GPS Timing and Synchronization: Characterization and Spatial Correlation

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think beyond the possible

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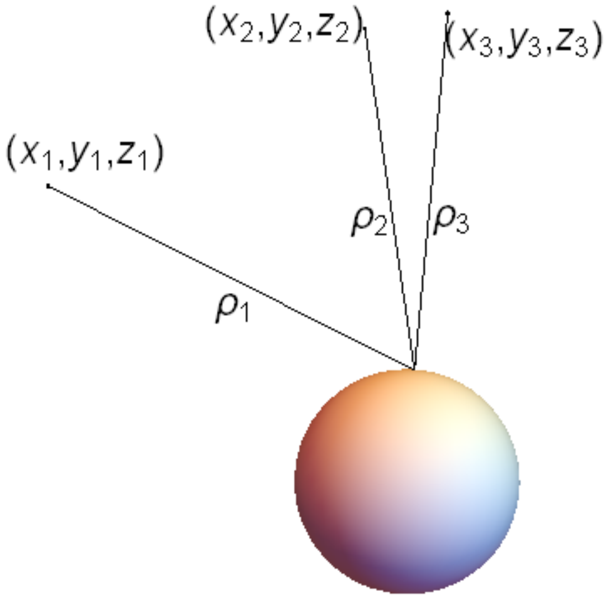
GPS Basics

GPS Constellation: 30+ Satellites, orbiting earth at 26.6Mm, each carrying a Cesium atomic clock, updated periodically by the US Air Force (~ every 4 hrs)



$$|r - r_i| = \rho_i \qquad \rho_i = c(t_r - t_i)$$

$$(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2 = c^2(t_r - t_1 + \Delta t)^2$$

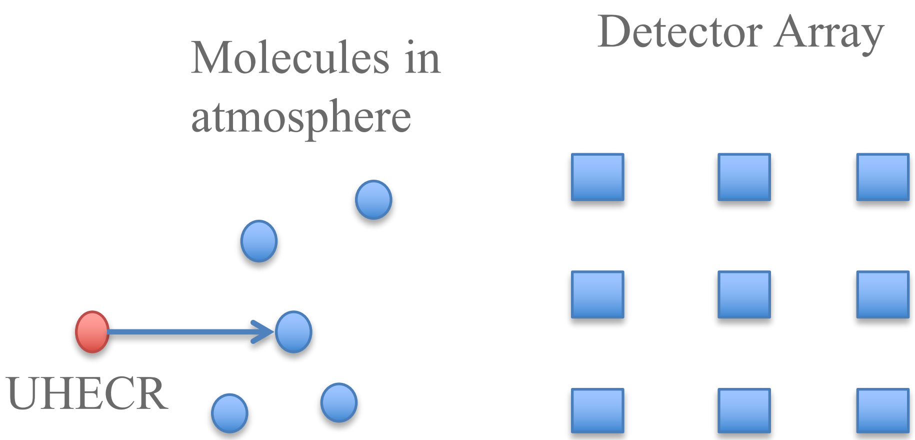
$$(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2 = c^2(t_r - t_2 + \Delta t)^2$$

$$(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2 = c^2(t_r - t_3 + \Delta t)^2$$

t_r is the time the message is received, and t_i is the broadcast time of each satellite.

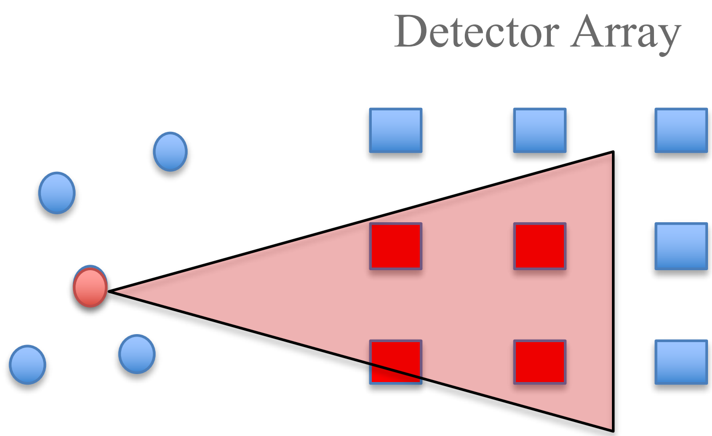
GPS works by finding 'pseudoranges' from satellites through timing, then solving the above equations. If position is not needed, they can be used as an over-determined system to obtain the time and time error.

Why do we care? – Auger



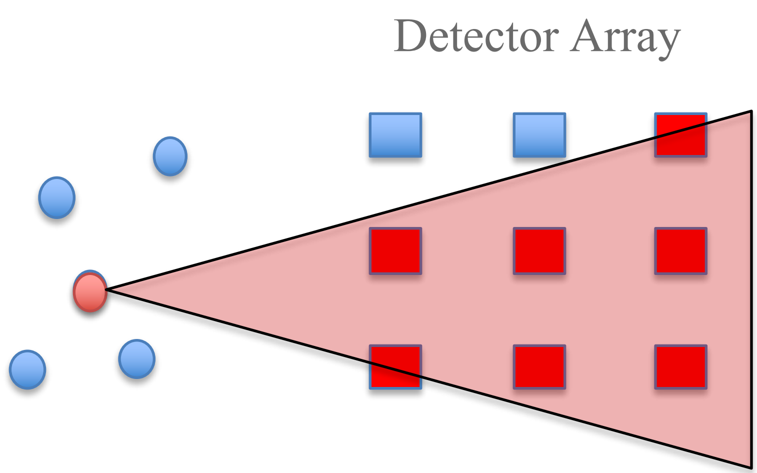
Timing is used to reconstruct point of first interaction, which along with shower core gives arrival direction

Why do we care? – Auger



GPS is used to synchronize the clocks between Auger stations

Why do we care? – Overall



Many experiments in disparate fields use GPS for time synchronization:

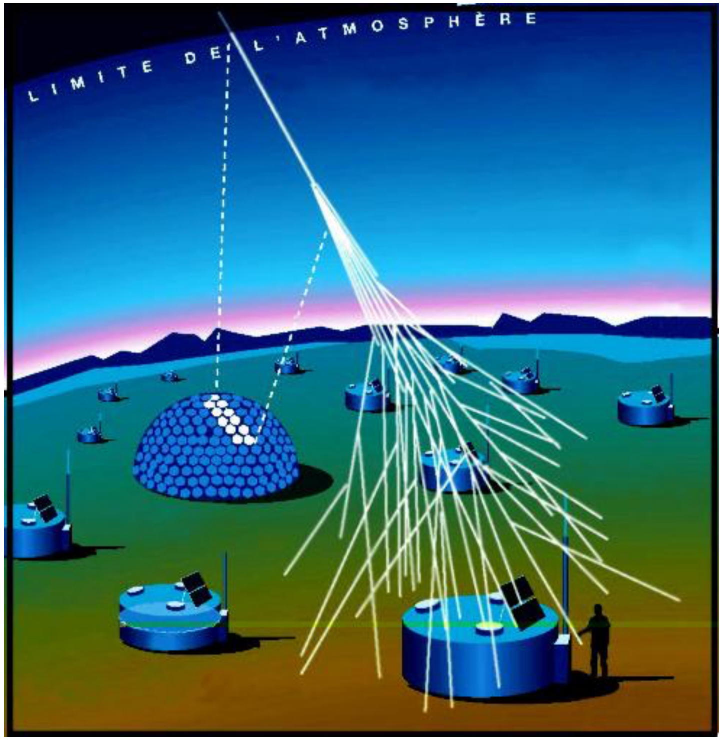
- Auger
- LIGO
- ICARUS
- Axion Dark Matter Detection

The Question

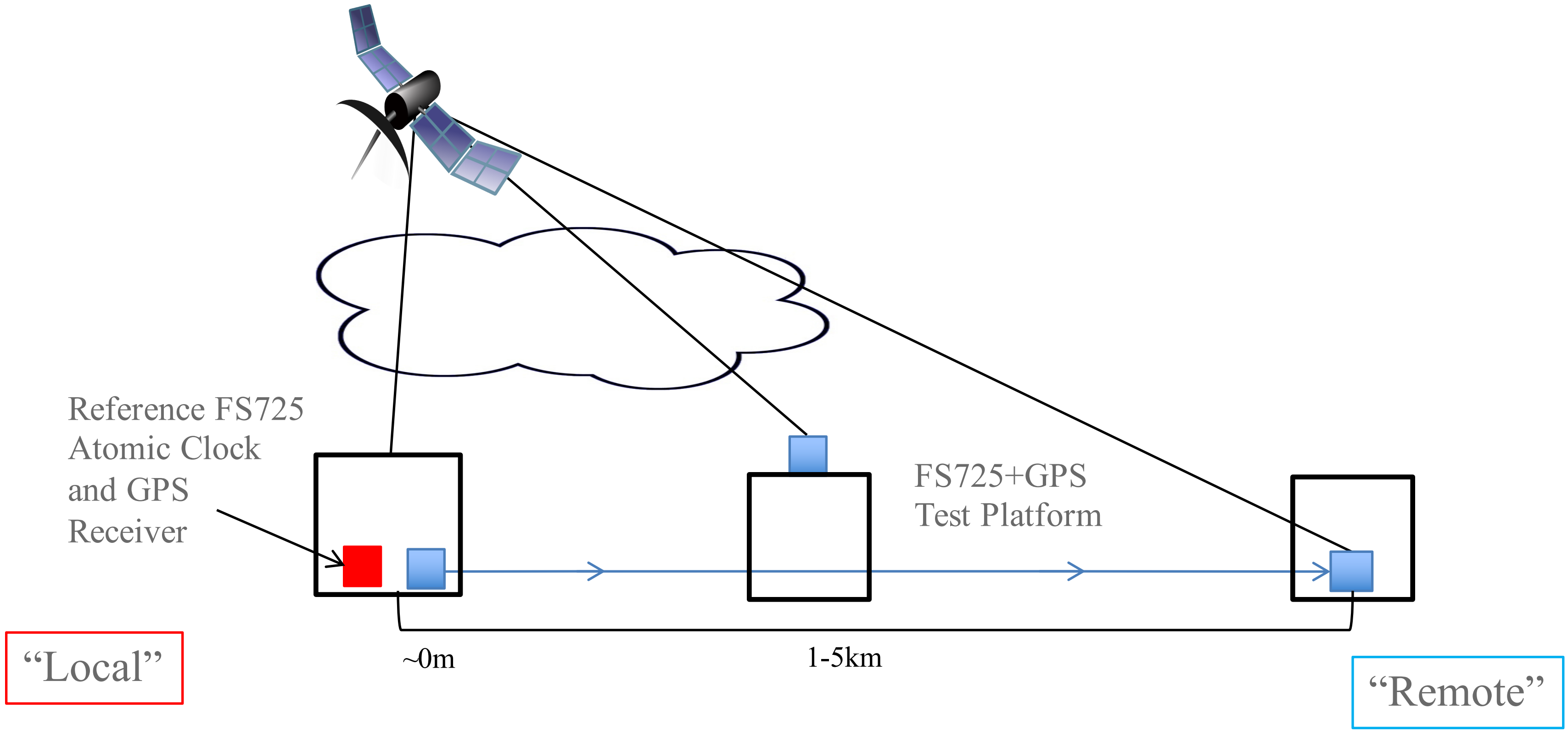
Occasionally overheard at Auger meetings:

"GPS receivers can have fluctuations between then as large as 30ns which will affect our timing"

How independent or correlated are two GPS receiver's timing solutions as a function of distance?



The Experiment: Setup

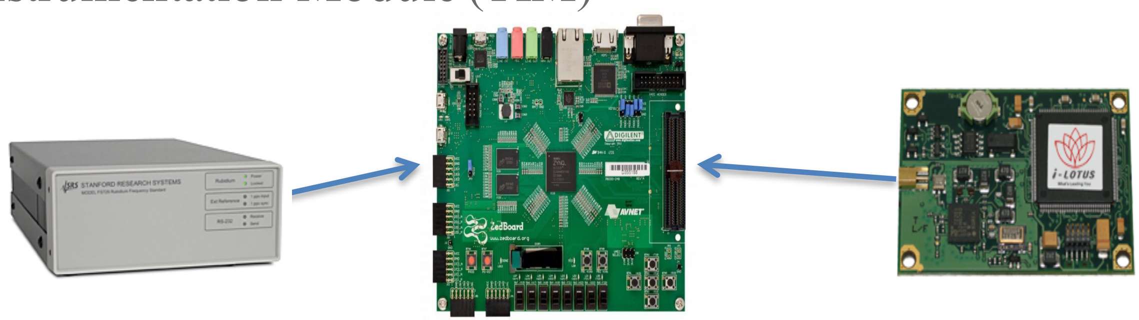


The Experiment: Timing Instrumentation Module

Ideally you have:

- A time-tagging (TTAG) system with a higher resolution than the accuracy of the GPS Receiver
- A frequency standard that is more stable than GPS on short and medium time scales

We use an FS725 Rubidium Frequency Standard (aka Atomic Clock or AC) and ZedBoard (SoC+FPGA) to measure timing of M12M GPS Receiver make up Timing Instrumentation Module (TIM)



FS725
~.2ps/100s
1ns TTAG resolution

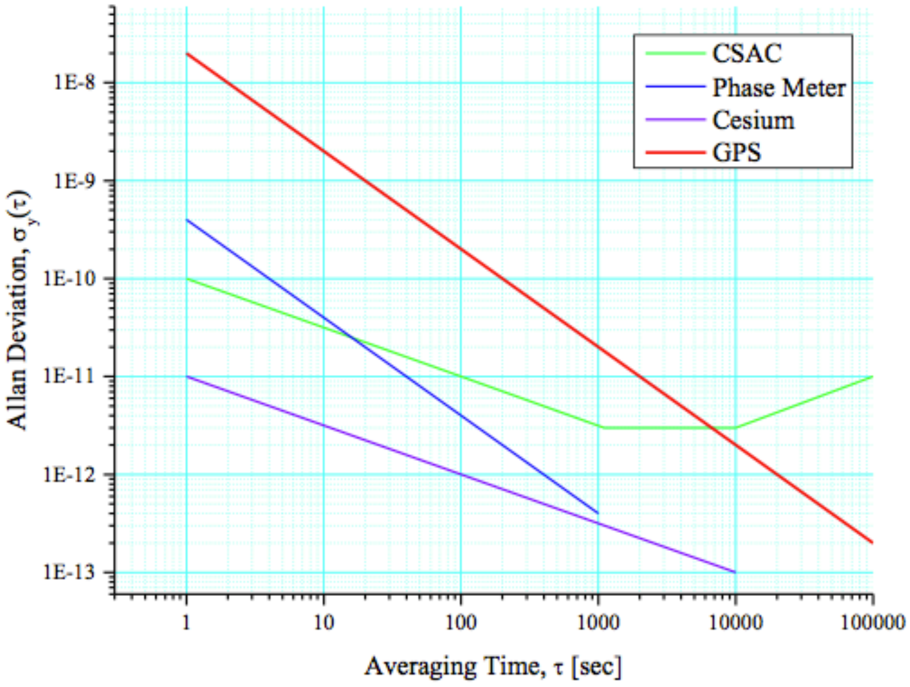
ZedBoard
Timetagging:
750Mhz, 1.33ns

M12M GPS Timing Receiver
“2ns”, really ~4ns

Procedure: Atomic Clock Training

There are a few caveats to using an atomic clock to measure GPS:

1. They must be trained/disciplined to a GPS unit to maintain long term stability

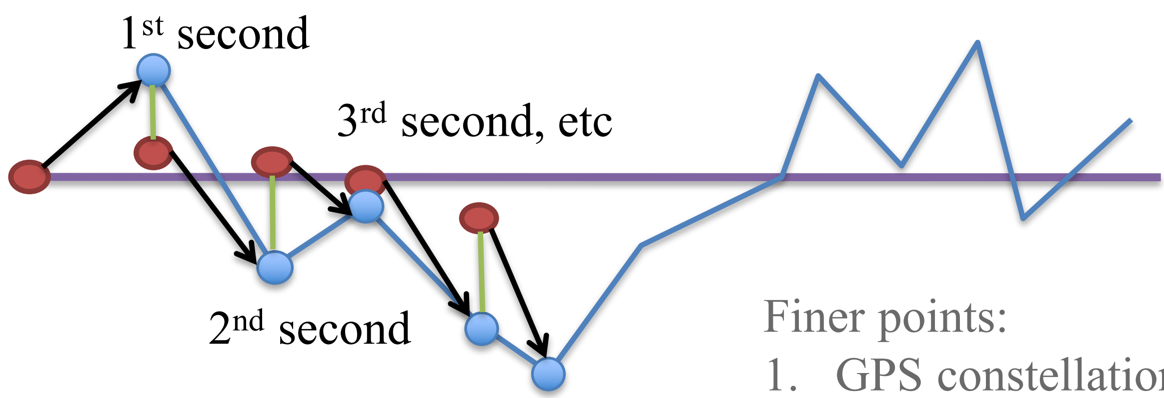


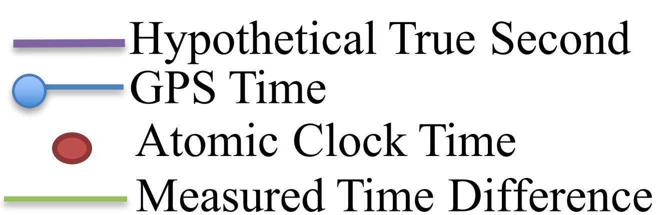
Allan Deviation (ADEV) is a measure of frequency stability- basically the running standard deviation of the difference in frequency between successive measurements

Procedure:
Atomic Clock Training

There are a few caveats to using an atomic clock to measure GPS:

1. They must be trained/disciplined to a GPS unit to maintain long term stability – Acts as low-pass filter for timing, training accuracy increases over operating time





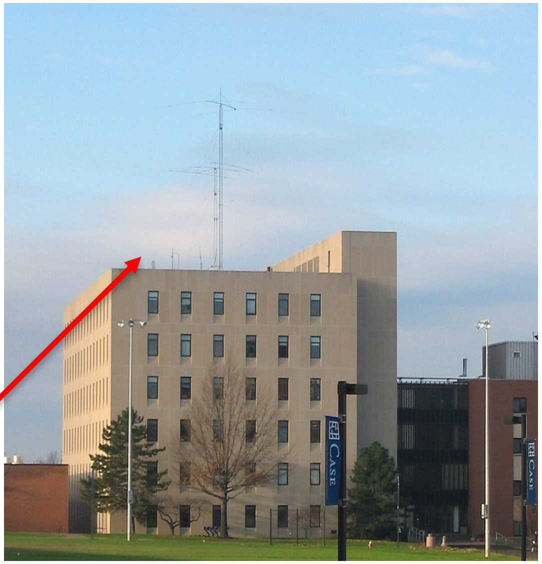
Finer points:

1. GPS constellation trains to UTC
2. GPS receiver trains to constellation
3. Atomic clock trains to receiver and attempts to pick out the true frequency corresponding to 1PPS

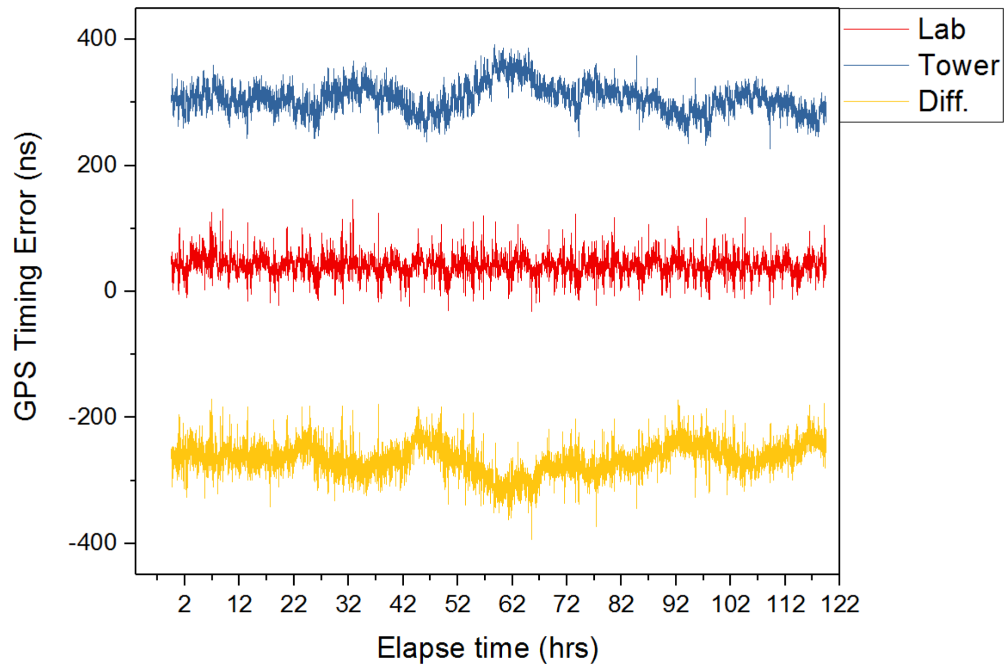
Procedure:
Data Taking

We made a handful of separate attempts to measure this quantity:

1. Using Chip Scale Atomic Clocks and about 30 min data runs
2. Fixed set-up in radio tower using week long data runs
3. Moving setup in running car, stopping and surveying for 4 hours at a time
4. **Move set up between "sites"**
    1. **Clocks must be running for 6-8 hours to fully acquire the 1PPS frequency of the GPS constellation**
    2. **Antennae mounted for maximum sky coverage**
    3. **Run for 24-48 hours and move**

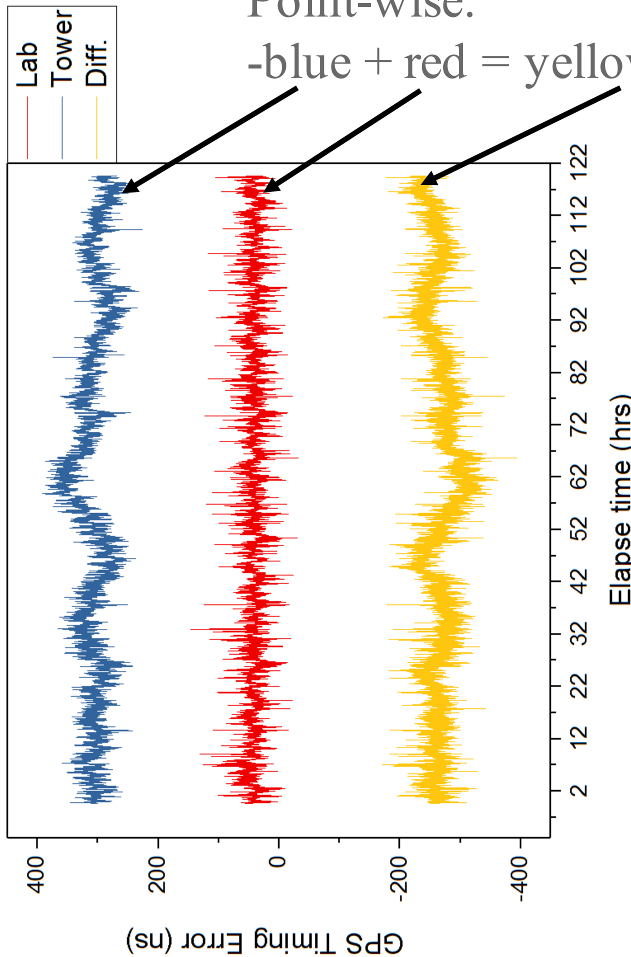


Analysis:
The Measurement

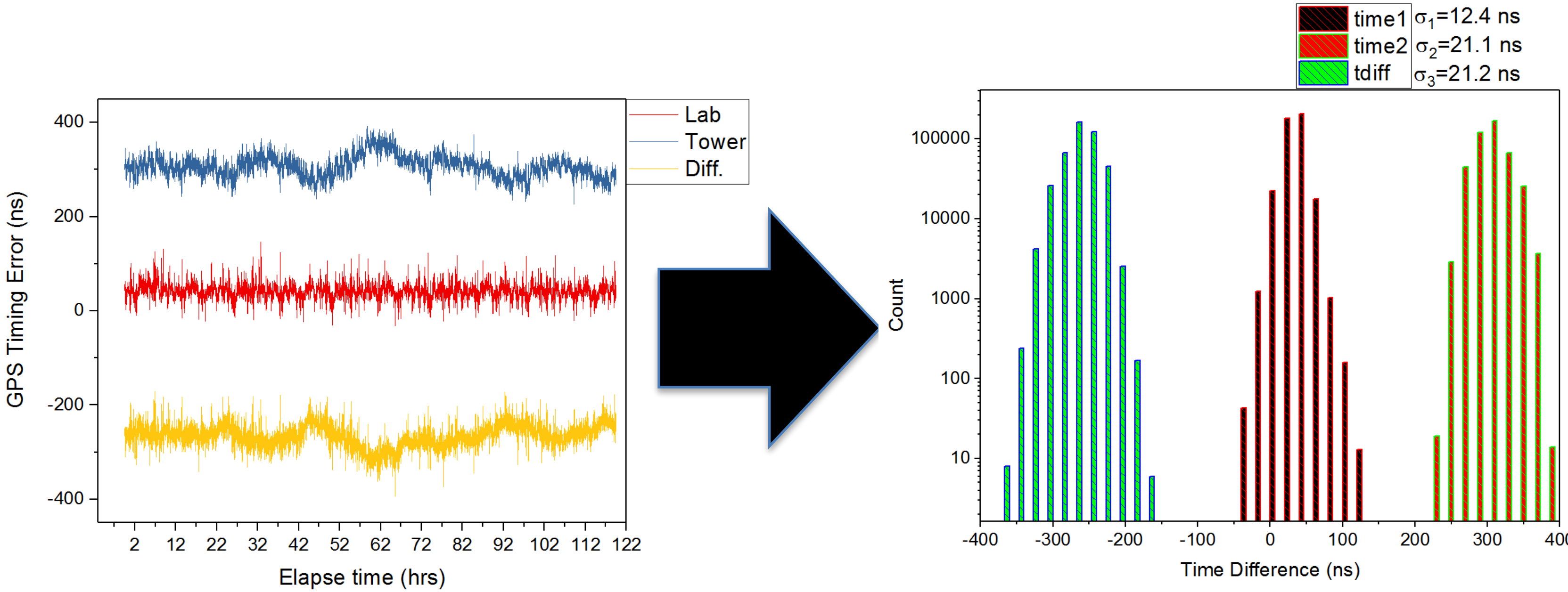


Analysis:
The Measurement

Point-wise:
-blue + red = yellow



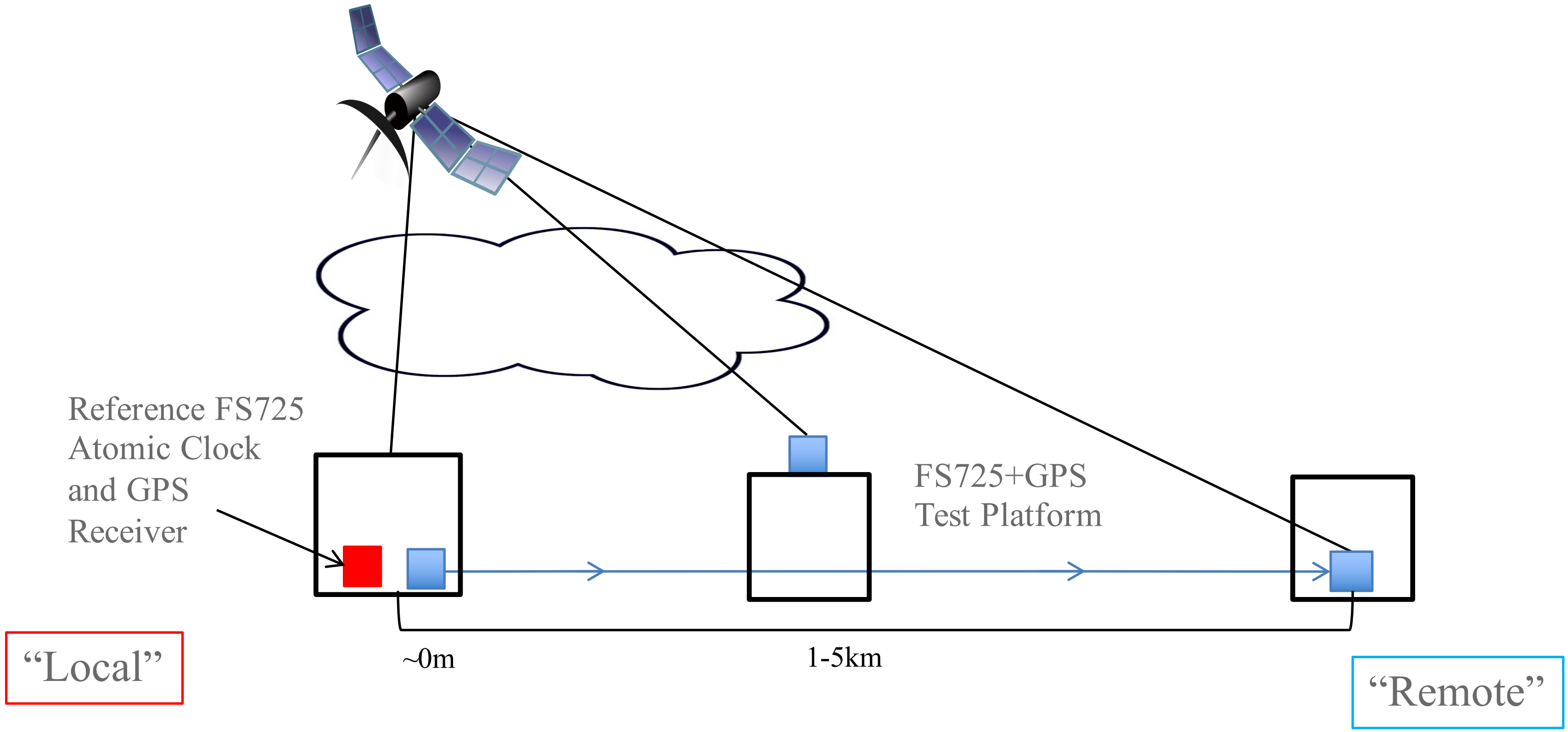
Analysis:
The Measurement



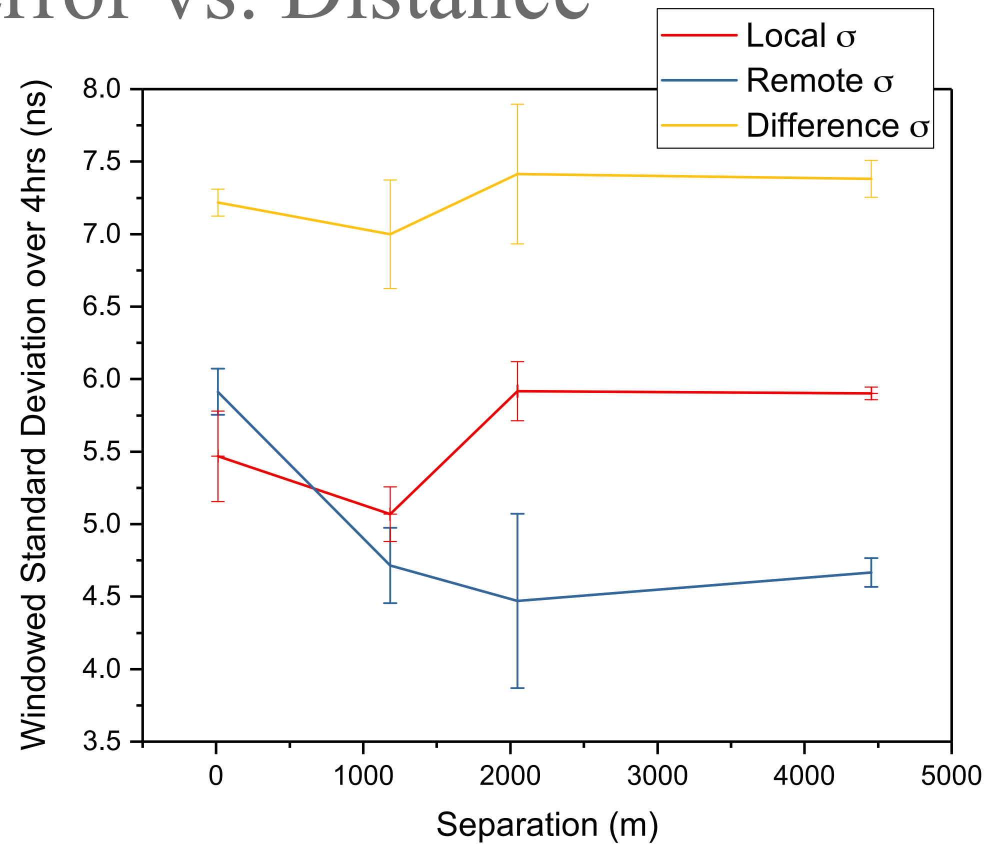
Gives one data point

(From an engineering run, not actual measurement data)

The Experiment: Setup



Results:
Error vs. Distance

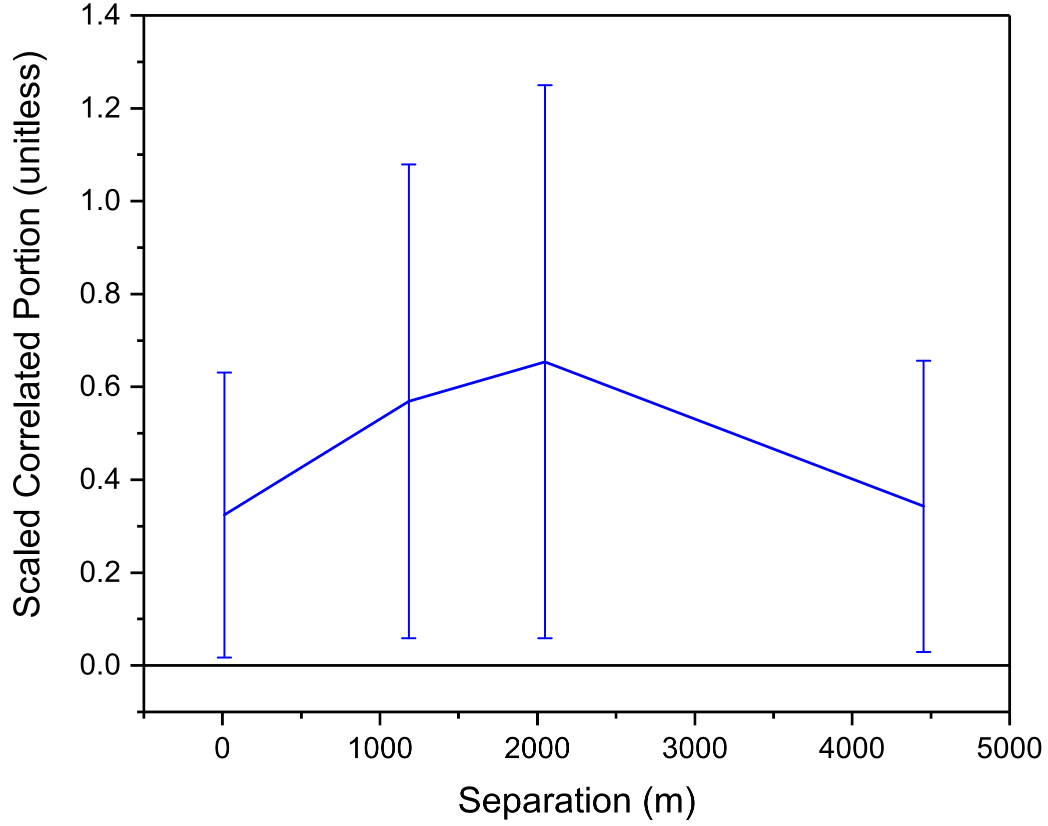


Window chosen by looking for lowest error sampling from previous versions of the experiment

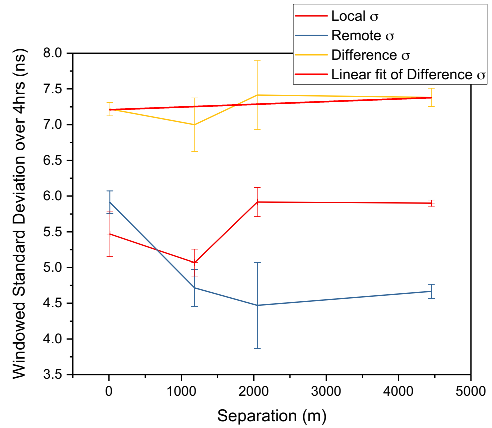
Error bars are statistical, sky coverage, run duration and weather are folded in

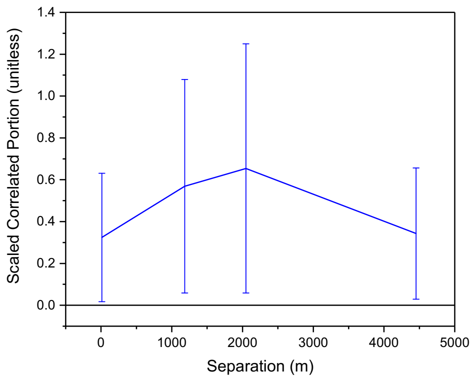
Results: Correlation

*Note: This plot has been adjusted to exclude training errors from the atomic clocks



Conclusions: Correlation





- GPS timing solutions are correlated, but the inaccuracies in the solution due to the receiver, at least for the M12M, dominate the noise of the units. For practical purposes, they can be viewed as being independent timing sources.

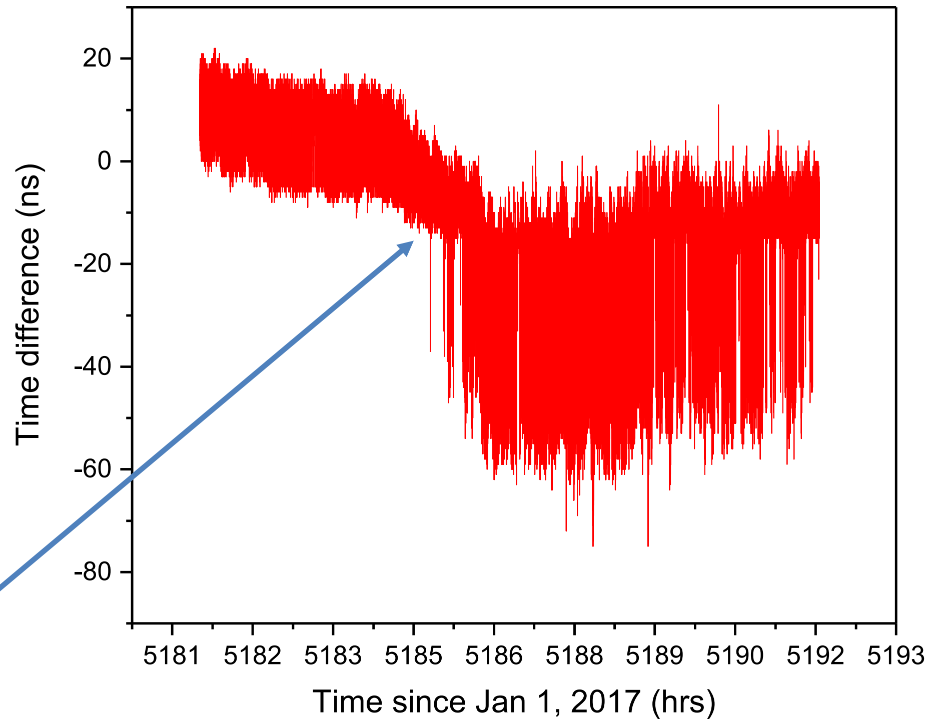
- In the context of Auger, the lack of correlation is only worrisome if the deviation of each receiver is greater than one time bin.
  - For the current Auger detector, even the largest fluctuations are within one bin, that said, the m12m receivers will only be installed in the upgrade
  - For the Prime upgrade, we may want to have each station collect it's own calibration histogram (as is currently done), since the largest fluctuations can be as much as 4 timing bins, however the standard deviation of the timing coming out of the M12M is about half a bin.

- We plan to do another run of the experiment to try to get more data points with better statistics at each one over the course of the next month.

Results: Characterization

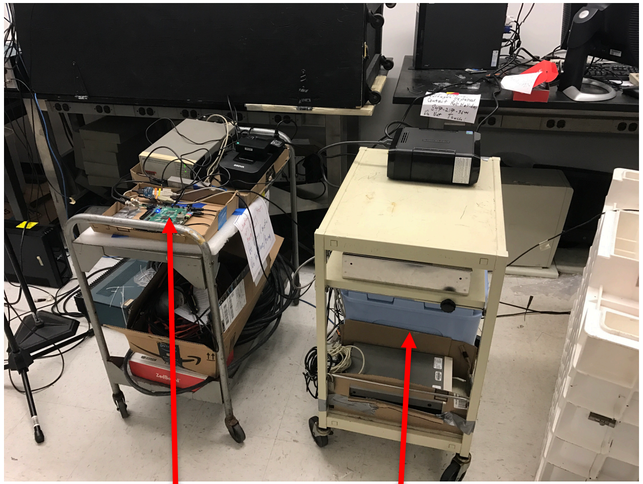
- Weather effects:
  - Before storm: SD=6.7 ns
  - During Storm: SD=15.0 ns

Data from “site4”, unused



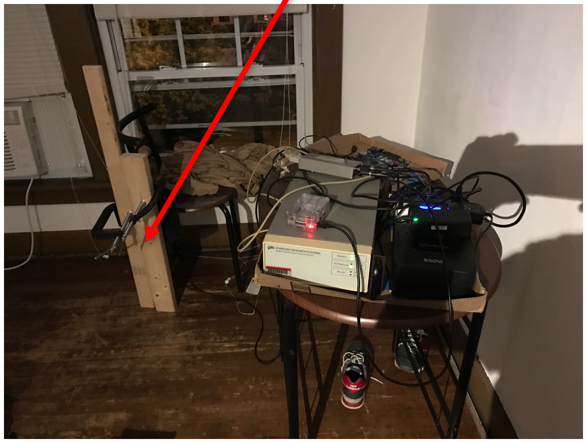
Fairly violent thunderstorm hits

Thank you for listening!

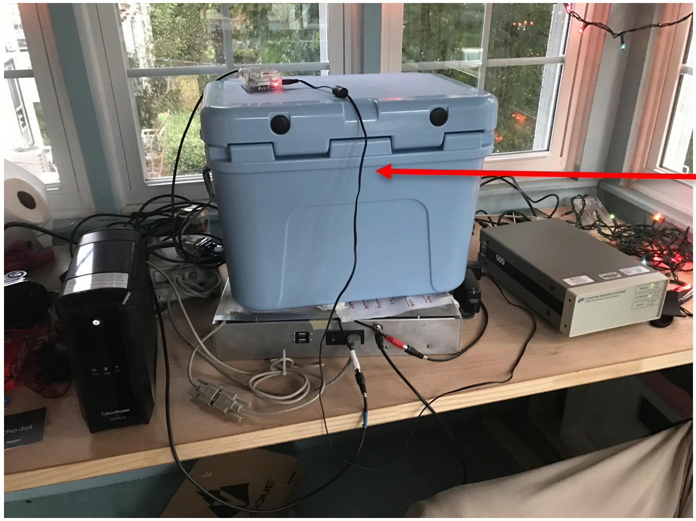


Local Remote

Extremely high tech mounting hardware (c-clamps and leftover woodshop pieces)



Contact me at rph32@case.edu for more information



Thermal low-pass filter aka cooler

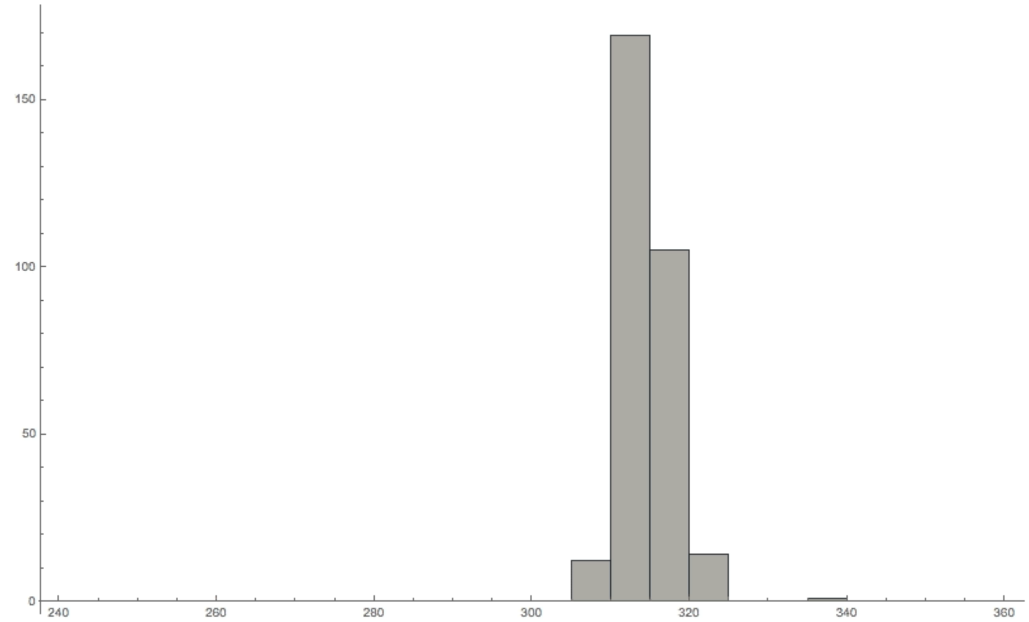
Thanks to Sean Quinn, Ryan Lorek, Jackson Kishbaugh-Maish, and Corbin Covault for their help in completing this measurement. Special thanks to Patrick Allison and Jim Beatty for lending us their clock and vetting some of our ideas!

BACKUP

Results: Characterization

- Gaussian of Gaussians:

As small shifts in ionospheric conditions and satellite visibility occur, the distribution being sampled moves around.



BACKUP

Conclusions: Characterization

- Gaussian of Gaussians
- Weather effects:
  - Before storm: SD=6.7 ns
  - During Storm: SD=15.0 ns
- Minimum and maximum differences:
  - -29 ns to 24 ns
- A finer point- the sawtooth correction varies in how necessary it is, there are different "phase alignments" that the receiver can have relative to the GPS constellation
  - This is its own talk

BACKUP

Procedure: Atomic Clock Training

There are a few caveats to using an atomic clock to measure GPS:

1. They must be trained/disciplined to a GPS unit to maintain long term stability
2. They are exceptionally sensitive and therefore need to train for 8+ hours to obtain a good fix on the GPS constellation's frequency
   1. Training can be played with to be faster but less accurate
   2. Chosen to minimize "co-training" error
   3. Moving them tends to destabilize training (~200ns tops, ~20ns min)

BACKUP

Results: Unadjusted Correlation