

White Noise dominates over shortest averaging times
RandomWalk FM=Random Run PM over longest averaging times



Problem

Allan Deviation can't distinguish between

white phase noise and flicker phase noise.

NO PROBLEM

Use Modified Allan Deviation (MDEV)

How MDEV is Defined

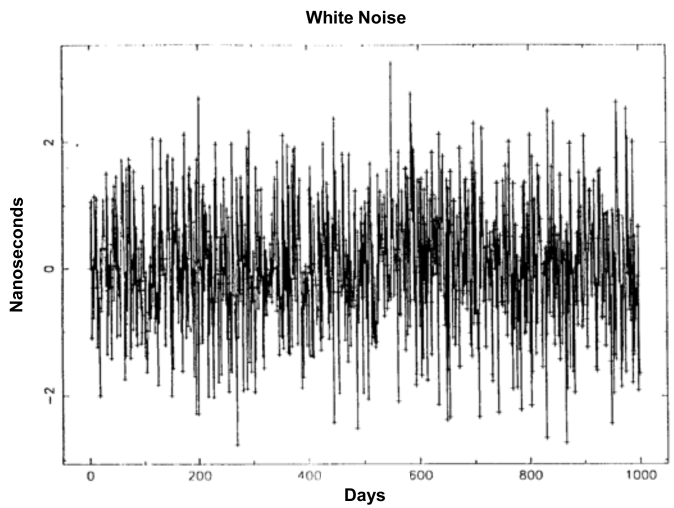
Like ADEV, except replace each freq by an average of frequencies of nearby points

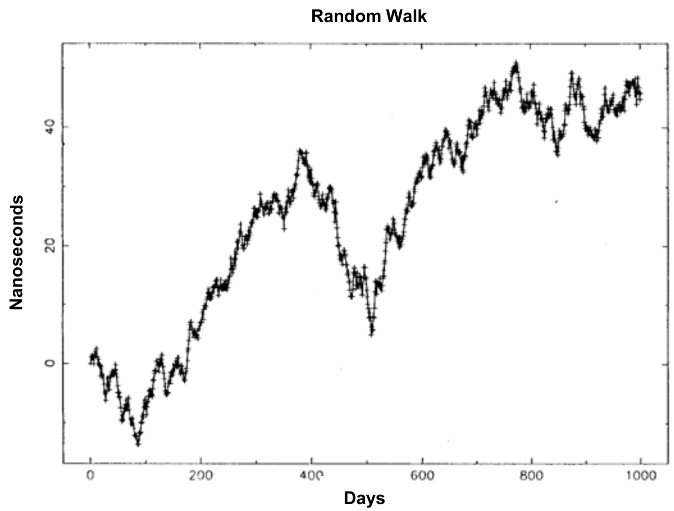
If you multiply MDEV by τ/sqrt(3), you get the

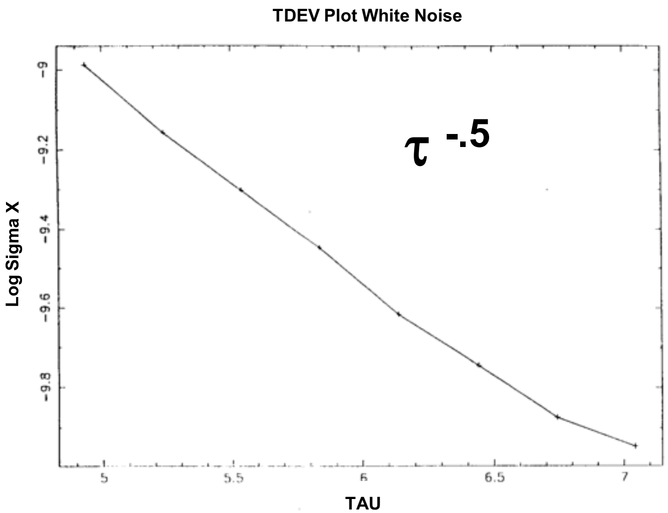
Time Deviation, TDEV. TVAR is the square of TDEV.

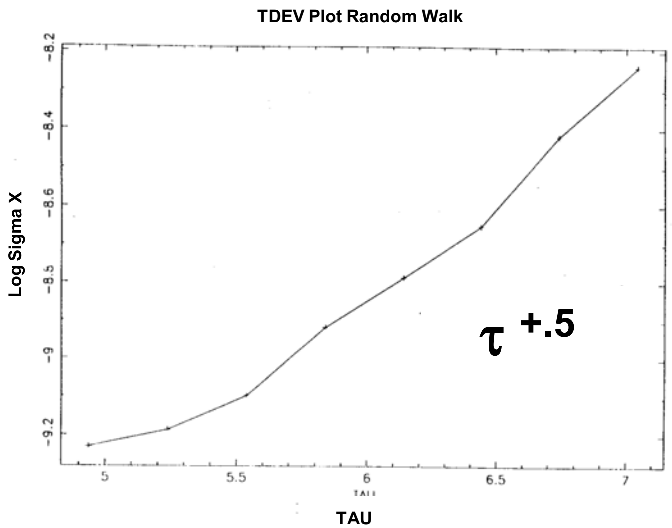
How does the Time Deviation (TDEV), depend upon the kind of noise in the data?

Example: TDEV of White Phase and Random Walk Noise Models

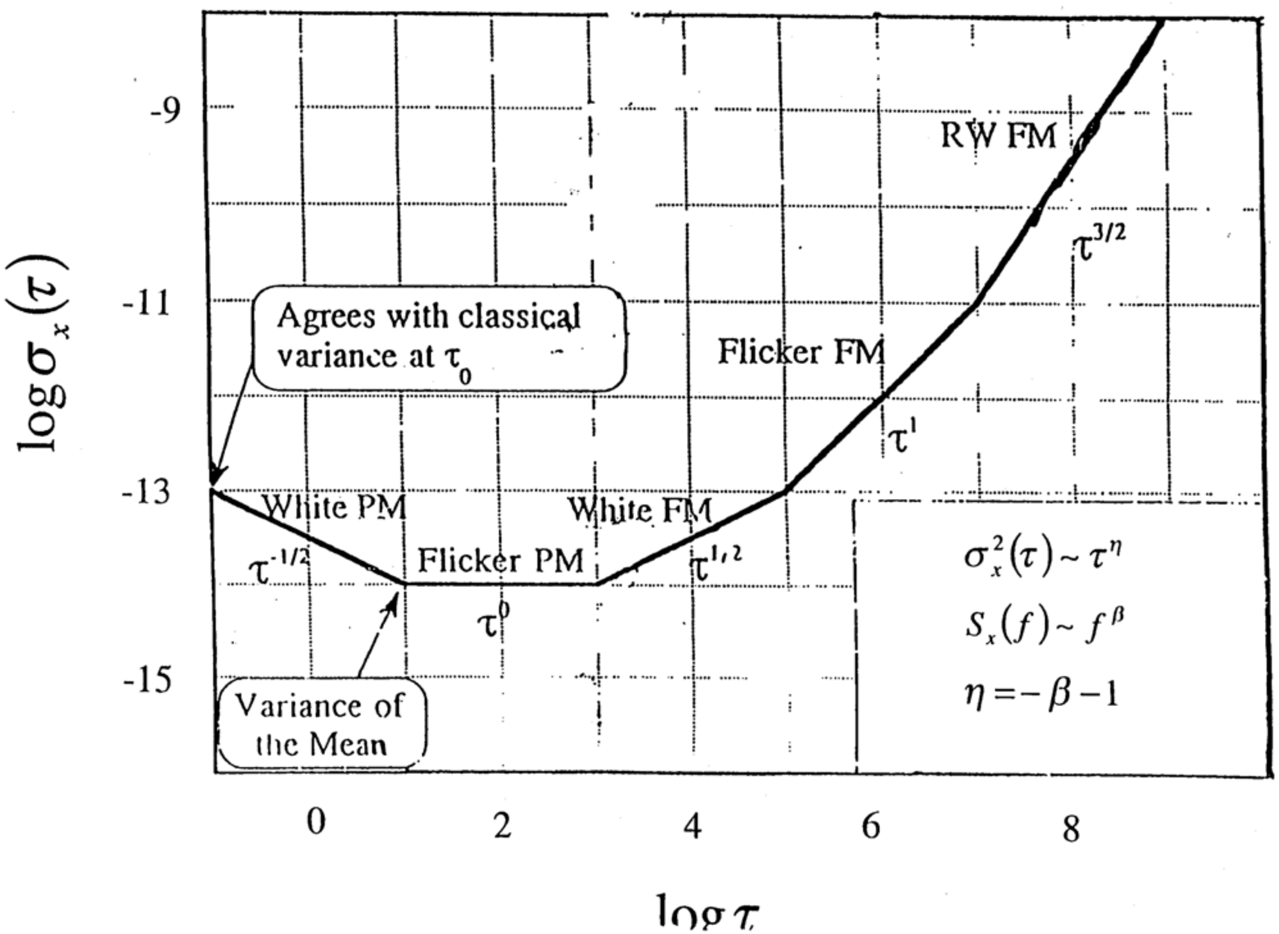








TDEV distinguishes White PM from other noise types



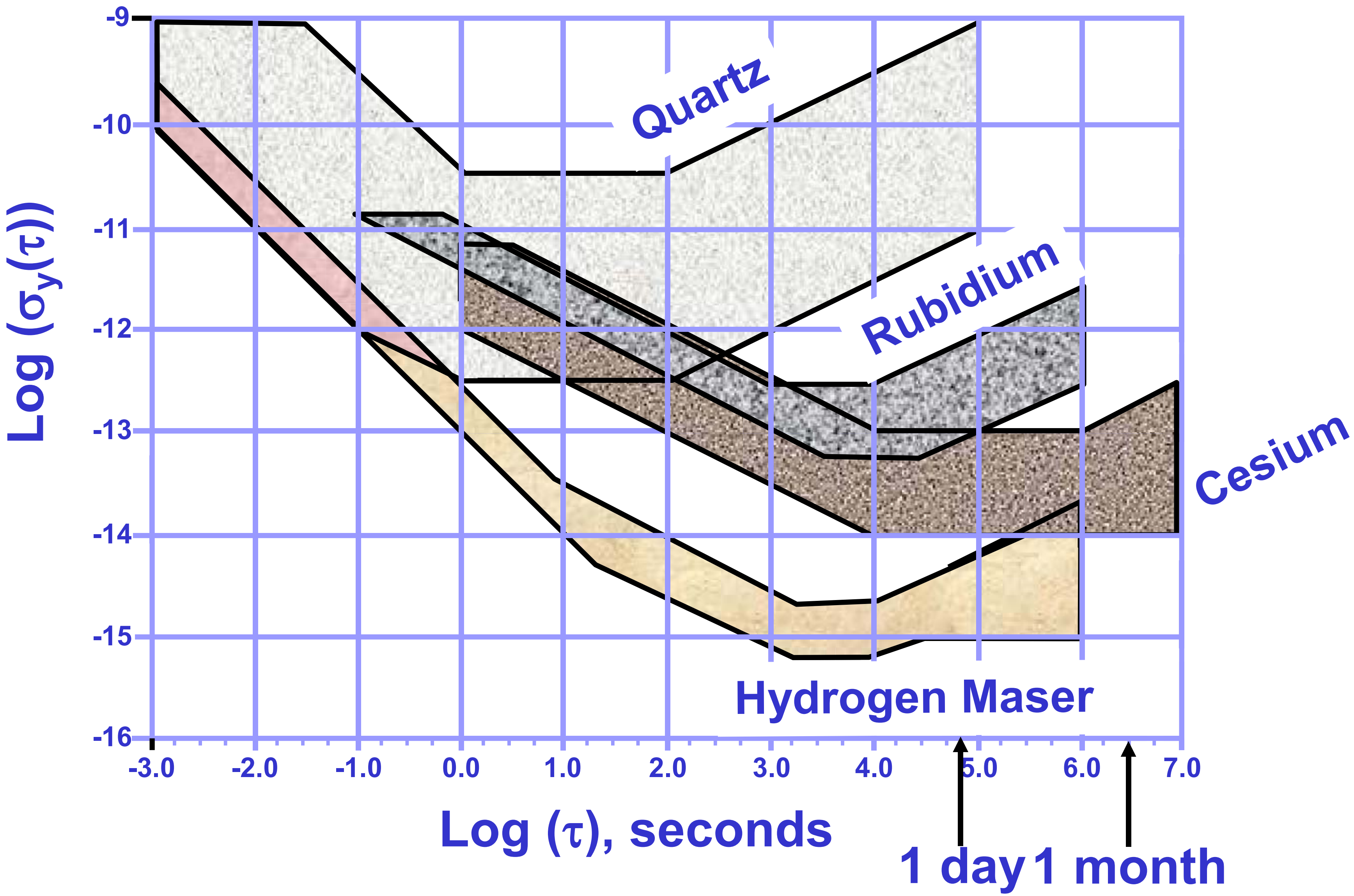
TDEV= Time Deviation

One of Many Statistical Pitfalls

All of the discussed measures are insensitive to overall Phase/time slopes, so there is no harm in removing or adding such slopes to data. In fact, you usually should remove slopes to avoid binning quantization problems.

BUT… If you detrend data with a higher-order fit, you will artificially force the statistic towards 0 for large tau. You should *never* remove a second-order term to compute an Allan deviation.

Stability of Various Frequency Standards



Source: http://www.ieee_uffc.org/fc (John Vig and R. Sydnor)

What is a Timescale?

- A useful average of clocks
  - Usually a weighted average of observed minus predicted data.
  - Timescales must not jump
- Goal is to measure time better than any individual clock
  - Can't optimize everything at the same time
  - Should be optimized for goals of interest
    - Measure "absolute time" of a clock ensemble?
    - Produce a constant frequency?
      - How much do you care what that constant is?
    - Track a reference clock or timescale (steering)?
    - Trade precision for robustness?
    - Save money on computers and mathematicians?

Continuity Constraint

- Timescale must not jump
- A clock model helps when
  - Clocks are added
  - Clocks are removed
  - Clock weights are changed
  - A clock misbehaves
    - By making identification easy
- Some prediction algorithms in use today (details in appendix):
  - Polynomial
    - BIPM (Algos), USNO (Percival Algorithm)
  - Exponential Filter
    - NIST, NICT
  - Adaptive ARIMA (Auto-Regressive Integrated Moving Average)
    - INPL
  - Kalman Filter
    - GPS Composite Clock, IGS

In Modeling, Try To Work with White Noise

- Quantities are well-defined
- Most theorems apply only to white noise
- If the noise or parameter variation isn't white, whiten it if possible:

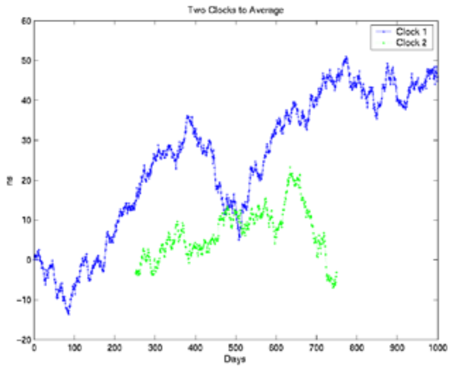
A. Add another parameter

B. Replace data by their Nth order differences

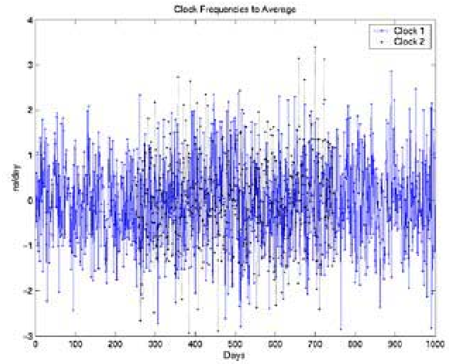
(e.g. convert time to frequency)

C. Chose the time-interval where it is white

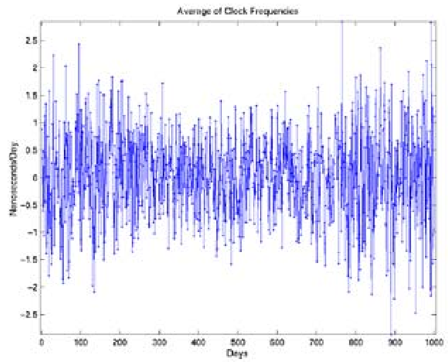
Continuity from Averaging Frequencies



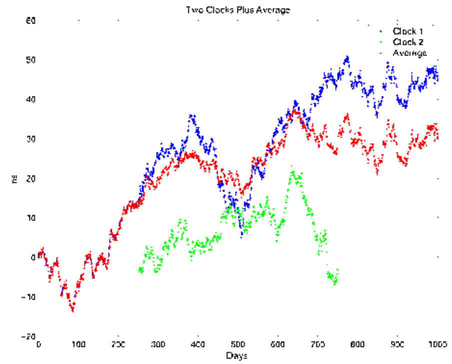
1. Phase data from two clocks (simple average would jump when clock 2 availability changes



2. Data of the two clocks after conversion to frequency (freq point= difference of 2 time points)



3. Average the frequencies of the two clocks



4. Sum frequency average to create time average (Plotted with original phase data of two clocks)

Clock Weights in Timescales

Optimal weighting depends upon

- **Clock Statistics**
  - **If Gaussian, weight by (1.0 /Variance)**
- **Stability interval of interest**
  - **Could weight by 1.0/(Allan Variance)**
- **Effects if highly weighted clock fails**
  - **If you can determine it is failing**
- **How well above are known**

Timescale Summary

Timescale algorithms can differ in:

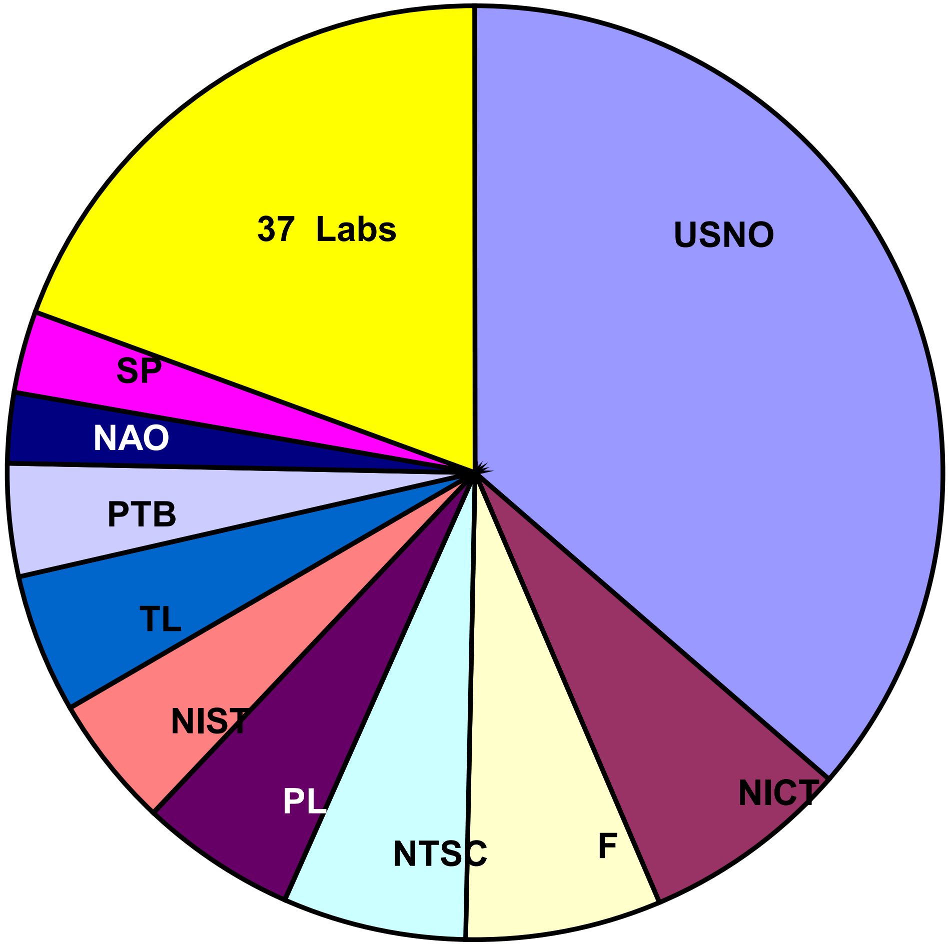
1. Continuity constraint
2. Clock prediction method
3. Clock weighting
4. Data editing

Each of these points is a matter of active research.

Coordinated Universal Time (UTC)

- **International Time Standard**
  - **Treaty of the Meter**
- **Computed by International Bureau of Weights and Measures (BIPM)**
  - **BIPM located near Paris France**
  - **Data from ~50 institutions**
  - **Data from > 200 atomic clocks**
- **Computed and distributed by months**
  - **5-day spacing, precise to 0.1 ns**
  - **Emailed 10-15 days after month ends**

Contributors To EAL (UTC) By Weight



Source: BIPM Circular T, April 2006

How BIPM Computes UTC

- Step 1: Generate EAL
  - EAL=Echelon Atomique Libre
    - French for Free Atomic Time Scale
  - EAL=Average of "secondary standards"
    - Clocks whose calibration is not maintained
- Step 2: Generate TAI
  - TAI=International Atomic Time
  - Adjusts frequency of EAL towards primary standards
  - Primary standards have calibrated frequency
    - Maintained by few institutions
- Step 3: Generate UTC (next viewgraph)

How the BIPM Computes UTC from TAI

- Problem: 1 day=24*60*60*9,192,631,700 cs oscillations
  - What happens if the Earth slows down (or speeds up)?
- Compromise solution: Add and subtract seconds
  - Do not change the frequency of cesium atom
  - UTC=TAI+ integer number of seconds
  - Decided by Time Lords in 1971/2
- Additional second is called a ***Leap Second***
  - So far, have only inserted, never subtracted a second
- Could add at the end of any month
  - But so far have only added at end of December or June
  - Decision is made by the Earth Rotation Service (IERS)
- Some people want to stop inserting leap seconds

Multi-Cultural Time

Free-running time scales: EAL(BIPM), A.1(USNO), AT1(NIST), TA(Lab_X)
- Based only on available clock data, with no overt steering

International Atomic Time (TAI) and Coordinated Universal Time (UTC)
- EAL is average of all "secondary standards", or clocks that are not accurately and independently calibrated against definition of second.
- UTC is EAL after steering towards "primary frequency standards" of the PTB, NIST, SU, and BNM. Computed every month in 5-day points and distributed in middle of following month.
- UTC=TAI with leap seconds to correct for variable Earth rotation

Terrestrial Time (TT)
- UTC recomputed with hindsight, but offset by 32.184 seconds for historical continuity with Ephemeris time.

Real-time realizations of UTC
- Steered time scales such as UTC(USNO), UTC(NIST), UTC(Lab_X)

All are Atomic Time, as they all get time from atomic oscillations

What is Clock Steering?

Usually, adjusting the rate of a clock to bring its phase (time) or frequency closer to a reference clock.

But one can also step the clock in time (phase), or accelerate it by changing the frequency's rate of change

Steering Definitions

Synchronization

Alignment of two sources of time

Syntonization

Alignment of two sources of frequency

Equivalent to

Alignment of two sources of time,
except for unknown calibration bias

Why do we steer clocks?

To create synchrony and syntony.

For most communication applications, syntony is all that is required.

For navigation and GPS synchrony is crucial, yet asyntony results in asynchrony

Omnipresence of Steering

TAI = EAL + frequency steers to primary frequency standards

(calibrated to meet definition of the second)

(EAL = ave of >200 clocks, including USNO's)

UTC = TAI + leap seconds

(crude steers, in phase, to Earth's rotation)

UTC(k) = TA(k) + steers to UTC = realization of UTC by laboratory k

(TA(k) = ave of Lab_k's clocks)

GPS* = Unsteered GPS clocks + steers to UTC(USNO) [in acceleration]

(Composite Clock= implicit average of steered satellite and monitor station clocks)

Telephone's Time = crystal + steers to UTC(k) or GPS*

Atomic Clock's time = clock's crystal + steers to atomic frequencies

(GPS* denotes GPS Time with leap seconds added)

Proportional Steering (similar to PID Steering)

Change frequency of clock by:

G_X times its Time Offset

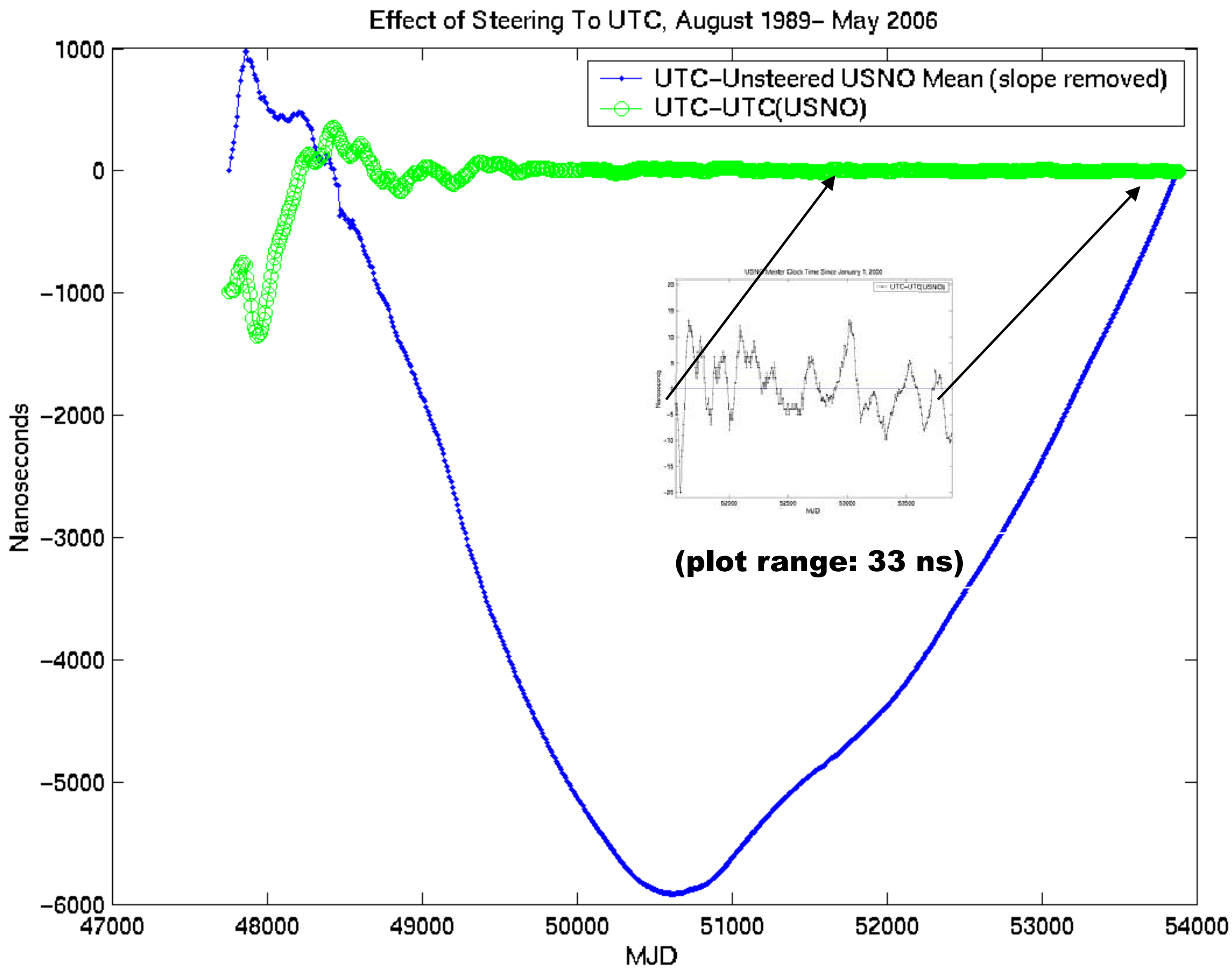
+ G_Y times its Frequency Offset

ALL steering involves a trade-off between frequency stability, time stability, and control effort. For proportional steering, Linear Quadratic Gaussian (LQG) theory can compute the optimal gains (G_X and G_Y) for your stability goals.

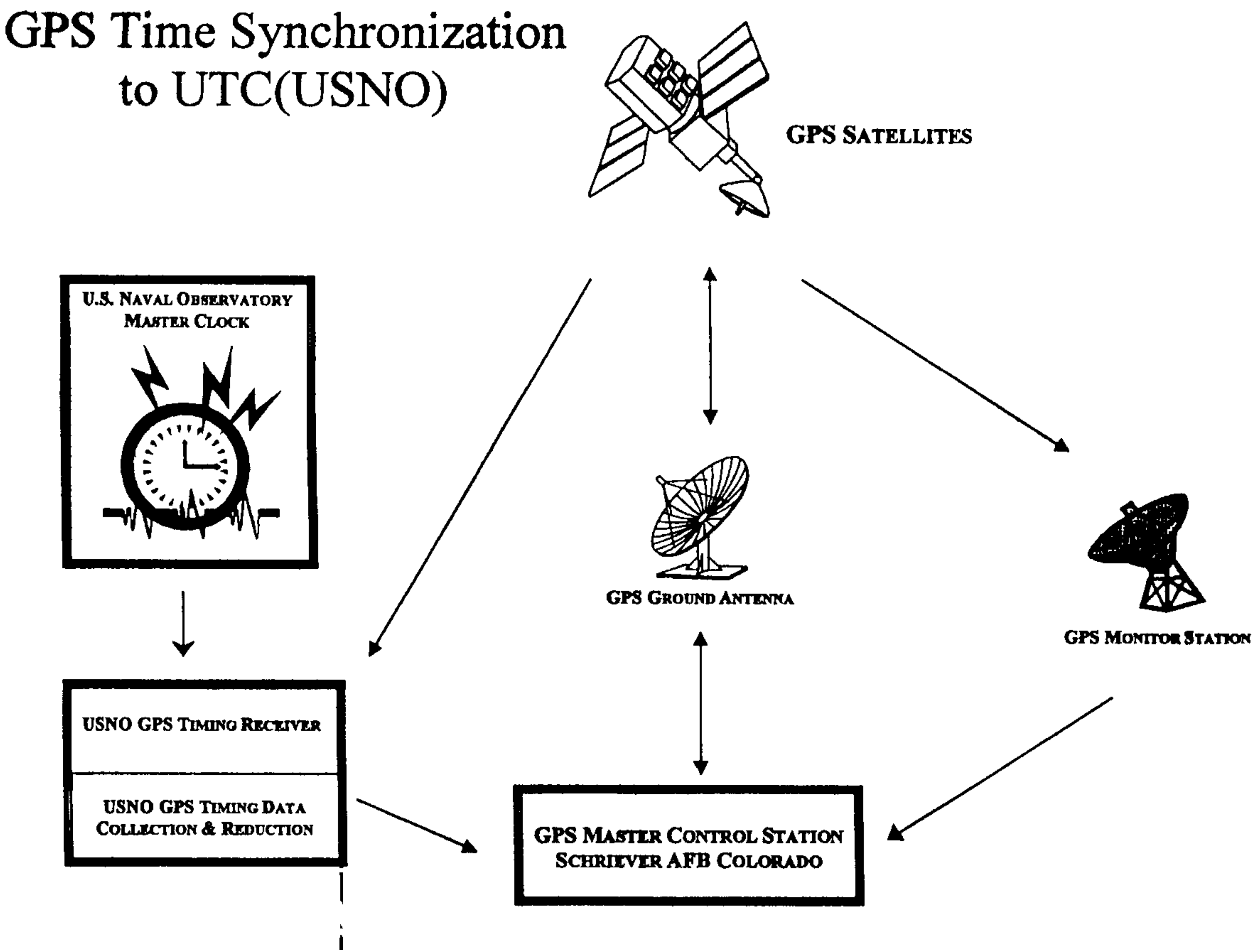
See Koppang and Leland, 1999, IEEEE Trans. Ultrason. Ferroelect., Freq. Control 46, pp 517-522.

See also Appendix IV.

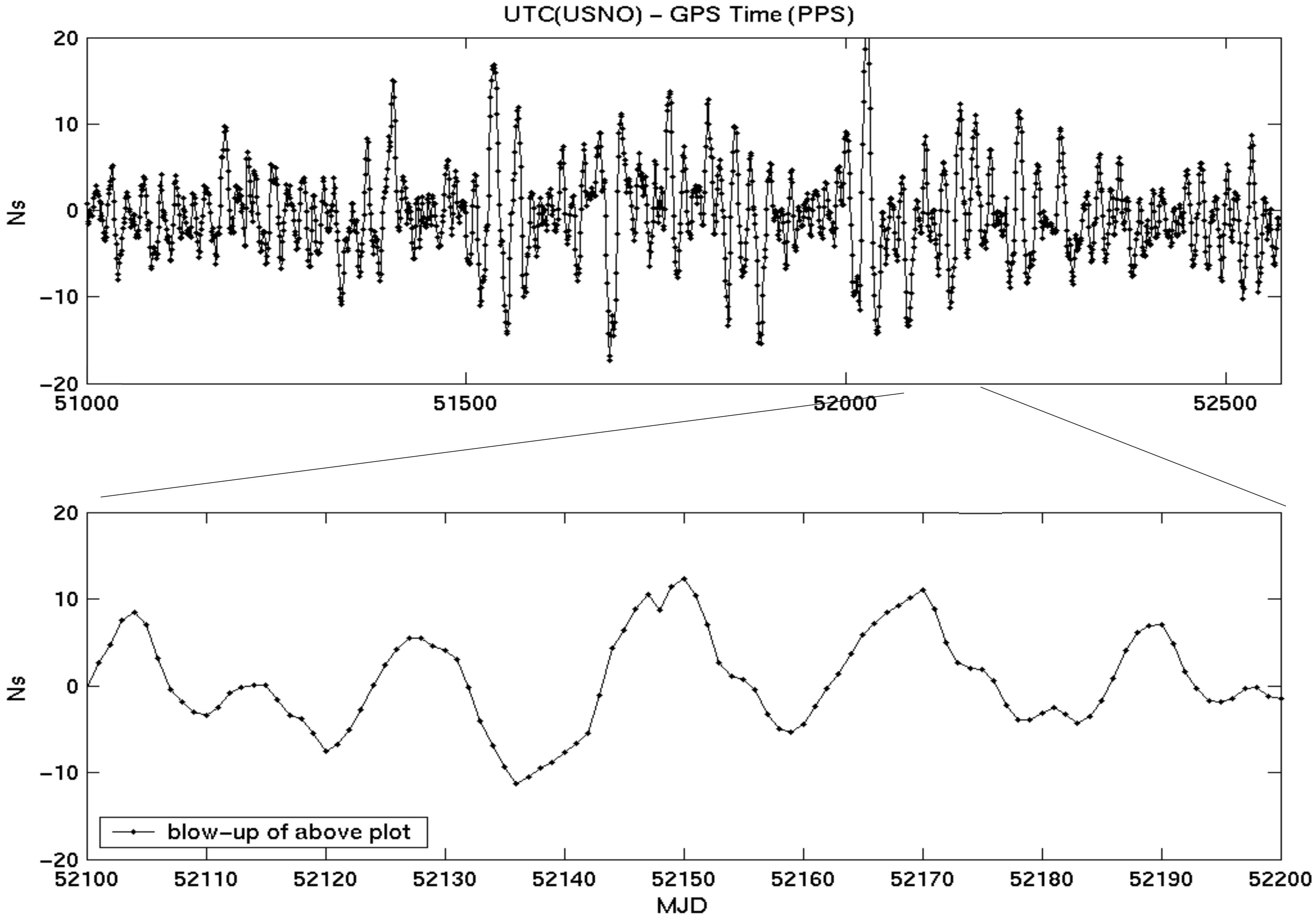
Improvement Due to Steering



GPS Time Management/Steering

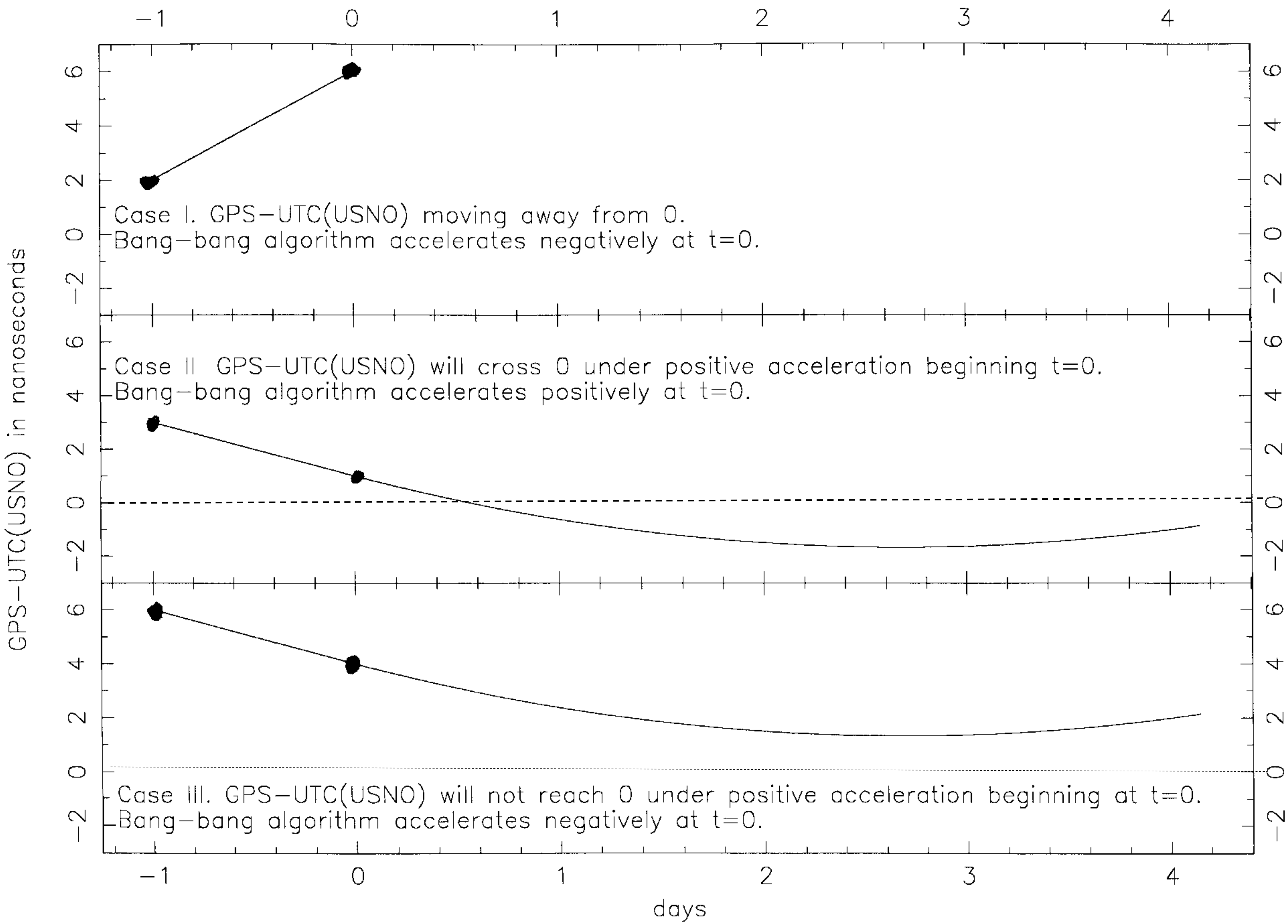


GPS Time As Measured, modulo 1 sec



Broadcast Corrections to Correct to UTC(USNO) improve performance to almost 1 ns RMS.

GPS "Bang-bang": 3 examples



Time Transfer

Definition: The comparison of two sources of time.

Terminology: Clock (A) - Clock (B)

+ Value: Clock (A) is ahead of Clock (B)

- Value: Clock (B) is ahead of Clock (A)

Frequency Transfer

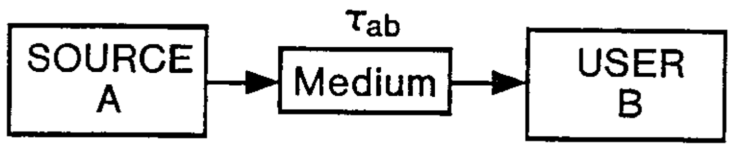
Definition: The relative change in time between two time sources.

$$[(Clk(A) - Clk(B))_{T2} - (Clk(A) - Clk(B))_{T1}]/(T2 - T1)$$

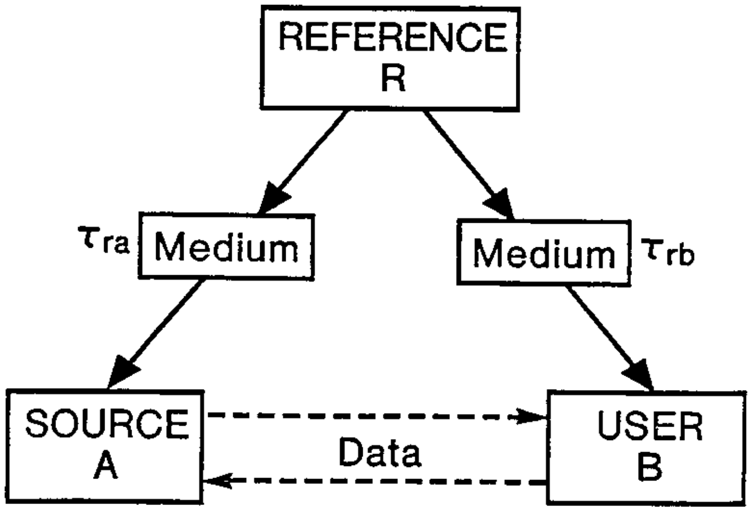
+ Value: Clk(A) is higher in frequency than Clk(B)

- Value: Clk(B) is higher in frequency than Clk(A)

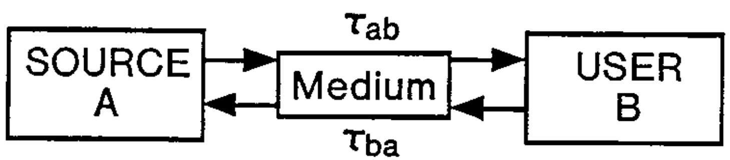
The medium should not be the message …



a) One-Way Time Transfer



b) Common-View Time Transfer



c) Two-Way Time Transfer

Time Balls

Operational for USNO: 1845 - 1936

Ceremonial at USNO: 2000 - ?

Telephone Time Transfer

I. Voice Announcers: 1 second at best

- – human response time a factor

II. Modems: As good as 1 ms, provided

- – Sender's system delay subtracted (USNO's delay is 1.7 +- .4 ms)
- – Can use remote loopback feature to measure line delay
- – No satellite connection (would add about .25 seconds)

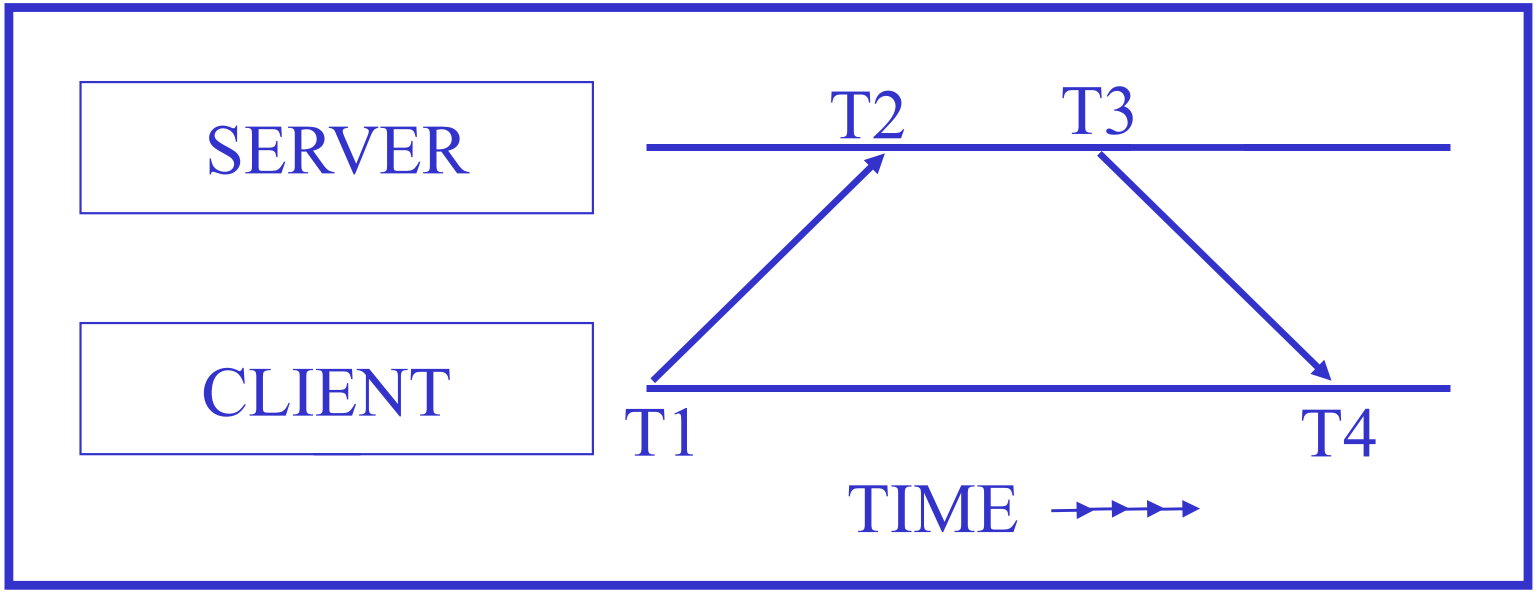
Network Time Protocol (NTP)

- Computer to Computer Time Transfer
  - via LAN or Internet

- Server synchronized to UTC (USNO) via GPS receiver, or to UTC (NIST) via modem, or directly to any realization of UTC

- User sends NTP signal to server, analyzes response to get time
  - Limited by non-reciprocity in path
  - If over LAN: <1 msec
  - If over Internet: 1-100 msec
    - Gets worse as number of hops increases
    - Vagaries of internet routing can result in long-lasting biases
    - Transoceanic can be much worse if go by wildly different routes

NTP Assumes Reciprocity



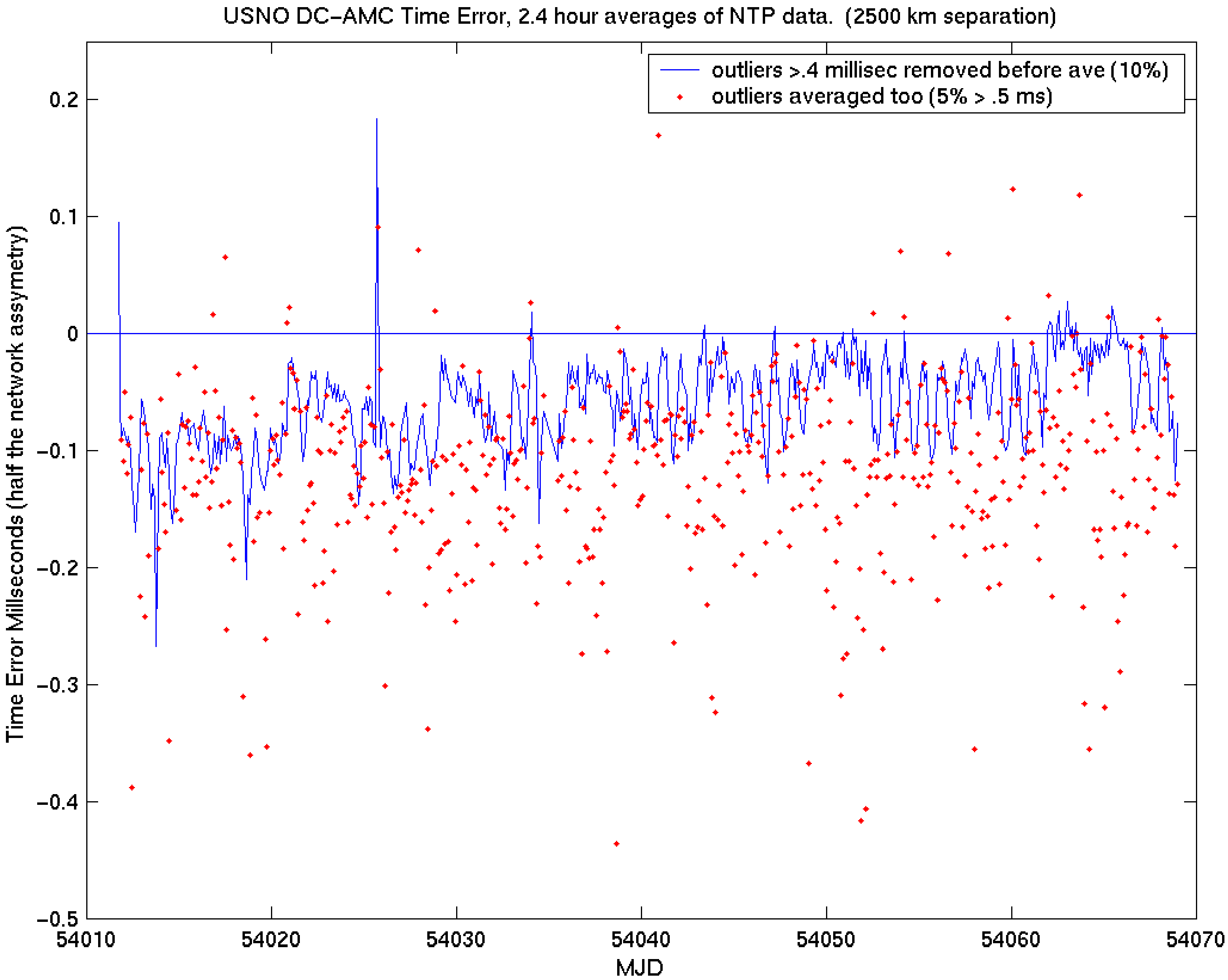
network delay:

$$\delta = (T_4 - T_1) - (T_3 - T_2)$$

clock offset:

$$\Theta = \frac{(T_2 - T_1) + (T_3 - T_4)}{2}$$

NTP: Illustrative Data



NTP Applications

- Millions of direct users
  - Such as your children and the White House
  - Unknown number of secondary users
- Some uses and applications of NTP
  - LAN networks – monitoring, control, database
  - Teleconferencing, radio and TV programming
  - Bank and stock market computers
  - Encryption
  - Time-stamping for patents, etc.
  - Interactive simulation
  - Electrical power grid synchronization

IEEE 1588, "Improved NTP"

- Intended for small networks
- Fixed packet size,
- Keeps time-transfer processes at physical layer
- Each server sets its clock to that of closest server
- Only one route between servers
  - reciprocity is assured
  - impedes internet-wide applications
- Much greater precision: 20-100 ns
- Under development: http://ieee1588.nist.gov
- Large-network analog being initiated
  - See http://www.dspcsp.com/tictoc

One-way Earth-based Radio Broadcasts

I. Low-Frequency (code only)

WWVB (NIST)

60 kHz

Accuracy: 500 microsec if known location

Precision: 1 microsec

LORAN (U.S. Coast Guard)

100kHz

No time tags*

Use Time of Coincidence

Accuracy: <300 ns*

Precision: 100 ns*

Limited by weather patterns*

* E-Loran would have enhanced

Terminated Feb. 8, 2010

II. High-Frequency (code & voice)

WWV and WWVH (NIST)

CHU (Canada)

2.5-20 MHz

Accuracy: a few milliseconds

Limited by number of ionospheric hops in travel path

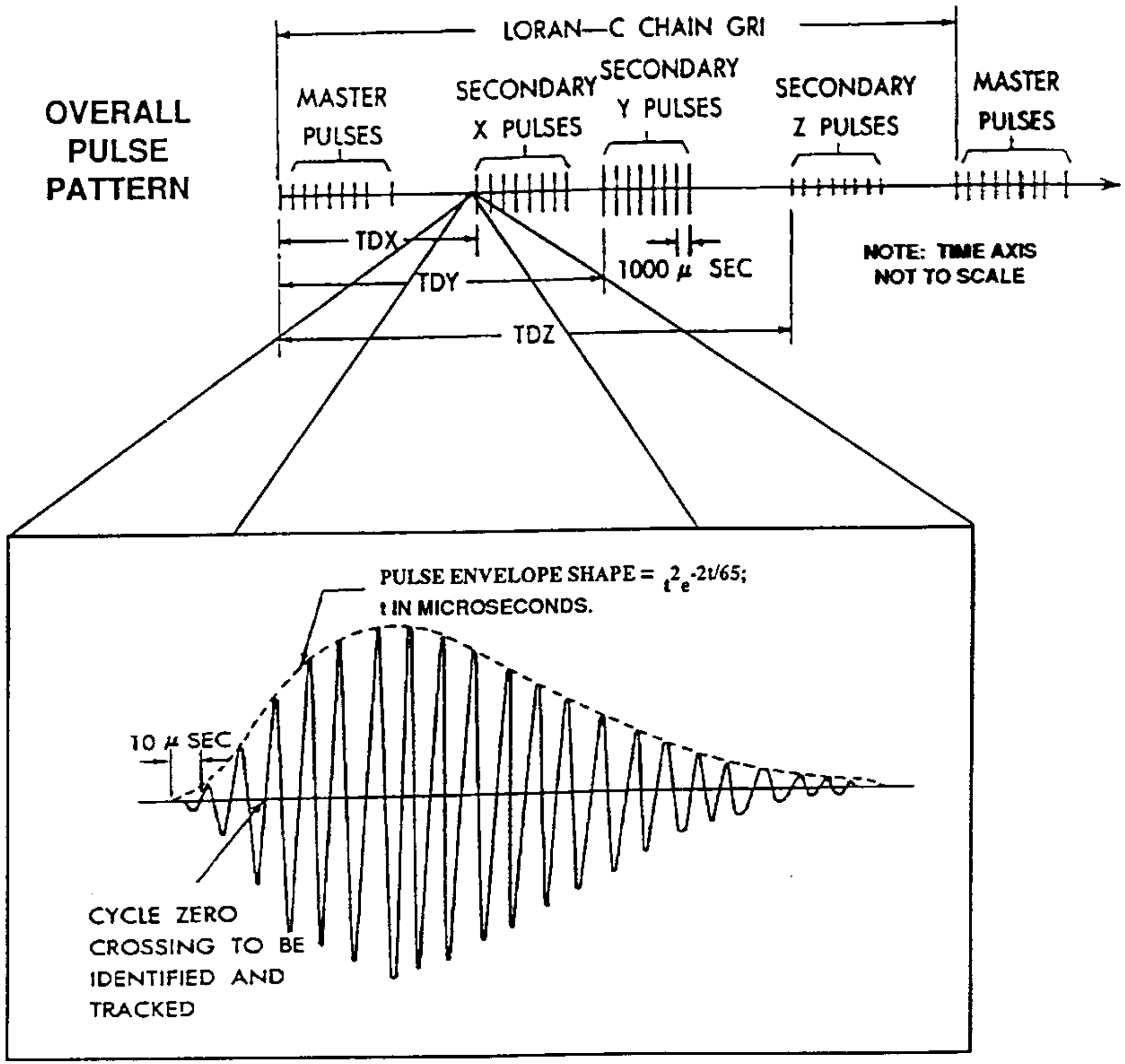
III. European and Asian Services

DCF77 (Germany)

77.5 kHz

http://www.ptb.de/en/org/4/44/442/dcf77_1_e.htm

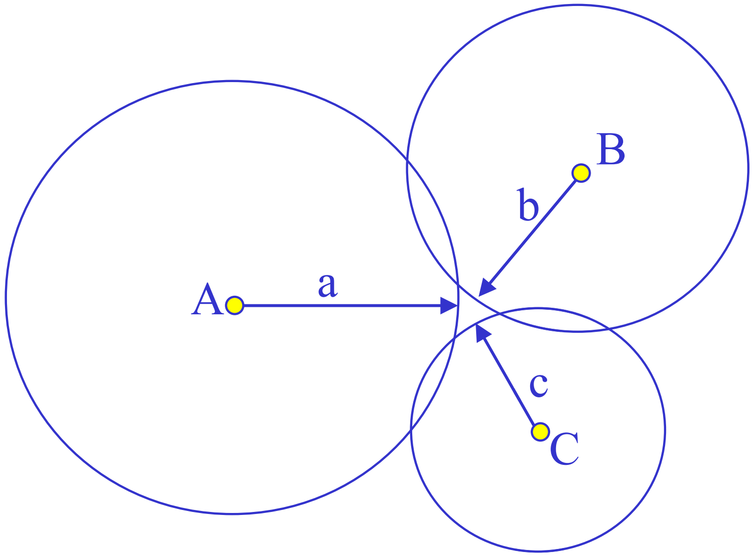
Detailed View Of Individual Loran Pulse



Enhanced Loran

- LORAN shut down in USA on February 8, 2010
  - Formal cut off was supposed to be end of 2000
- Better clocks at transmitters
- All-in-view rather than chain concept
- Users can have H-field (static free) antennas
- Broadcasts GPS corrections
- Broadcasts time directly
- Broadcasts more refined Loran corrections

Time is at the Core of GPS



GPS receivers measure distance from satellites A, B, and C by the pseudoranges a, b, and c. Pseudoranges are measured as travel times, and converted to distances.

If the receiver is at known position and calibrated, time can be obtained from observing one satellite.

If the receiver's time is known and its timing delays are calibrated, its antenna's position is at the intersection of spheres centered on the satellites with radii a, b, and c.

If the receiver's time and position are not known, they can be inferred from observations of four satellites - but the time offset must be calibrated.

GPS Timing Receivers

- Extract either UTC (USNO) or GPS Time
  - GPS Time is for navigational solutions only and does not include leap seconds
    - Users who mistake GPS time with UTC sometimes think their receiver is off by 10’s of seconds.
- Time Comparison: 2 ways
  1. Receiver’s internal time interval counter

     (You input your own signal, it compares)
  2. Receiver’s output 1-PPS signal

     (You compare to your own signal, externally)

Receiver Calibration: 2 ways

1. Absolute Calibration

2. Relative Calibration

Absolute Calibration

Determine Receiver Component Delays

- antenna delay
- antenna cable delay
- receiver internal delays
- delays to any external measurement systems

Calibrated GPS Simulator Required

Relative Calibration

Determine correction relative to a standard receiver through "side-by-side" comparisons

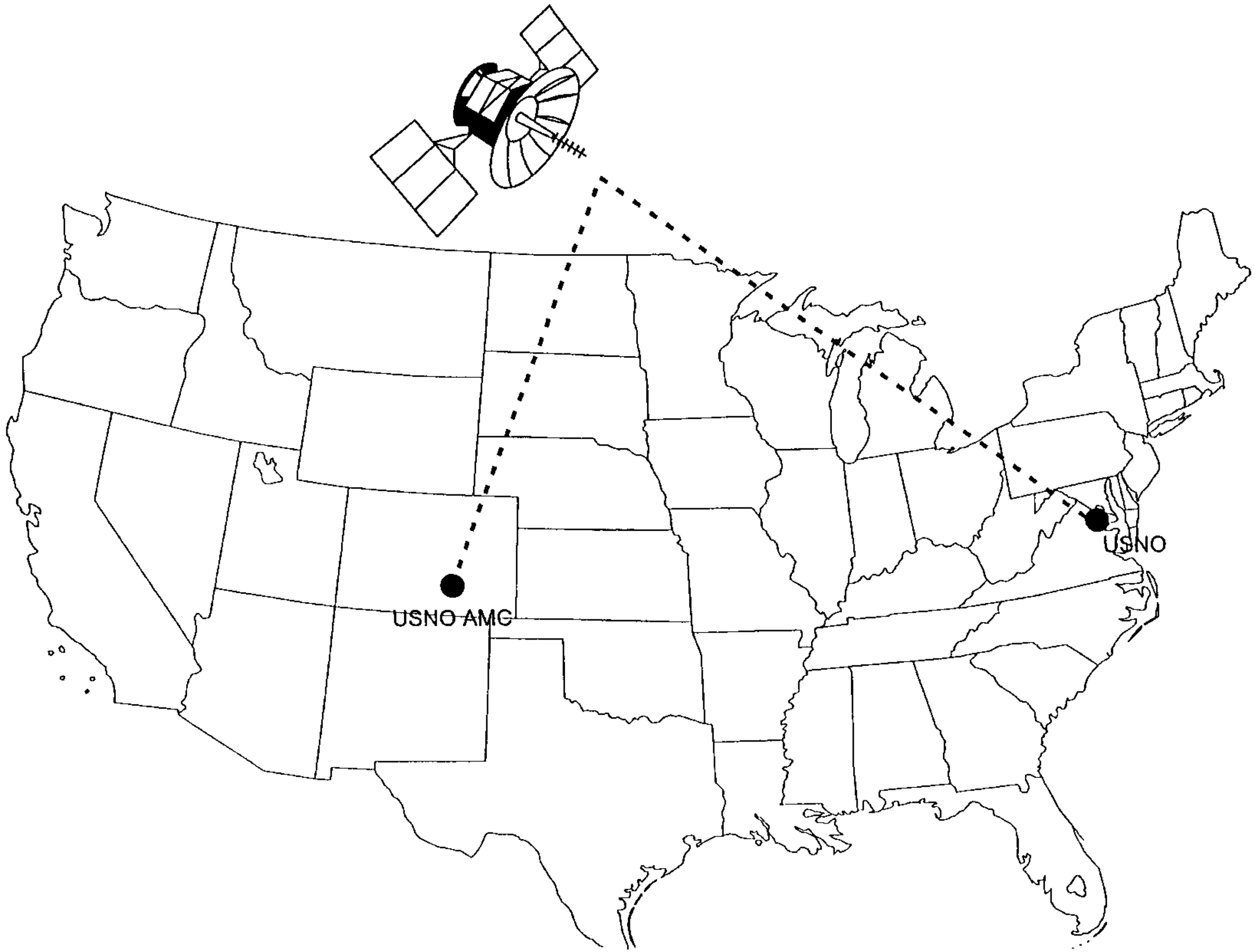
Relative Calibration

- Common clock
- Common antenna, or precise antenna coordinates
- Track same satellites with both receivers

Time Transfer via GPS

- Direct Access
  - Observe time directly off GPS code
  - Best to average over satellites
- Melting Pot or All-in-View
  - Average over satellites and/or time to obtain GPS-Clock
  - ClockA - ClockB = (GPS - ClockB) - (GPS - ClockA)
- Common View
  - Averages difference with individual satellites instead of differencing the average of individual satellites
  - ClockA - ClockB = AVE{(Sat_i - ClockB)-(Sat_i - ClockA)}

GPS Common-View



Some Sources of Error

Multipath

Calibration

Environment (temp, humidity, etc.)

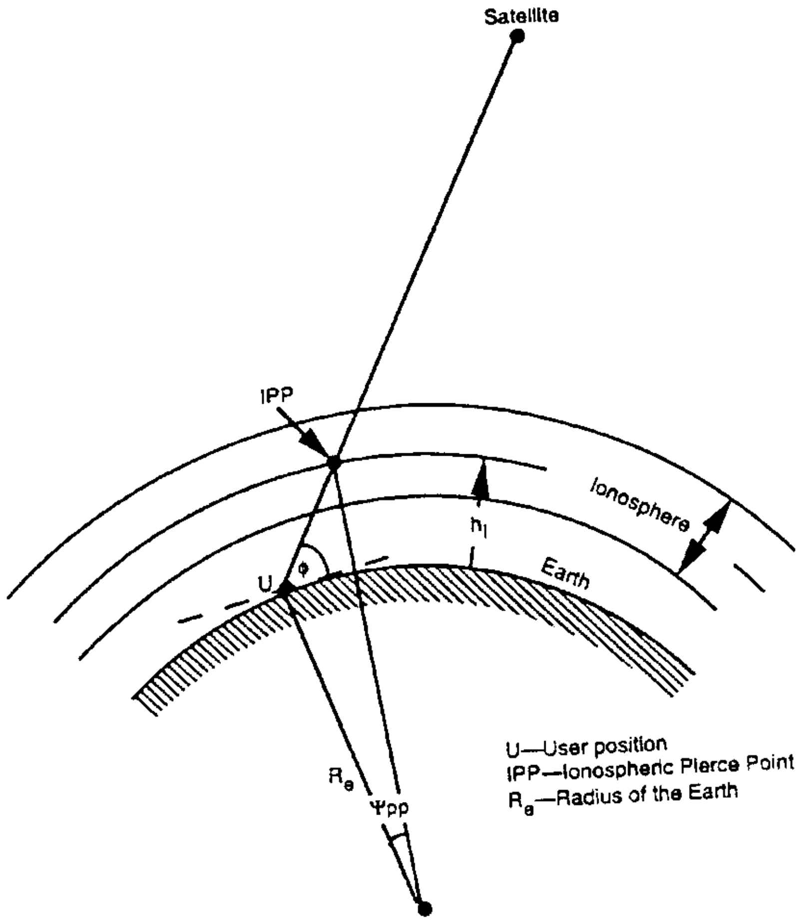
Ionosphere & Troposphere Corrections

Antenna position

Satellite clock errors

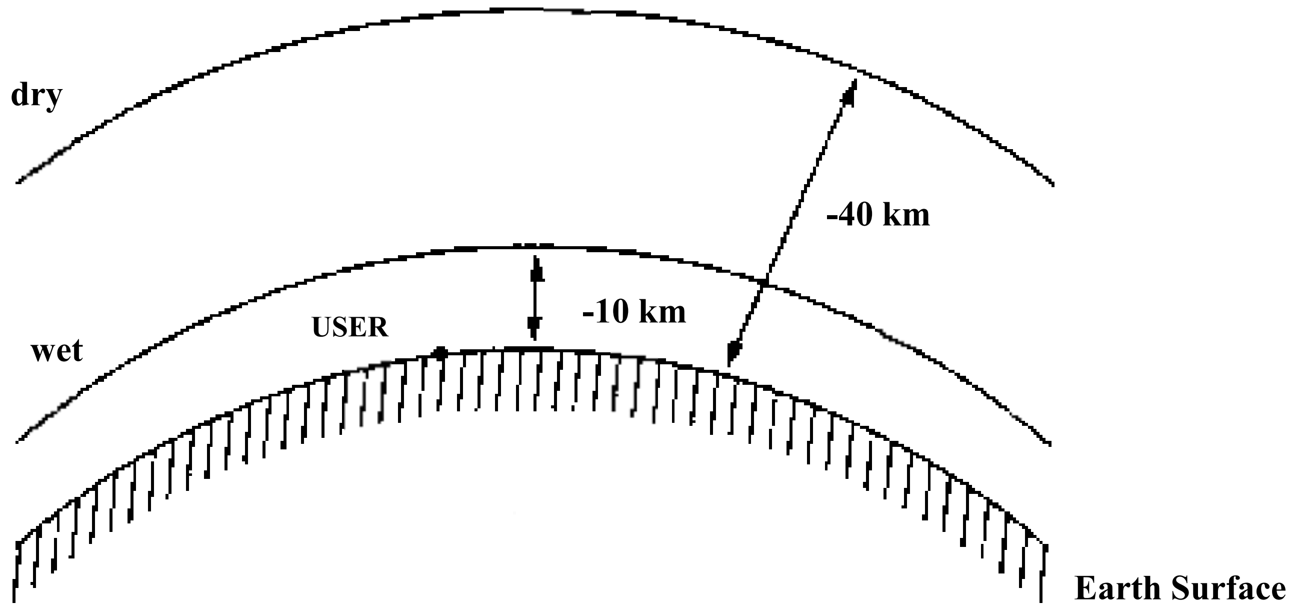
Satellite position (orbit) errors

Ionospheric Modeling Geometry



- Highly variable
  - 11-year cycle
  - Much less at night
  - Latitude (and longitude) dependant
  - Stronger at low satellite elevation
- Klobuchar model (broadcast)
  - ballpark accuracy: 10 ns
- Wavelength-dependent (L1 vs. L2)
  - Allows very exact removal
  - If you have two-frequency data
  - Civilians will shortly have two-frequency data from L5
  - Carrier phase techniques can infer

Dry and Wet Components of the Troposphere



6.6 nanoseconds vertical delay, on average. Stronger at low elevations

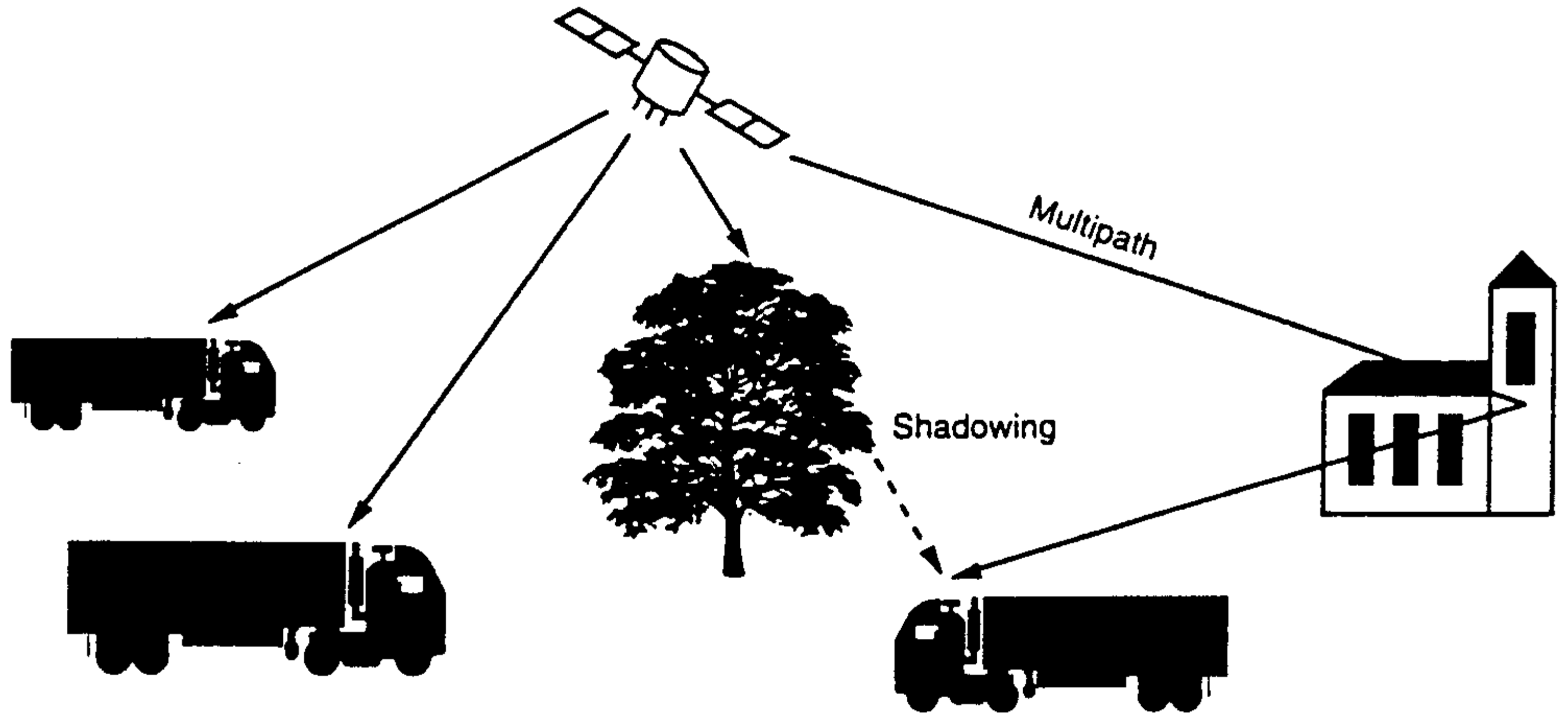
90% due to nitrogen, proportional to ground pressure.

10% due to water, not proportional to ground humidity and anti-correlated with ground pressure. Can fit using elevation dependence.

Price of mismodeled atmosphere and/or ionosphere:

- You will get the wrong time and the wrong position, and the error will be systematic
- The position offset will mostly be in the vertical direction (if you observe GPS satellites evenly over the sky).

Multipath

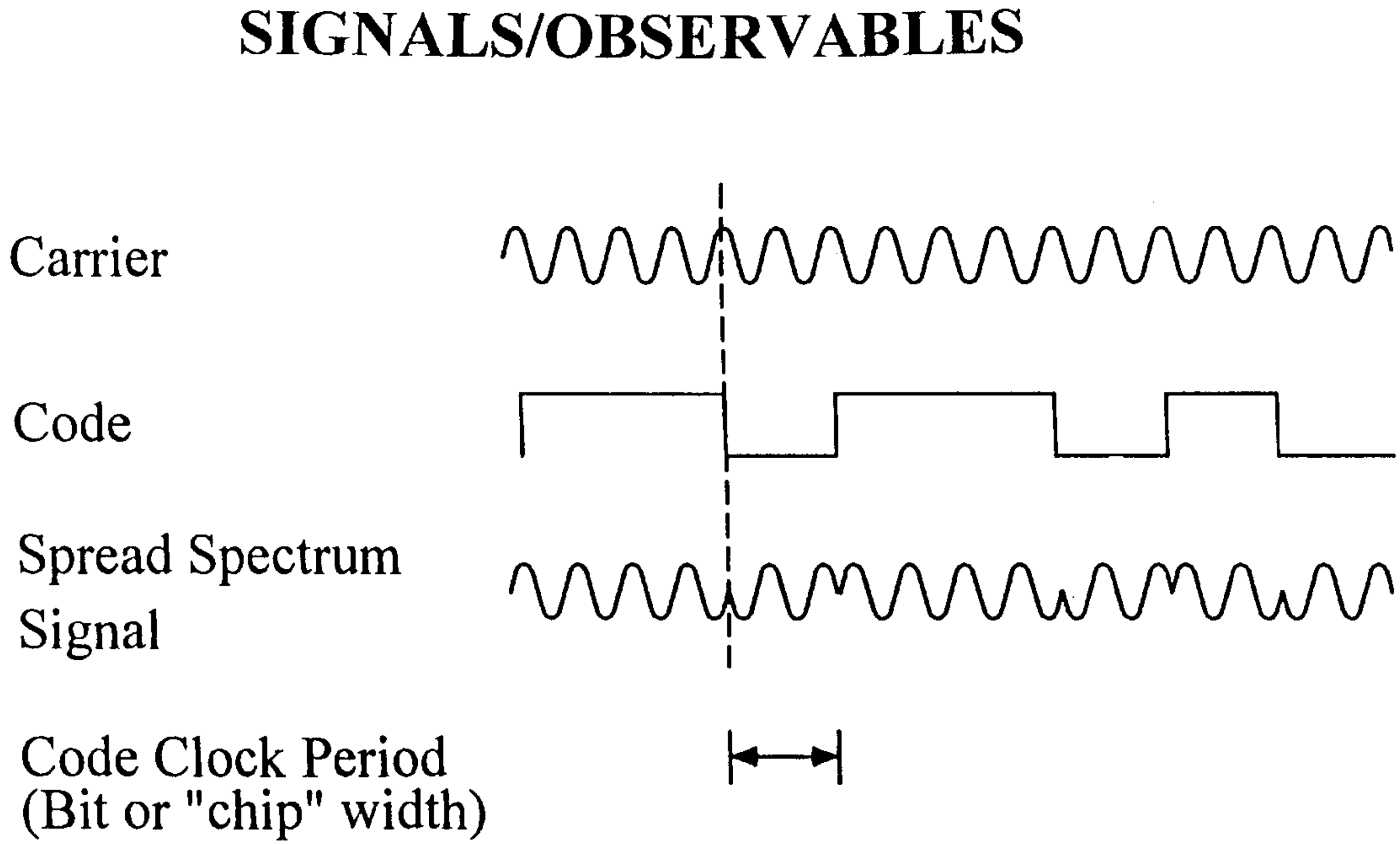


Multipath

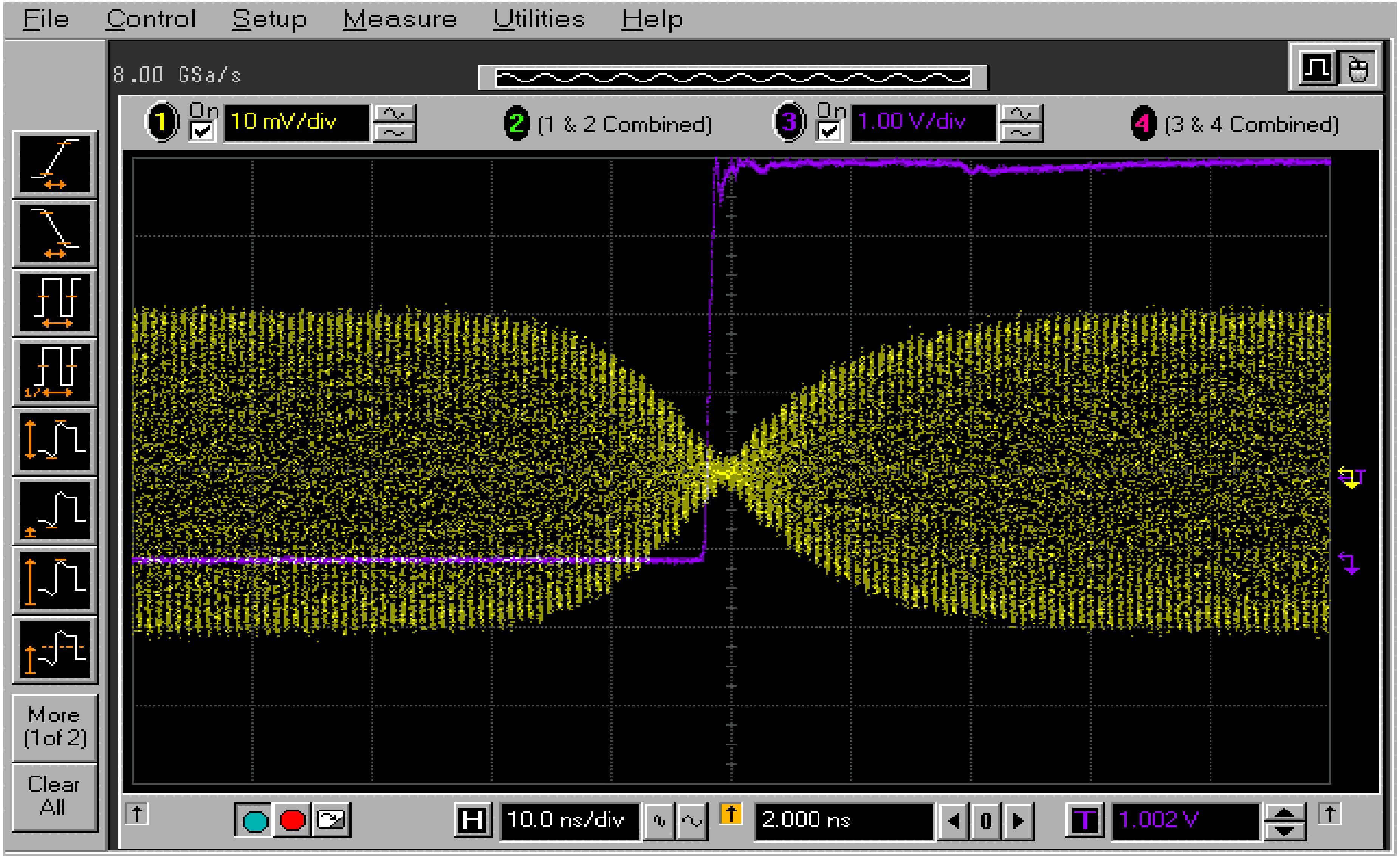
- Optimal antenna location:
  - ground level
  - empty parking lot
- Receivers have rejection algorithms
- Affects code more than phase
- Actually helps in urban canyons!

  "better late than never"

GPS Carrier-Phase

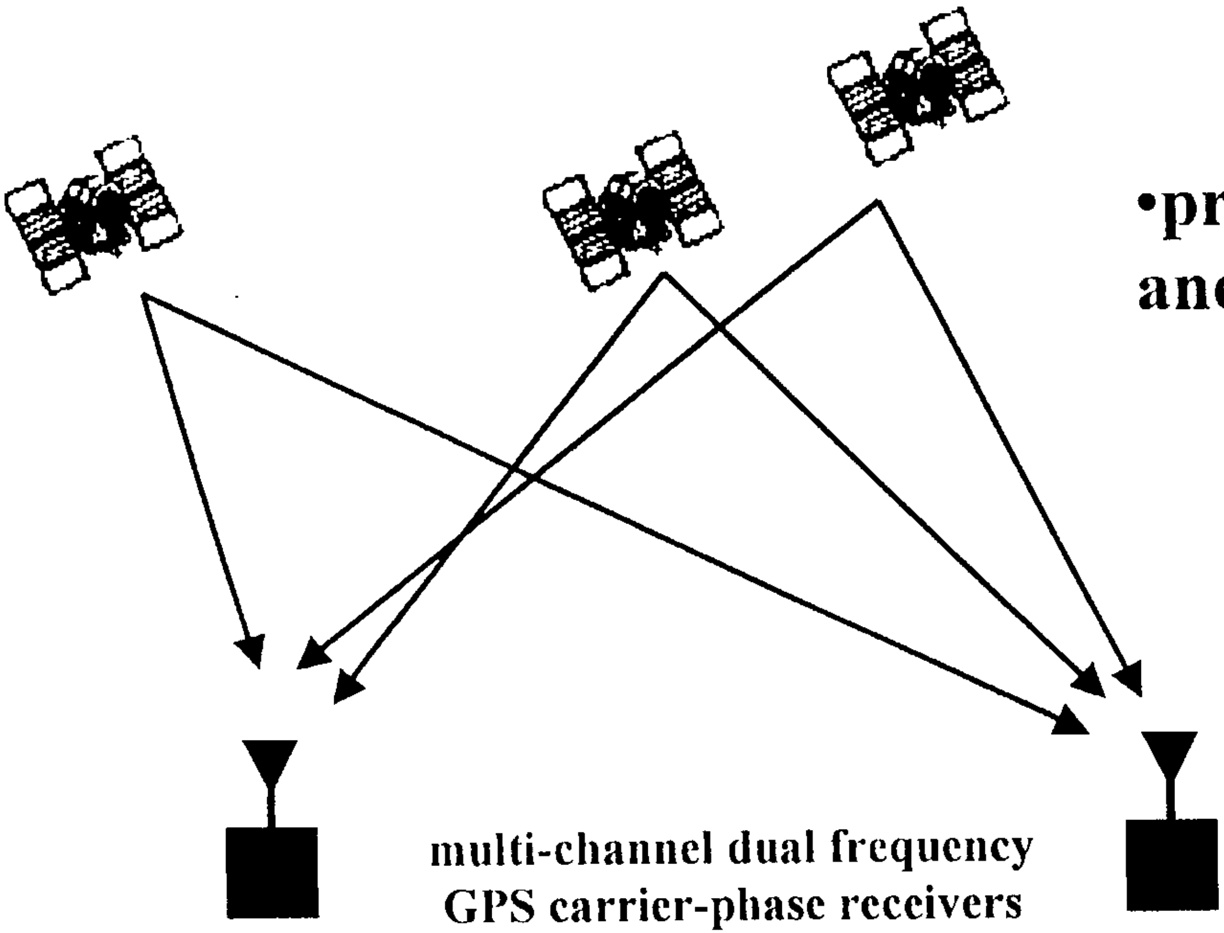


GPS C/A Code Transition



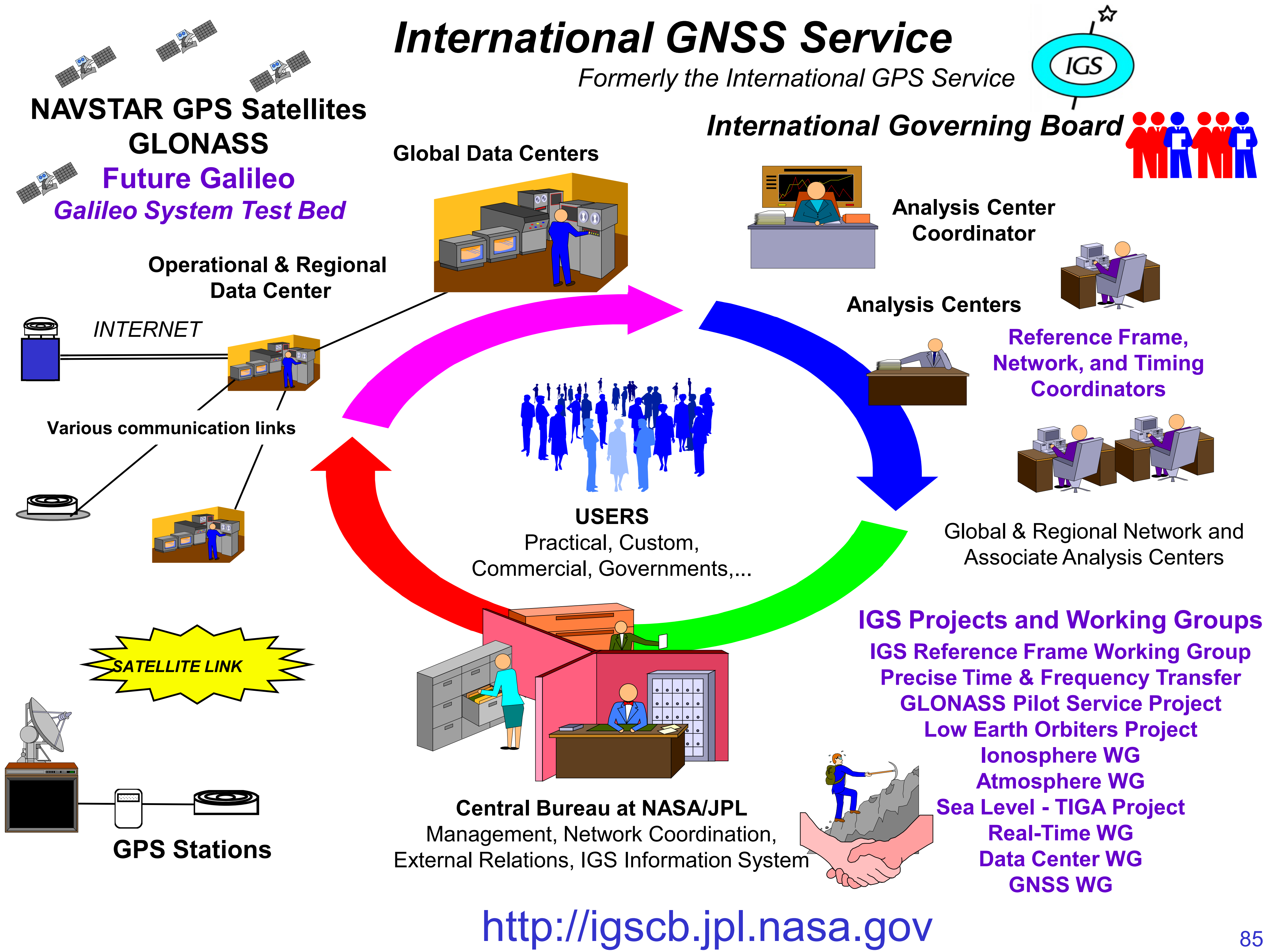
Source: Powers et al., EFTF-02

GPS Carrier-Phase Time Transfer



•precise orbits (e.g. IGS) and earth orientation

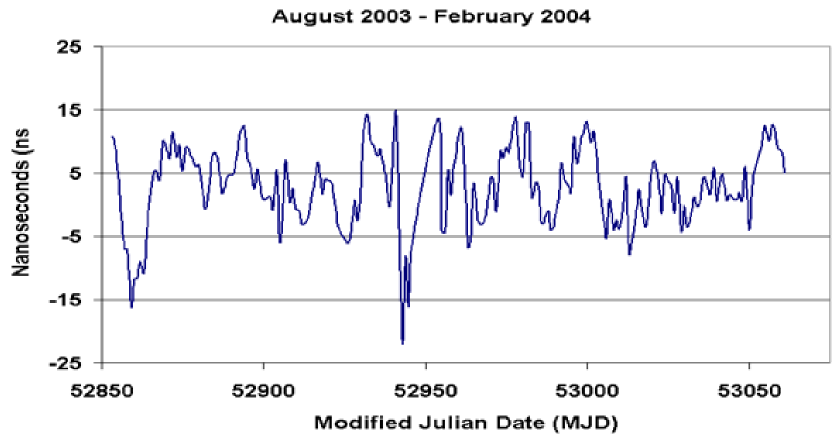
calibration ~ ??
precision ~ 10ps
accuracy < 1ns (?)


International GNSS Service
Formerly the International GPS Service
IGS
International Governing Board
NAVSTAR GPS Satellites
GLONASS
Future Galileo
Galileo System Test Bed
Global Data Centers
Analysis Center
Coordinator
Operational & Regional
Data Center
INTERNET
Analysis Centers
Reference Frame,
Network, and Timing
Coordinators
Various communication links
USERS
Practical, Custom,
Commercial, Governments,...
Global & Regional Network and
Associate Analysis Centers
IGS Projects and Working Groups
IGS Reference Frame Working Group
Precise Time & Frequency Transfer
GLONASS Pilot Service Project
Low Earth Orbiters Project
Ionosphere WG
Atmosphere WG
Sea Level - TIGA Project
Real-Time WG
Data Center WG
GNSS WG
SATELLITE LINK
GPS Stations
Central Bureau at NASA/JPL
Management, Network Coordination,
External Relations, IGS Information System
http://igscb.jpl.nasa.gov

WAAS for Time Transfer

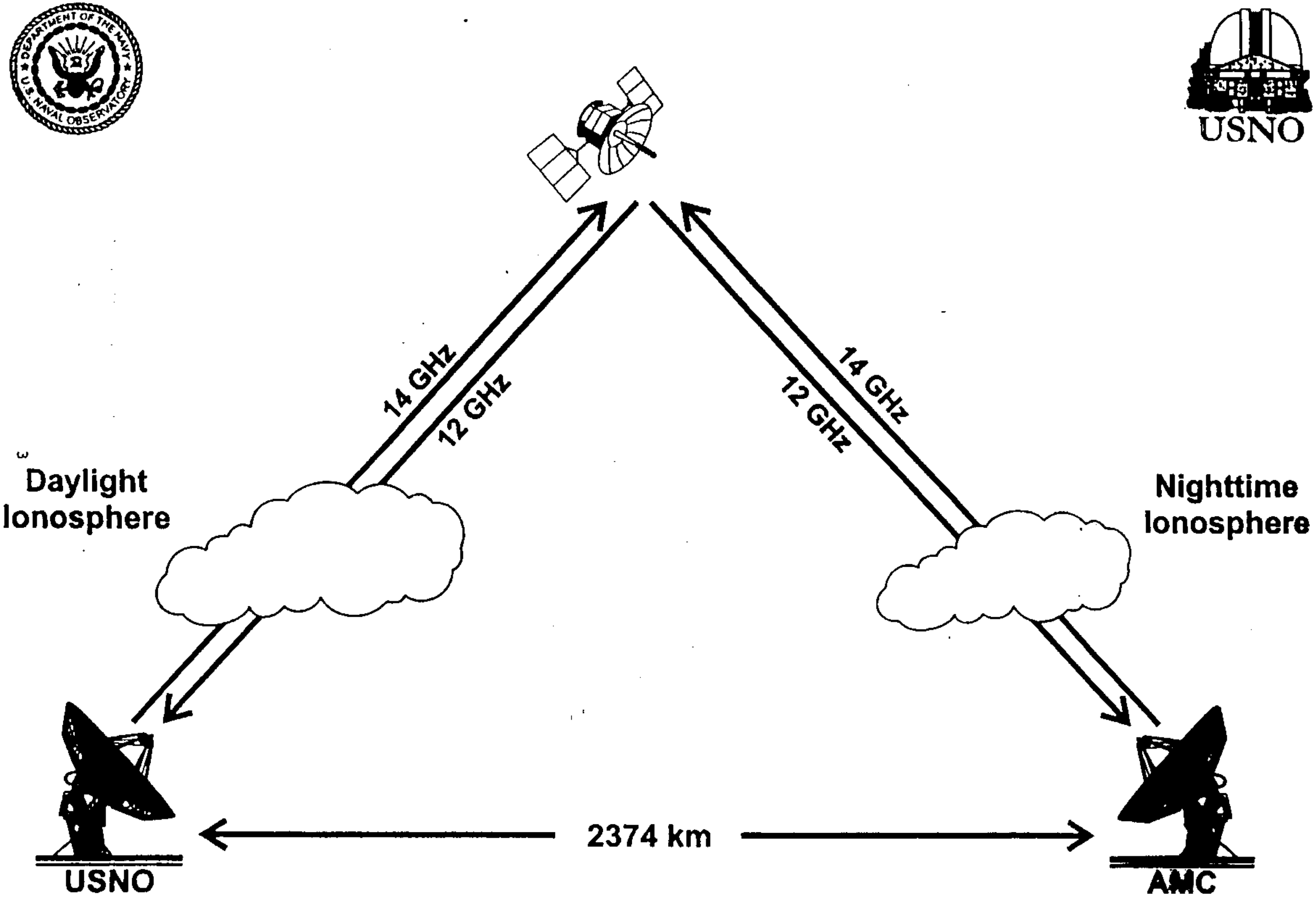
Satellites at fixed position, so

- Can use directional antenna
  - harder to jam
- Can use high-gain antenna
  - more signal to noise
- Continuous coverage
  - carrier-phase simplified
- Steered to GPS time, UTC (USNO)
  - excellent backup potential



UTC(USNO)-WAAS NT (offset removed)

Two-Way Satellite Time Transfer

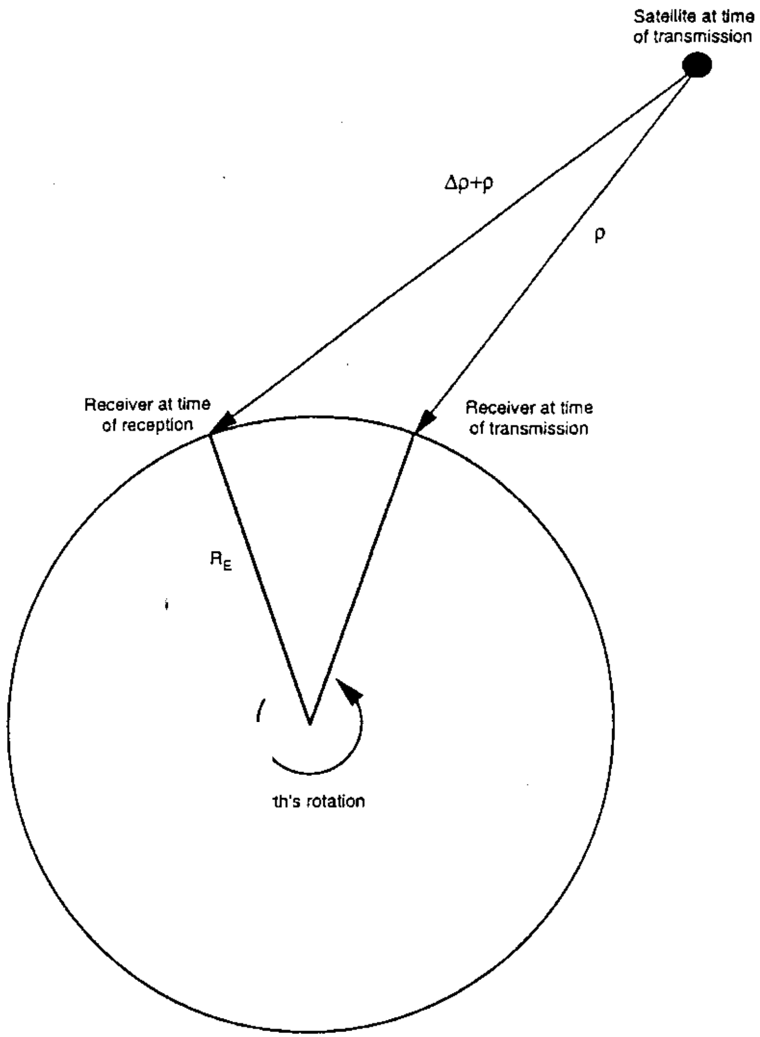


USNO Two-Way Satellite Time Transfer Earth Terminals

USNO BASE STATION ANTENNAS

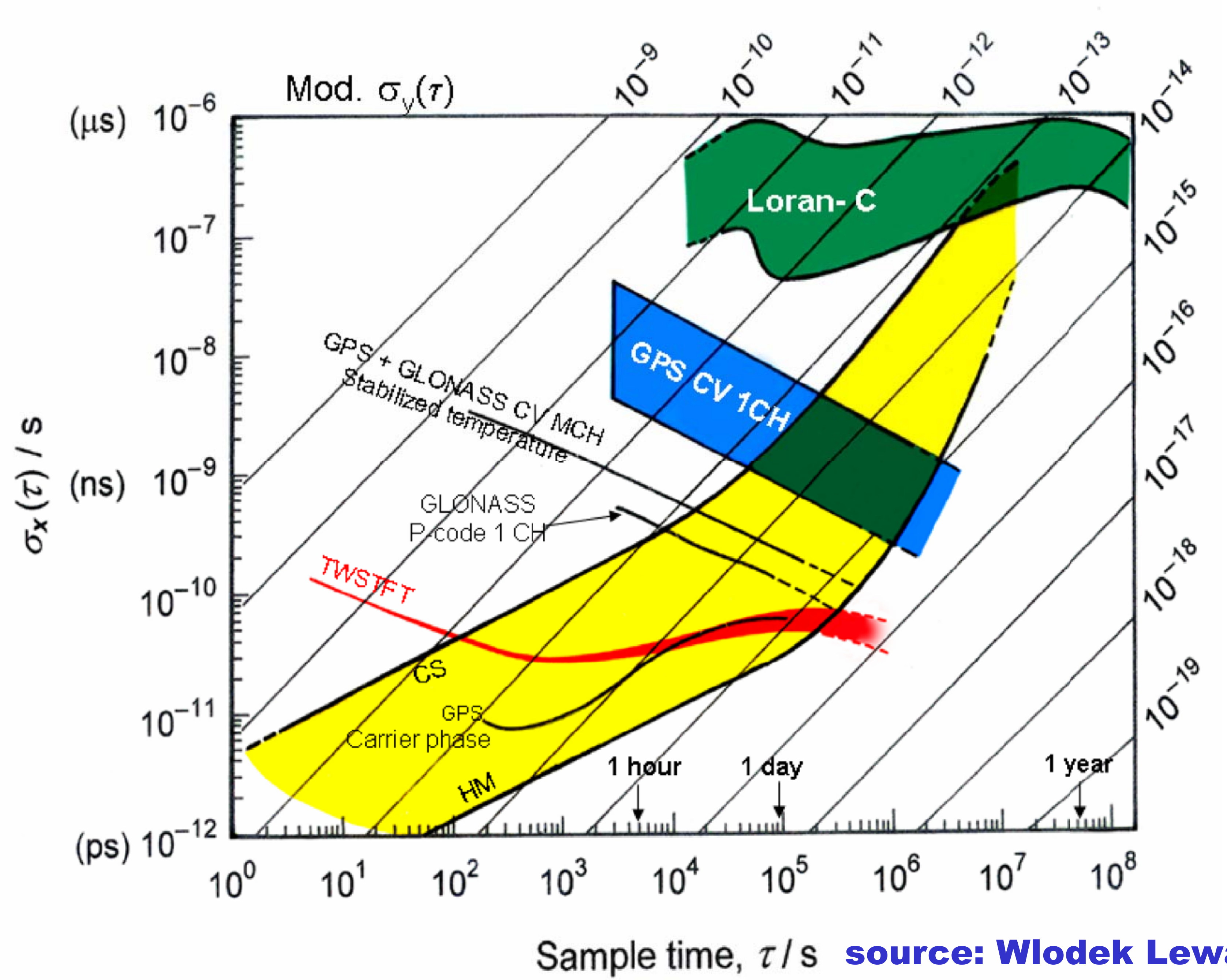
USNO MOBILE EARTH STATION

Sagnac Effect



Galilean, not "relativistic frame-dragging"

TDEV for Time Transfer Modes



source: Wlodek Lewandowski

GPS Frequency and Time Users

Communications and IT

- Cell phones and pagers
- Large bandwidth transmissions
- Network Time Protocol (NTP)
- Satellite communication systems
- Military communication systems

Surveillance

- Space debris, and worse
- Missile launches, good and bad
- Nuclear explosion detections

Science and Engineering

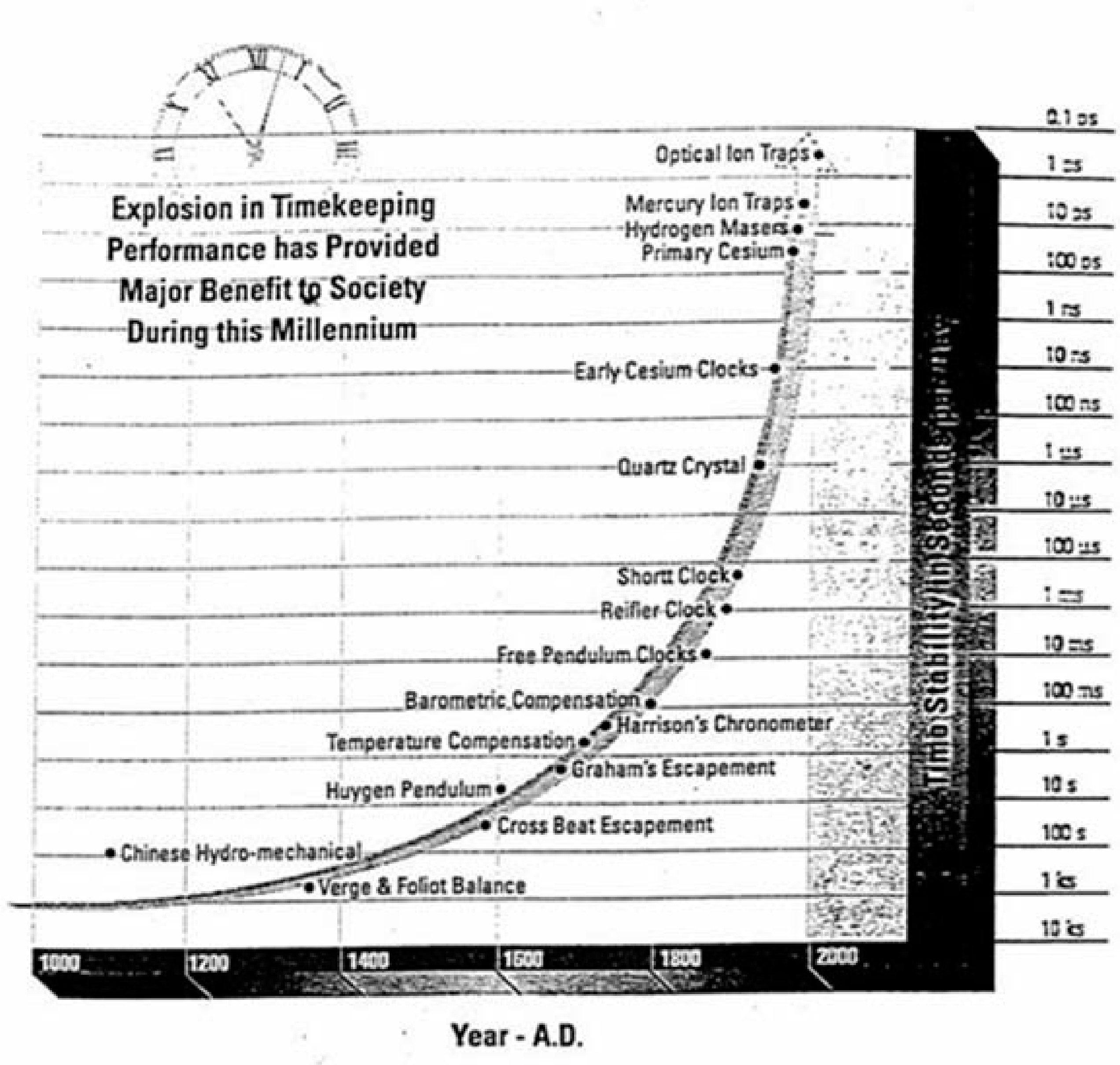
- Power Grid Synchronization
- Generation of UTC
- Very Long Baseline Interferometry
- Pulsar Observations
- Neutrino detectors
- Gravity Wave Search
- DoD and Civilian Laboratories *
- Earth rotation, UT1 *
- Ionosphere measurements *
- Troposphere measurements *

*use GPS carrier-phase data

Appendices

I. Parade of Clocks
II. Philosophy of Time (and Relativity)
III. Statistical Details
IV. Timescale Details
V. Control Theory
VI. Time Transfer Details

Appendix I: Parade of Clocks



Source: Hewlett-Packard Appl. Note 1289

Each one has a High-Tech aspect

Rotating Earth: sundials => hour angle, seasonal corrections

Water clocks: Sung Dynasty's Time Service

Spring-loaded clocks: escapements serve to regulate

Pendulum clocks: master/slave (master/disciplined oscillator)
nitrogen/air conditioning

Quartz clocks: pure crystals to resonate, temperature-controlled

Rotating Earth: stars with photographic zenith tubes
->quasars with Very Long Baseline Interferometry

Atomic Clocks

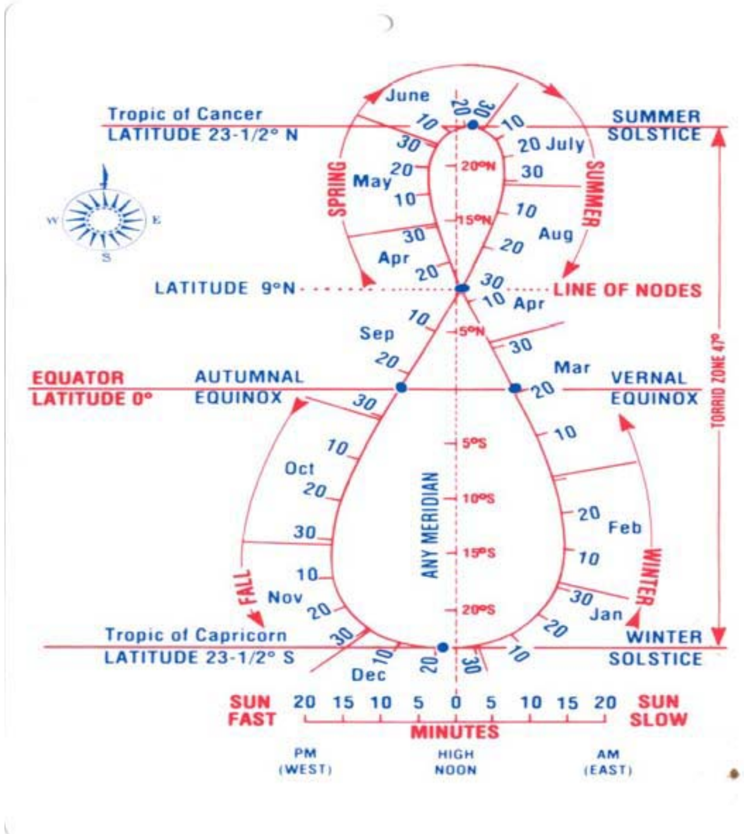
- Cesium Standards: beam tubes => fountains
- Hydrogen Masers: cavity-turned
- Trapped Ions: spherical => linear trap
  many ion => single ion => coherent few-ion
- Optical Frequency Standard
  Optical Comb

Rotating Neutron Stars (pulsars)

- pulsar => millisecond pulsar

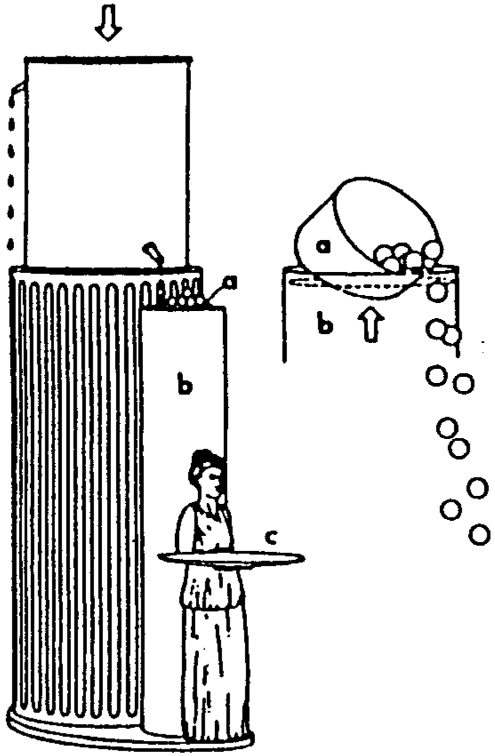
Stonehenge: ~2975 BC

Sundials can be high-tech …



- **Left Picture: Variable spacing of hour-dividers**
- **Right Picture: Analemma**
  - **Seasonal compensations for Earth's orbital eccentricity**
  - **Source: Marvin May**

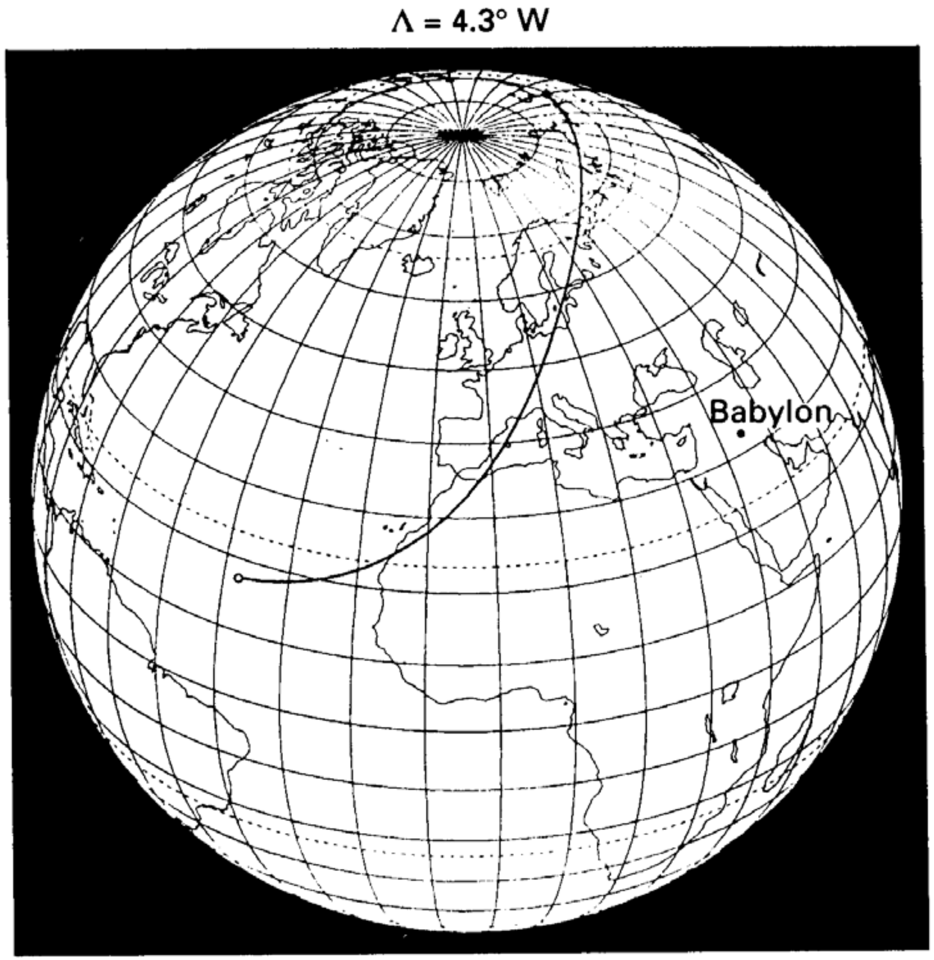
Plato’s Water-Powered Alarm Clock

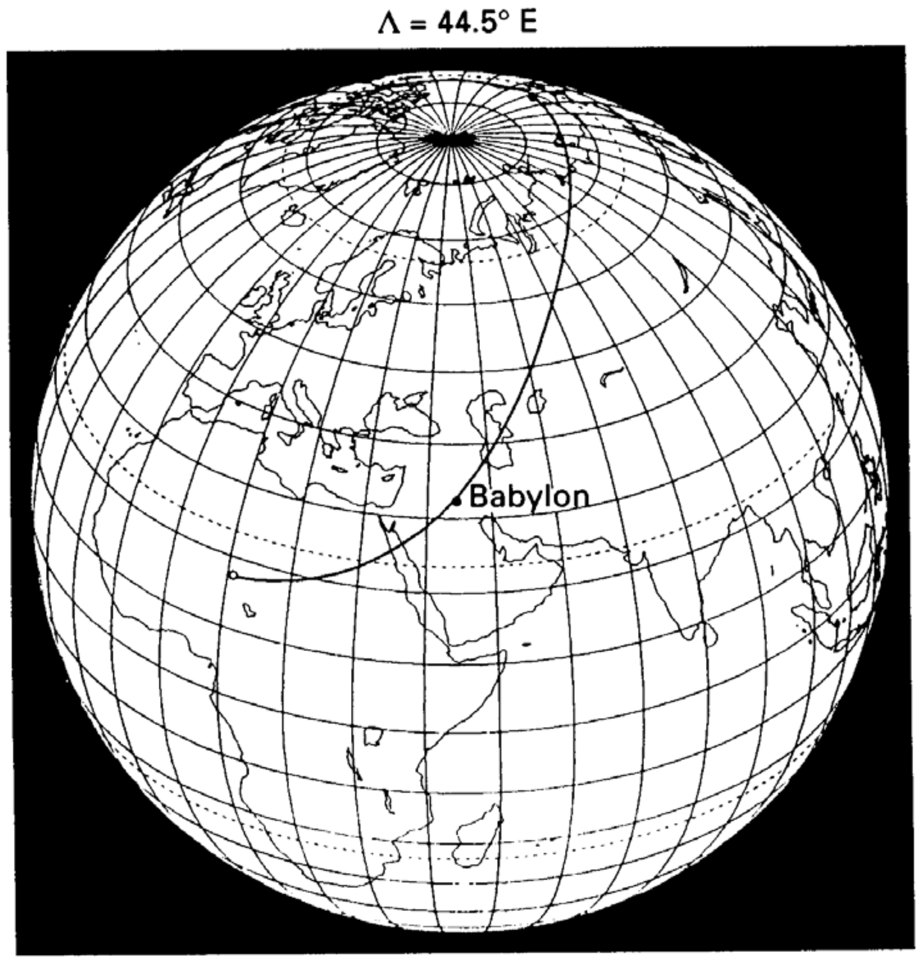


5. Plato’s inflow type water alarm clock. Water entered the (usually) graded vessel (b) at a constant rate. The vessel filled during the night. When the water reached the top, it tipped over a bowl containing lead balls (a), which was hinged to the top of the vessel. The balls then fell onto the copper platter (c) below, and woke up Plato’s students.

Source: J. Barnett, *Time’s Pendulum*, Plenum Press

Eclipse of 136 BC observed from Babylon





$\Delta T = 0$

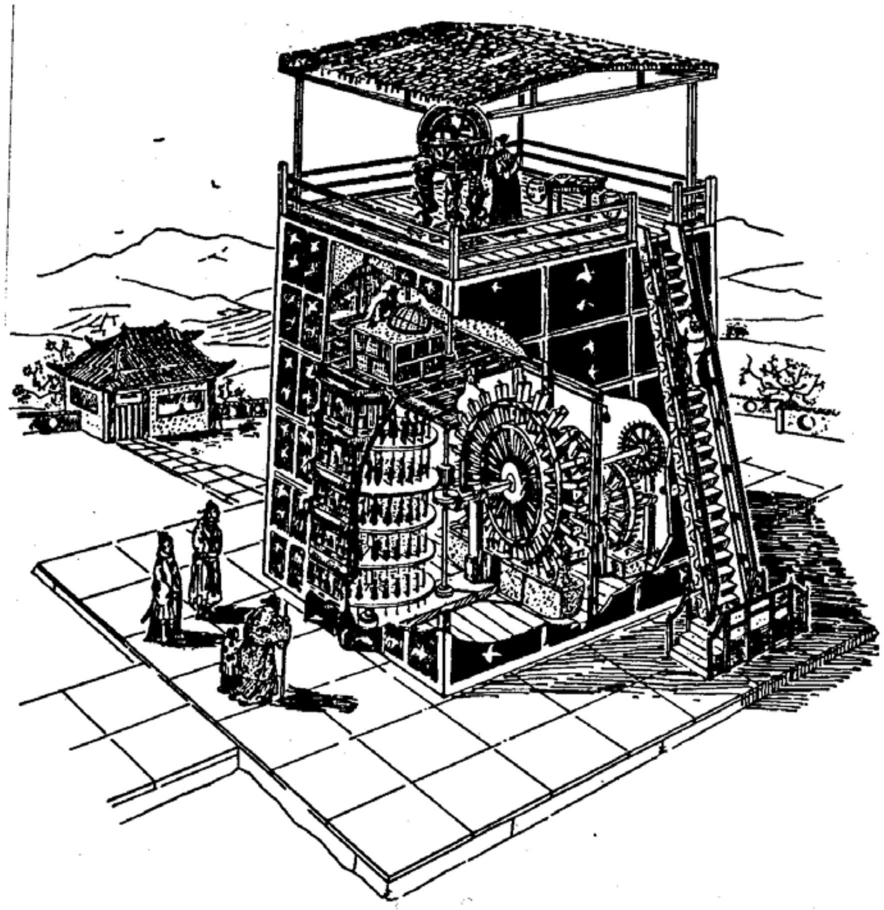
ΔT = 11 700 s = 3.25 h

Reference: F.R. Stephenson, *Historical Eclipses and Earth's Rotation* (Cambridge, 1997), p. 66

Chinese Constant-Level Water Clocks

Display at National Time Service Center, China

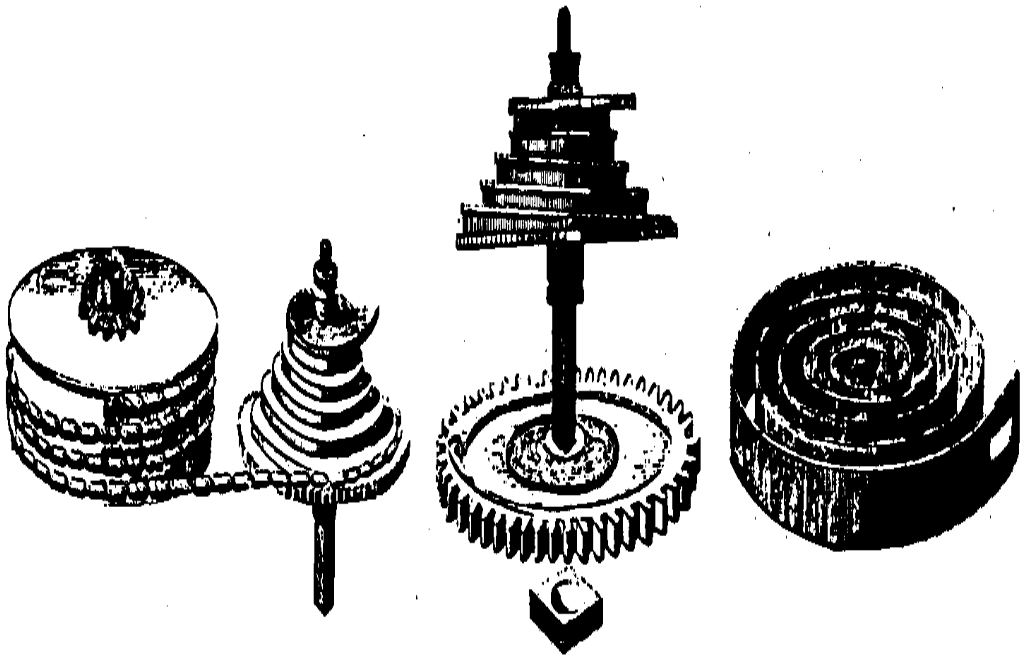
11th Century Chinese Water Clock



Source: Landes, *Revolution in Time*, Harvard Press

Crab Nebula
Remnant of Supernova of 1054 AD

Spring-Loaded Clocks, 1430

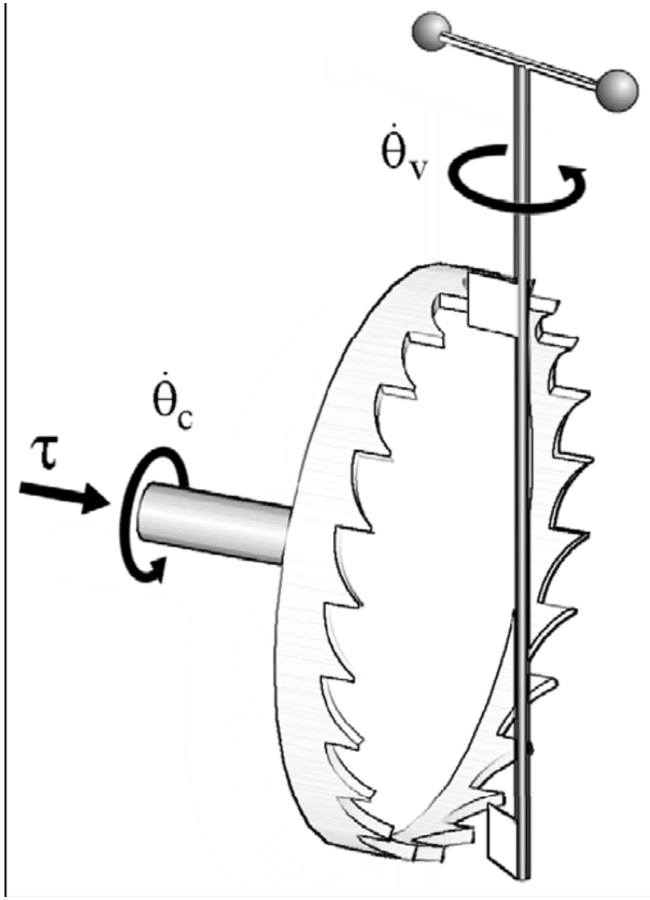


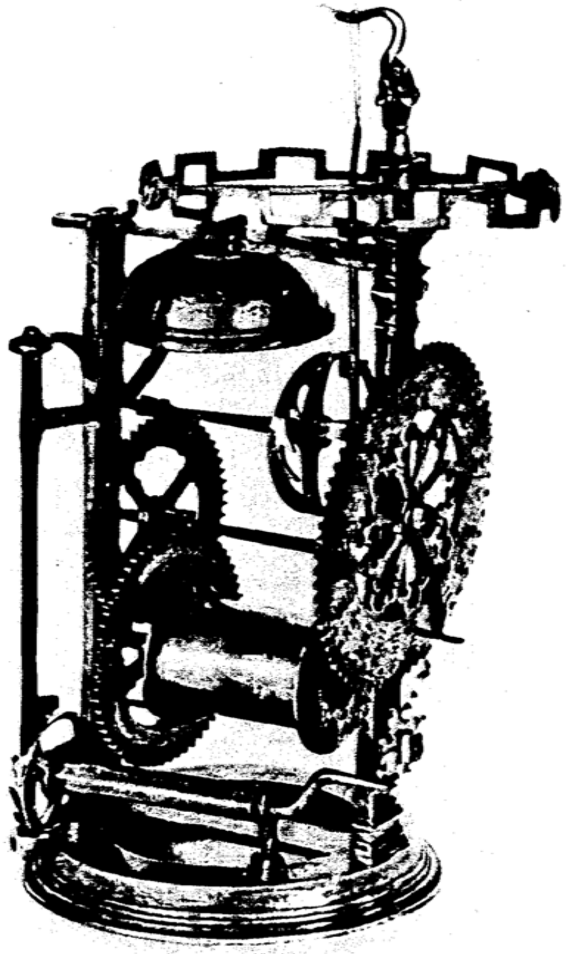
Note geometric compensation as spring loses tension

Source: Landes: *Revolution in Time*, Harvard Press

Verge and Foliot

Verge and Balance-Wheel, 1450

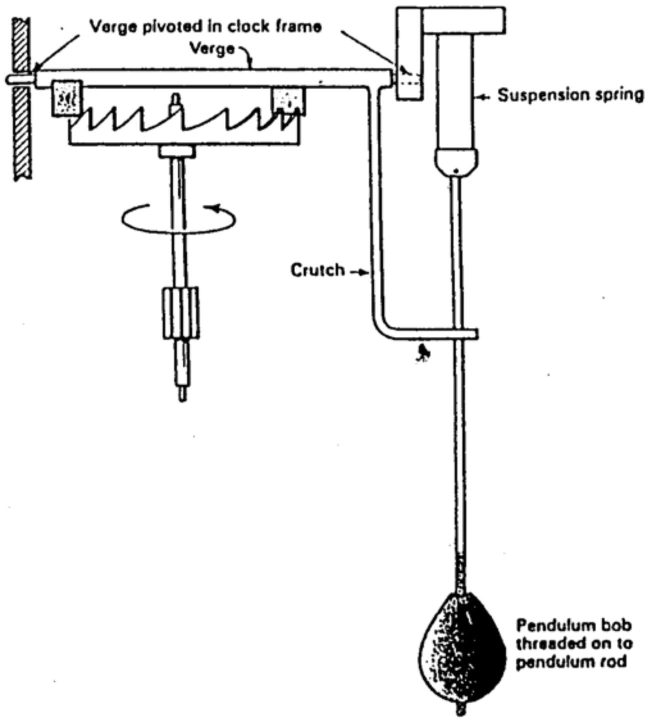




- **Roup *et al.* Int. J. Control 2003, 76, 1685-1608**
- **Landes: *Revolution in Time*, Harvard Press**

Galileo Galilei (1554-1642)

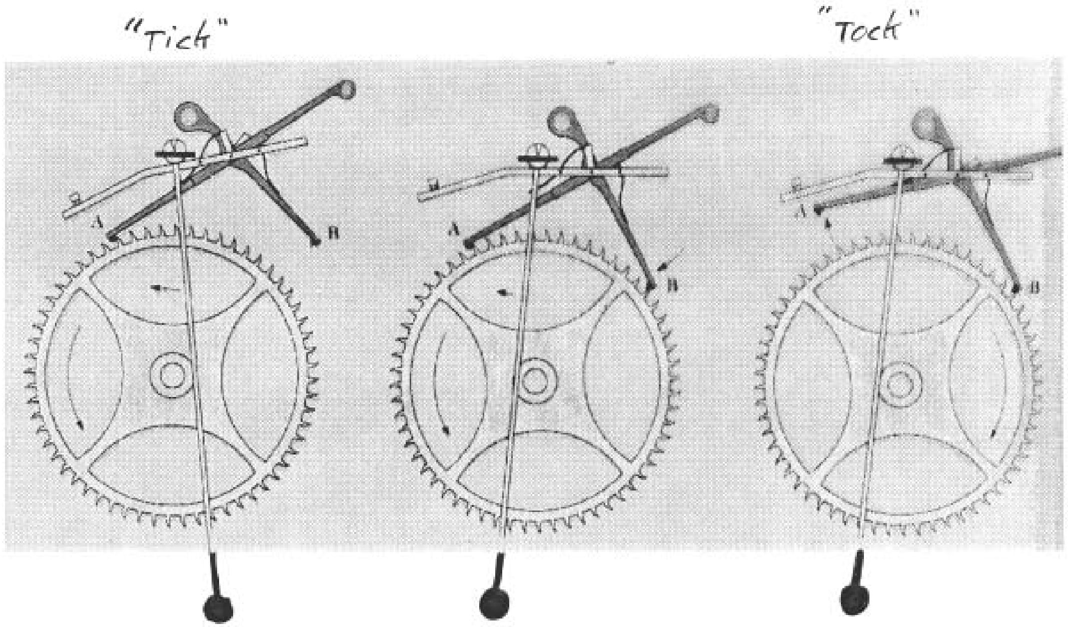
Pendulum Clock



12. Pendulum clock. The natural oscillation of the pendulum has replaced the mechanical oscillation of the old horizontal foliot with its weights. Otherwise, the instrument is essentially the same. Now it is the beat of the pendulum that controls the speed at which the verge with its pallets turns. As the pallets catch and release each saw tooth of the crown wheel, the pendulum's beats are counted, and the count is subsequently transmitted by the gear train (not shown) to the clock face.

Source: J. Barnett, *Time's Pendulum*, Plenum Press

Escapements in 1676



Source: J. Barnett, *Time's Pendulum*, Plenum Press

Big Ben

Frequency adjusted with pennies

The Great Contest

Fact: Must know the time to know longitude

Fact: Navigation error caused 2,000 British sailors to drown in 1707

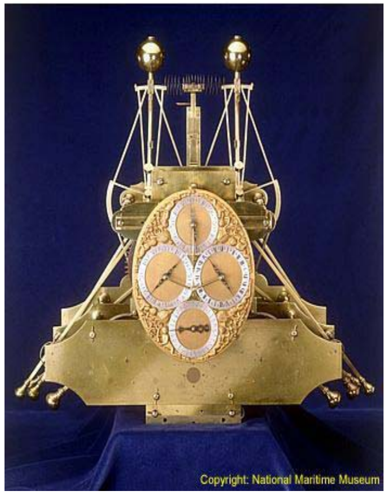
Contest Prize: 20,000 pounds of solid gold

Goal: Measure time to 2 minutes accuracy after 5 months at sea.

- Astronomers "upper class" tried Moon's motion
- Clockmakers "lower class" tried better clocks

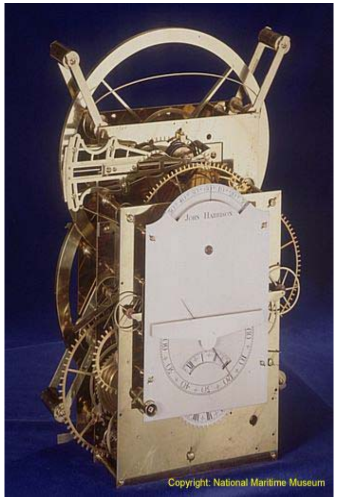
The Winner: John Harrison

The Chronology



H1, 1730-35

H2, 1737-40



H3, 1740-55

H4, 1755-59

H5, 1772

H3: Bimetallic strip invented for thermal stability
H3: Caged roller-race (equivalent of caged ball-bearings)
1769 K1, a copy, was used by Captain Cook to explore Pacific
1772 H5, also passes test, after nearby magnets removed
1773 King George III intercedes and gives full payment

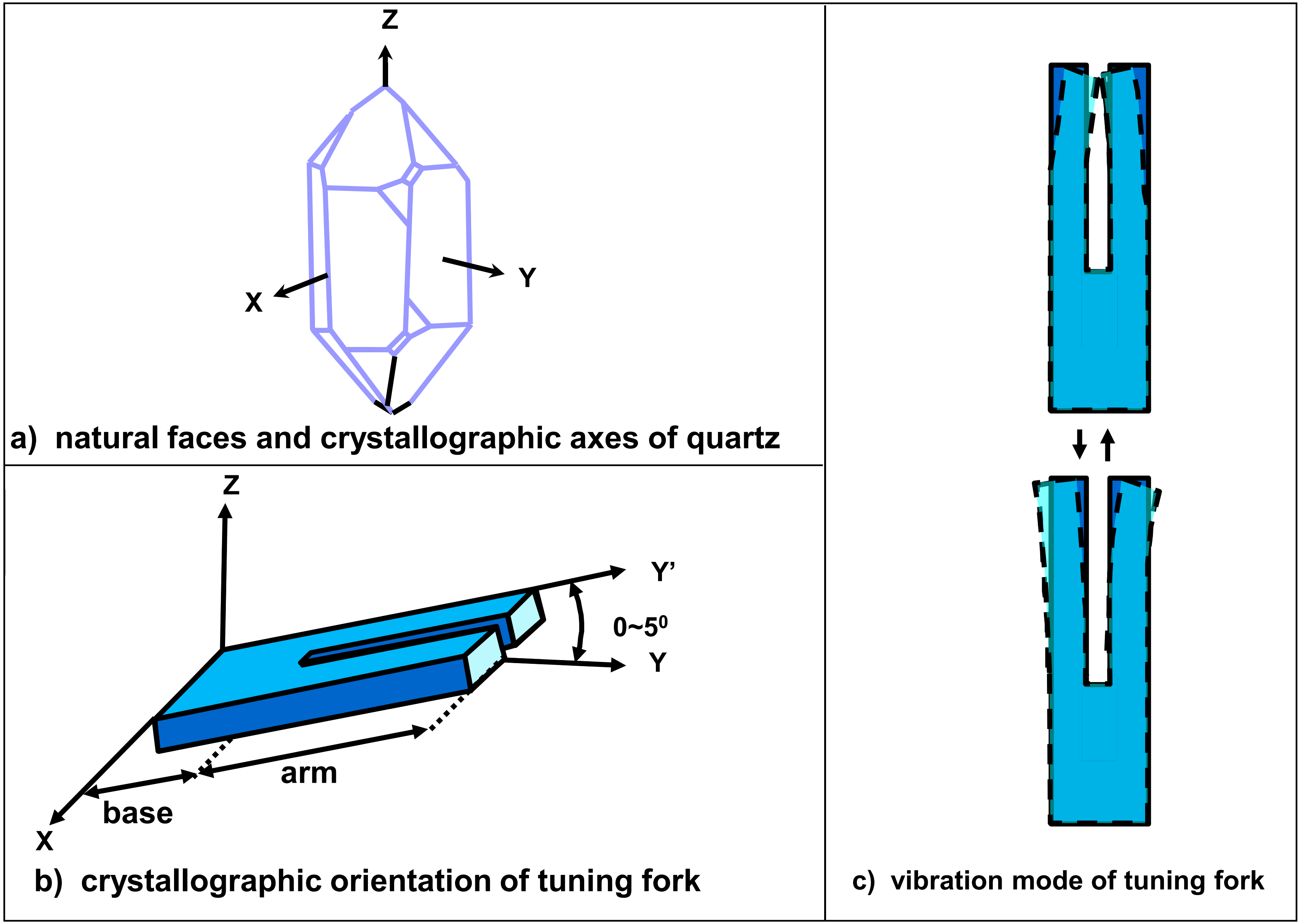
Pendulum and Spring Clocks Improved …

Ming Dynasty Collection

Shortt Clocks Master/Controlled

And by 1928 they had reached perfection!

Quartz Revolutionizes Timekeeping



Source: John Vig http://ieee_uffc.org/fc

Frequency Control Device Market

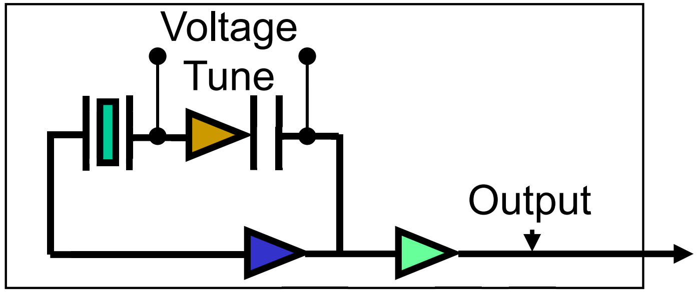
(as of ~1997)

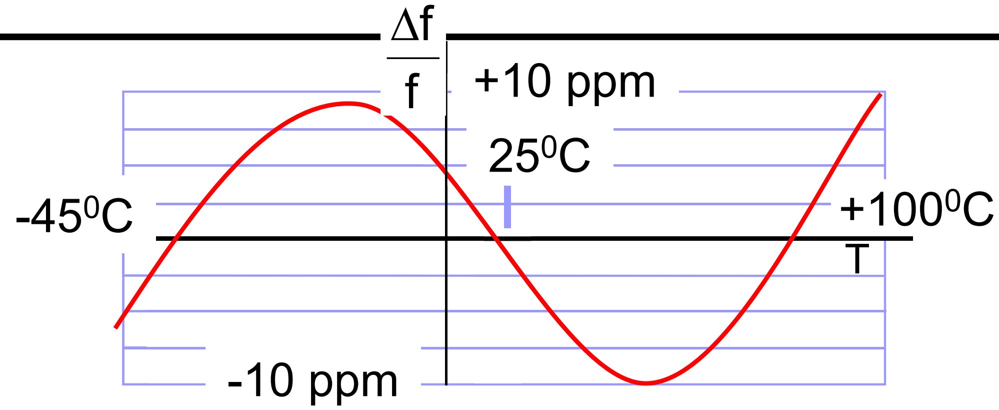
Technology	Units per year	Unit price, typical	Worldwide market, $/year
Crystal	~ 2×10^9	~$1 ($0.1 to 3,000)	~$1.2B
Hydrogen maser	~ 10	$200,000	$2M
Cesium beam frequency standard	~ 300	$50,000	$15M
Rubidium cell frequency standard	~ 20,000	$2,000	$40M

Oscillator Acronyms

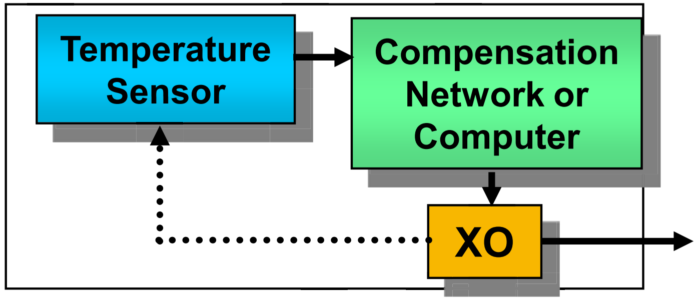
- **XO…………..**Crystal Oscillator
- **VCXO………**Voltage Controlled Crystal Oscillator
- **OCXO………**Oven Controlled Crystal Oscillator
- **TCXO………**Temperature Compensated Crystal Oscillator
- **TCVCXO..…**Temperature Compensated/Voltage Controlled Crystal Oscillator
- **OCVCXO.….**Oven Controlled/Voltage Controlled Crystal Oscillator
- **MCXO………**Microcomputer Compensated Crystal Oscillator
- **RbXO……….**Rubidium-Crystal Oscillator

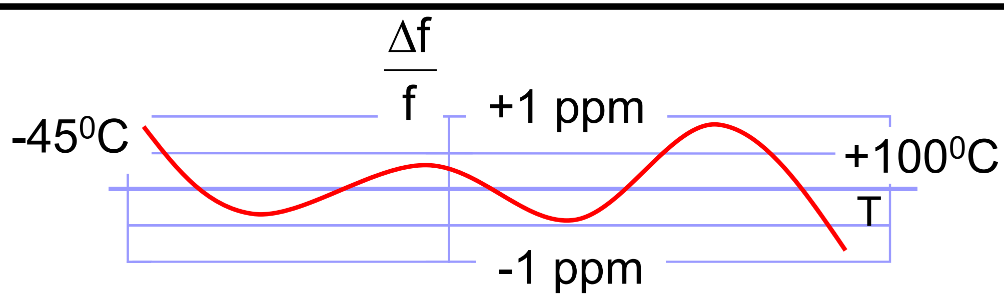
Crystal Oscillator Categories



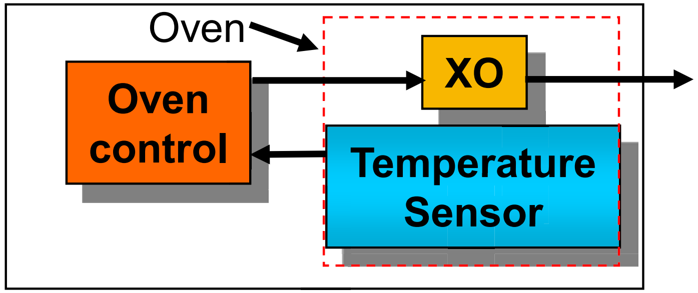


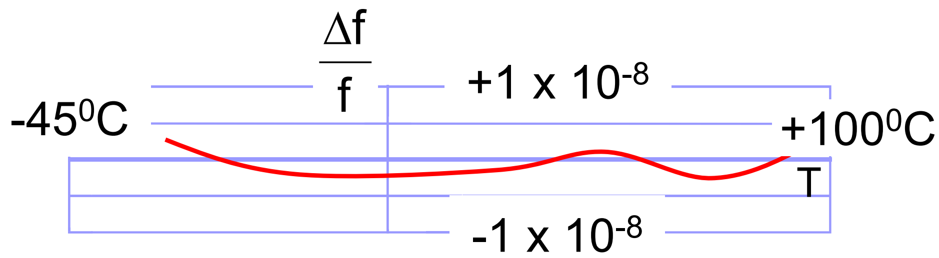
- Crystal Oscillator (XO)





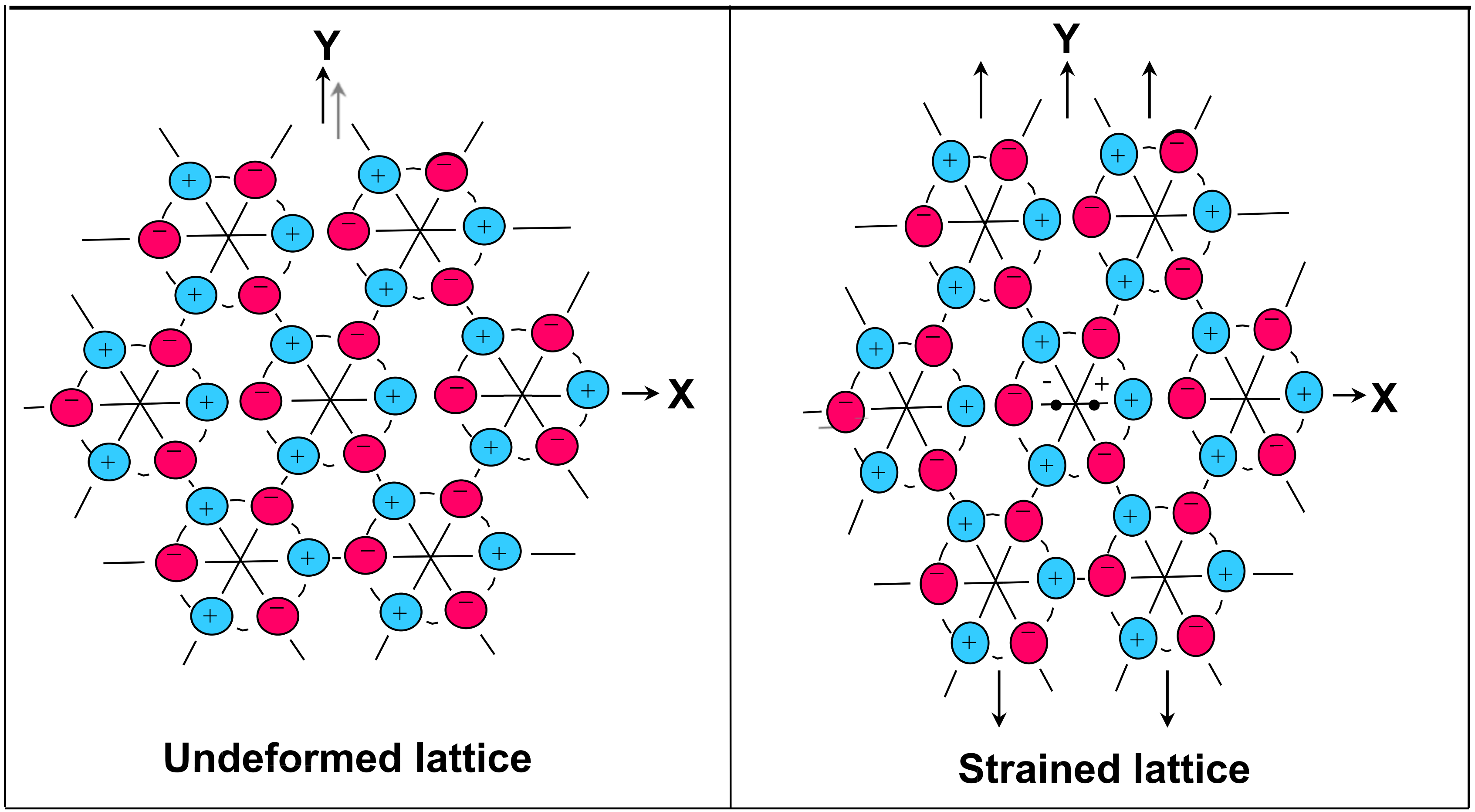
- Temperature Compensated (TCXO)





- Oven Controlled (OCXO)

The Piezoelectric Effect



The piezoelectric effect provides a coupling between the mechanical properties of a piezoelectric crystal and an electrical circuit.

Milestones in Quartz Technology

1880	Piezoelectric effect discovered by Jacques and Pierre Curie
1905	First hydrothermal growth of quartz in a laboratory - by G. Spezia
1917	First application of piezoelectric effect, in sonar
1918	First use of piezoelectric crystal in an oscillator
1926	First quartz crystal controlled broadcast station
1927	First temperature compensated quartz cut discovered
1927	First quartz crystal clock built
1934	First practical temp. compensated cut, the AT-cut, developed
1949	Contoured, high-Q, high stability AT-cuts developed
1956	First commercially grown cultured quartz available
1956	First TCXO described
1972	Miniature quartz tuning fork developed; quartz watches available
1974	The SC-cut (and TS/TTC-cut) predicted; verified in 1976
1982	First MCXO with dual c-mode self-temperature sensing

Oscillator Comparison

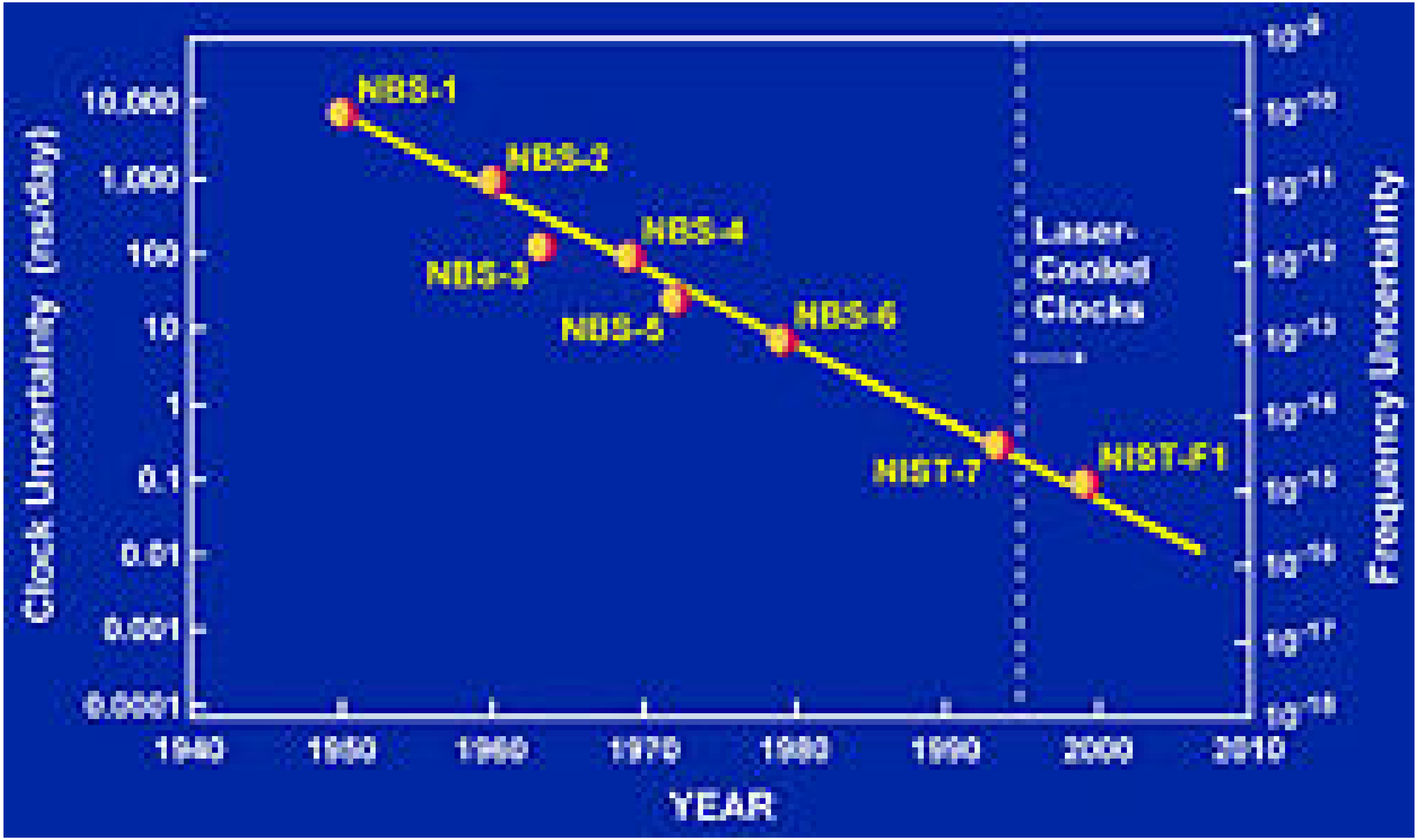
	Quartz Oscillators			Atomic Oscillators		
	TCXO	MCXO	OCXO	Rubidium	RbXO	Cesium
Accuracy * (per year)	2×10^{-6}	5×10^{-8}	1×10^{-8}	5×10^{-10}	7×10^{-10}	2×10^{-11}
Aging/Year	5×10^{-7}	2×10^{-8}	5×10^{-9}	2×10^{-10}	2×10^{-10}	0
Temp. Stab. (range, ^{0}C)	5×10^{-7} (-55 to +85)	3×10^{-8} (-55 to +85)	1×10^{-9} (-55 to +85)	3×10^{-10} (-55 to +68)	5×10^{-10} (-55 to +85)	2×10^{-11} (-28 to +65)
Stability, $\sigma_y(\tau)$ (τ = 1s)	1×10^{-9}	3×10^{-10}	1×10^{-12}	3×10^{-12}	5×10^{-12}	5×10^{-11}
Size (cm^3)	10	30	20-200	200-800	1,000	6,000
Warmup Time (min)	0.03 (to 1×10^{-6})	0.03 (to 2×10^{-8})	4 (to 1×10^{-8})	3 (to 5×10^{-10})	3 (to 5×10^{-10})	20 (to 2×10^{-11})
Power (W) (at lowest temp.)	0.04	0.04	0.6	20	0.65	30
Price (~$)	10 - 100	<1,000	200-2,000	2,000-8,000	<10,000	50,000

* Including environmental effects (note that the temperature ranges for Rb and Cs are narrower than for quartz).

All of Mahatma Gandhi's Possessions, Jan 30,1948

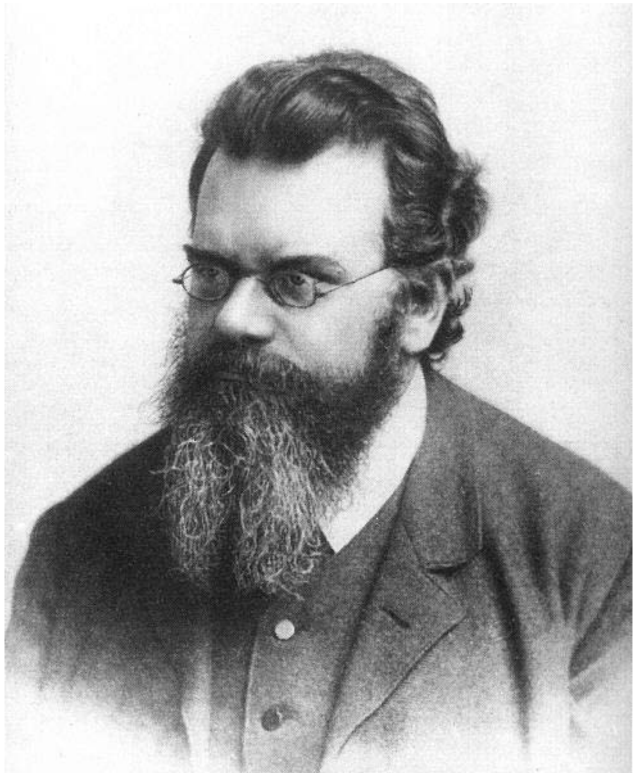
Photograph from the M.K. Gandhi Institute for Nonviolence

The Atomic Age



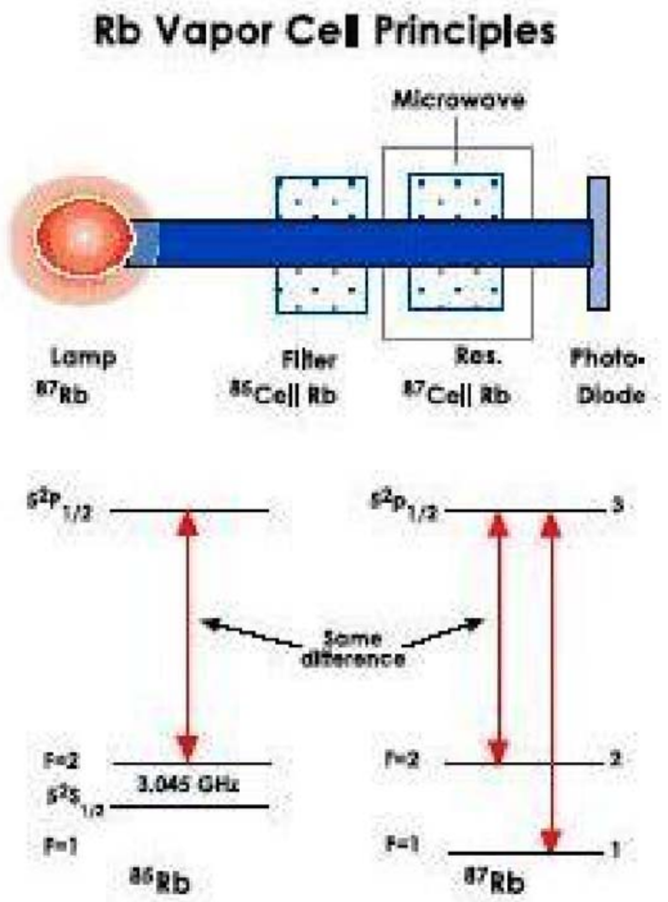
Source: NIST

Ludwig Boltzmann (1844-1906)

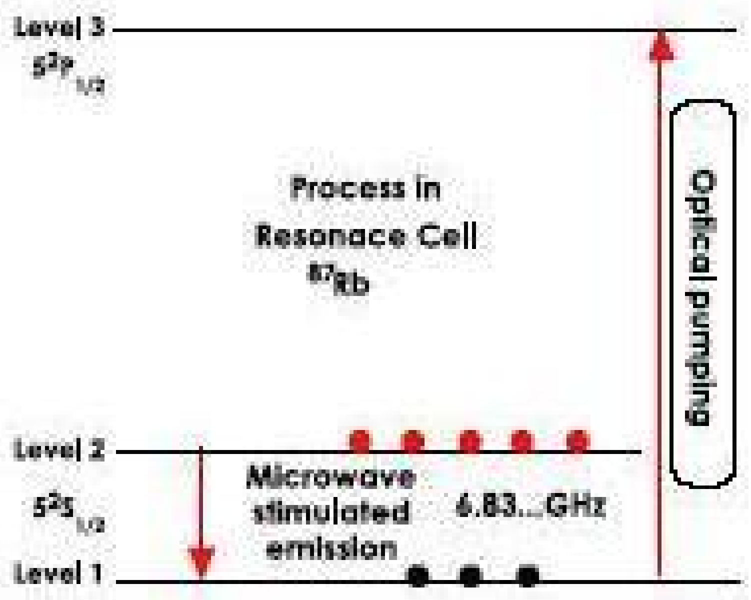


- Atoms Exist
- In equilibrium, each state is populated according to $e^{-E/kT}$
  - Where E=Energy, T=Temperature
  - k= Boltzmann's Constant = 1.3810^{-23}J/K
- Low T favors lower energy states
- High T equalizes population per state, but usually there are more high-energy states
- Quantum Mechanics adds: Atoms can only be in specific states

Even the cheapest atomic clock is more precise than the Earth



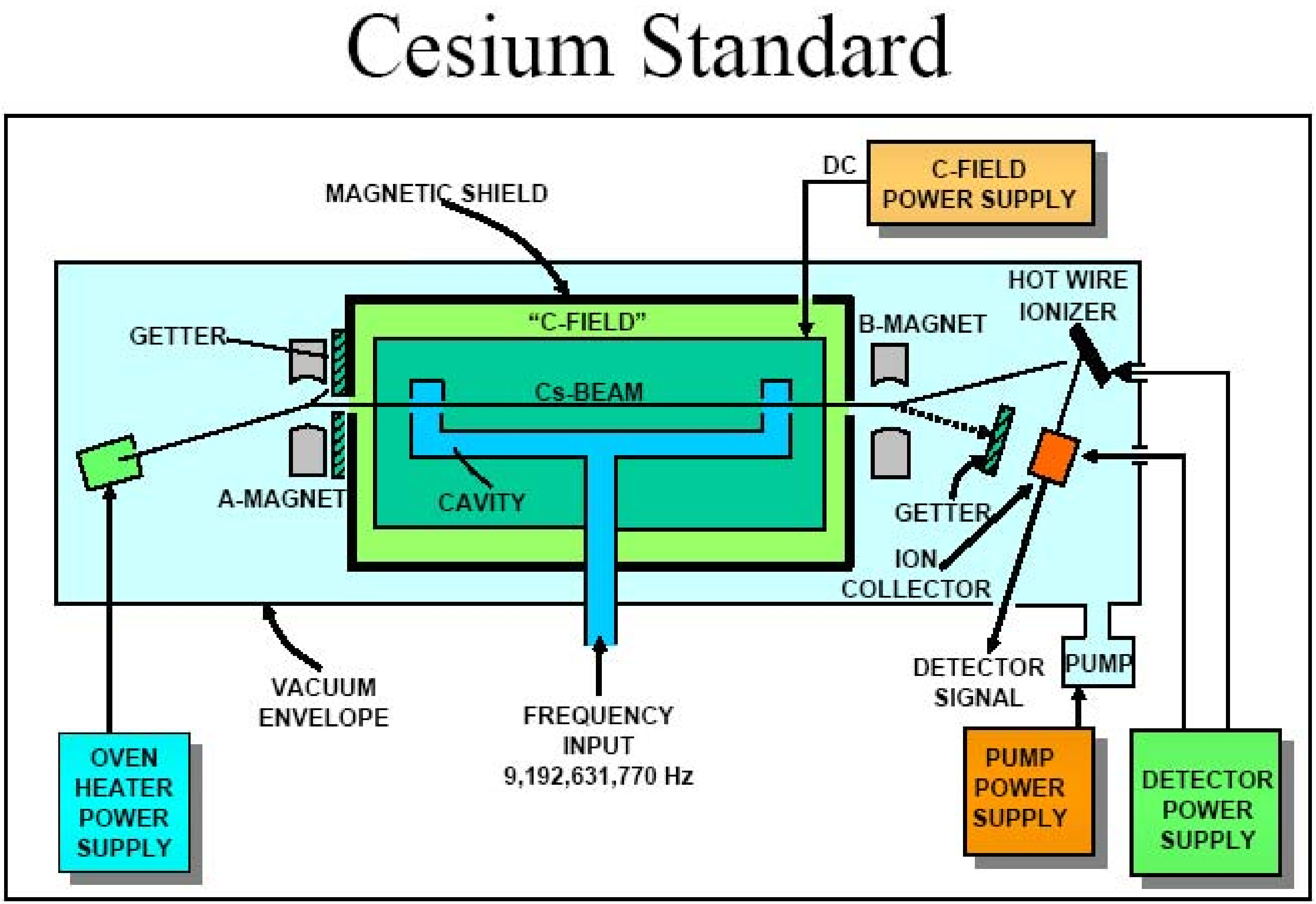
1. Light from ^{87}Rb lamp contains both 3-1 and 2-1 lines.
2. ^{85}Rb Cell filters out the 2-1 line and transmits the 3-1 line.



3. The filtered light "optically pumps" the ^{87}Rb atoms in the resonance cell from level 1 to 3.
4. A Microwave signal at a frequency of 6.84 GHz is injected into the cell and induces transition from level 2 to 1.
5. When the injected wave frequency matches the difference of the 2-1 line, the photo-diode detects a reduction in the intensity of the transmitted light.

Source: www.accubeat.com

Cesium is the PTTI Workhorse



Source: John Vig

First cesium clock was 1955

Masers and Lasers

MASER = Microwave Amplification by Stimulated Emission of Radiation

LASER = Light Amplification by Stimulated Emission of Radiation

How to make a maser or laser

1. Prepare atoms or molecules to radiate
2. Cause or allow radiation to stimulate them
   - All will radiate in unison (coherently)
   - Razor-sharp beam
   - Can be very intense

Hydrogen Maser Frequency Standard

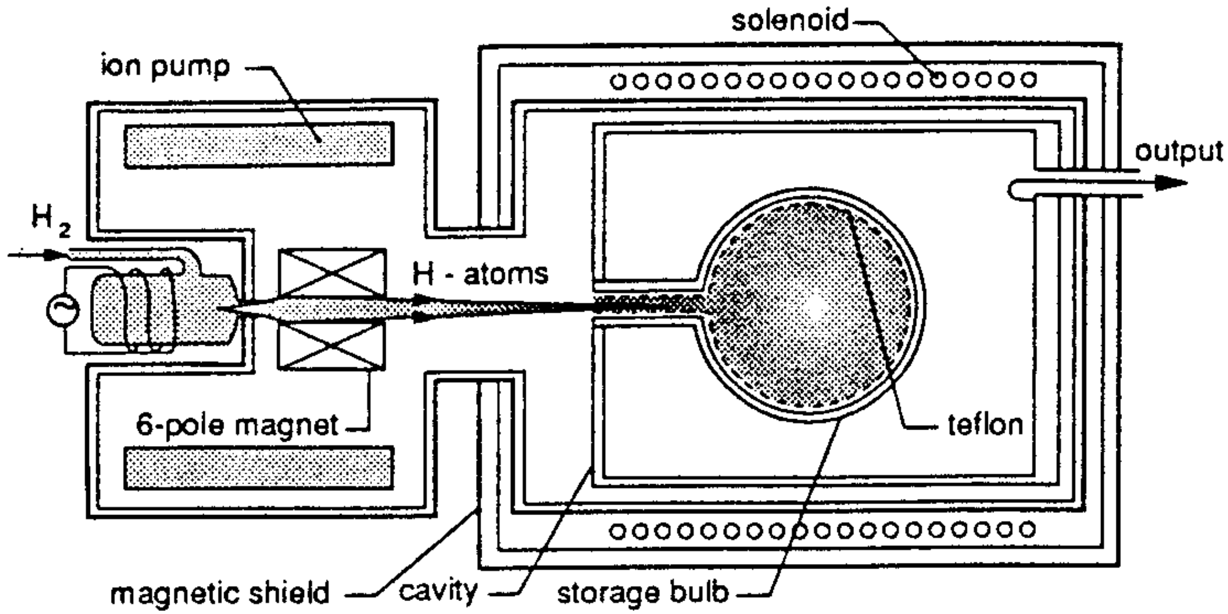


Figure 11.2 The basic elements of a hydrogen maser

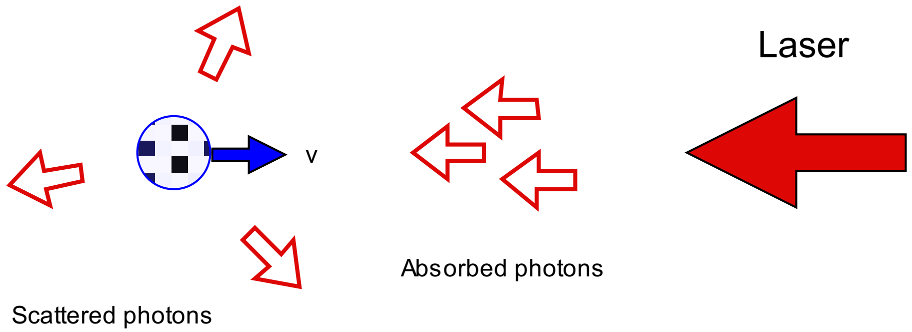
F.G. Major Springer, “The Quantum Beat”, 1998

Doppler Shift

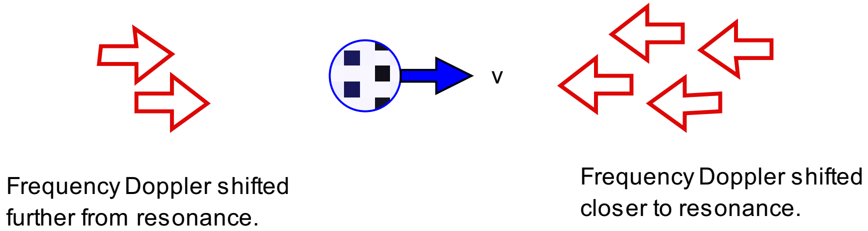
Christian Doppler
1803-1853

- Observer moving towards source of radiation sees frequency increased (blue-shifted)
- Observer moving away from source of radiation sees frequency decreased (red-shifted)
- Works for microwaves, light, sound, whatever.

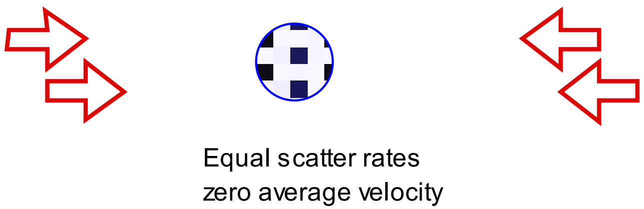
Manipulating Atoms With Lasers



Laser in one dimension exerts a scattering force on atoms in the direction of the laser



Lasers in two dimensions, red detuned, exert a velocity-sensitive force on the atoms



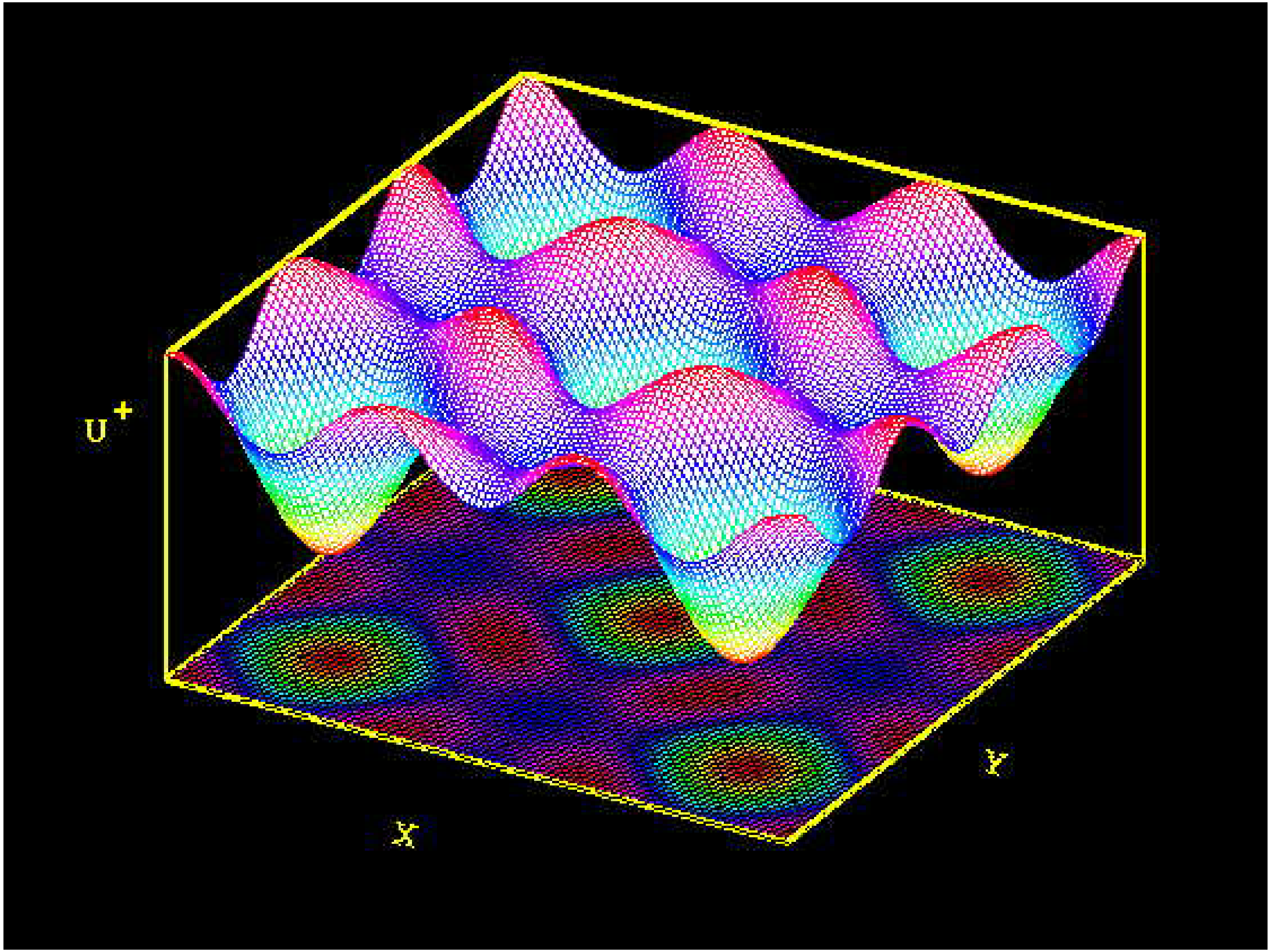
Atoms can be brought to zero average velocity, with very little residual motion (i.e. cold)

(Source: Tom Swanson, USNO)

Sisyphus Effect

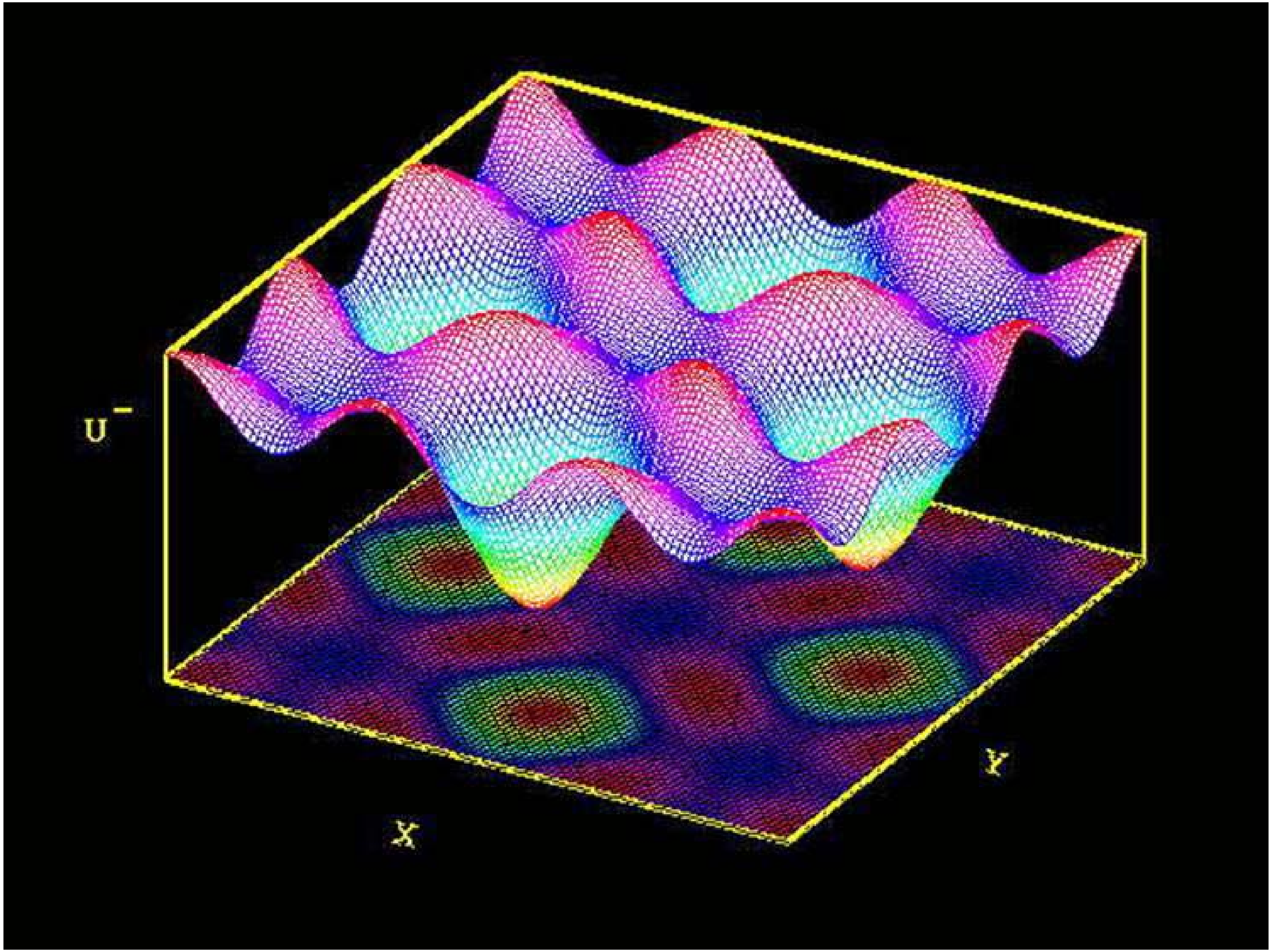
Ref: Encyclopedia of Greek Mythology http://www.mythweb.com/encyc/gallery/sisyphus_c.html

Potential Field of a Ground State Sublevel of an Atomic Ground State in an Optical Polarization Gradient



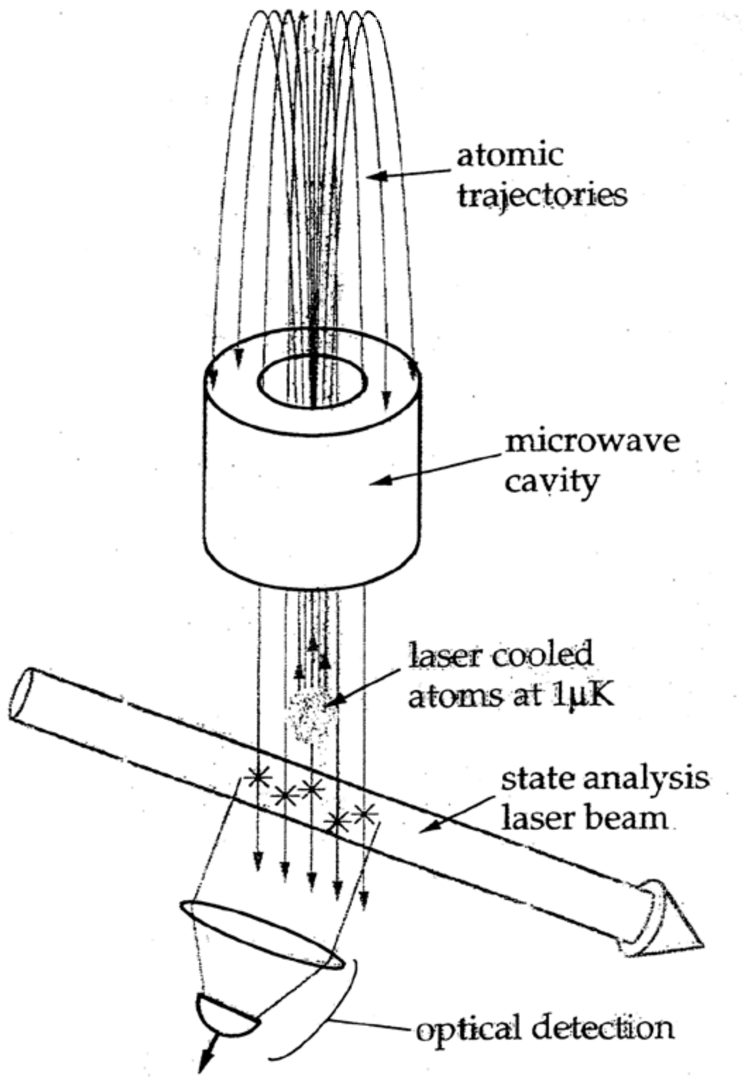
Ref: http://www.physics.helsinki.fi/~jpiilo/coolpr.html

Potential Field of a Different Sublevel



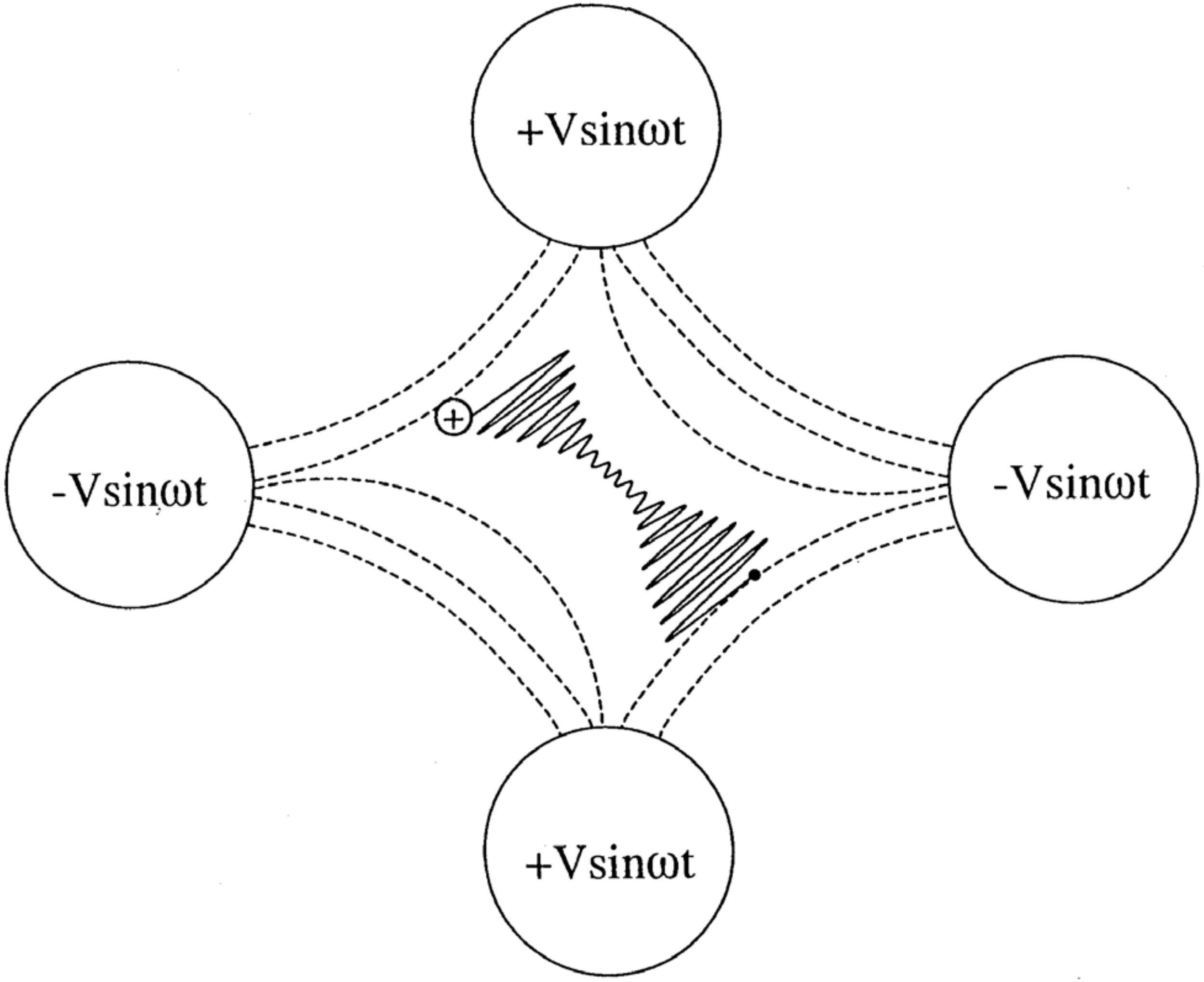
Ref: http://www.physics.helsinki.fi/~jpiilo/coolpr.html

The Cesium/Rubidium Fountain



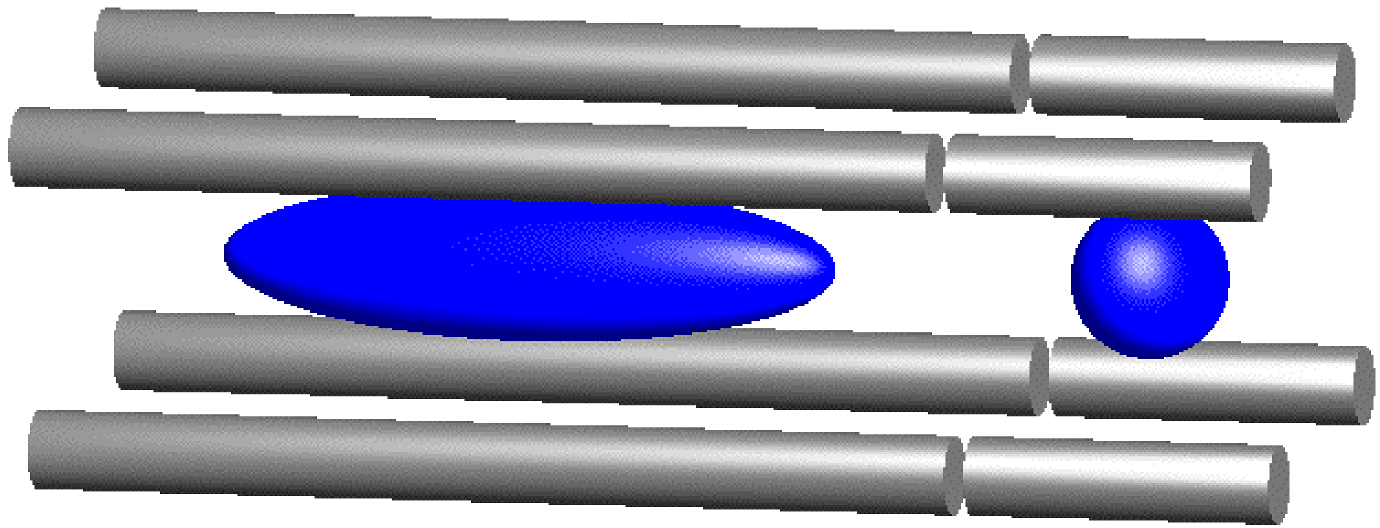
Source: Chris Ekstrom

Ion Trapped In Quadrupole Force Field



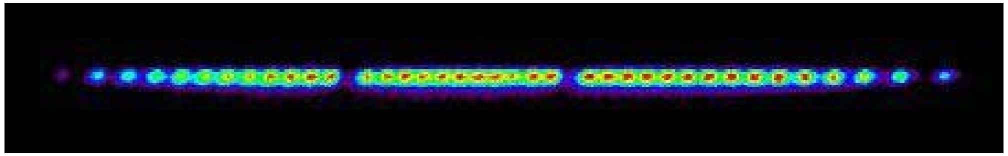
Source: Dr. Demetrios Matsakis

Linear Ion Trap Extended (LITE)



Source: John Prestage and Bob Tjoelker, JPL

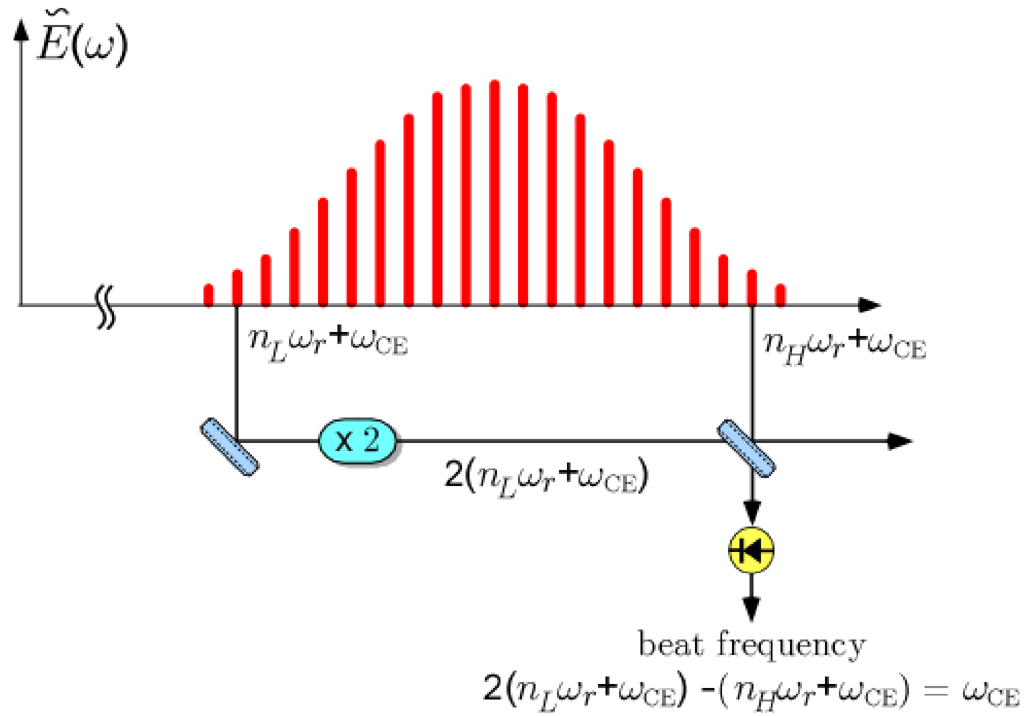
Individual Ions in NIST’s Ion Trap



(Gaps are position of different Hg isotope)

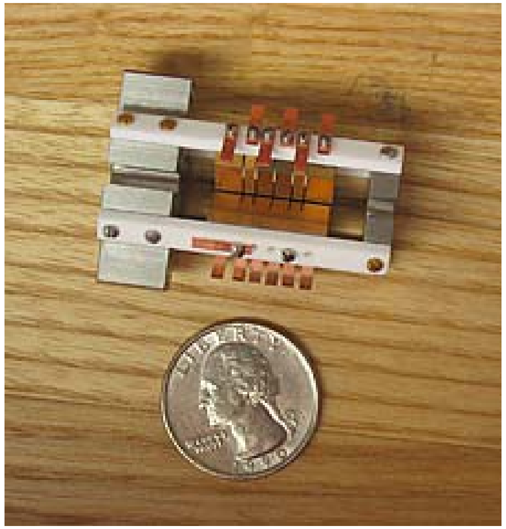
Enter the 21st Century: Optical Comb

Translates Optical Frequencies to Microwave

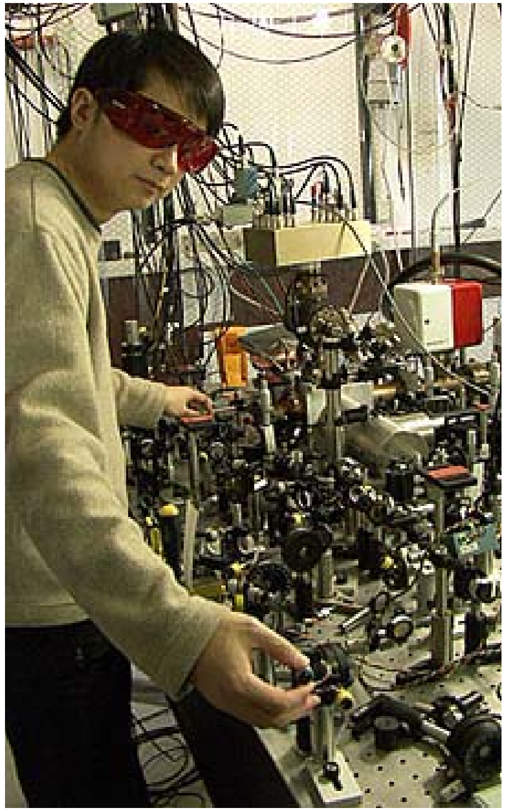


Ref: http://www.mpq.mpg.de/~haensch/comb/research/combs.html

Quantum Clocks



- Aluminum “entangled” with Magnesium or Beryllium
- Excite Aluminum
- Observe Magnesium
- Precision < 10 $^{-17}$



Chip-Scale Atomic Clocks

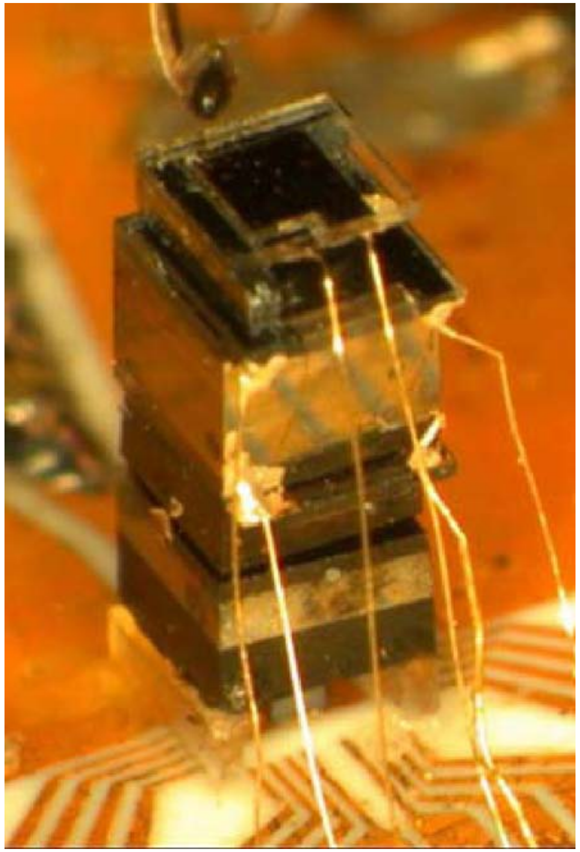
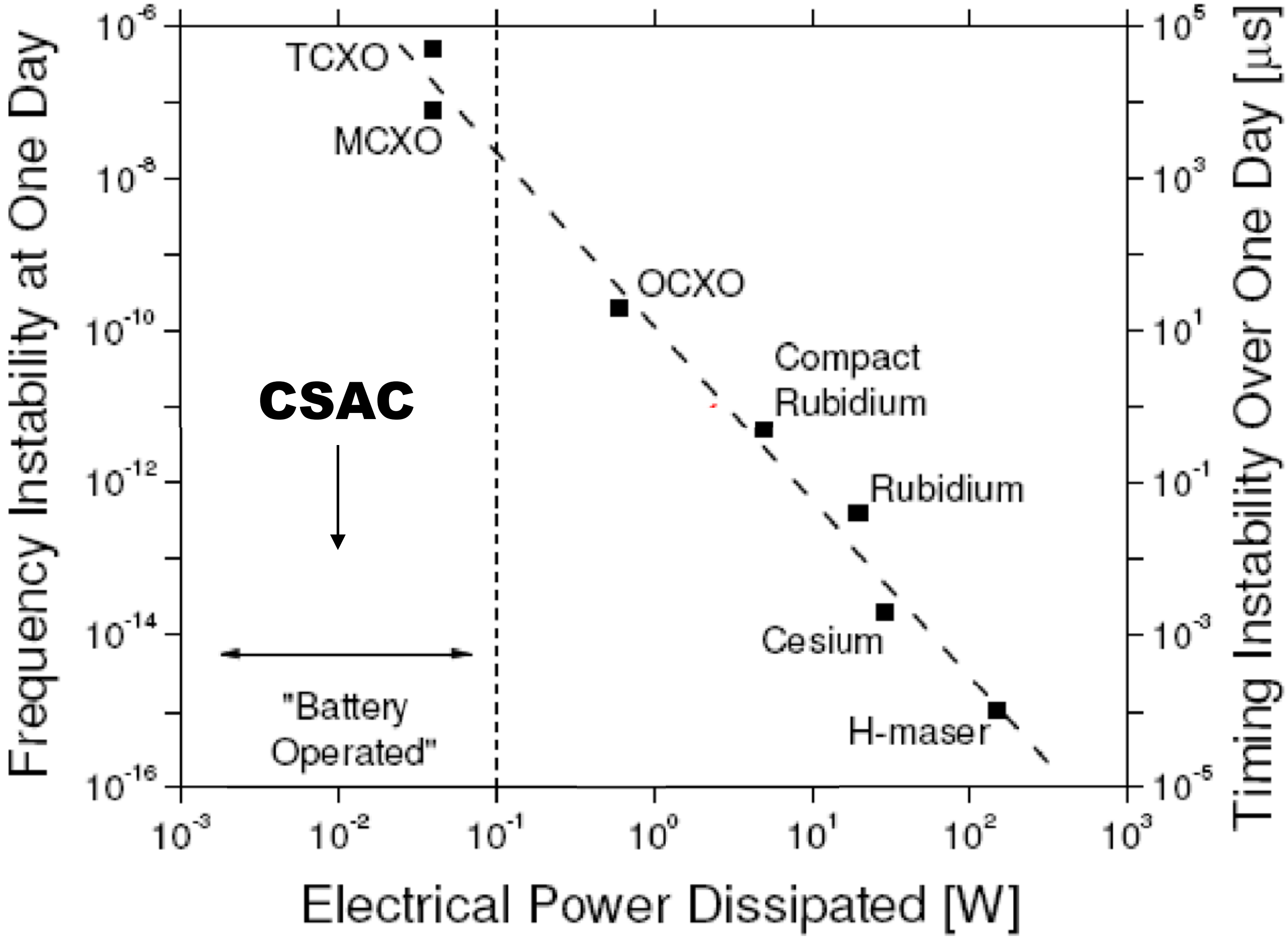


Photo from NIST web pages

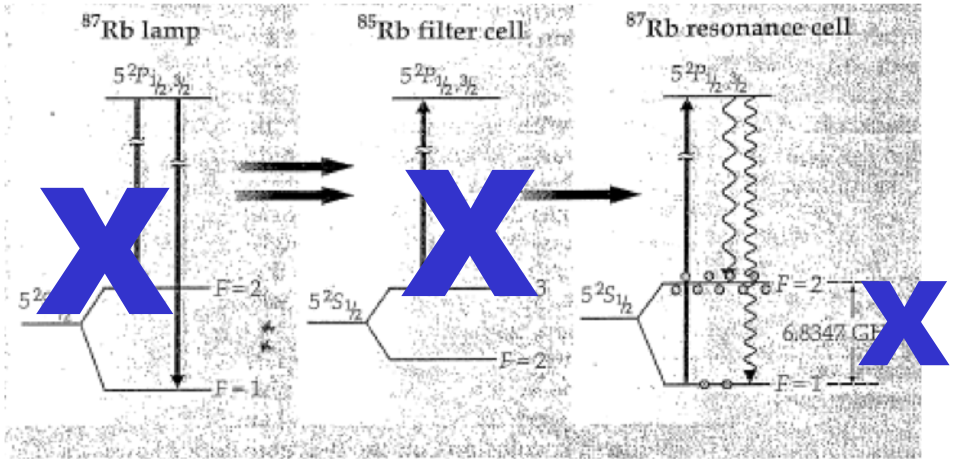
- Specifications
  - Size in mm
  - Power in mW
  - Precision in10^{-11}@1sec
- Applications
  - GNSS receivers
  - Hand-held wireless
  - Replace quartz?

Electrical Power and Chip-Scale Stability



Source: Mike Garvey, Symmetricom

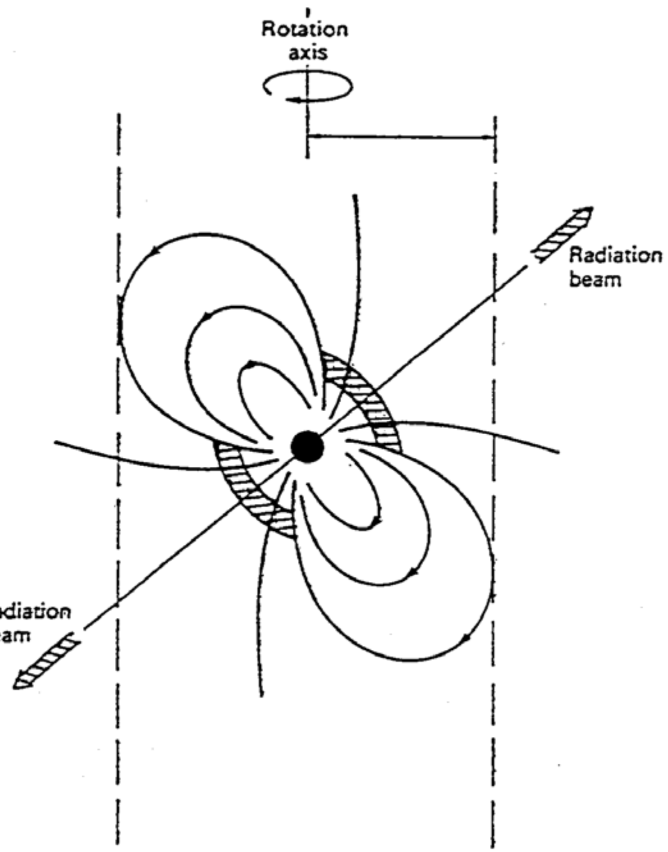
Biggest Change From Normal Rb



- **Eliminate lamp/filter/resonantor**
- **Install all-optical system**
  - **laser modulated @ 6.8 GHz**
- **Less power, fewer parts**

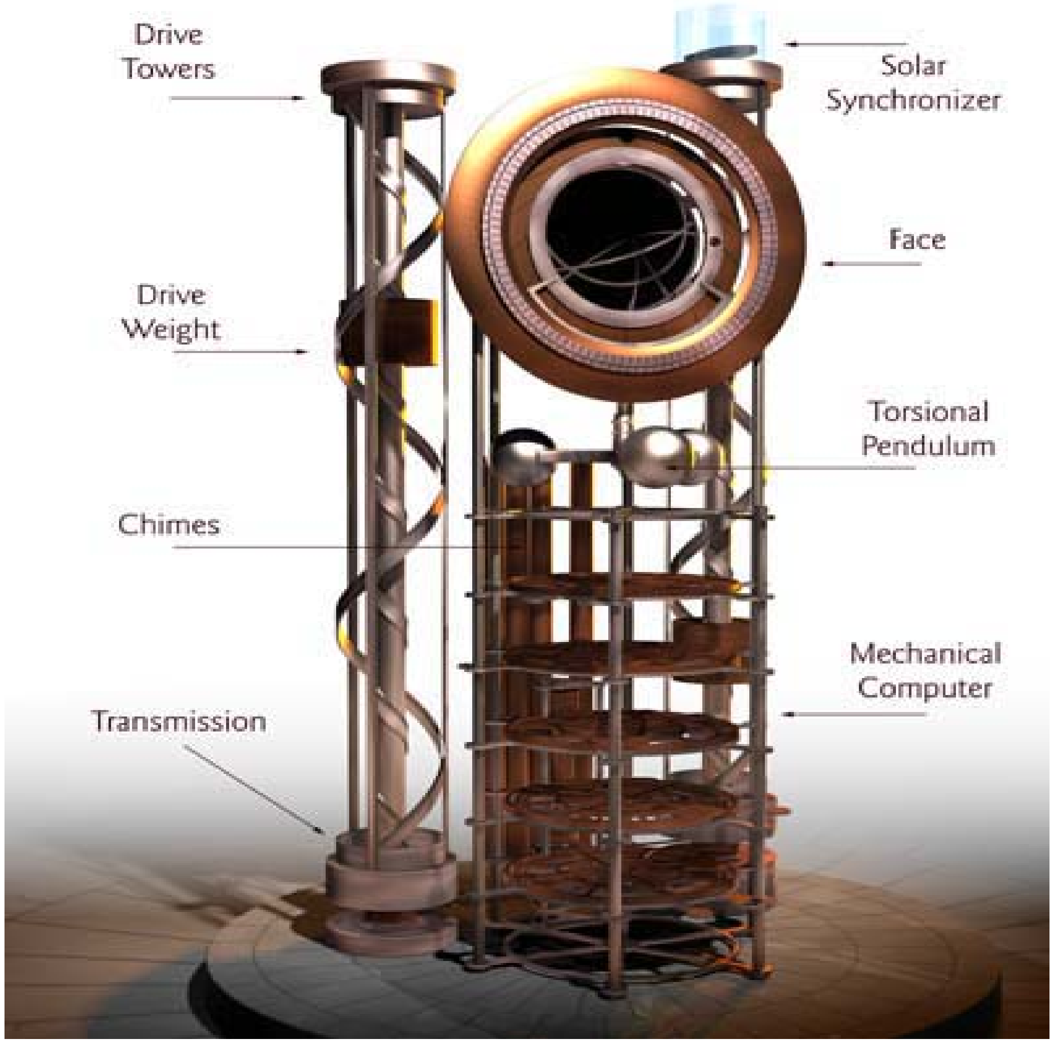
Millisecond Pulsars

Fig. 2.2. The essential features of a pulsar magnetosphere. Within a radial distance $r_c = c/\omega$ of the rotation axis there is a charge-separated, co-rotating magnetosphere. The magnetic field lines which touch the velocity-of-light cylinder at radius r_c define the edge of the polar caps. Radio emitting regions in the polar caps are shown cross-hatched.



Source: Lynne and Graham-Smith, *Pulsar Astronomy,* 2nd Ed., Cambridge University Press

Clock of the Long Now



http://www.longnow.org

Prediction: State-of-the-Clock-Art, 2020

UTC will be computed hourly using:

- Masers for hours to weeks
- Atomic Fountains for weeks to years

Exciting clocks, just becoming operational, will include

- Optical Frequency Standards
  - Some may be trapped-ion
- Space-based trapped-ion and beam clocks
  - [space clocks delayed by launch problems]

Predictions For Time Transfer

Direct GNSS: 1 ns (as seen by calibrated receiver)

Post-processed carrier-phase GNSS: 10 ps accuracy

Real-time carrier phase GNSS almost as good, using predicted orbit and reference clock data

Carrier-phase based Two Way Satellite Time Transfer will be at 10 ps level for experimental satellites

Optical time-transfer technology will be slowly advancing to operational levels

Predictions For End-User

Trend towards cheaper clocks, with greater reliance on time transfer to GNSS, etc.

Rubidium clocks steered to GNSS may be replaced by crystals steered to GNSS.

Improvements to middle-end clocks may languish, though they will never, ever stop.