Combined observations of GNSS and astronomical sources: Can you see both worlds through a single lens?

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Reference Frames

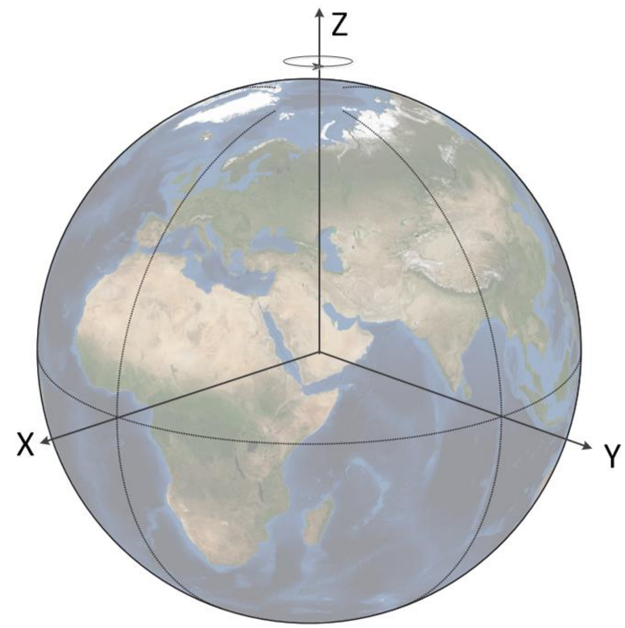
Geoscience measurements fundamentally linked to positions

- These days that often means GPS . . .

  . . .which means we are often implicitly tied to the GPS reference frame

Demanding measurements require accurate and stable reference frames

- We don't want error in reference frame leaking into results!
- Or dominating….



This work grew out of thinking about unconventional ways to make measurements that define reference frames

The reference frame for science

The International Terrestrial Reference Frame (ITRF)

– Realization of the International Terrestrial Reference System (ITRS)

– You access a realization every time you use a GPS measurement

- The WGS84 reference frame is intentionally aligned to the ITRF[1]
- ITRF comes to you through the broadcast (or precise) ephemeris

> "Stability and accuracy of the ITRF over long time periods is a primary limiting factor for understanding sea level change, land subsidence, crustal deformation, and ice sheet dynamics"

National Research Council Report on Precise Geodetic Infrastructure, pg 90

> "A target accuracy of 0.1 millimeters per year in the realization of the origin of the ITRF relative to the center of mass of the Earth system (geocenter stability) and 0.02 parts per billion per year (0.1 millimeters per year) in scale stability."

NRC Report, pg 95

[1]*NGA Standard, NGA.STND.0036_1.0.0_WGS84*

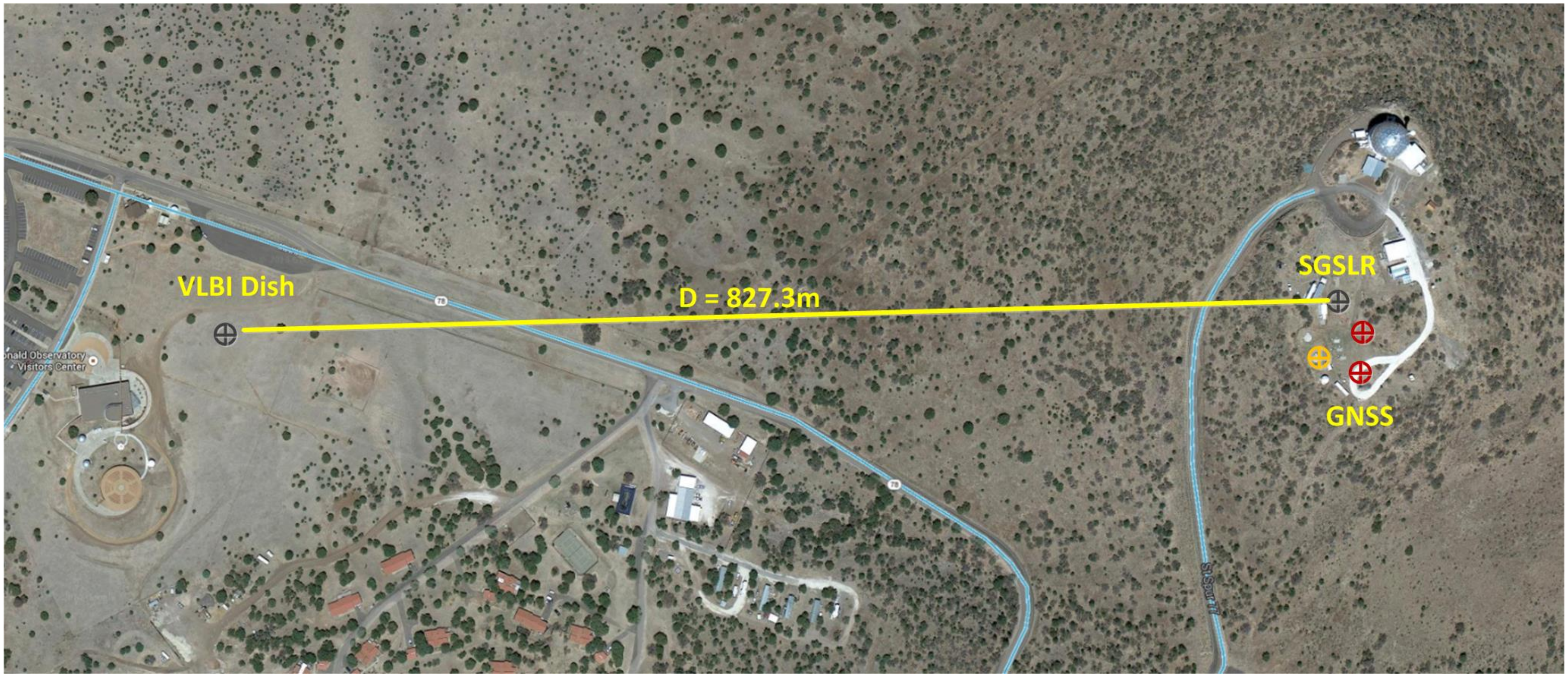
How are reference frames established?

Reference frames need data

- Satellite Laser Ranging (SLR)
- Very Long Baseline Interferometry (VLBI)
- GNSS, DORIS(?)

Fundamental Stations

- Bring all instruments together at one site
- Total station ranging between instruments



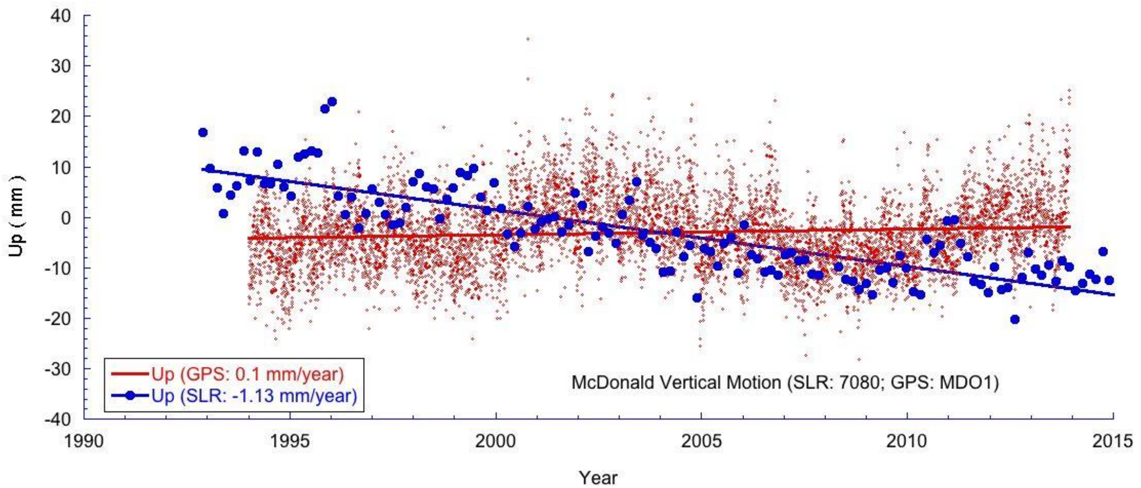
McDonald Geodetic Observatory Layout
NASA Space Geodesy Project

Measurements can and do disagree

Even closely placed instruments can show different trends

Electrical phase centers can move, especially so at the levels 0.1mm/year

Electrical phase centers of instruments are often not physically realized points



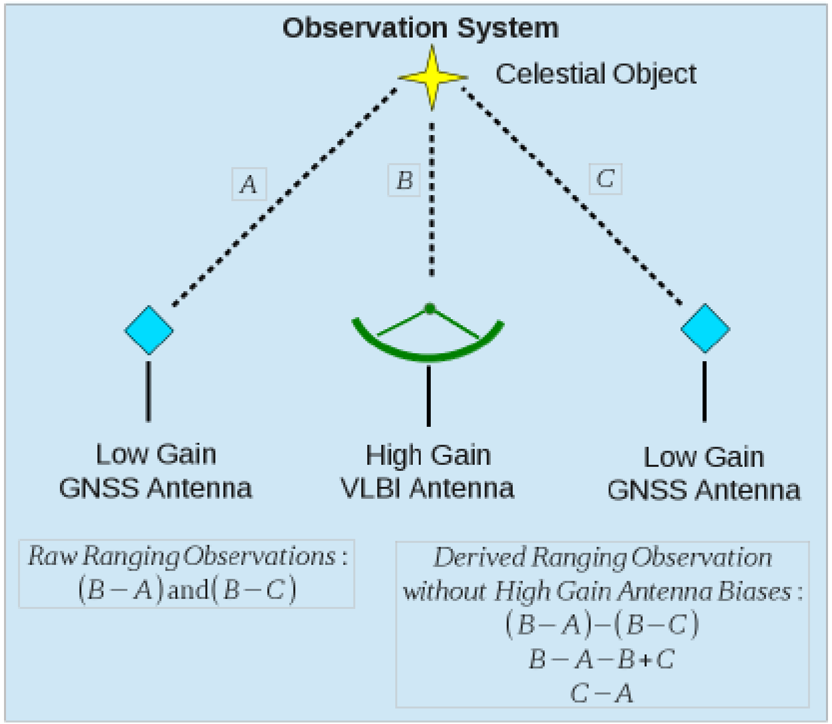
Courtesy S. Bettadpur, J. Ries, UT Center for Space Research

Closely placed GPS and SLR vertical residuals

- Distinctly different vertical motion trends over 20 years
- 40-50 ft separation

When measurements from differing techniques disagree, how do we seek truth?

What if we could combine instruments?



Is it possible to sense GNSS signals and astronomical source signals via the same signal chain?

- This is our fundamental question
- Combined VLBI-like and GNSS measurement system
- In this incarnation, an interferometer of mixed-antenna types

What would the measurements be?

- Time delay and frequency shift for known sources

What are the benefits?

- GNSS antennas
  - Have very stable phase centers, are cheap and ubiquitious
- Larger dishes antennas provide gain and directionality
  - Harder to characterize phase centers, and more costly to deploy

What could you do with these measurements?

Suppose we had one time delay measurement to a celestial source, what could we do with it?

- Earth orientation implicit in time delays
  - Assume
    - Known baseline (16 km)
    - A time delay measurement, $\delta\tau$
    - Known polar motion parameters (x,y)
  - Search for one unknown: dUT1

    dUT1 = UT1 – UTC

Our initial thought: Search for dUT1 value such that

$$dUT1 = \tau \text{ minimizes } |\Delta t_{meas} - \Delta t_{model}(\tau)|$$

With one measurement this wouldn't be a high precision measurement, but it would be a good first test

There are challenges!

GNSS antennas are small

- Small effective collecting area
- *Less energy collected → Longer integration times*

Sources with higher flux densities are spatially distributed

- Quasars are point sources (but fainter)
- *What sources can we potentially observe?*

We are using inexpensive oscillators

- Rb Oscillator noise dominates in about 10 secs
- *Integration times may require hundreds of seconds!*

Bands accessible to commercial GNSS antennas are noisy

- Short baselines means minimal time-delay, frequency resolution in sources
- Long baselines resolve spatial structure
- *May be no way to disentangle sources at short baselines, and reduced correlated power at long baselines!*

Guiding Philosophy

Use bright sources to illuminate our processes

- Satellites provide SNR
  - Known locations easy to get
- Then proceed to brightest possible celestial sources
  - Maximize chance for detection
  - Make problem determination easier
  - These measurements are the keystone of this effort

Proceed to sequentially dimmer sources

- Testing at each step
  - Are integration times as expected?
  - Is signal strength as expected?
  - What unmodeled effects do we see, that if removed, would allow us to see weaker sources?

A Two-Element Interferometer

Antenna elements

- Three meter dish
  - Right hand circularly polarized (RHCP) signal
- GNSS antenna (Topcon)
  - RHCP signal

Dish antenna (D = 3m)

- $A_{dish} = \frac{\pi D^2}{4} \varepsilon \sim 1.8\, m^2$
- ε measured to be $\sim 25\%$

GNSS antennas are small

- $A_{GNSS} = \frac{G\, \lambda^2}{4\, \pi}$ ~ 57 cm^2 at GPS L1

$$A_{int} = \sqrt{A_{dish} A_{GNSS}}$$
$$A_{int} \approx 0.10\, m^2$$

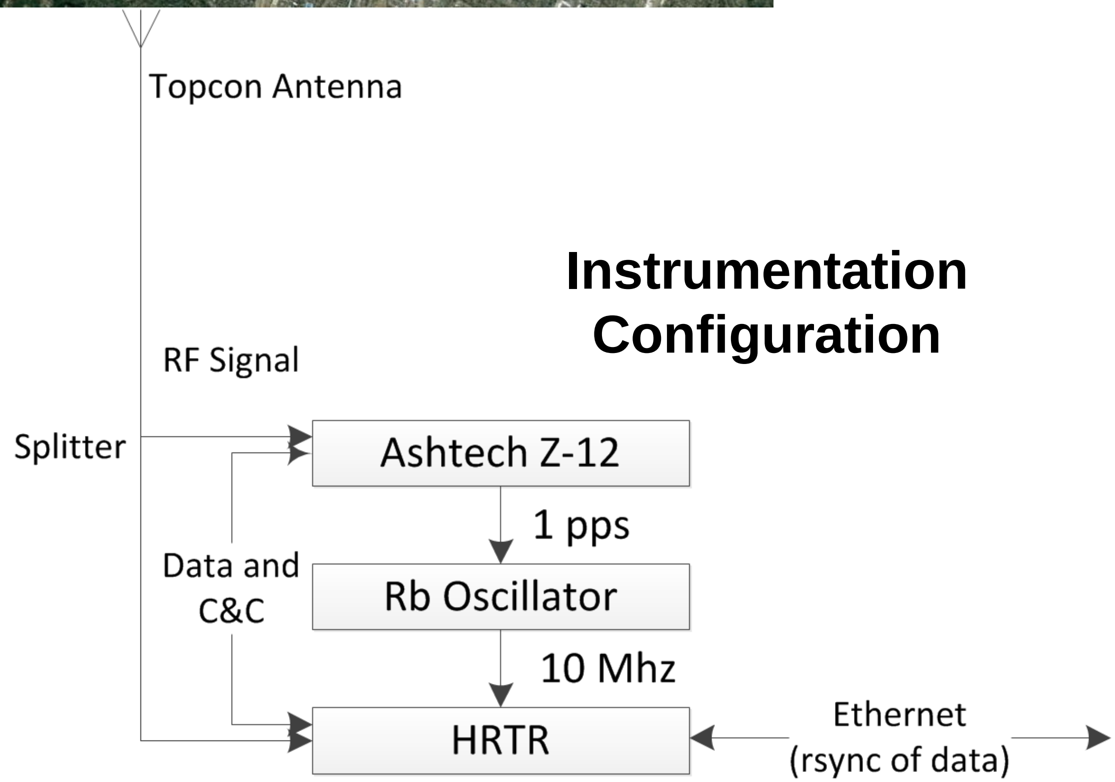
Small area → Bright sources

Layout & Instrument Configuration

Long Baseline
16 km

Short Baseline 140 m

Instrumentation Configuration



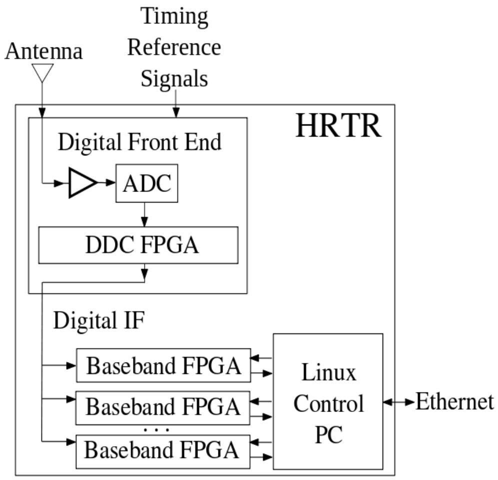
The High Rate Tracking Receiver (HRTR)

Almost direct to digital software receiver

– Intended for variety of scientific/engineering uses [1,2]

– Characteristics
  - 3 band configurations
    - 0.1-1 GHz, 1-2 GHz, 2-3 GHz
  - 1 GHz instantaneous direct sample bandwidth
  - FPGA-based digital downconversion and processing
  - Minimal analog front-end to minimize biases
  - Ethernet interface

– Two instruments



1. J. York et al., "A Direct-Sampling Digital-Downcoversion Technique for a Flexible, Low-Bias GNSS RF Front-end," ION GNSS Meeting, Sept. 2010

2. J. York et al., "A Novel Software Defined GNSS Receiver for Performing Detailed Signal Analysis," ION ITM meeting, Jan. 2012.

HRTR Signal Chain

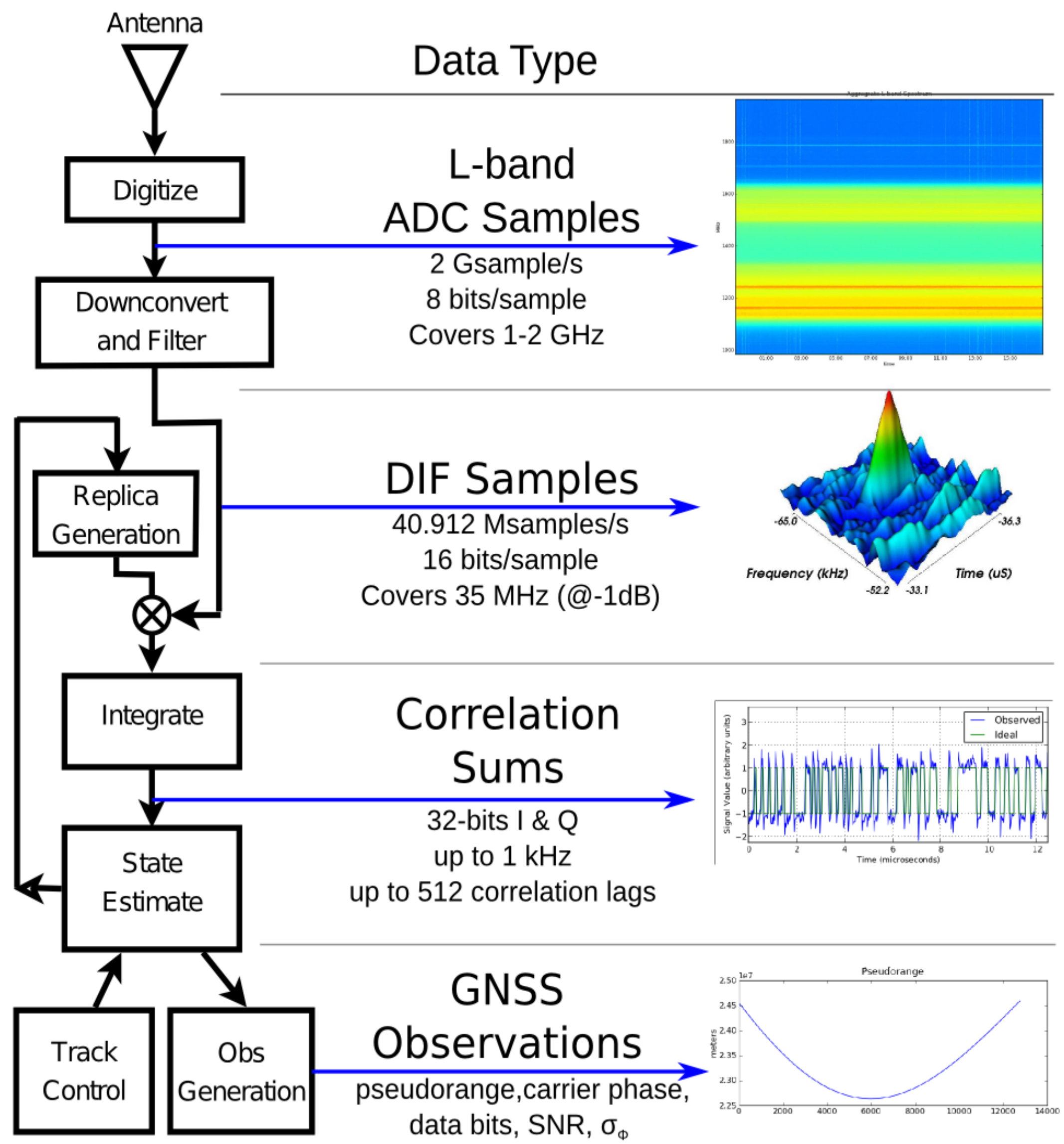
Flexibility in where we tap into data stream

- Directly into raw data stream
- Post-down conversion and filtering
- For GNSS applications
  - Intermediate frequency samples
  - Post-correlation samples
  - Standard observables

Is the datastream usable for both GNSS and celestial source observations – tapped off at the DIF samples level ?

We have augmented this processing for this effort

- Expanded beyond GNSS passband (antenna alteration)
- Combining multiple bands to achieve wider bandwidth
- Polyphase & Time Domain approach



Initial Observation Target: Cygnus A

Cygnus A is a radio galaxy

- Supermassive black hole powers two jets
- Strong radio source

Flux Density (Baars1977)

- ~ 1800 Jy @ 1200 MHz
- ~ 1400 Jy @ 1600 MHz

1 Jy = 10^{-26} W/m^2/Hz

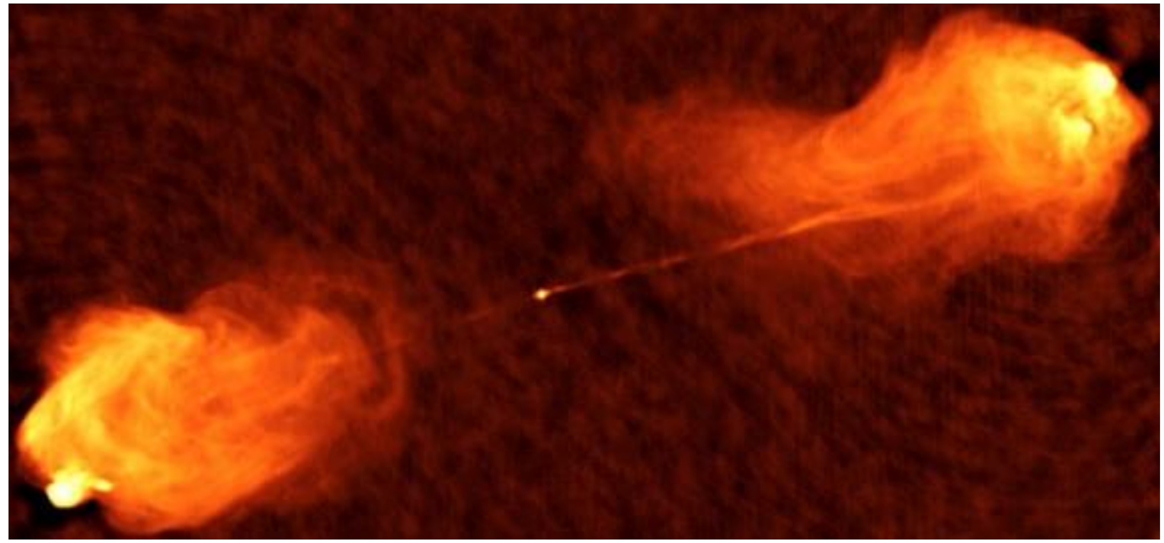


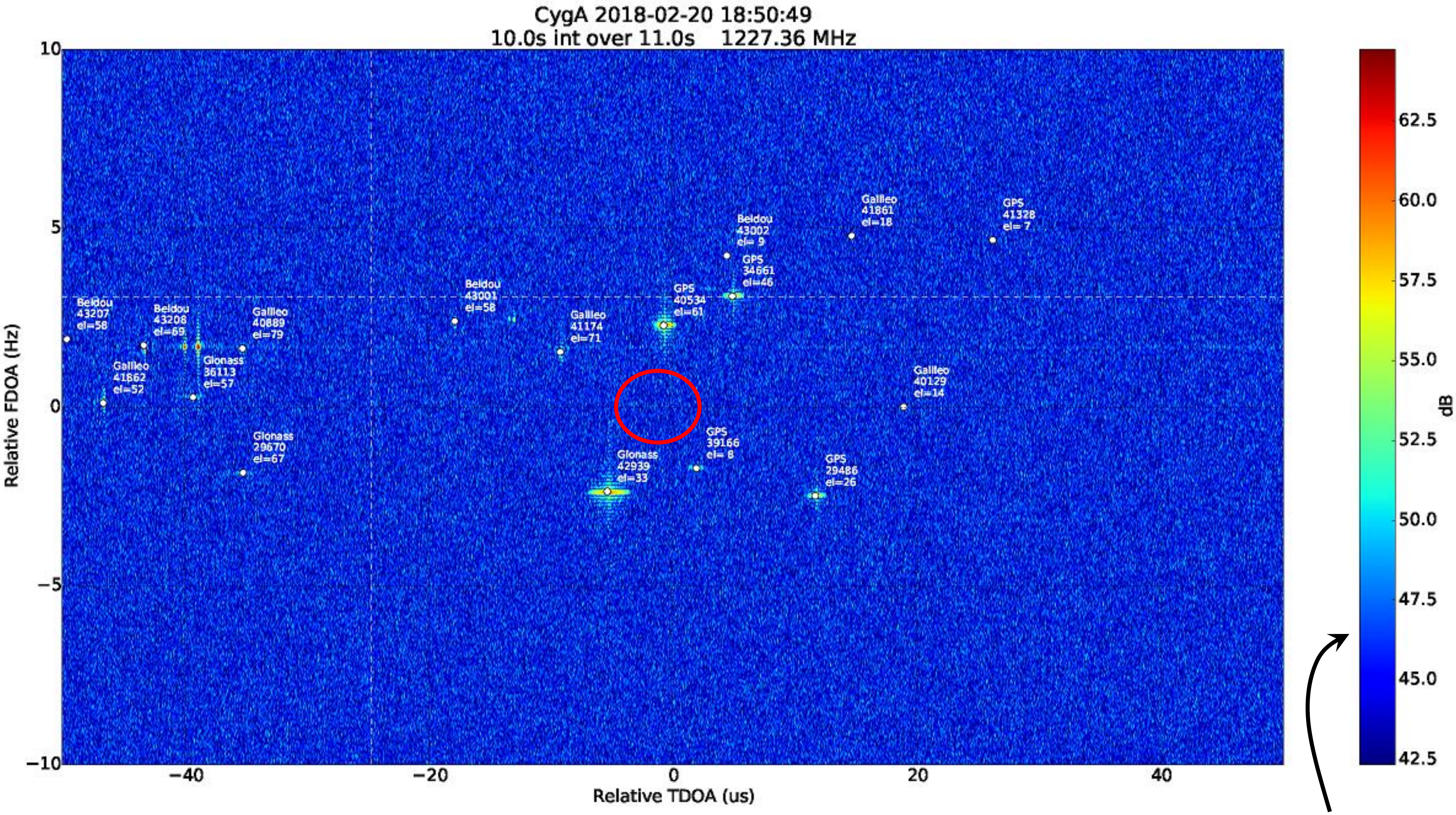
Image courtesy of NRAO
(R. Perley, C. Carilli, J. Dreher 1983, 5 GHz)

This source has a high flux density.
Estimate integration time τ ~ 15 seconds for 10:1 SNR if point source

But on long baselines, source resolves into multiple components

Example correlation surface: 10s Integration

Dish pointed at Cygnus-A, 16 km baseline



Estimated Cyg A power level

Integration time is too short to see Cygnus-A

Longer Integration Times

Longer integration times require better clock stability

- Rb clock stability at 10s ~ 10^{-12} → phase variations in signal
- Shows up as a loss of SNR

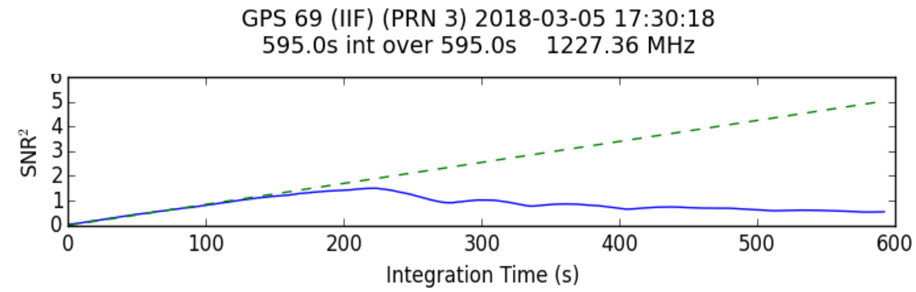
The HRTR is a GNSS receiver!

- Correlate on GNSS SV and extract the phase
- Phase should reflect clock + iono + trop
- Use this as a correction to align clocks

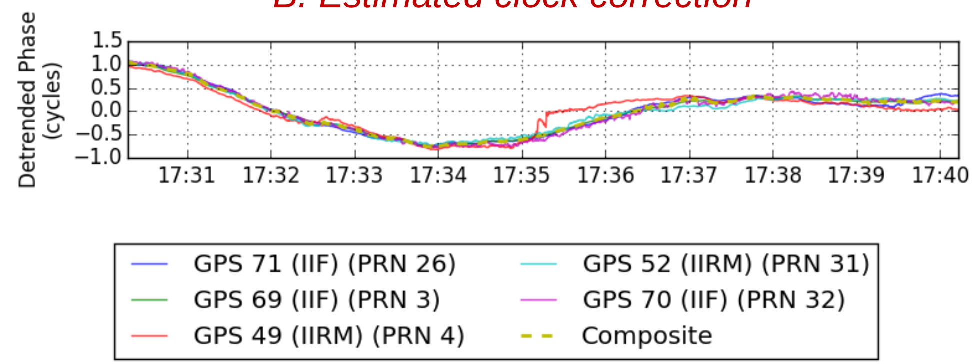
Clock correction makes longer integration possible

- Loss of power occurs as SV moves out of sidelobe

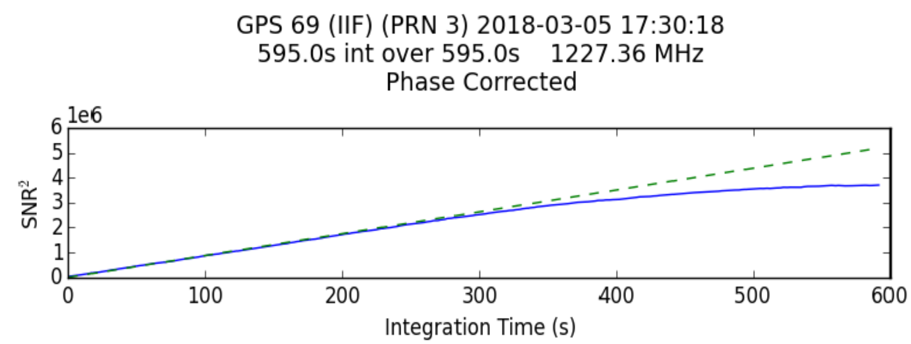
A. No clock correction



B. Estimated clock correction



C. Clock correction applied



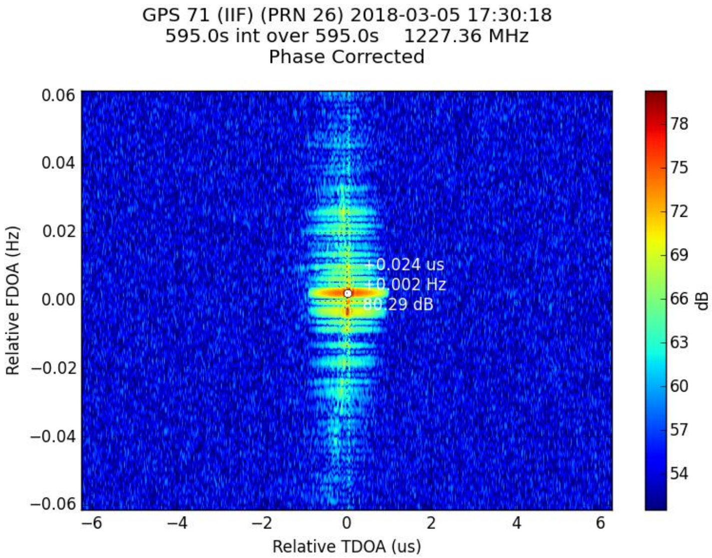
Longer Integration – 600 secs

Two 595s integrations from 05 Mar 2018 collect

– 16 km baseline

– GPS satellite

– CygA

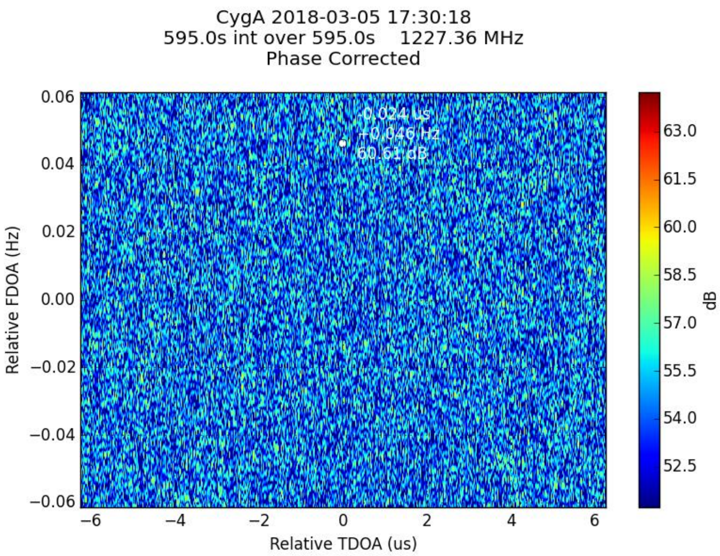


Full end-to-end correlation product

– Parallelized time domain correlator

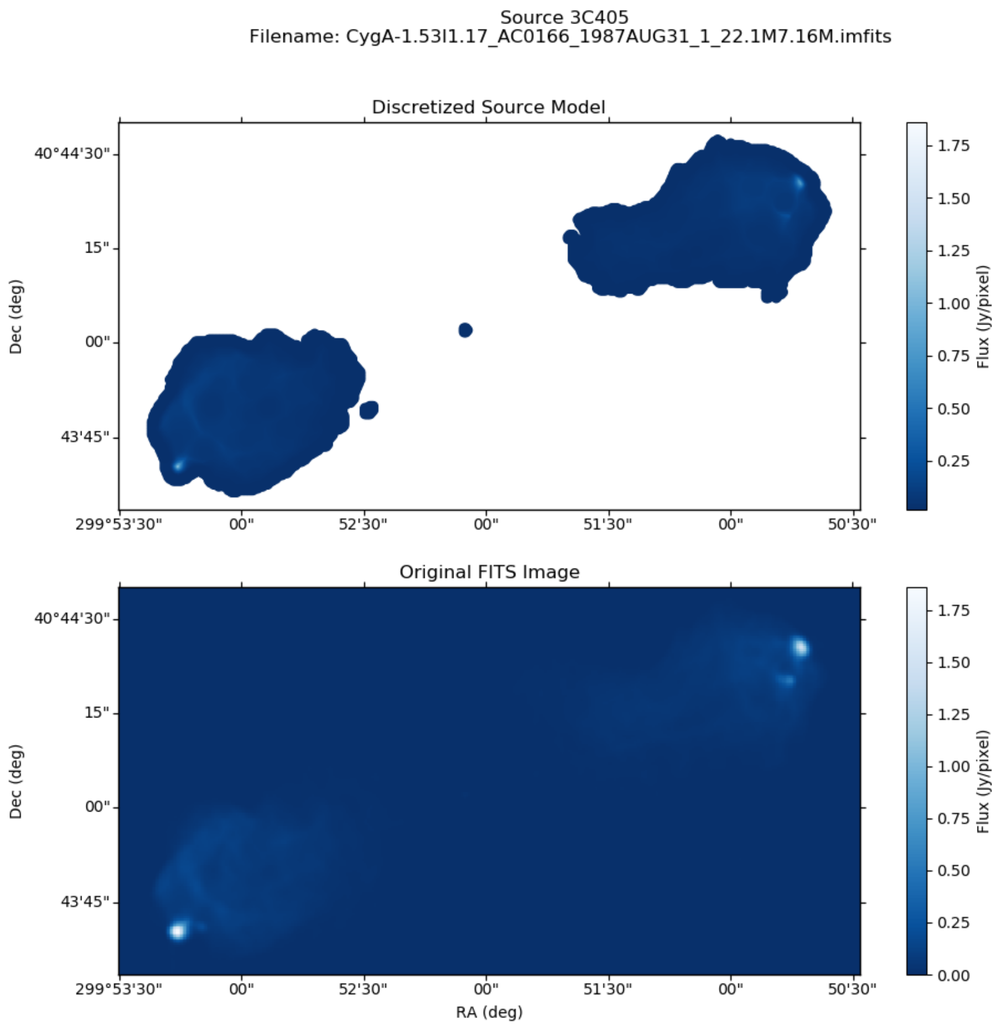
– Fringe stopping

– Clock compensation

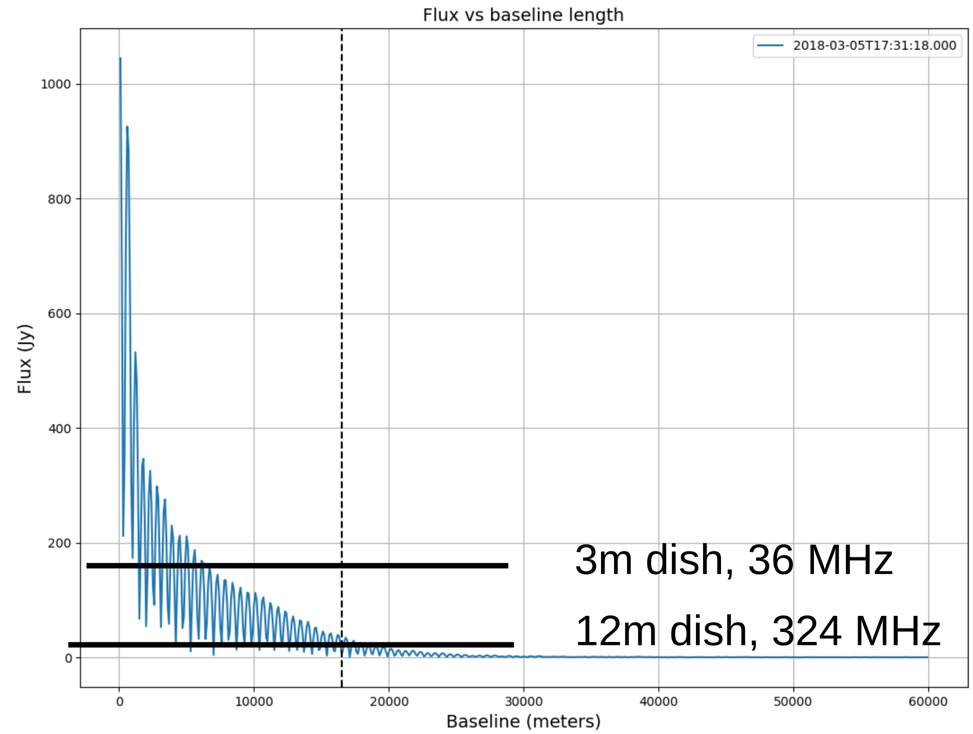


Cyg A still not visible

Visibility Simulation



Zoomed raw image
Image courtesy of NRAO
31 Aug 1987



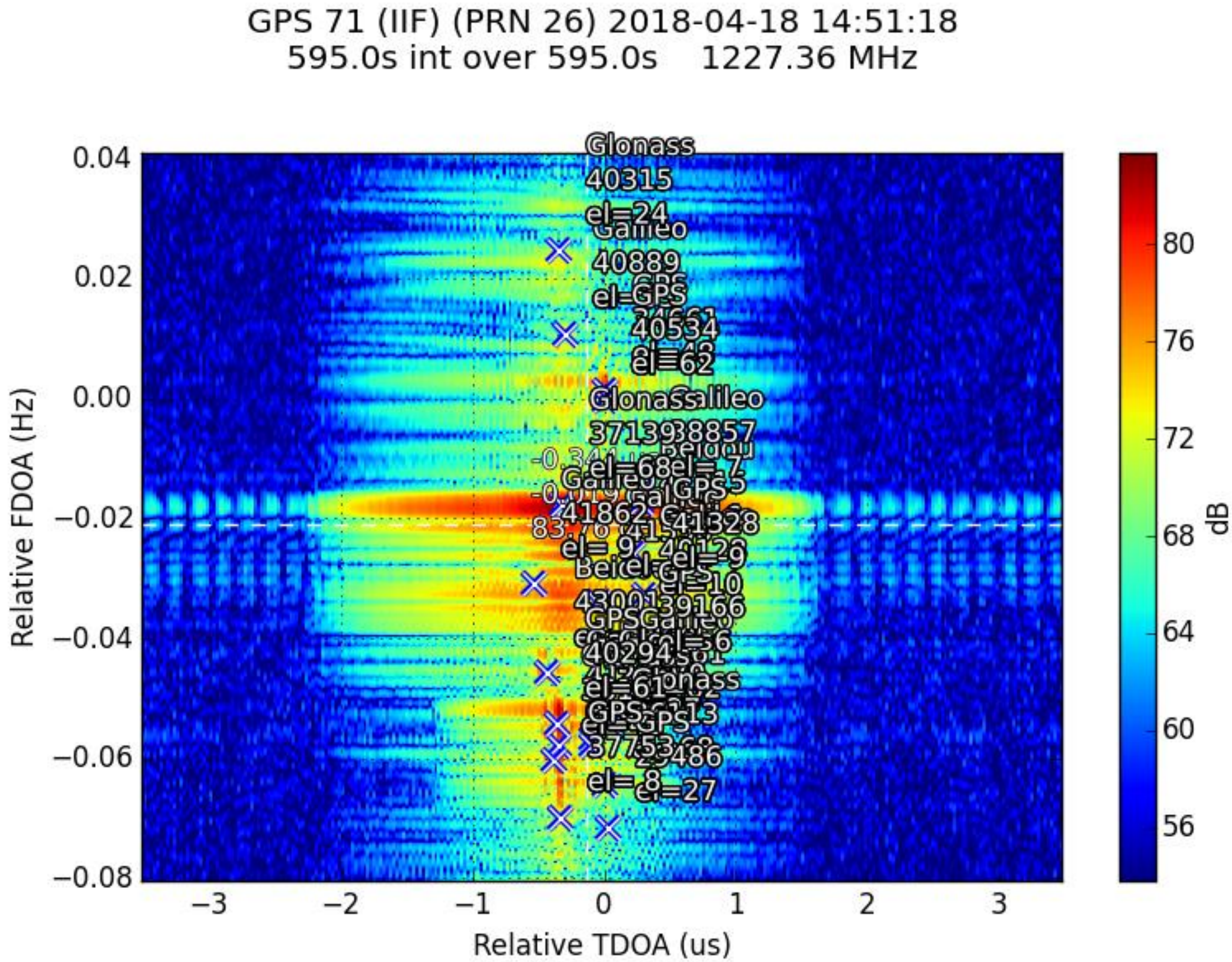
Filter raw image to keep 1% highest flux pixels

Compute complex visibility from discretized model

$$V = \sum_k e^{2j\pi\left(\frac{\mathbf{b}\,.\,\mathbf{n}}{\lambda}\right)}$$

At longer baselines structure resolves and results in interference

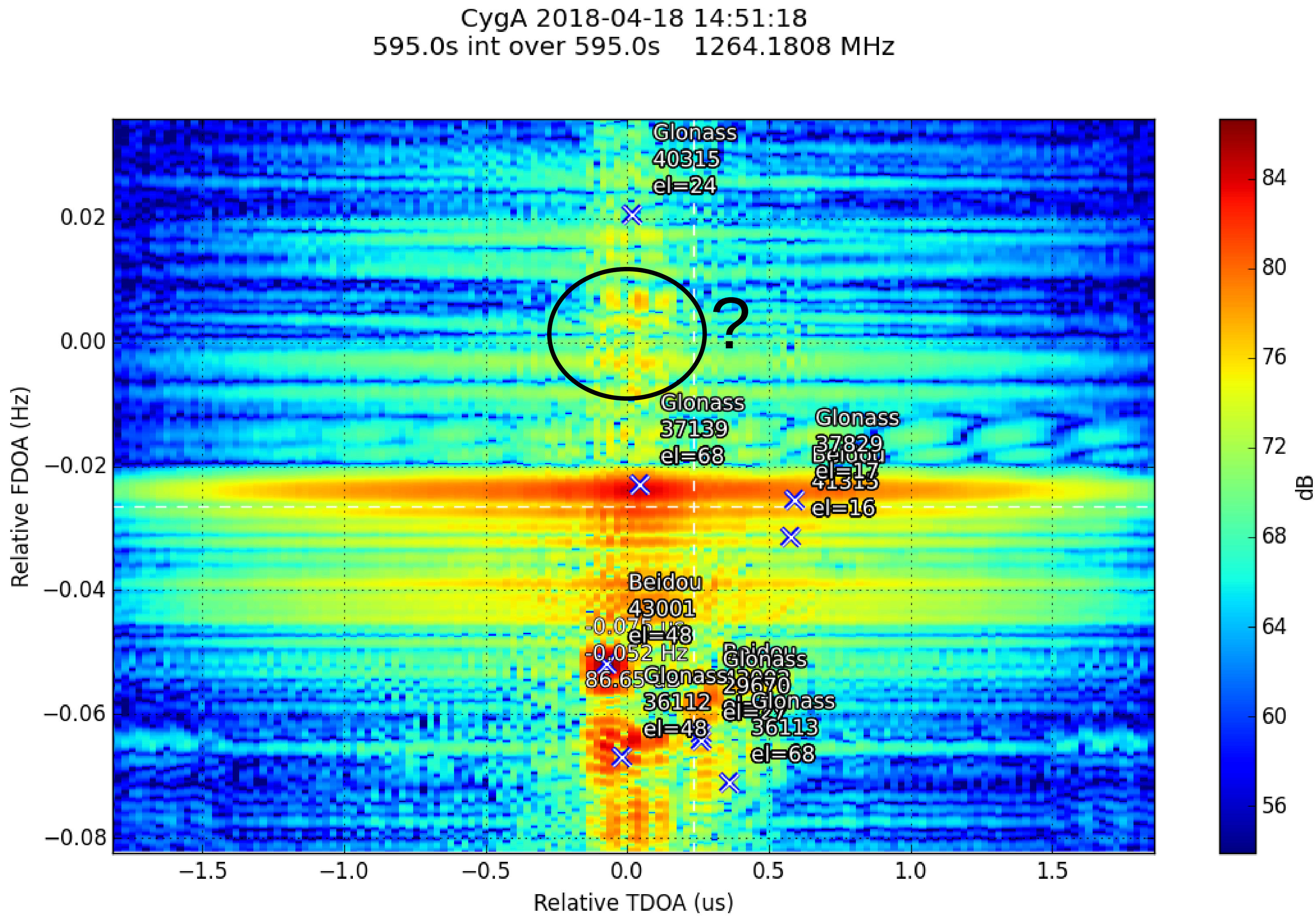
Early short baseline results



Shorter baselines reduce TDOA/FDOA spread . . .

. . .makes CAF surface crowded!

Short baseline – Somewhat Quieter RF Band



Still not quiet enough. . . will be repeating experiment in an even quieter RF band using an GPS antenna with modified preamp

Conclusion

This work, if successful, will allow VLBI observation of celestial sources tied at the observation level to the GNSS reference frame

- Path towards establishing direct ties between VLBI/GNSS observations
- Helps us understand truth when measurements disagree

Work is on this effort is ongoing

- Investigating possible existing short-baseline detections
- Replace GNSS preamplifier to allow operation in quieter RF bands
- Increase the RF bandwidth (from 36 to 324 MHz) to increase sensitivity

Future plans

- Develop techniques on easily accessible equipment:
  small dish, short baseline, small bandwidth, bright sources
- Longer-term utilize more capable equipment:
  - Increase dish size
  - Increase baseline length, bandwidth
  - Target weaker sources

BACKUP SLIDES

Sensitivity Analysis

Minimum detectable spectral flux density (L2)

	Dish Diameter (m)					
Integration Time (s)	3m		10m		100m	
	Full BW	36 MHz	Full BW	36 MHz	Full BW	36 MHz
60	249	739	75	222	7.5	22
600	79	234	24	70	3	7
1200	56	165	17	50	2	5

While maintaining a 10:1 SNR level

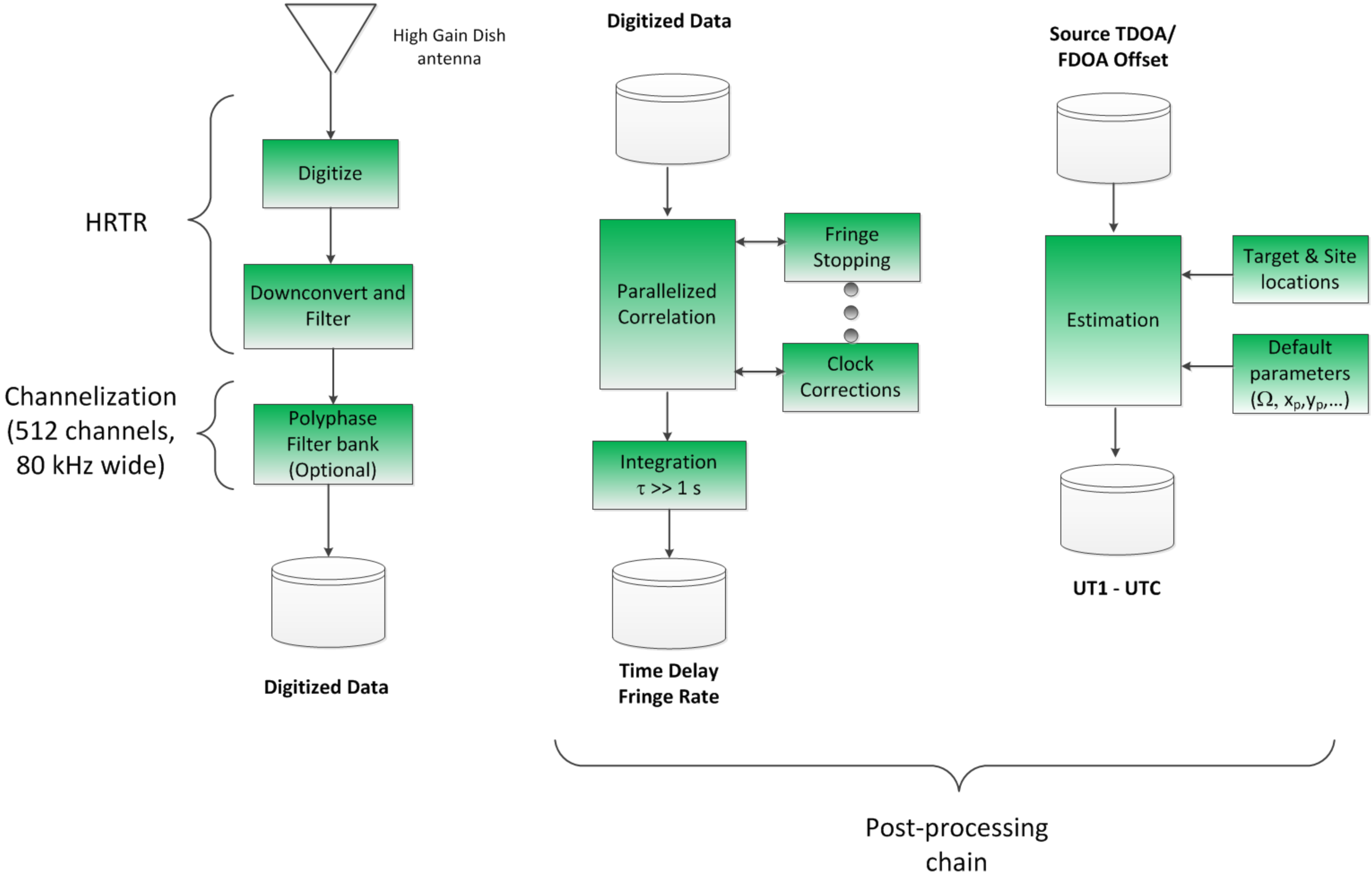
Units are Jy: 1 Jy = 10^{-26} $W/m^2/Hz$

Source	***Flux (Jy)***	***Single Band(s)***	***Full Bandwidth (s)***
Cas A	1638	12	1.4
Cyg A	1495	15	1.7
Centaurus A	1330	18	2.1
Crab Nebula	875	43	4.7
W51	576	99	11.0
Orion A	520	121	13.4
Sag A	254	507	56.4
M87	198	835	92.7
W44 (3c392)	171	1119	124.3
Orion B	65	7745	860.5
Galaxy 3C353	57	10071	1119.0
Quasar 3c273	46	15464	1718.2
Tycho SNR	44	16902	1878.0
Quasar 3c147	23	61856	6872.9
3C295	23	61856	6872.9

The sources in red will not be visible given the limitations of our dish antenna.

Single band - 36 MHz Full Bandwidth - 324 MHz

Dataflow & Processing



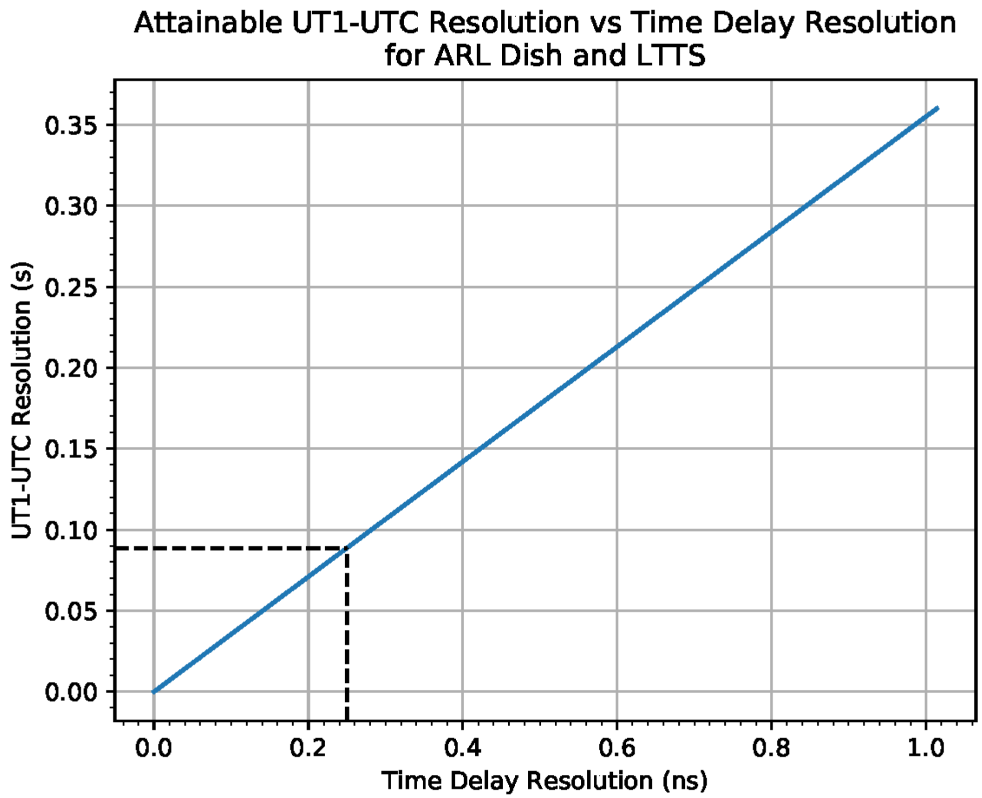
Attainable accuracy

Given

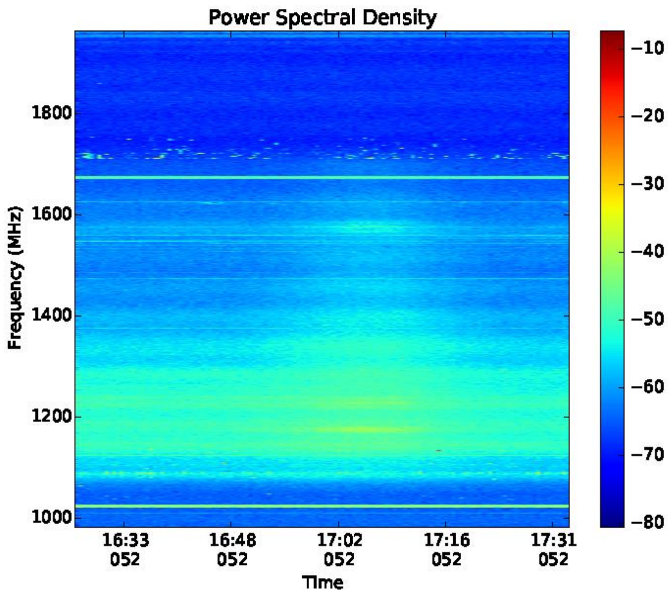
- Known baseline (16 km)
- Two elements
- x,y polar parameters (IERS)

How well can we do?

- Resolution dUT1 limited by measurement resolution
- Time delay resolution limited by our baseline and our bandwidth.
- 90 ms at 250 ps time delay resolution



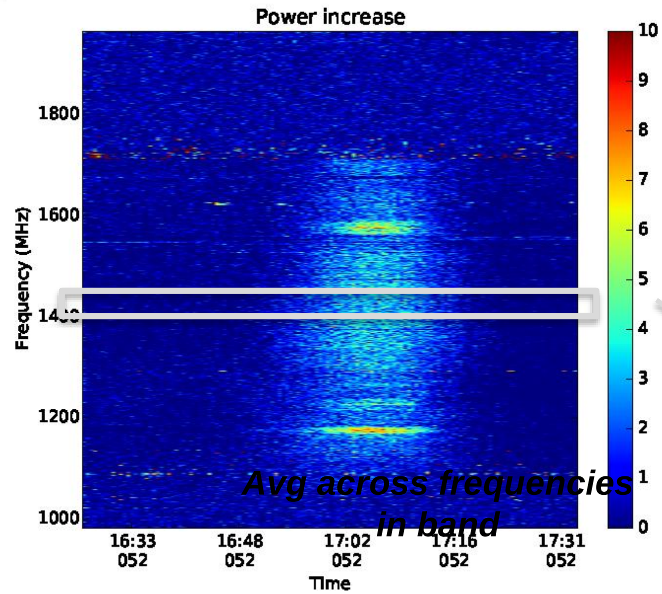
Dish Beam Width Check



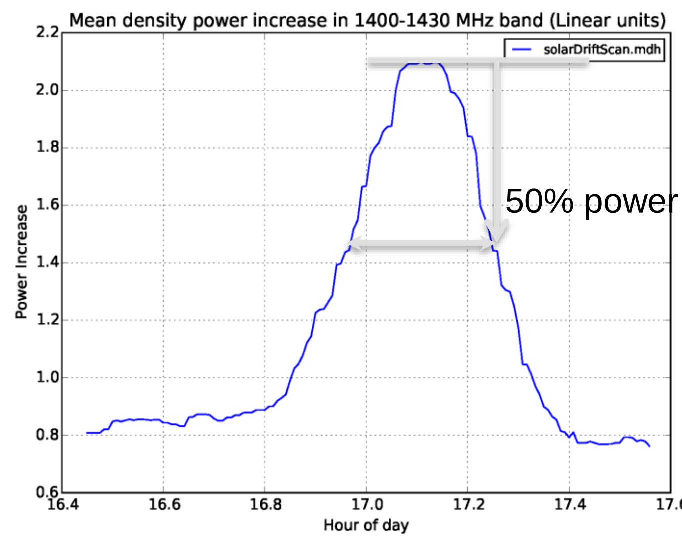
L1 band

L2 band

Remove background



Avg across frequencies in band



50% power

Example from 21 Feb 2018

Process

- Compute power increase
  - Remove mean (in time) power spectrum
  - Examine 1400-1430 band

Full beam width 5.0º ± 0.5º

Dish Gain Check

Y-Factor

- $Y = P_{sun}/P_{cold\ sky}$
- P_{sun}
  - median PSD within
  - $|t - t_{peak}| < 2$ min
- $P_{cold\ sky}$
  - $|t - t_{peak}| > 20$ min

Compute G/T

- From Y
- Estimate from
  - Component noise characteristics
  - Environmental noise estimates

1-2 dB difference

Conservatively, set $e = 0.25$