PRECISION FREQUENCY SOURCES

Tom VanBaak

TIME

- Is what keeps everything from happening all at once
- One of the seven fundamental physical quantities like length, mass, temperature, luminosity, amount of substance, and charge that measures the progress of existence from the past, through the present, to the future
- Used to define other quantities such as velocity (the rate of positional change) and frequency (the rate of state change)
- Since 1967, defined to be the vibrational frequency of Cesium 133 or 9,192,631,770 Hz.

FREQUENCY

- Change in signal measured in one second (exactly)
- Many waveform shapes in radio
  - Sine wave
  - Square wave
  - Triangle wave
  - Aperiodic (not a fixed frequency - noise)
- Radio frequencies: 3 kHz - 300 GHz
- FCC requires both <u>accuracy</u> and <u>stability</u> of frequency

FREQUENCY (CONTD.)

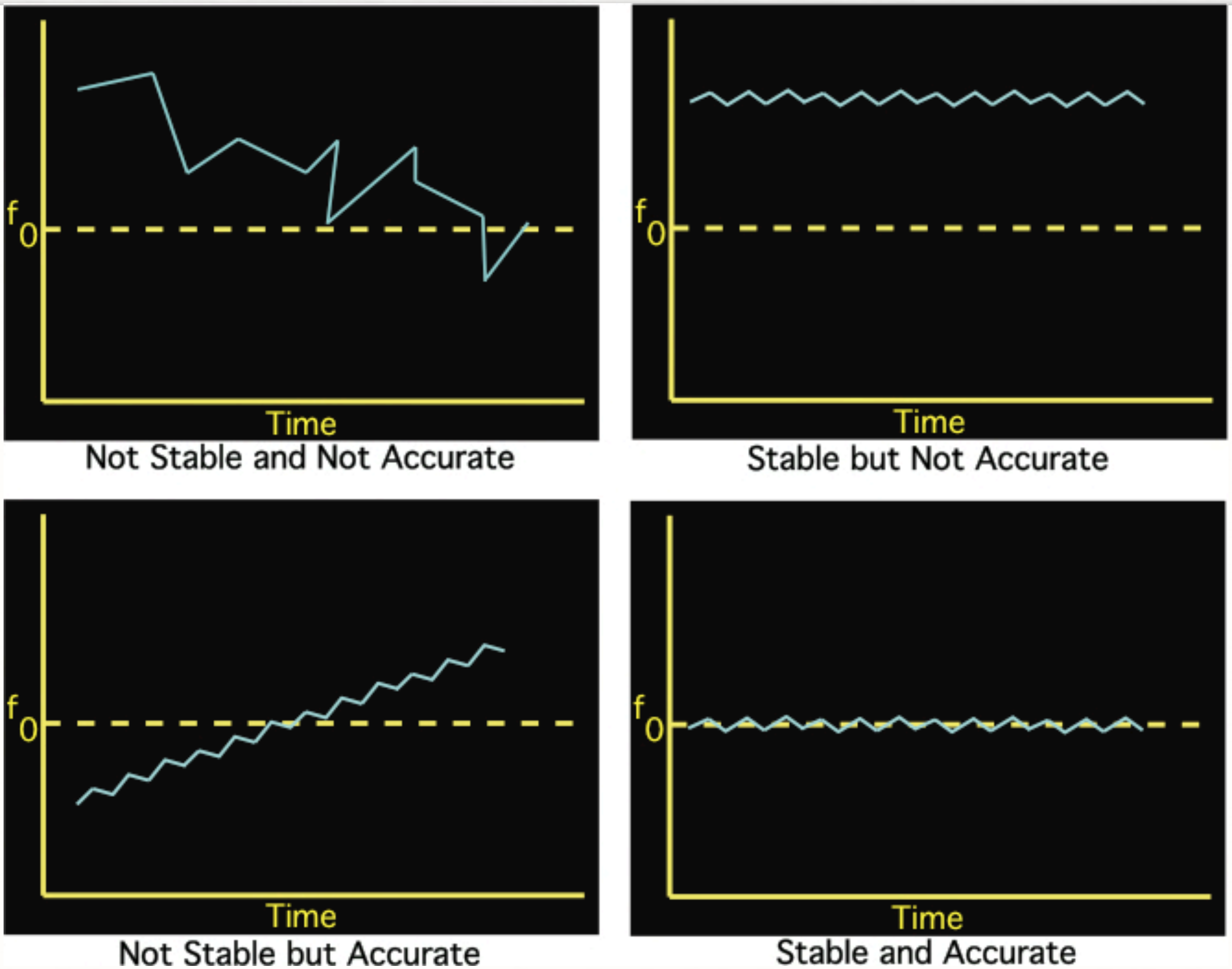
- Unstable (many ways to generate)
  - Temperature has the most effect, then component variation
  - Resistor + Capacitor ($f = 1/2\pi RC$)
  - Inductor + Capacitor ($f = 1/2\pi\sqrt{LC}$)
- Stable (also several ways to generate)
  - Crystal
  - Rubidium
  - Cesium
  - Hydrogen MASER
- Disciplined: high cost performance from a low cost approach

OSCILLATOR ATTRIBUTES

- Frequency
- Accuracy
- Stability
  - Short term drift
  - Long term drift (aging rate)
- Purity
  - Harmonic distortion
  - Phase noise

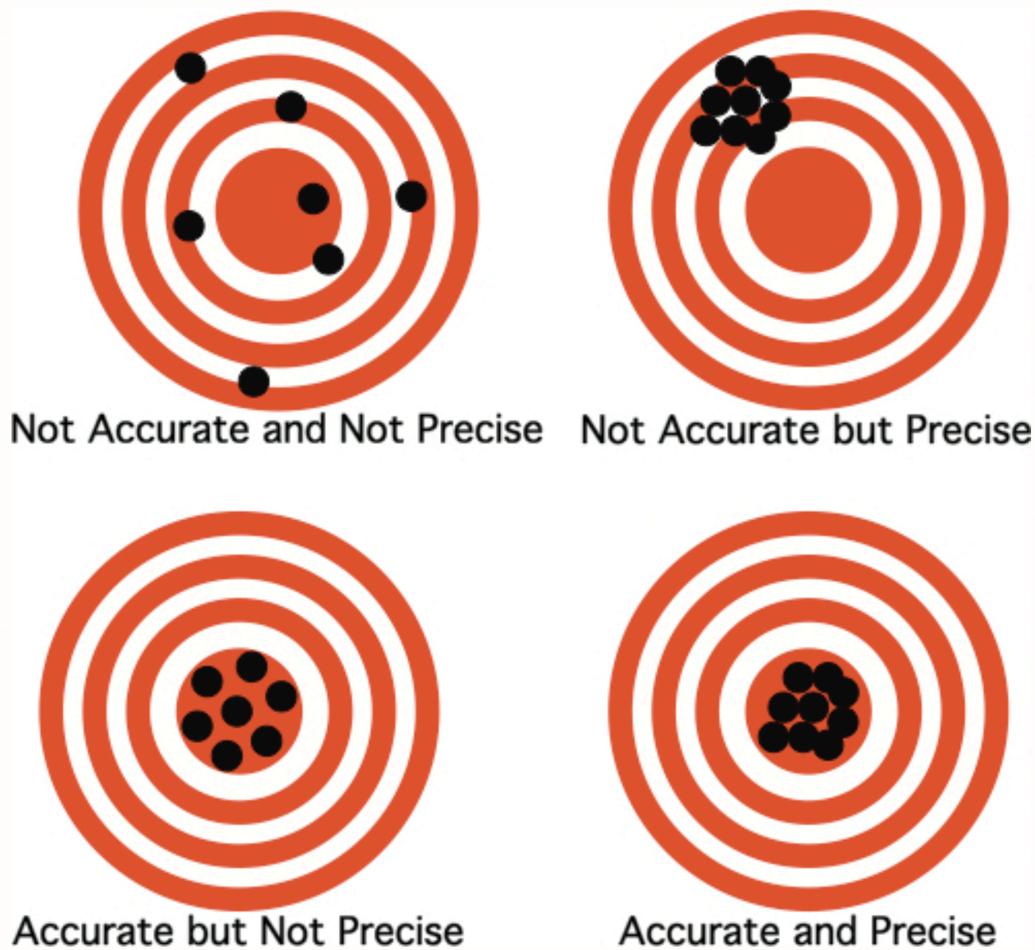
OSCILLATOR ATTRIBUTES

Accuracy and Stability



OSCILLATOR ATTRIBUTES

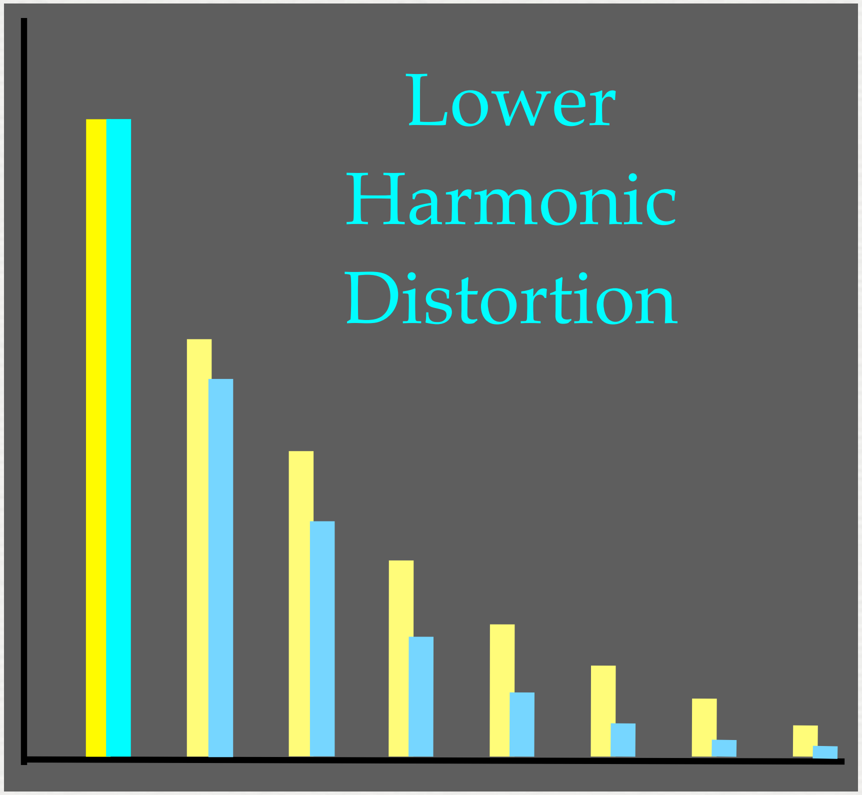
Accuracy and Precision



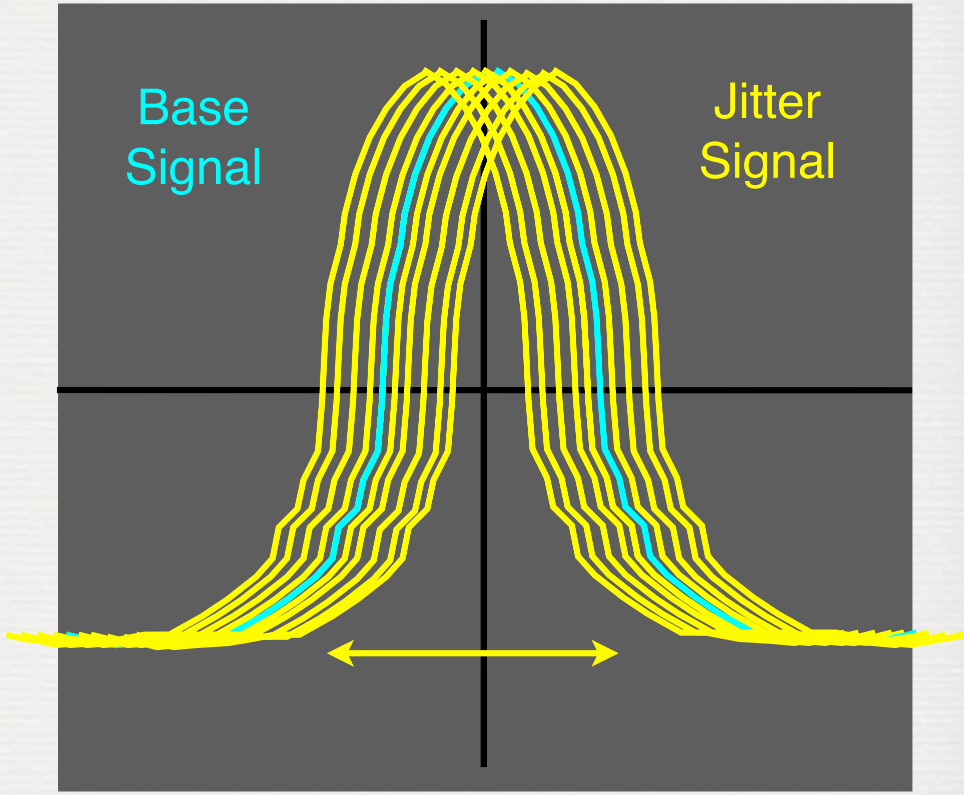
OSCILLATOR ATTRIBUTES

Purity

Harmonic Distortion



Phase Noise or Jitter



CHARACTERISTICS

	OCXO	Rb	Cs	H
Accuracy	1E^{-10}	1E^{-12}	5E^{-13}	1E^{-15}
Stability	1E^{-10}	2E^{-12}	5E^{-14}	1E^{-15}
Aging	5E^{-10}/Day	5E^{-11}/Mo	N/A	N/A
Phase Noise	-140dBc	-130dBc	-130dBc	-150dBc
Warm Up	30 Min	2-30 Min	10 Min	1 Day
Cost	$500	$4K	>$60K	>$100K

CHARACTERISTICS (CONTD.)

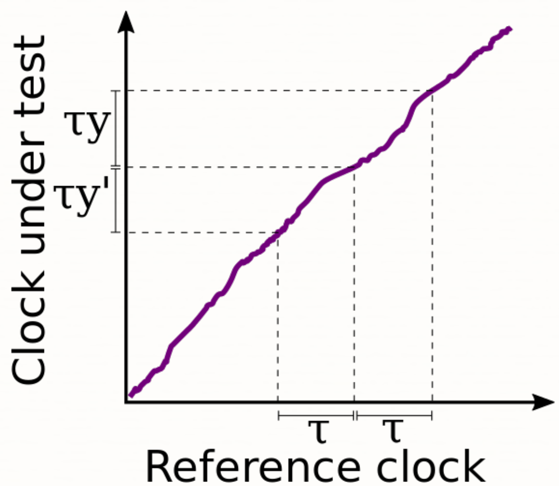
	Earth
Accuracy	$1.3E^{-8}$ LOSD*
Stability	+/-.29-.34E^{-3} Sec
Aging	-2.3E^{-6}/Day/100 Yr
Phase Noise	+/-5E^{-3} Sec (core-mantle coupling)
Warm Up	4.54E^{9} Yr
Cost	?

*Locally Observed Solar Day

ALLAN VARIANCE

- A measure of frequency stability using two samples
- 1/2 of the average of the squares of the differences between successive readings of the frequency deviation sampled over the sampling period.

$(y - y')^2 / 2$



ALLAN DEVIATION

- A way to quantify noise
- Indicator of frequency stability in oscillators/clocks
  - Masters thesis of David Allan (Time & existence group, NIST Boulder, CO)
- Called ADEV
- Square root of Allan variance between measurements
- Lower is better ($1E^{-9}$ is worse than $3E^{-14}$)
- Includes noise but not drift or temperature

ROUGH COST PER ADEV

- \- For 1e-11, you can buy almost any XO, TCXO, or risky OCXO for $10.
- \- For 1e-12, you can find a reputable OCXO on eBay for under $100.
- \- For 1e-13, you can find an old but maybe working cesium clock for 1 k$.
- \- For 1e-14, spend 10 k$ and get a certified working HP 5071A Cesium Standard.

ROUGH COST (CONTD.)

- \- For 1e-15, spend 100 k$ and find a used active H-maser.
- \- For 1e-16, spend 1 M$ to hire physicists and build a Cs fountain.
- \- For 1e-17, spend 10 M$ to fund a national research institute to build ion or
- Optical lattice (Strontium) clocks: 430 THz, accurate to 1 second in 15 billion years.

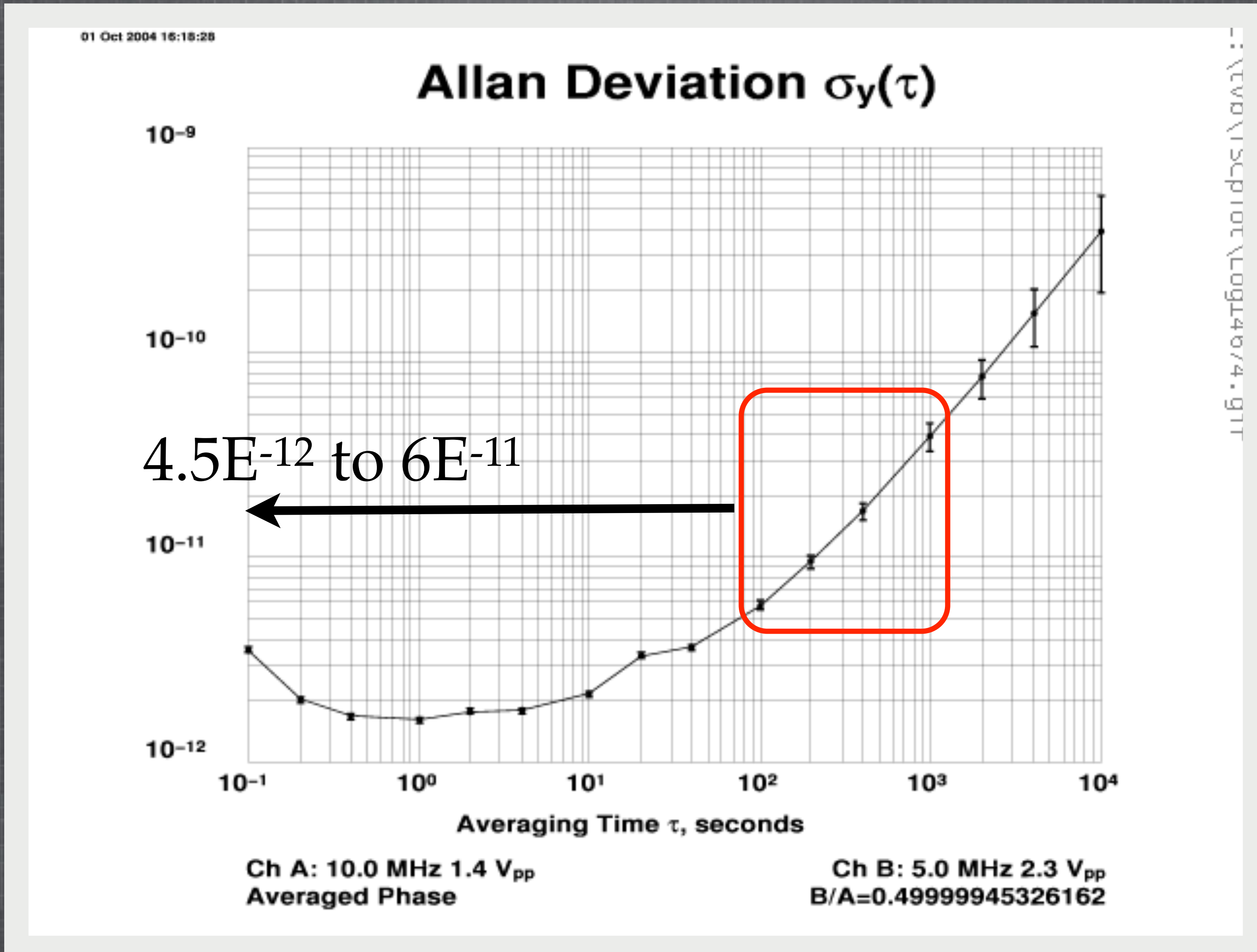
CRYSTAL

- Most common, least costly very high precision
- HP10811A one of the best ever developed
- Frequency: 10.000000 MHz
- Harmonic distortion: <-25 dBc
- Spurious Phase Modulation: <-100 dBc
- Coarse Tuning Range: >+/-1E^{-6} (+/-10 Hz)

CRYSTAL (CONTD.)

- Fine Tuning Range: 1Hz total for -5V to +5V
- Long Term Stability: <$5E^{-10}$/day, <$1E^{-8}$/year
- ADEV 1-10s <$5E^{-12}$, 1000s <$1E^{-11}$
- Phase Noise 10Hz: <-130 dBc, 100Hz: <-150 dBc
- Frequency Change: <$4.5E^{-9}$ 0-71˚C
- Oscillator Circuit: 11-13.5 Vdc 40 mA
- Oven Circuit: 20-30Vdc 720 mA

HP10811A CRYSTAL OSCILLATOR



HP10811A CRYSTAL OSCILLATOR

Tom Van Baak

ATOMIC

- Intrinsically More Stable - resistant to:
    - Temperature
    - Pressure
    - Humidity
    - Vibration
    - Acceleration

RUBIDIUM STANDARD

Tom Van Baak

RUBIDIUM

- Very alkaline metal, 72% not radioactive
    - 28% slightly radioactive half life 48.8 billion years, 3 x age of universe
- Atomic number 37 same group as potassium, cesium
- Single electron in outer shell
- Melts at 103˚F
- 23rd most common element, more than copper

WHY RUBIDIUM?

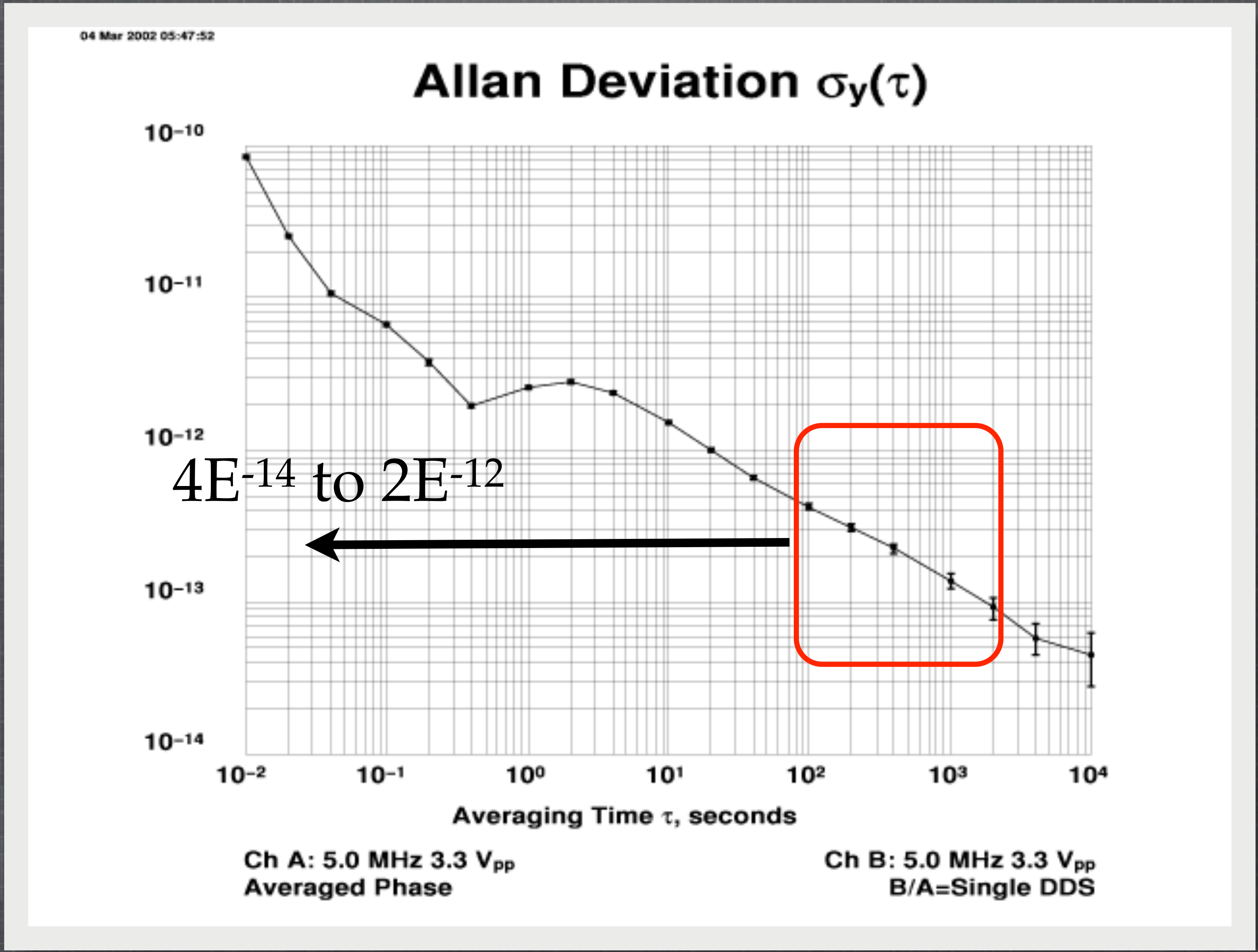
- More common & lower cost than cesium
- New development results in higher stability than cesium
- Nuclear Physics
  - Gross Structure: quantum number (describe energy levels of electrons)
  - Fine Structure: spectral lines caused by magnetic moments of electron spin
  - Hyperfine Structure: orders of magnitude smaller due to interaction of nucleus with internally generated magnetic fields
- 6.834,685 GHz

CESIUM STANDARD

Tom Van Baak

CESIUM

- Very alkaline silvery metal, 45th most abundant
- Atomic number 55, same group as rubidium, potassium
- Single electron in outer shell
- Melts at 82˚F
- Spectral emission lines define the second and meter
- 9,192,631,770 cycles of the radiation = 1 Hz, 1 M



HP5071A CESIUM STANDARD

Tom Van Baak

HYDROGEN MASER

- <u>M</u>olecular <u>A</u>mplification by <u>S</u>timulated <u>E</u>mission of <u>R</u>adiation
- Essentially a 12 GHz oscillator in a refrigerator cooled to 4 K with liquid helium
- Water freezes at 273 K (0˚ C)
- System noise temperature of 17 K looking at a 2.4 K sky
- Allowed reception of 15W Mariner IV photos of Mars received at -169 dBm by Deep Space Network 60M antenna at 8.5 bps in 1965
- FET development in 1982 allowed DirecTV RO 12 GHz K Band feed horn amp at system noise temperature of 45 K without cooling

HYDROGEN MASER

MicroSemi MHM 2010 Active Hydrogen Maser

ADEV: 2.0 10^{-15}

Weight: 475 lbs without batteries

Phase Noise: -150 dBc

Design life: 20 YR

JPL DEEP SPACE NETWORK

- 3 Tracking stations (Goldstone, Madrid, Canberra) 120° apart
- Built to track Explorer I, transferred from Army to NASA in 1958
- Voice and data comm to Apollo spacecraft
- Now comm to all planetary exploration spacecraft



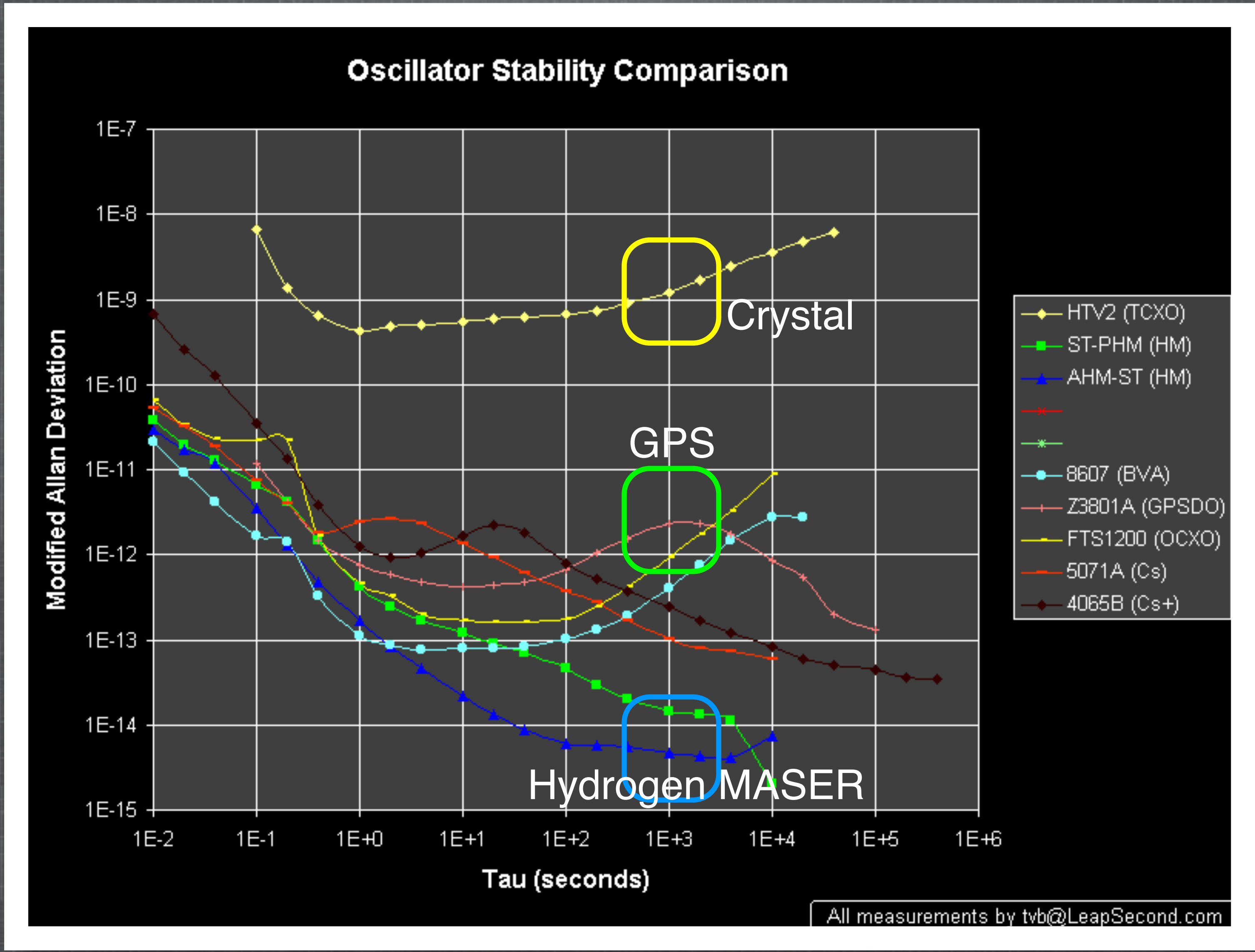
WHAT IS $1E^{-13}$?

- 1 in a million (1 ppm) = $1E^{-6}$ or 10 parts in 10 million or about +/-145 Hz at 2 Meters (145 MHz)
- 0.5 or 0.05 ppm = $0.5E^{-6}$ or 5 E^{-7} = modern Icom rig stability = 1 part in two million
- $1E^{-13}$ = 1 part in a 10 million million = 1 second in 317,097 years
- $1E^{-14}$ = 1 second in 3,170,970 years
- $1E^{-11}$ is +/-0.1Hz at 10 GHz

RANGE OF CLOCK PRECISION

- 10-2 = 1%≈15min/day
- 10-4 = 0.01%≈1min/week (good wrist watch)
- 10-6 = 1ppm≈0.1s/day
- 10-8 ≈ 1ms/day
- 10-10 ≈ 10μs/day ≈1s/300 years (quartz oscillator)
- 10-12 = 1ppt≈100ns/day
- 10-14 ≈ 1ns/day ≈1s/3,000,000 years (rubidium)
- 10-16 ≈ 3ns/year≈3s/billion years
- 10-18 ≈ 1 s / 30 billion years

From Tom VanBaak



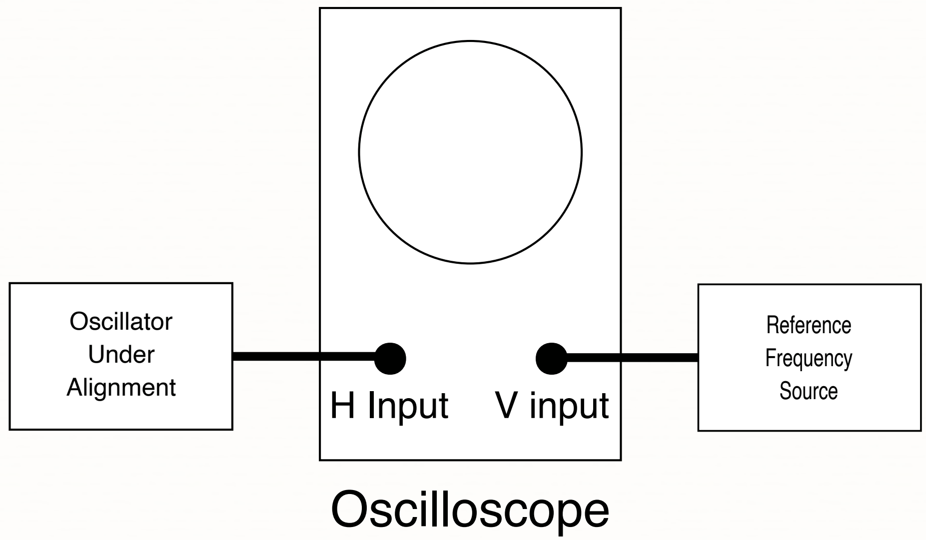
VARIETY OF OSCILLATOR STABILITY CURVES

Tom Van Baak

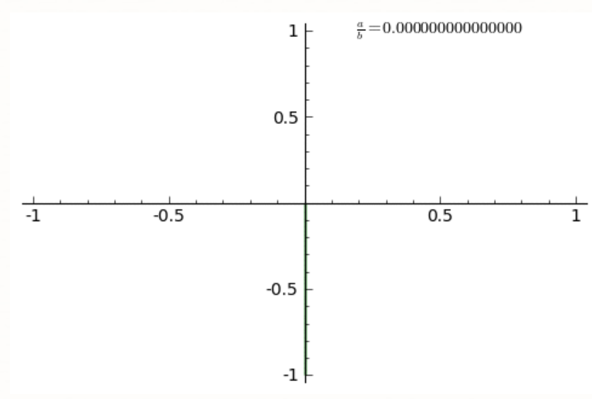
My Personal Quest For Precision

- 1982 Heathkit frequency counter with 10 MHz ovenized oscillator
  - 10^{-6} to 10^{-8}
- 1986 WWVB receiver to calibrate the Heath oscillator
  - 10^{-9} to 10^{-12}
- 2000 Shera GPS DO to calibrate the Heath oscillator
  - 10^{-12} to 10^{-13}
- 2019 SRS GPS DRO to calibrate the Heath oscillator
  - 10^{-14}

OSCILLATOR CALIBRATION



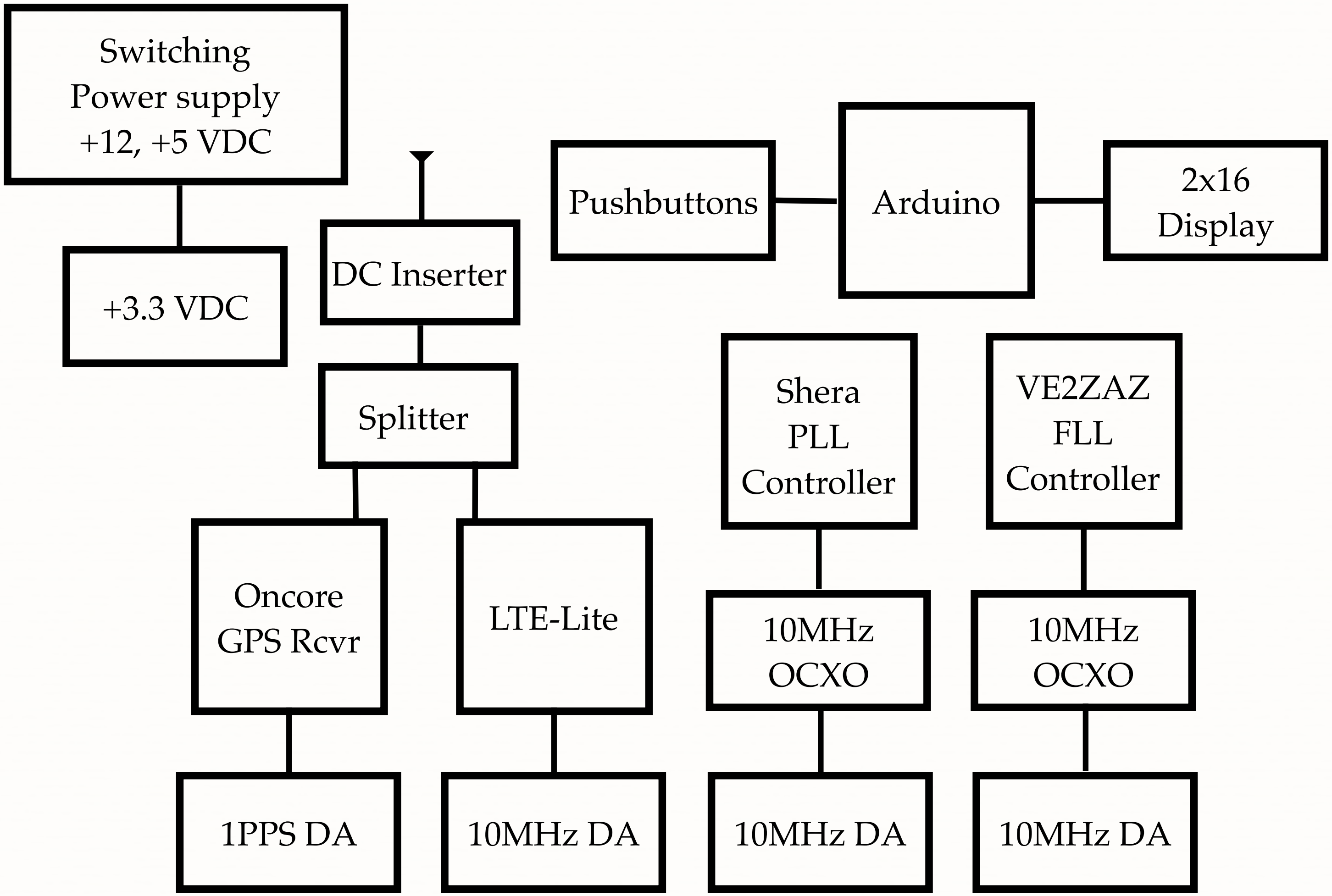
Adjust oscillator under alignment for a stable Lissajous figure on oscilloscope



PRECISION OSCILLATOR

- Brooks Shera PLL device in 1998 (QST)
- GPS disciplines crystal oscillator to HM/Cesium levels
- Boards acquired in 2000
- VE2ZAZ had different FLL approach
- Enclosure (2-4 revs) and software hardest parts
- Commercial (tiny) Jackson Labs oscillator only $178
- TAPR kits very helpful

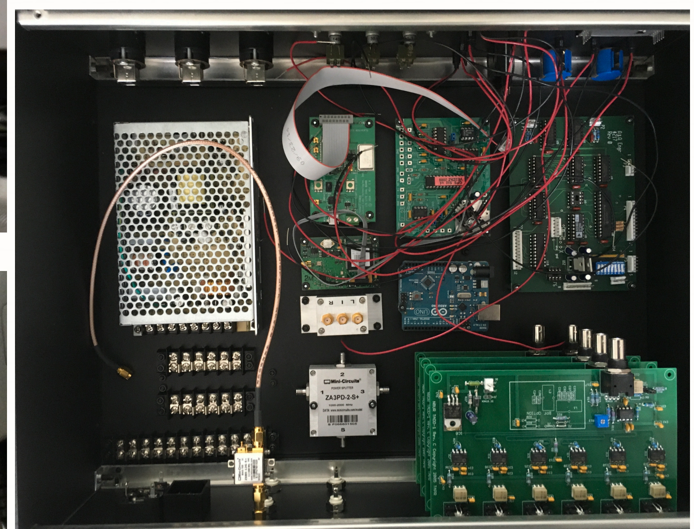
VERSION 1


Switching
Power supply
+12, +5 VDC
+3.3 VDC
DC Inserter
Splitter
Oncore
GPS Rcvr
LTE-Lite
1PPS DA
10MHz DA
Pushbuttons
Arduino
2x16
Display
Shera
PLL
Controller
VE2ZAZ
FLL
Controller
10MHz
OCXO
10MHz
OCXO
10MHz DA
10MHz DA

COMPONENTS

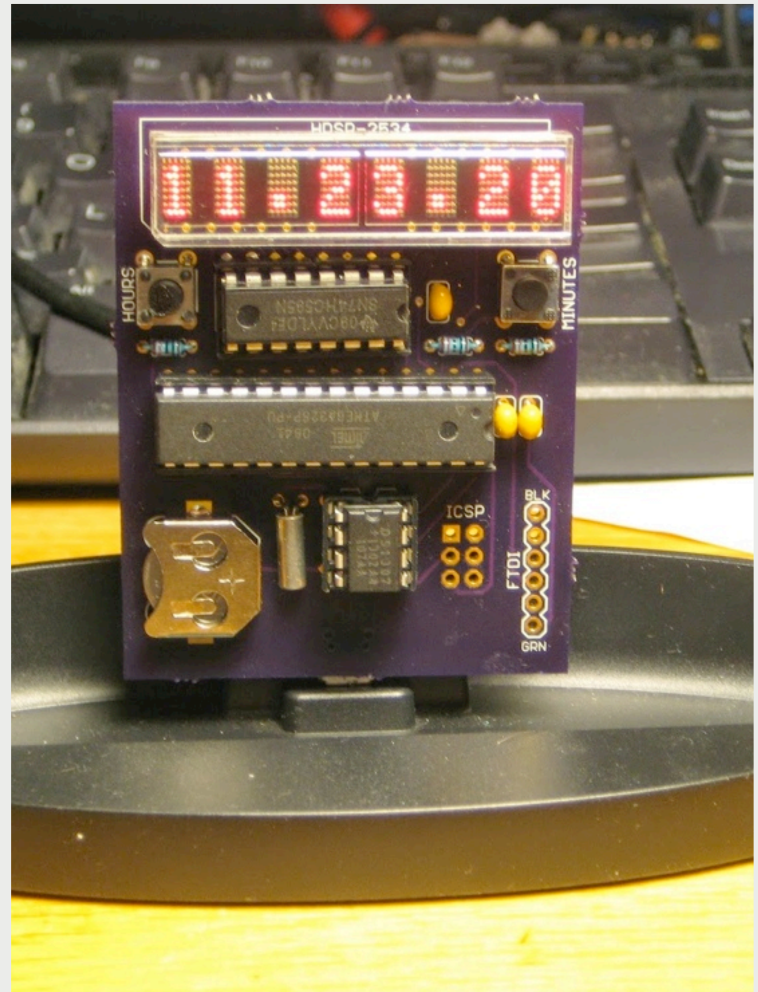
- Switching Power Supply (12V, 5V, 3.3V)
- Character Display Module (2x16)
- Enclosure (FrontPanel Express, Hammond)
- Computer Module (Arduino Mega)
- Controllers (Shera PLL, VE2ZAZ FLL, Jackson Labs)
- 10 MHz & 1PPS Distribution Amplifiers (TAPR)
- GPS Receiver (Motorola)
- Oscillators (3 different 10 MHz)
- I/O (Pushbuttons, USB Ports, Meter, Switches)

GPS OSCILLATOR



VERSION 2

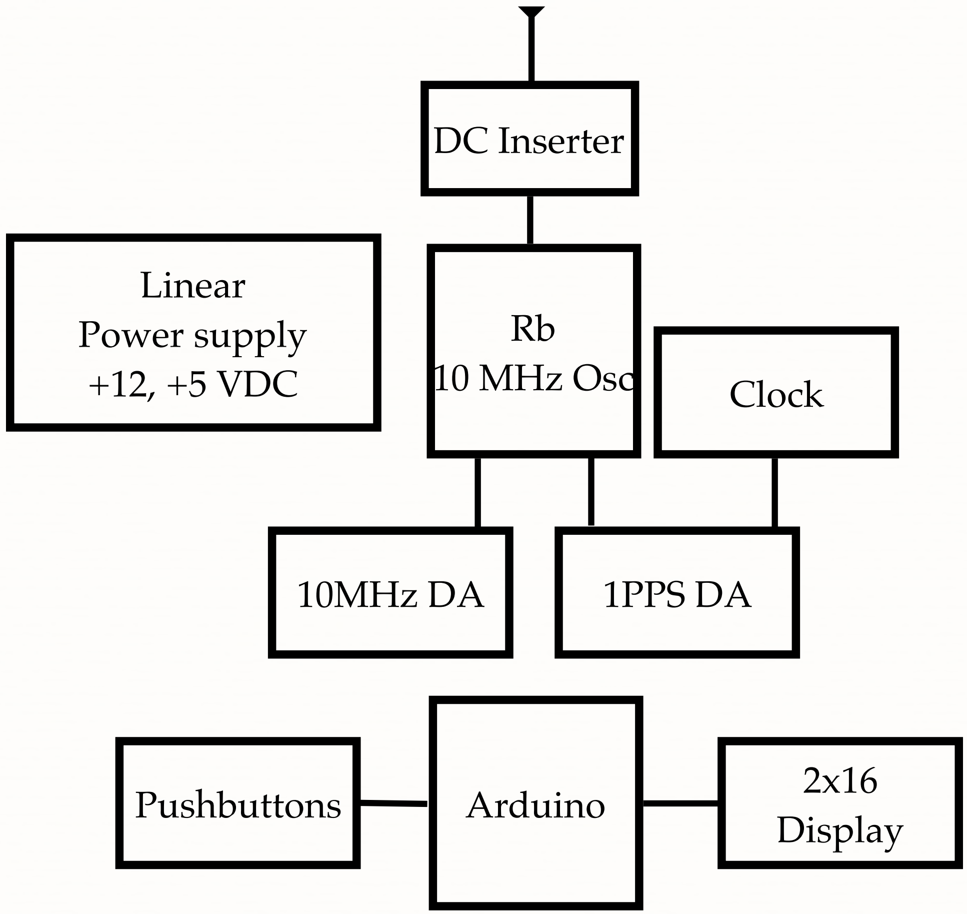
- HDSP Clock From Florin Chipri, Toronto
  - http://timewitharduino.blogspot.com
- Modified to accept 1PPS via DS1308 instead of DS1307
- Software improvements by W3SEH



VERSION 2

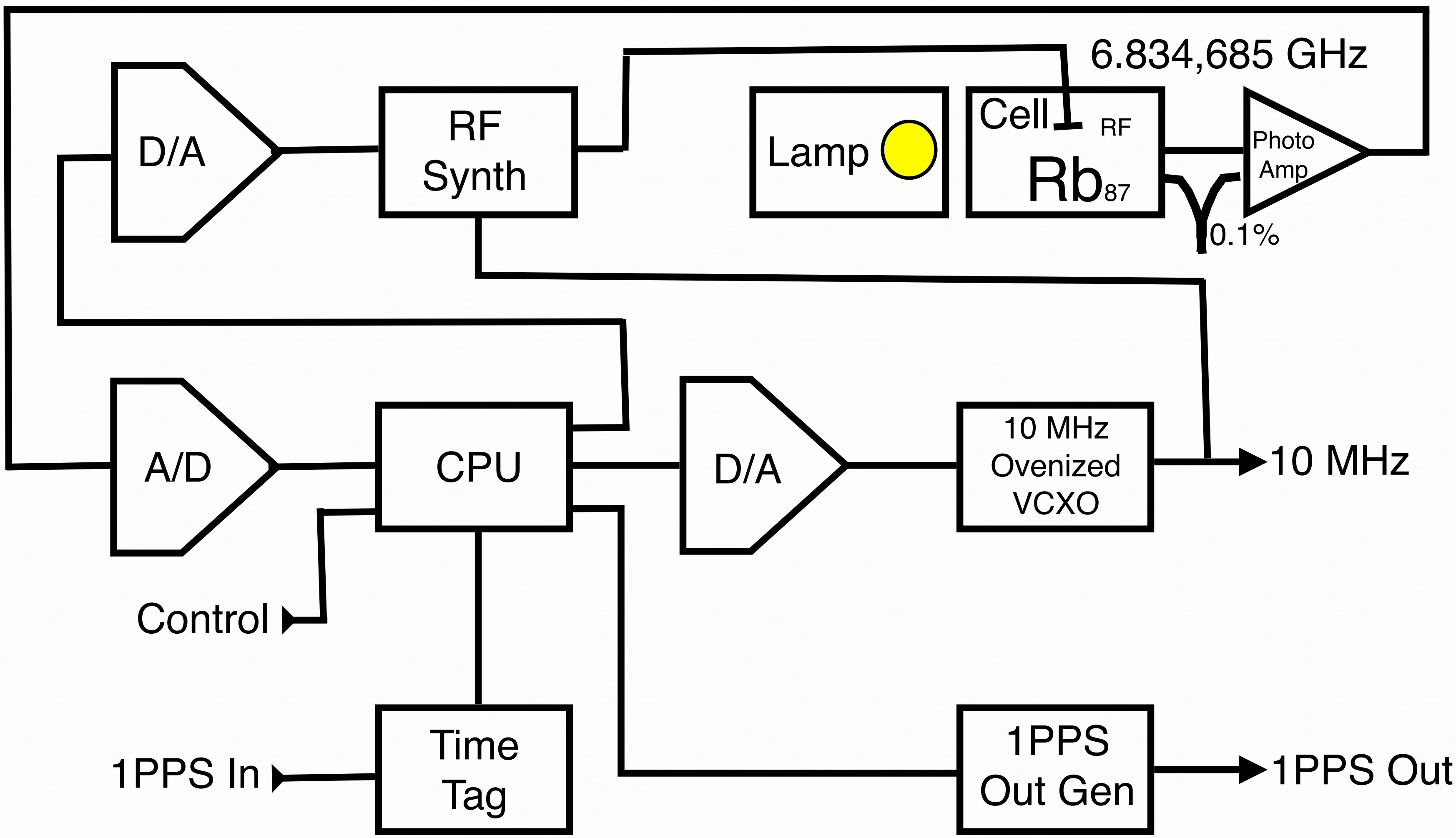
- Rubidium + GPS oscillator from Jackson Labs!
  - 1”x3”x4”
  - $3500
- 10 MHz distribution
- 1 PPS distribution
- Linear power supplies

VERSION 2


DC Inserter
Linear
Power supply
+12, +5 VDC
Rb
10 MHz Osc
Clock
10MHz DA
1PPS DA
Pushbuttons
Arduino
2x16
Display

ATOMIC GPS CLOCK II

RUBIDIUM OSCILLATOR

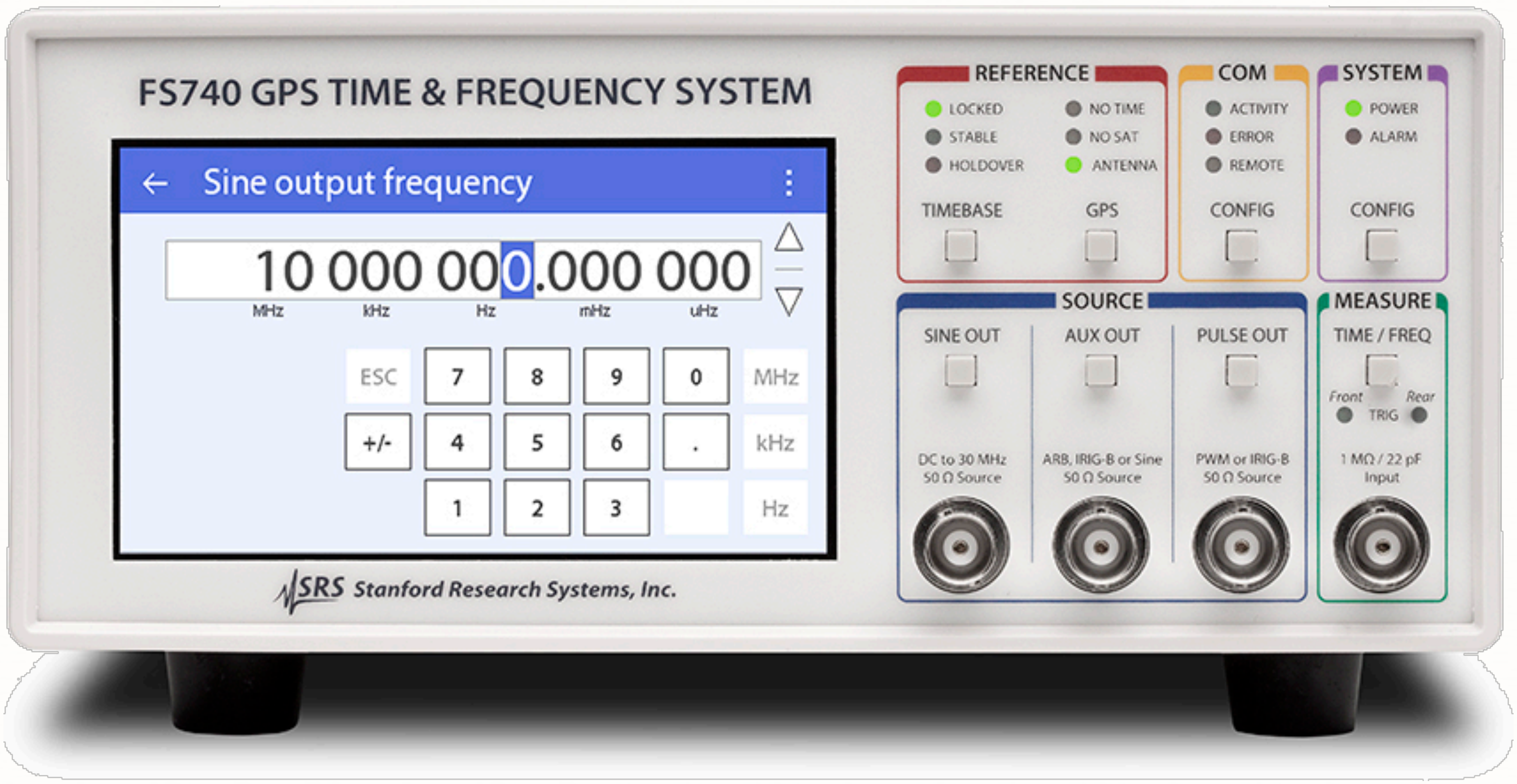


K6JEY

COMPONENTS

- Linear Power Supply (12V, 5V, 3.3V)
- Character Display Module
- Enclosure (FrontPanel Express)
- Computer Module (Arduino Mega)
- 10 MHz & 1PPS Distribution Amplifiers (TAPR)
- Rubidium Oscillator + GPS Receiver (Jackson Labs)
- Clock
- I/O (Pushbuttons)

A GPS DISCIPLINED RUBIDIUM PRECISION OSCILLATOR



GEPETTO GPS OCXO

SRS FS740 RUBIDIUM OSCILLATOR VS GEPETTO OCXO

FS740

- Achieves GPS cesium lock within ~5.5 hours
- Frequency stability ~5 E^{-13} to ~5 E^{-14}
- Generates 1 mHz to 30.1 MHz
- Measures up to 120 MHz
- Measures Allan Deviation
- Phase noise <-130 dBc/Hz
- Sine, square, triangle, IRIG time outputs
- Cost ~$6000

Gepetto OCXO

- Achieves GPS cesium lock within ~10 hours
- Frequency stability ~1 E^{-10} to ~1 E^{-11}
- Generates 10 MHz
- Cost <$350

FREQUENCY MEASUREMENT TEST

- www.arrl.org/frequency-measuring-test
- www.k5cm.com conducts the test
- 40, 80, 160 Meters for 2 minutes each once per quarter
- Entry level ~1/1000th of a Hertz to 1/10,000th Hz normal
- Speed of acquisition and reporting are important
- No prizes or certificates, just goofy