Using GNSS Slant TEC Measurement In Radio Astrometry Correction for BURSTT

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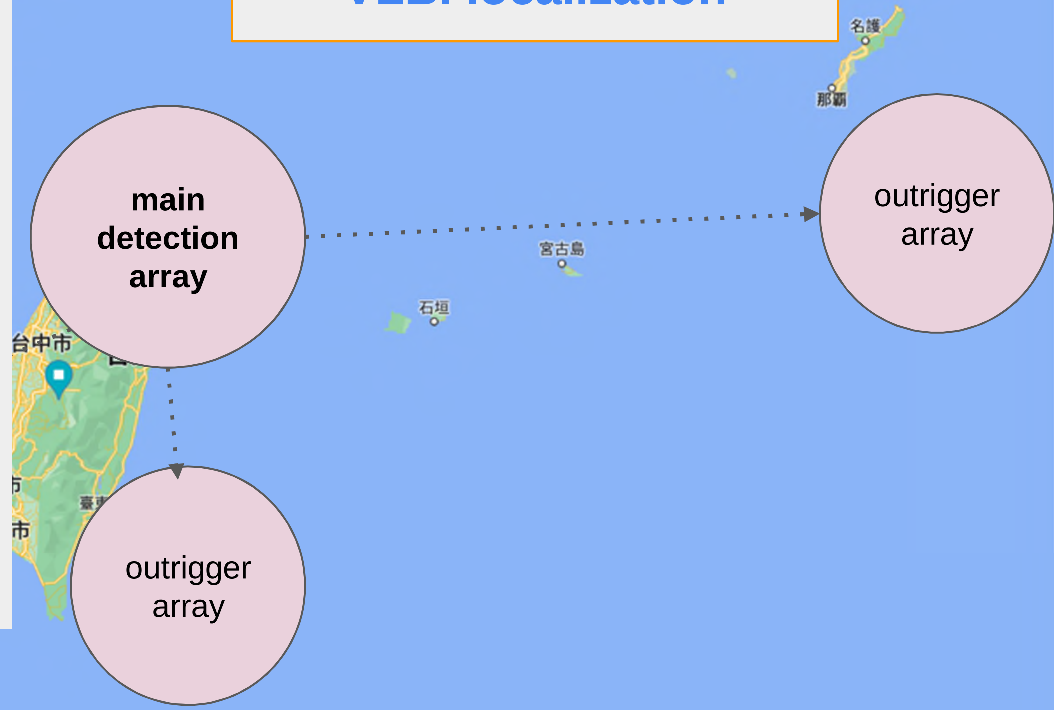
BURSTT Plan

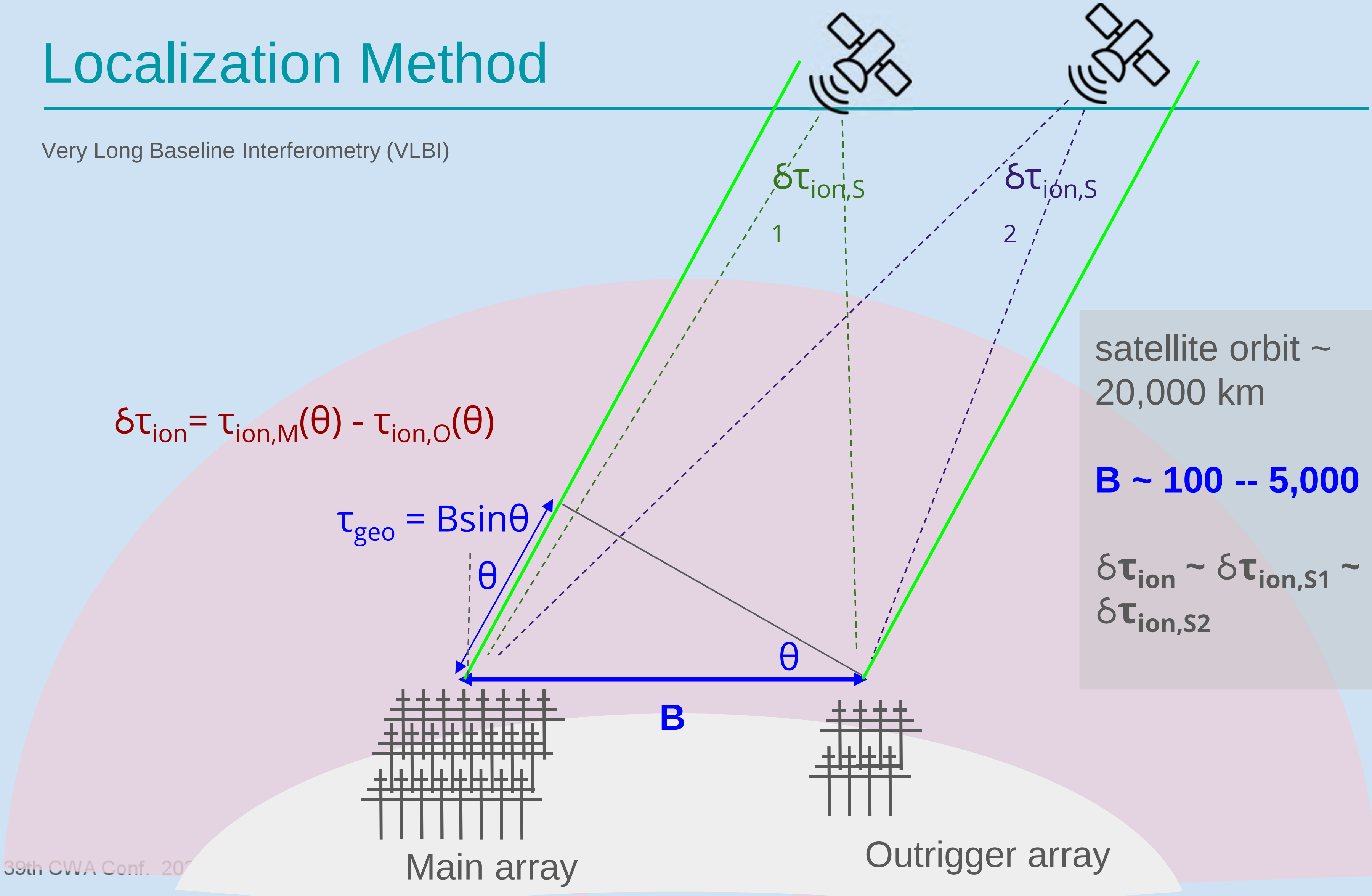
wide-FoV antenna array
+
VLBI localization

- **Detect** and **localize** Fast Radio Bursts (FRBs)
    - millisecond pulse
    - at 300-800MHz
    - mostly one-off events
    - extra-galactic sources unknown origin
- Event detection by Main Array
- Localization with triggered saves of Main+Outrigger arrays



Localization Method

Very Long Baseline Interferometry (VLBI)



satellite orbit ~ 20,000 km

B ~ 100 -- 5,000 km

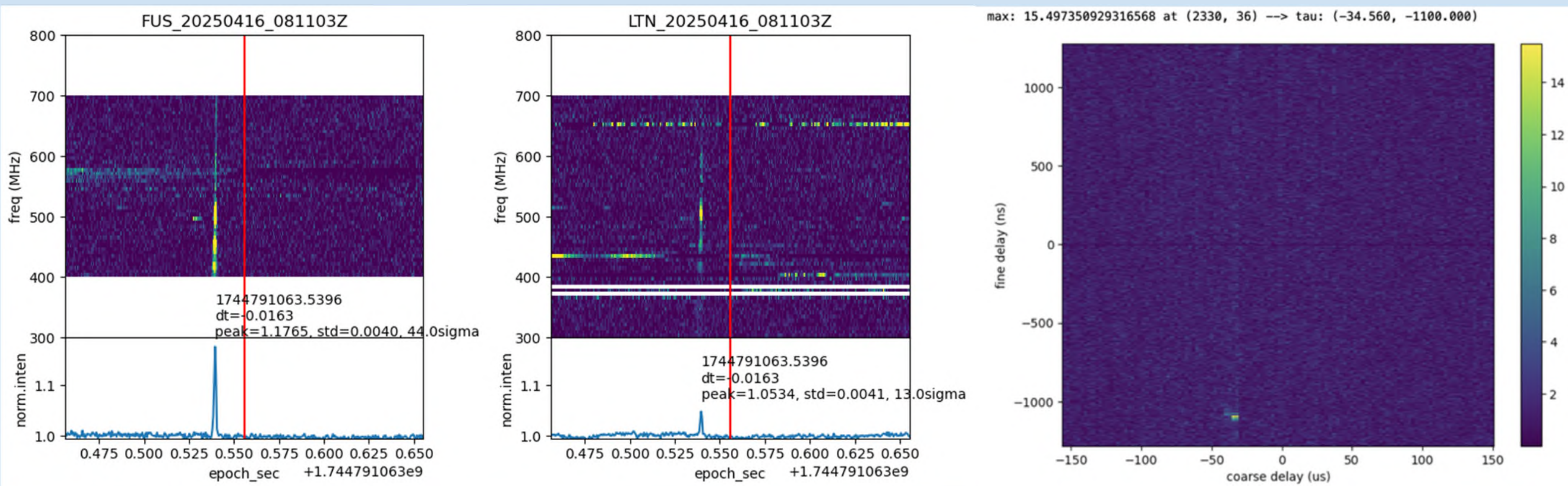
$\delta\boldsymbol{\tau}_{\mathbf{ion}} \sim \delta\boldsymbol{\tau}_{\mathbf{ion,S1}} \sim \delta\boldsymbol{\tau}_{\mathbf{ion,S2}}$

Domestic Sites

Global Sites

Triggered Baseband

- Example Crab giant pulse
  - bonsai SNR ~ 68
  - Fushan: 44-sigma, Nantou: 13-sigma
  - cross-corr: 15-sigma
- Potential improvement by reform 1st beam



Toward Localization

$$\tau_{geo} = \tau_{obs} - (\tau_{ion} + \tau_{clk\_err})$$

Goal

GNSS STEC

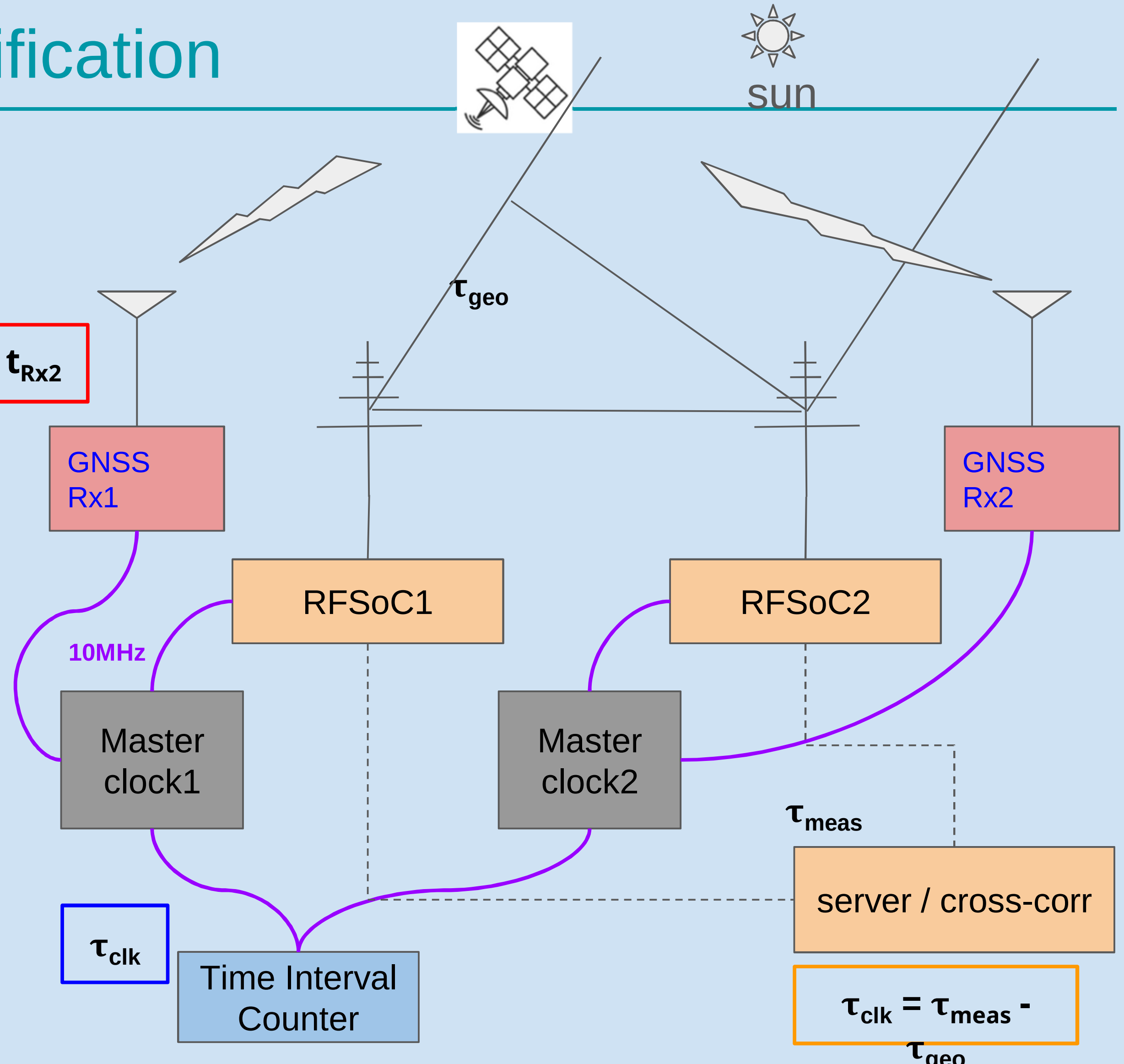
GNSS PPP

Clock Error Verification

(same site, $\delta\tau_{ion} = 0$)

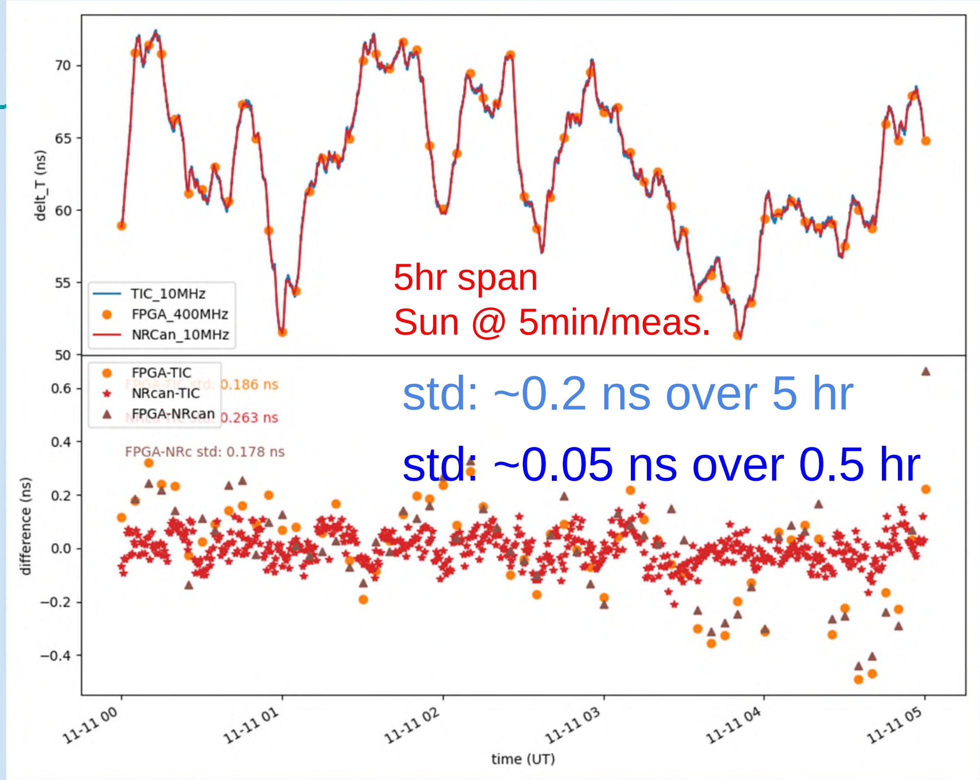
GNSS
ppp: precise
point positioning
-- receiver time
(offline process)

$\tau_{clk} = t_{Rx1} - t_{Rx2}$



Clock Error

- 10MHz ref dT by time interval counter
- 400MHz clock dT by Sun fringe
- 10MHz ref dT by GNSS-ppp



- 400MHz sampling → 2.5 ns
- 1” at 100km → 1.6 ns
- 0.1” at 1000km → 1.6ns

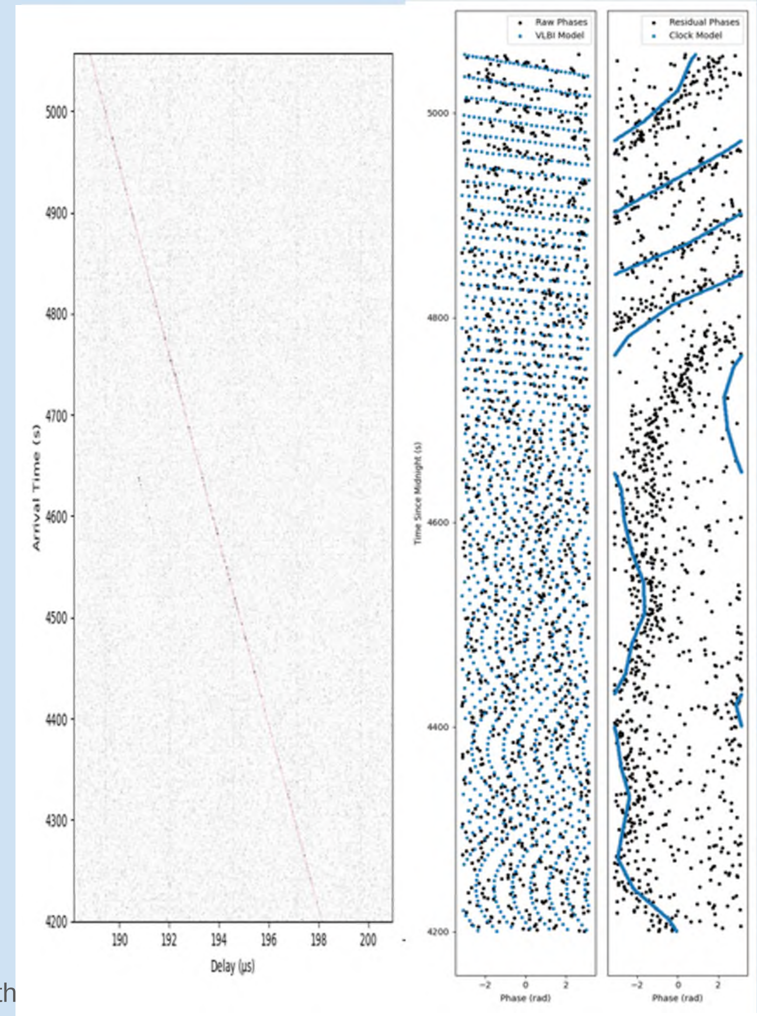
Timing goal: 0.2 ns

~ 0.024 TECU @ 400MHz

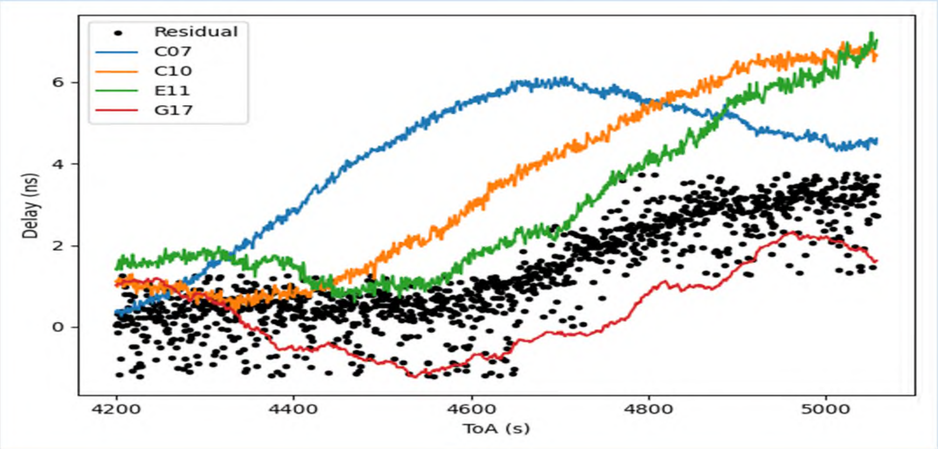
Verification test at the same site

VLBI: Fushan/Nantou

Credit: Daniel Baker



- Fringe delay of pulsar B0329+54 over 15min
- Geometric delay (by model) removed
- Clock errors (by ppp) removed
- Residual variation (~2ns=0.25TECU) has a similar trend as ionospheric delay measured by nearby GNSS satellites

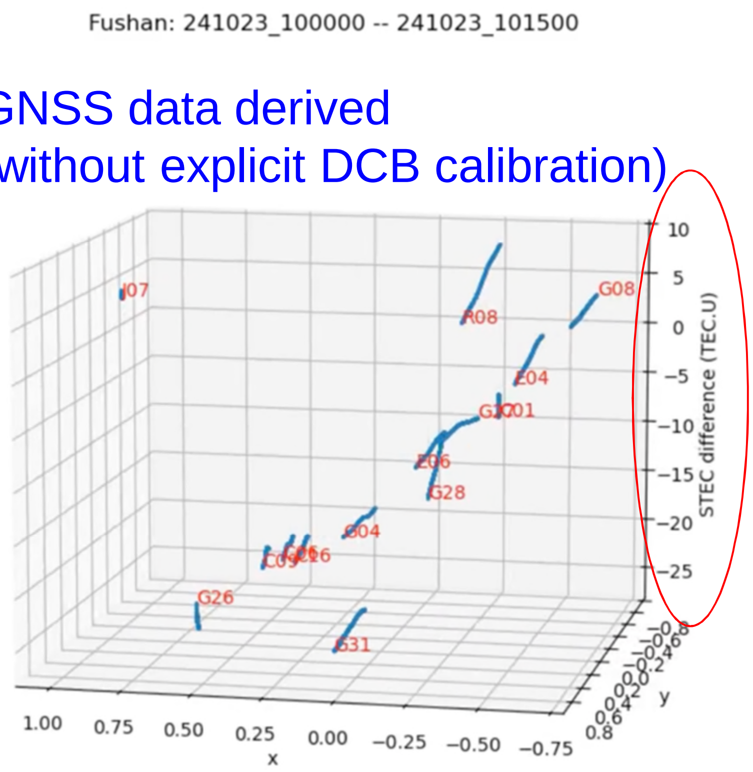


Summary

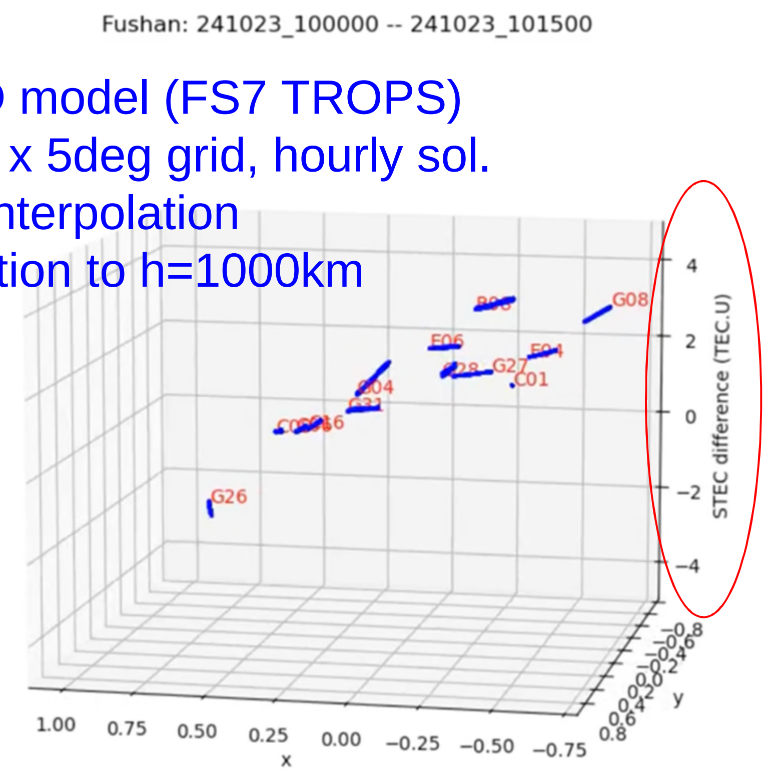
- BURSTT aims to achieve **0.2ns** timing error between any two stations
  - 1” localization @ 100km baseline
  - 0.1” localization @ 1000km baseline
  - corresponds to **~0.024 TEC unit accuracy @ 400MHz**
- GNSS PPP can satisfy the measurement of clock errors (at the same site)
- Residual timing variation **(~2ns=0.25TECU)** qualitatively matches the differential STEC of nearby satellites (over 15min)
  - 140km between the two sites
  - differential STEC **absolute offset** removed in this test
  - ongoing tests to verify timing offset is independent of targets
    - can calibrate with known targets
- Unfamiliar with how to derive absolute differential STEC toward a satellite between two sations

dSTEC: measured vs. GIS model

GNSS data derived
(without explicit DCB calibration)

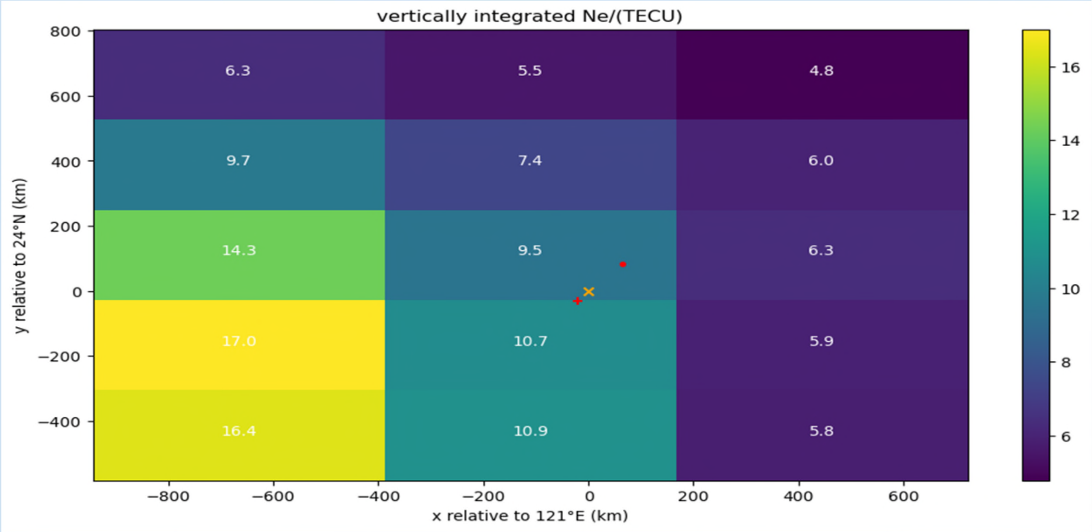


GIS 3D model (FS7 TROPS)
2.5deg x 5deg grid, hourly sol.
linear interpolation
integration to h=1000km



Current Investigation

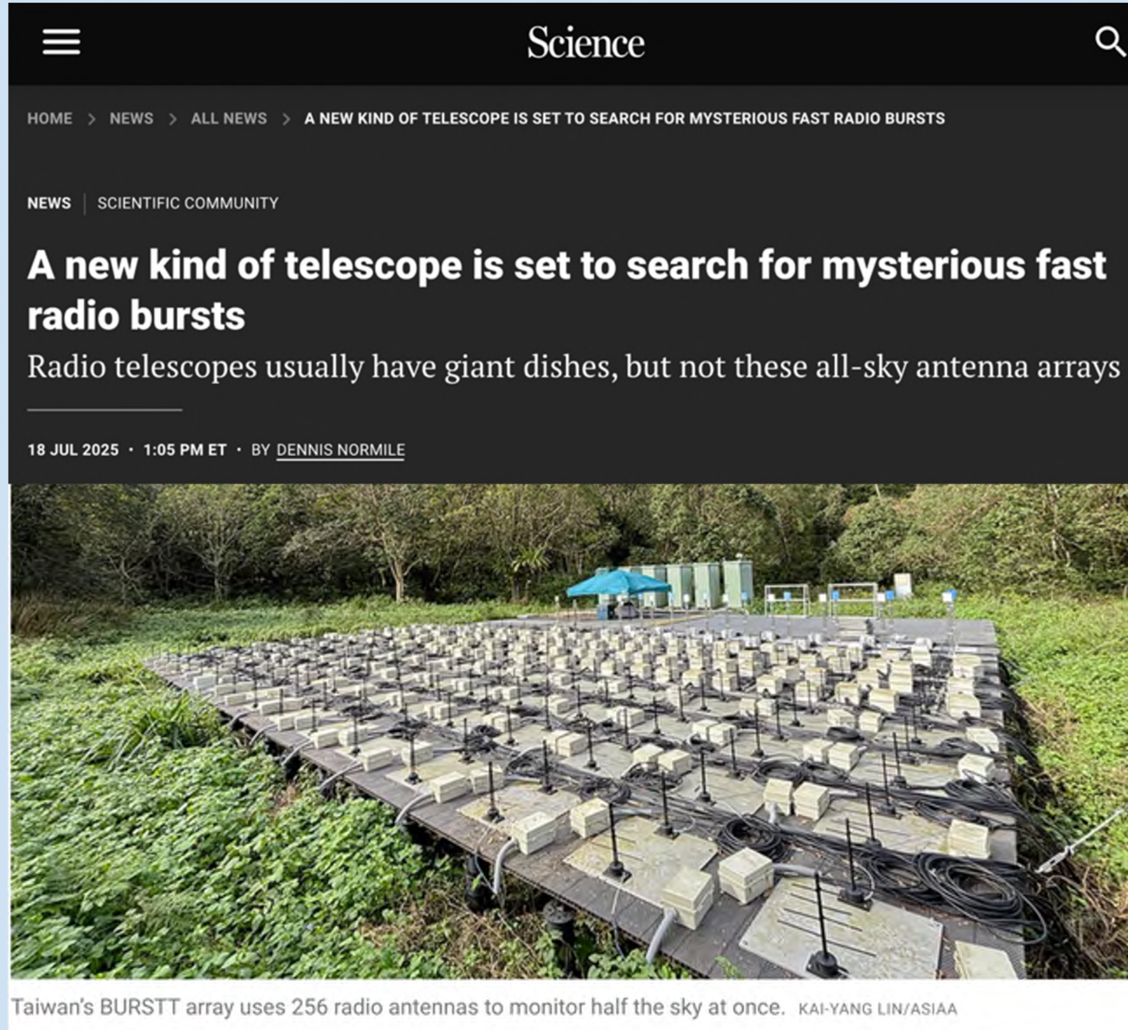
- Our own derived dSTEC shows a wider range than models
  - Overall offset is uncertain, but satellite variation should be real
- GIS model maybe too coarse for our short (100km) baseline
- also requested TWIM2 mock STEC (Prof. Tsai, Lung-Chih) toward these satellites
  - a similar trend with GIS interpolated results
- order of ~10TECU difference in dSTEC for a given satellite with different DCB calibration approaches (by different groups)
  - dominating uncertainty → ~1' localization
- Existing tool to use?



Thank you!

Featured in a Science News Article (2025, Jul, 18)

among the 4 mentioned telescopes, BURSTT is the only one to have started to detect FRB!


Science

HOME > NEWS > ALL NEWS > A NEW KIND OF TELESCOPE IS SET TO SEARCH FOR MYSTERIOUS FAST RADIO BURSTS

NEWS | SCIENTIFIC COMMUNITY

A new kind of telescope is set to search for mysterious fast radio bursts

Radio telescopes usually have giant dishes, but not these all-sky antenna arrays

18 JUL 2025 • 1:05 PM ET • BY DENNIS NORMILE

Taiwan's BURSTT array uses 256 radio antennas to monitor half the sky at once. KAI-YANG LIN/ASIAA

Main Array Beamform

beam voltage

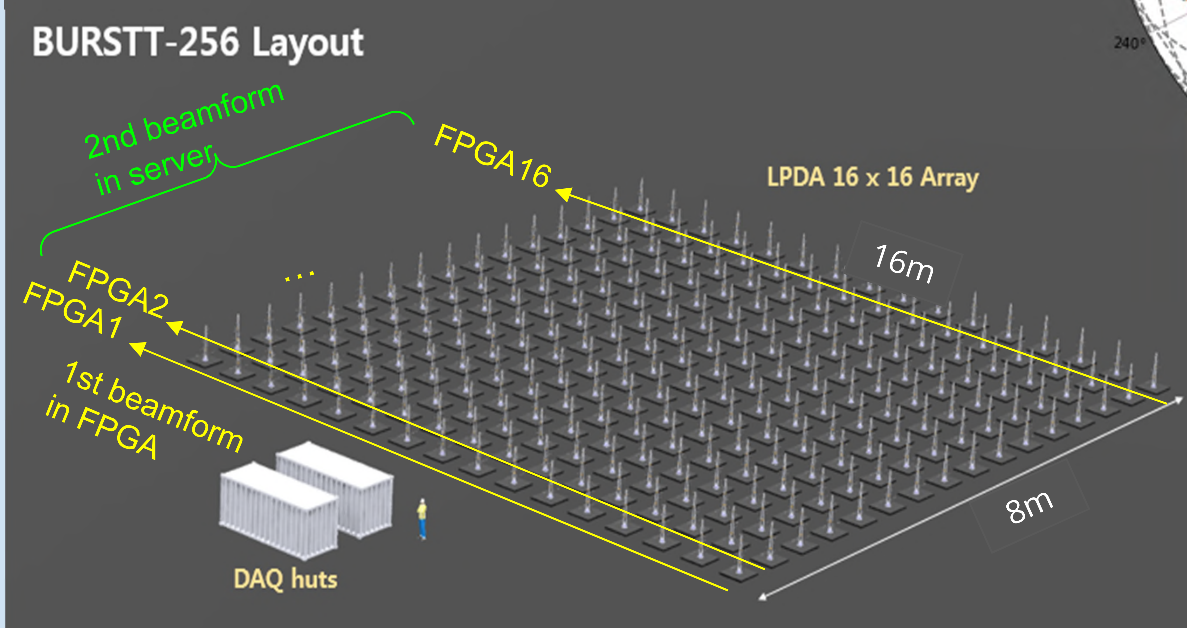
gain and delay correction

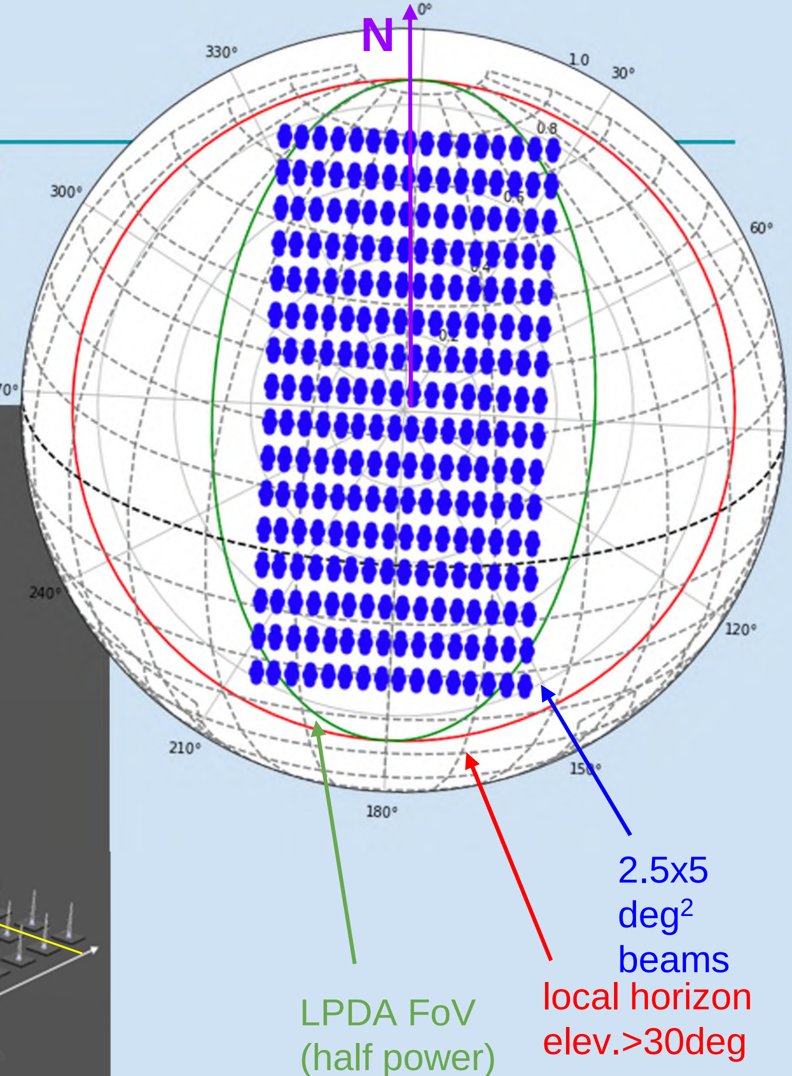
antenna voltage

$$B_i(\theta_E, \theta_N; t) = \sum_j S_{ij}(\theta_N) \sum_k F_{jk}(\theta_E) V_k(x, y; t)$$

1st beamform

2nd beamform





Clock system

- H-maser
  - bulky, very expensive, maintenance
  - very stable.
  - requires less frequent astrometry calibration
- atomic clock
  - more affordable for many outrigger stations
  - less stable
  - more frequent calibration:
    - GNSS satellites!

Fast Radio Burst (FRB)

A millisecond burst in the radio frequency

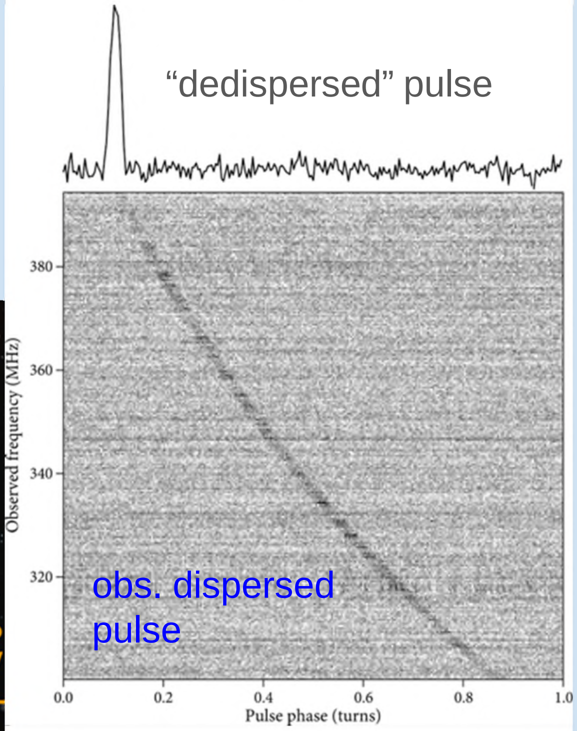
Propagation effect:

- Dispersion through ionized medium
  - Faraday rotation through magnetic field
  - Plasma scattering and lensing

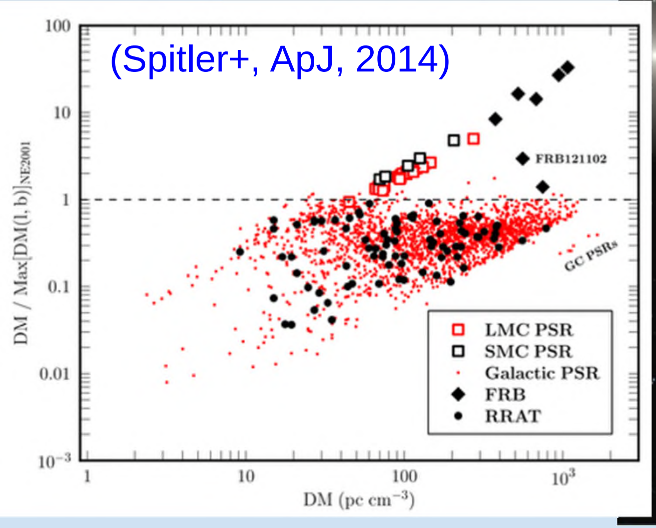
$$\left(\frac{t}{\text{sec}}\right) \approx 4.149 \times 10^3 \left(\frac{\text{DM}}{\text{pc cm}^{-3}}\right)\left(\frac{\nu}{\text{MHz}}\right)^{-2},$$

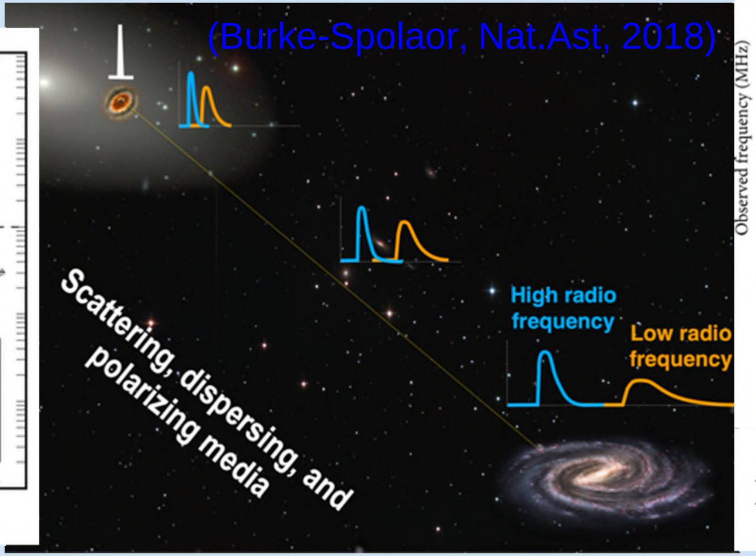
Dispersion Measure (DM)

$$\text{DM} \equiv \int_0^d n_e \, dl$$



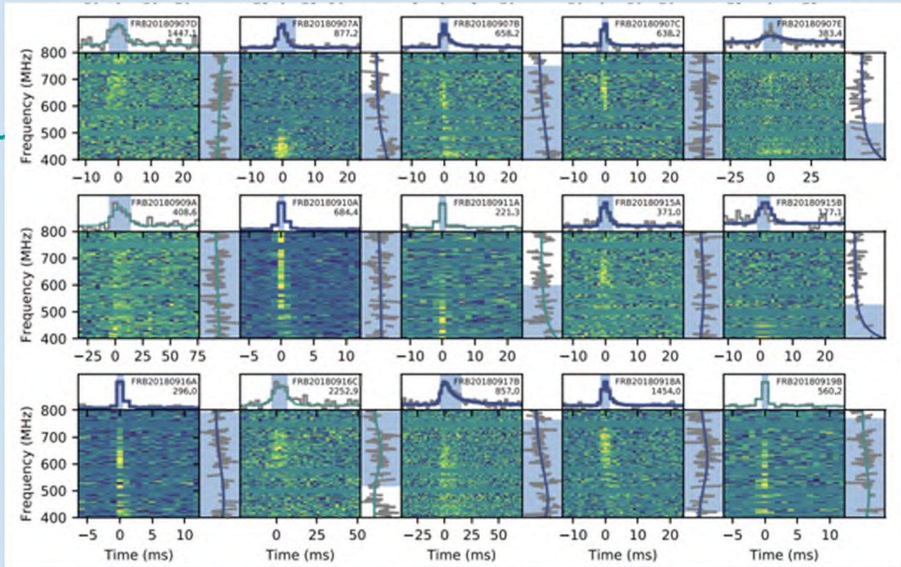
$$\text{DM}_{\text{IGM}} = \text{DM}_{\text{obs}} - \text{DM}_{\text{MW}} - \frac{\text{DM}_{\text{host}}}{1+z}$$



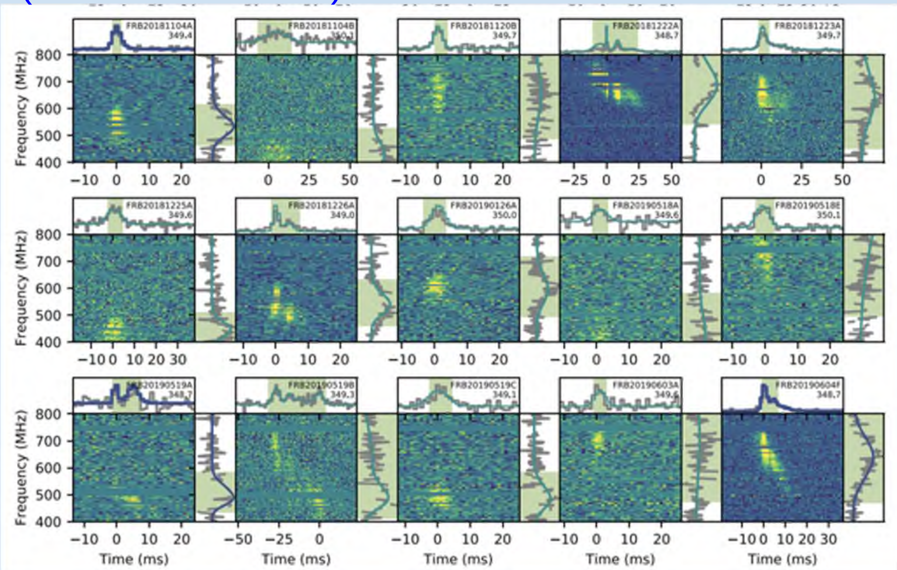


FRB Characteristics

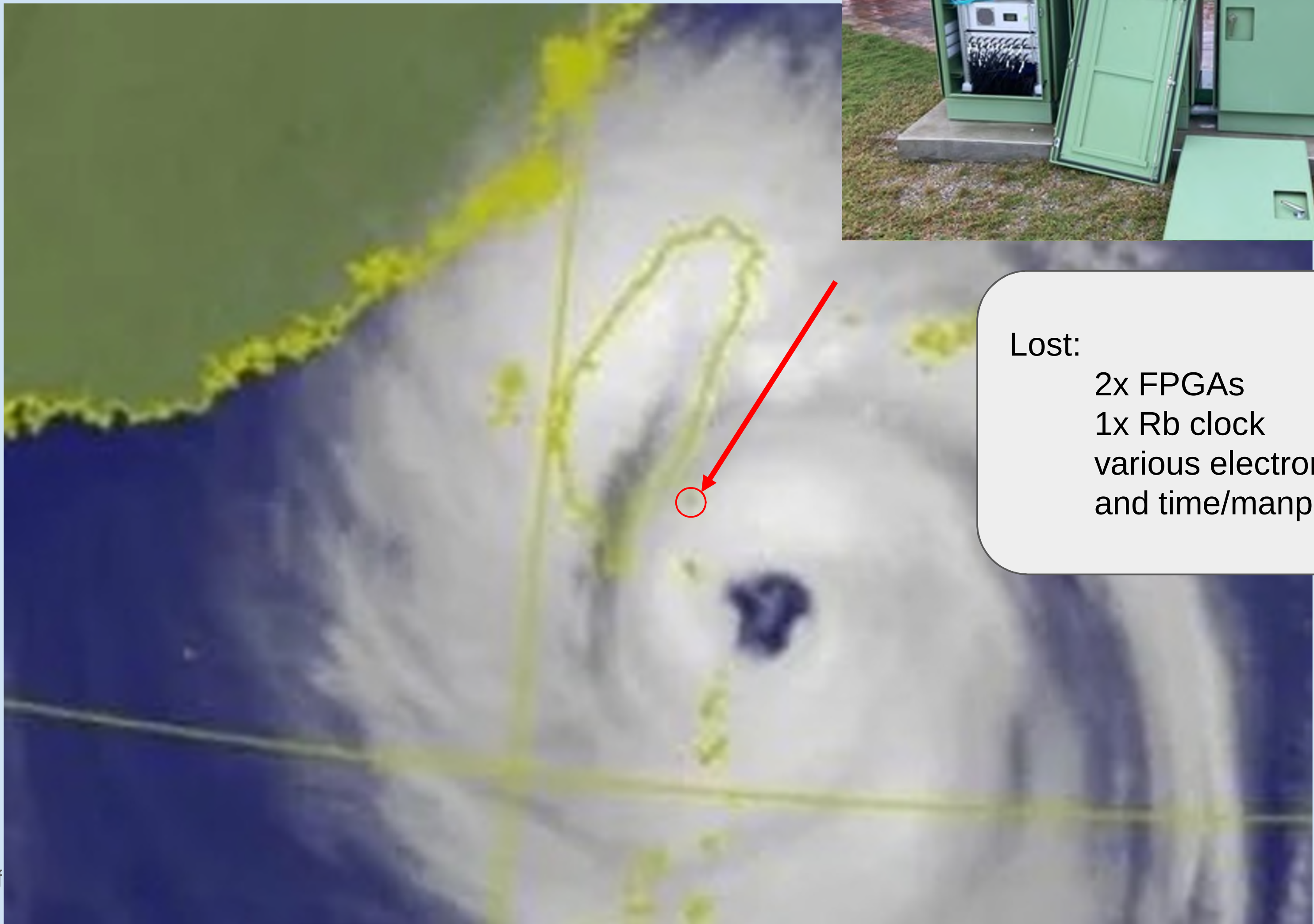
- Very energetic: a few days of energy output by the Sun in a millisecond
- >4000 detected (~1000 published)
- Not periodic
- ~10% known to repeat
  - true repeater fraction is unknown due to limited survey area
- ~1% localized to host galaxy
  - active repeater
  - CHIME outrigger will start to increase this number (CHIME/FRB 2025)
- diverse properties; mechanism(s) unclear (51 models on the FRB theory catalog)



(CHIME/FRB 2021)



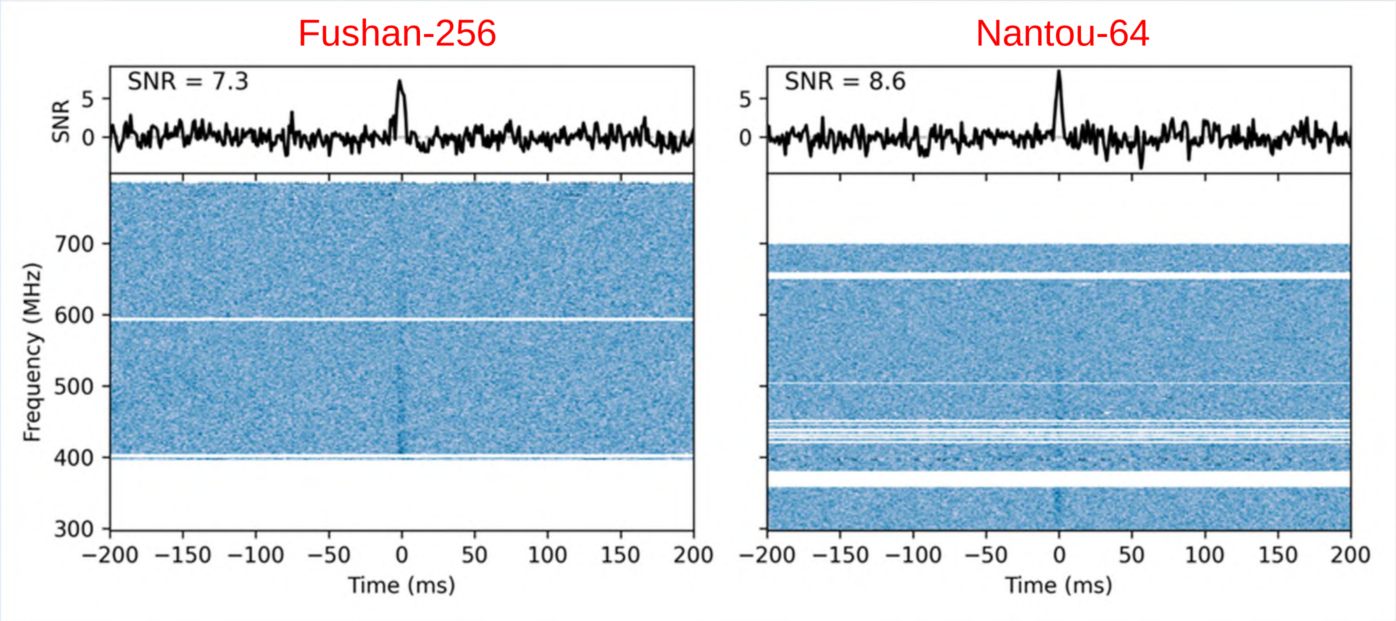
Nature’s challenge



Lost:

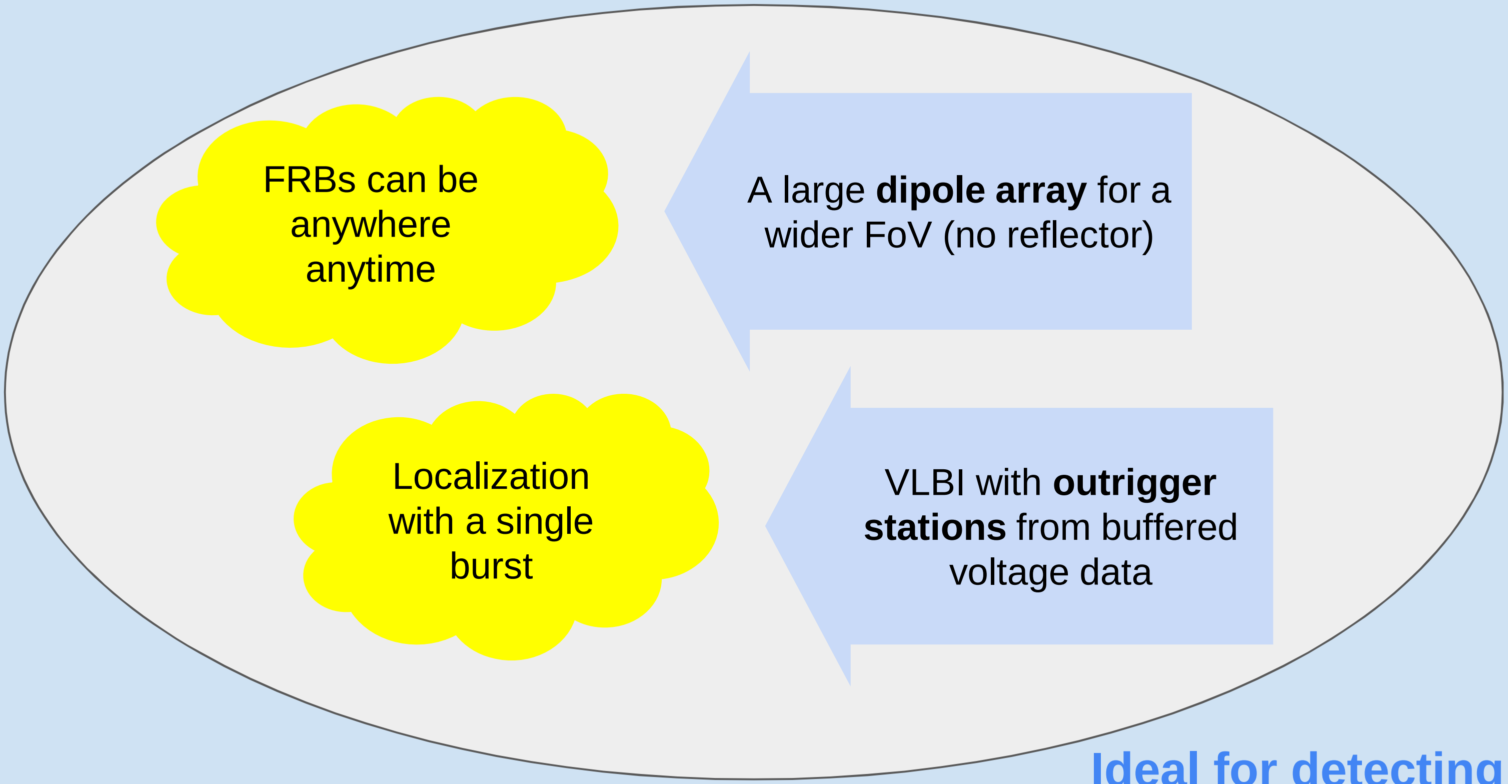
- 2x FPGAs
- 1x Rb clock
- various electronics
- and time/manpower

Same pulse of B0329+54



- Constraint on beamformed SEFD ~ 1.5x to 3x higher than expectation
- performance not yet optimized

Why BURSTT?



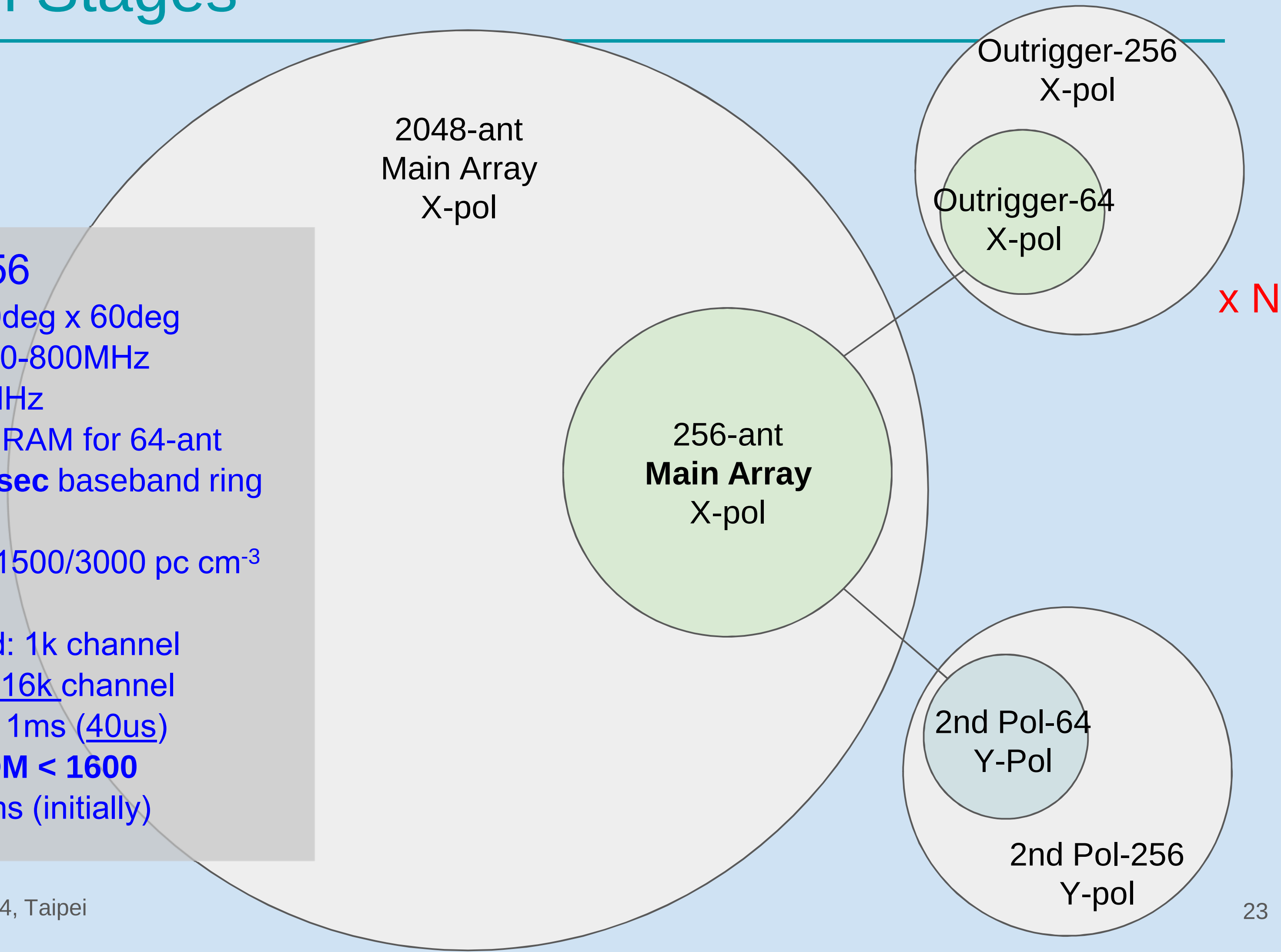
Ideal for detecting the rare bright events in the local universe.

multi-wavelength / multi-messenger follo up

Develop in Stages

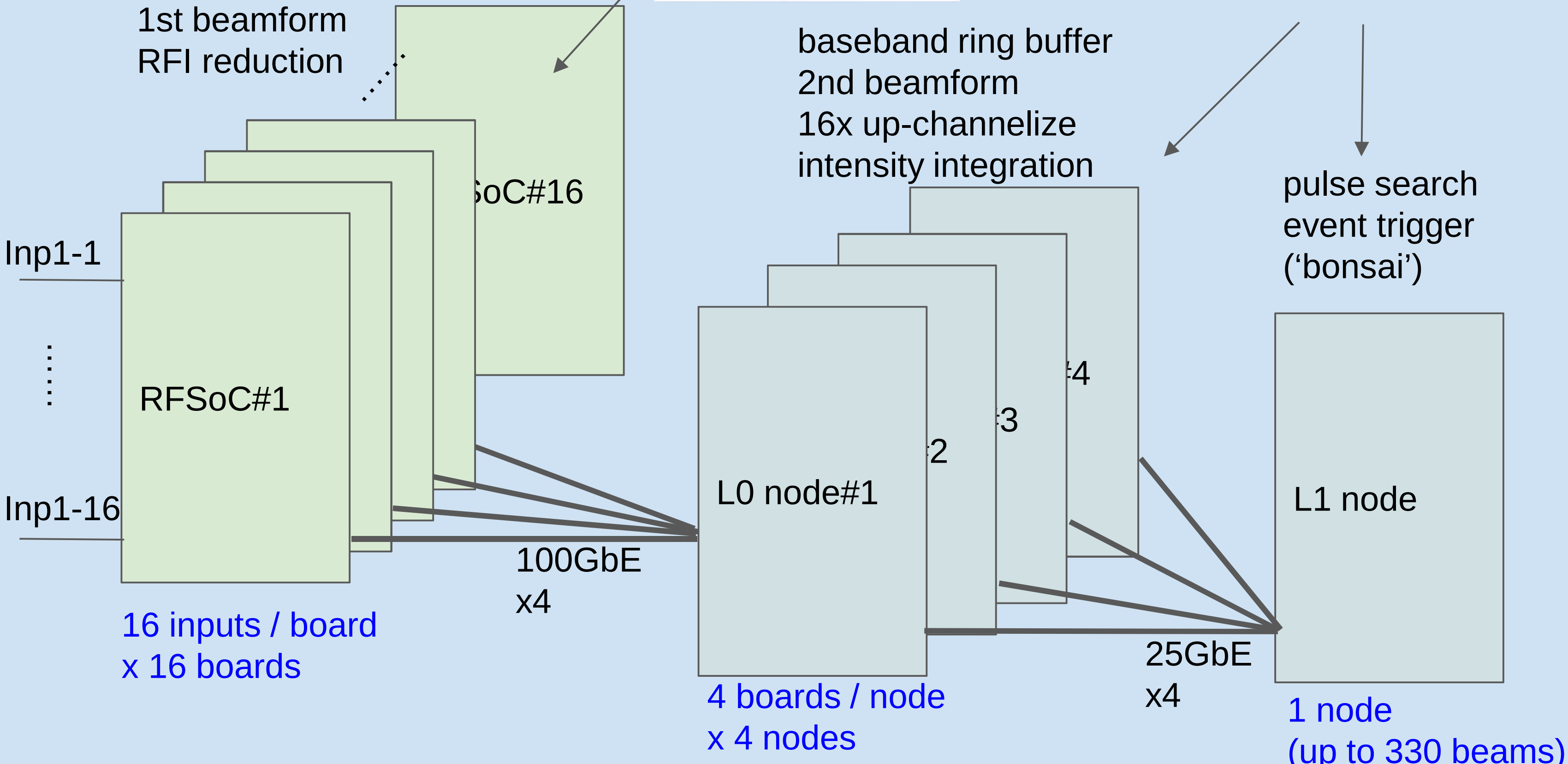
- BURSTT-256
  - FOV: 120deg x 60deg
  - range: 300-800MHz
  - bw: 400MHz
  - 1TB/**2TB** RAM for 64-ant
  - 30sec/**60sec** baseband ring buffer
  - max DM 1500/3000 pc cm^{-3}

  - baseband: 1k channel
  - intensity: 16k channel
  - time res.: 1ms (40us)
  - search: **DM < 1600**
  - 256 beams (initially)



Real-time Backend

(for BURSTT-256 main array)

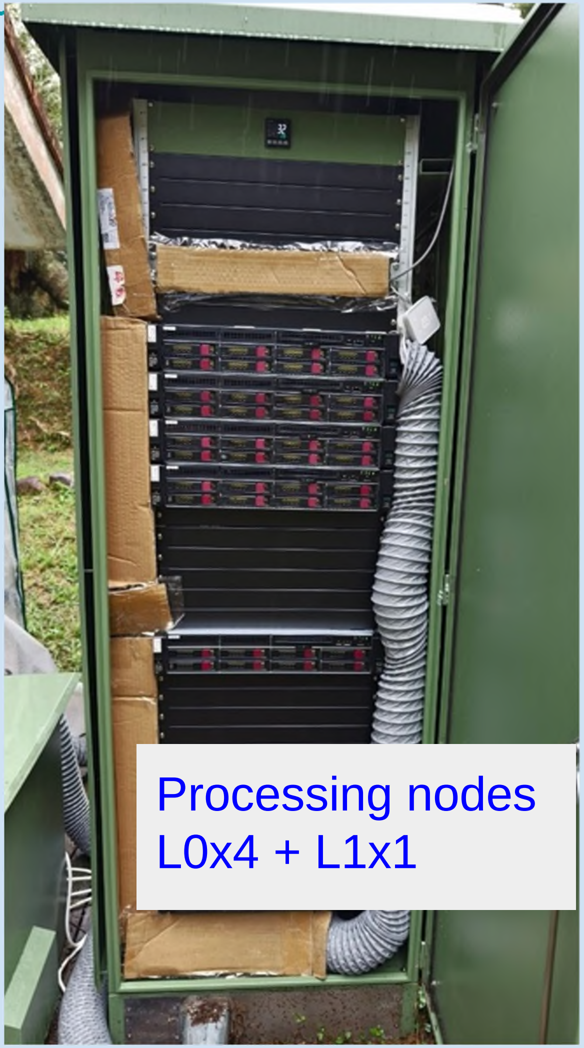


Electronics and Backend

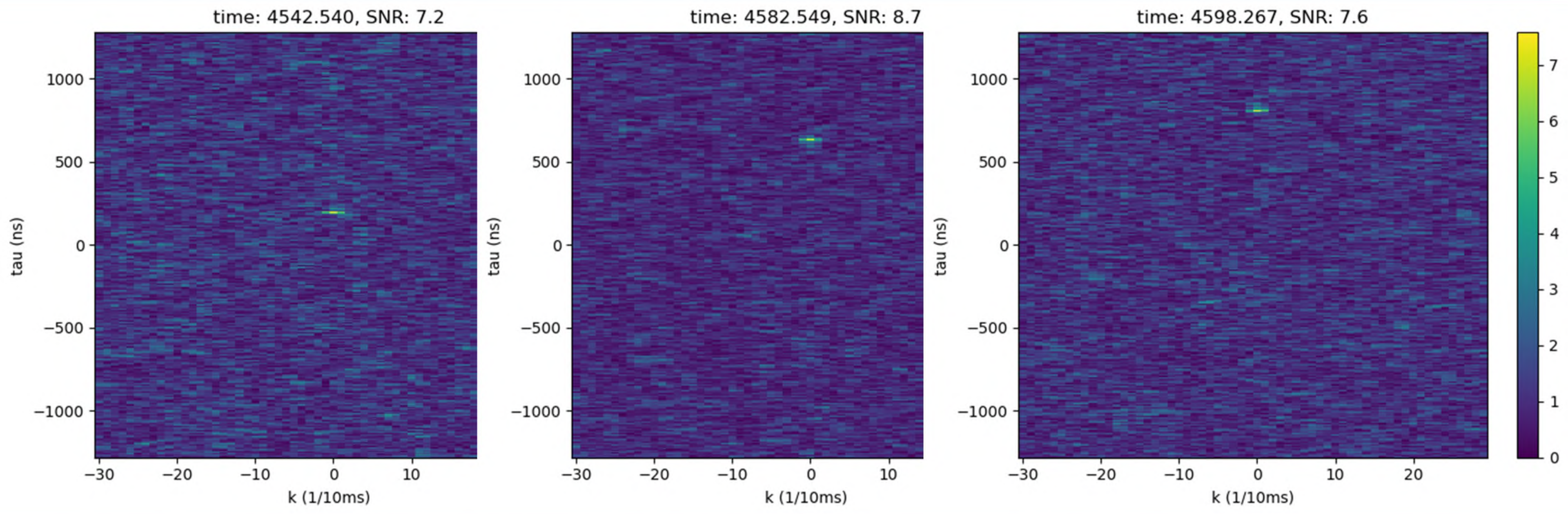
front-end electonics

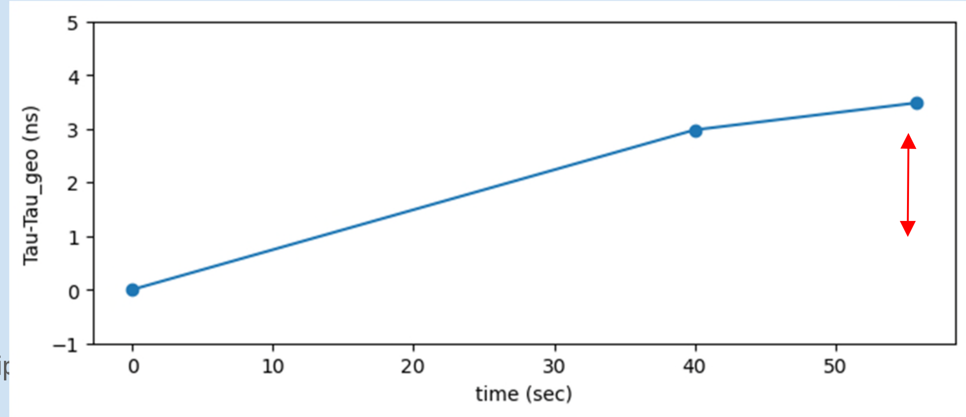
Electronics and RFSoC for 64-ant

Processing nodes
L0x4 + L1x1



Cross-correlation Test



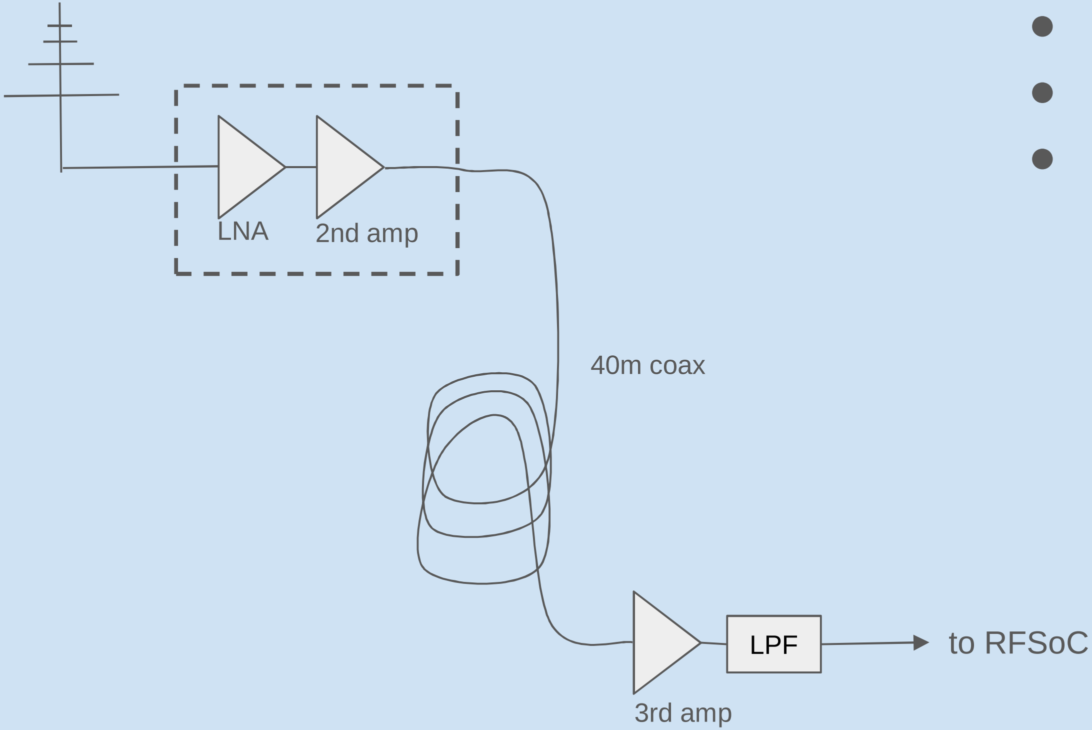


effect of ionosphere not yet accounted for

RFSoC: Xilinx Zynq UltraScale+ ZCU216

- input:
  - **16x** 14-bit 2.5Gsps ADC
- output:
  - SFP28 x 4 -- QSFP28 (100GbE)
- implementation
  - CASPER library
  - 400MHz clock (demux 4) → 1600Msps
  - **800MHz** bandwidth at 16-bit I and 16-bit Q
  - truncate to 4-bit I and 4-bit Q for 400--800MHz (52Gbps)

Frontend System

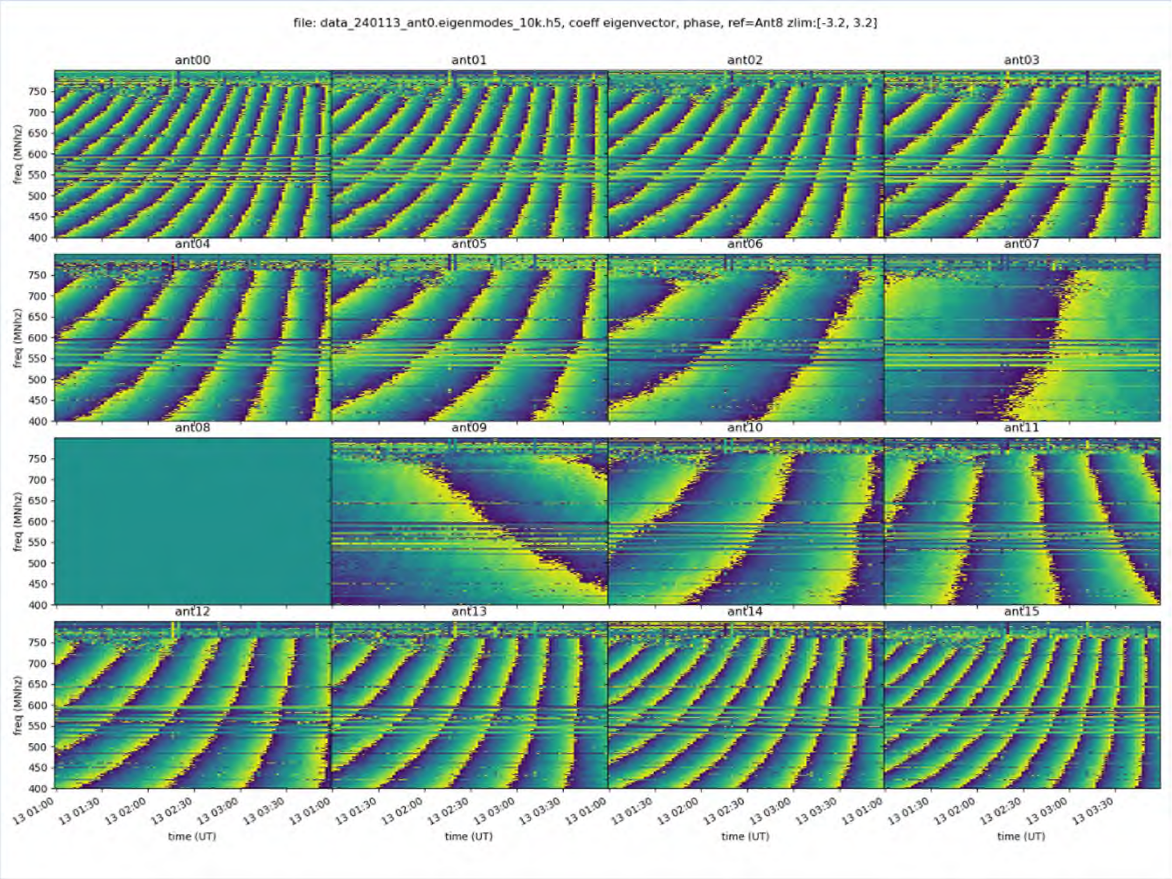


- T_{rx} ~ 35K (lab)
- T_{gnd} + T_{MW} ~ 50K (estimate)
- T_{sys} = 80 -- 150 K (measured)
- T_{RFI} varies
    - reduces by beamforming
    - may be further suppressed with spatial filtering

Fushan Main array

Calibration by the Sun

- characterize system noise (SEFD or Tsys)
- identify RFI
- determine antenna gain



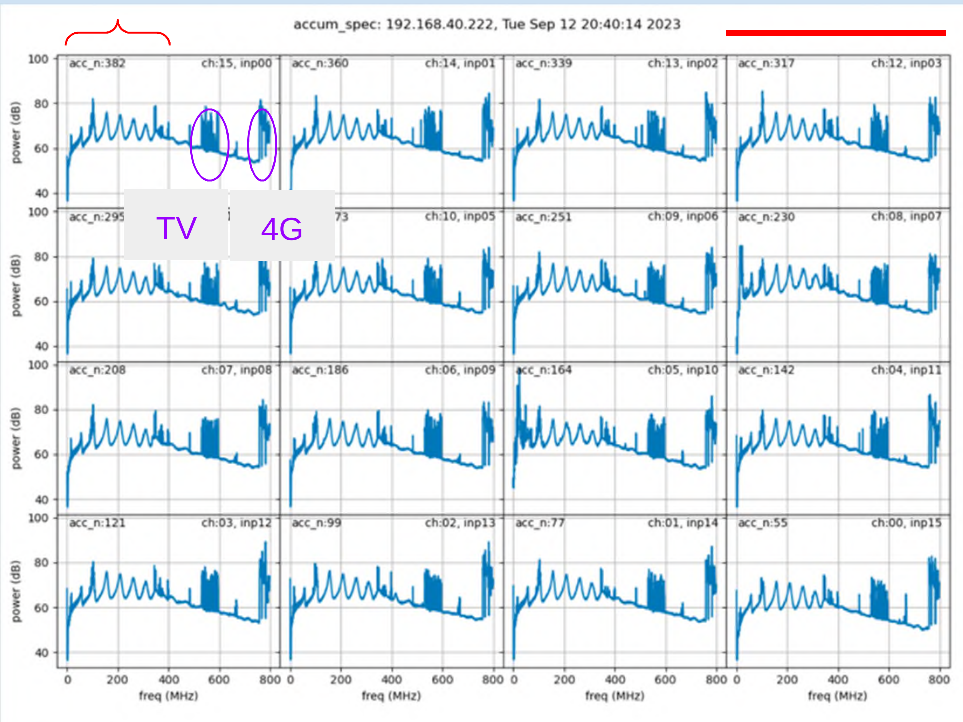
RFSoC Results from Fushan

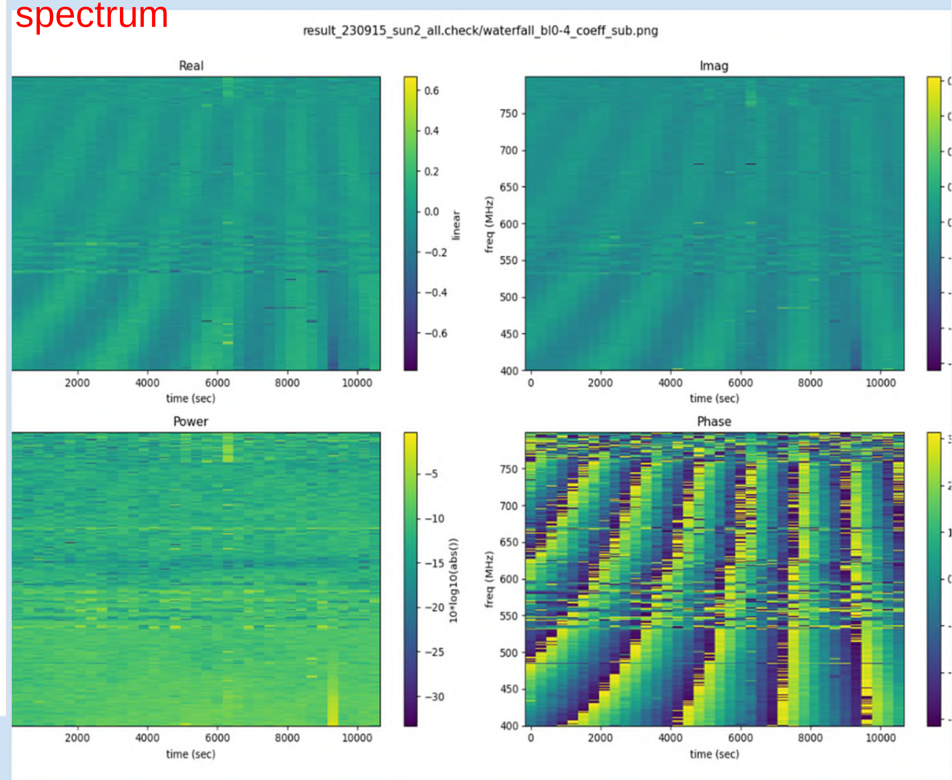
Strong reflection below 400MHz
due to commercial antenna design

sending only
400MHz out

full 800MHz
spectrum

Example:
Sun fringe
4m spacing





System Noise (SEFD)

- Characterized by correlation coefficients of the Sun
  - Solar flux at 400MHz ~ 0.4M - 0.6M Jy
- SEFD ∝ $1/\lambda^2$ (no reflector)
- SEFD_400 = SEFD*$(400/f\_MHz)^2$
- (preliminary numbers)
  - Single-ant: ~1.6M Jy (1.2M - 2.5M Jy)
  - bf16: ~0.1 MJy (0.08M - 0.2M Jy)
  - bf64: (?? - 0.05M Jy)

1/16

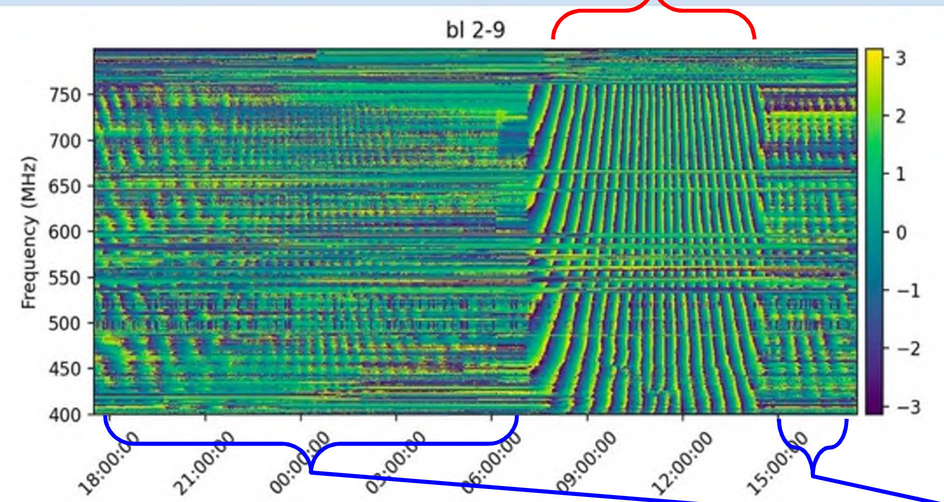
1/4

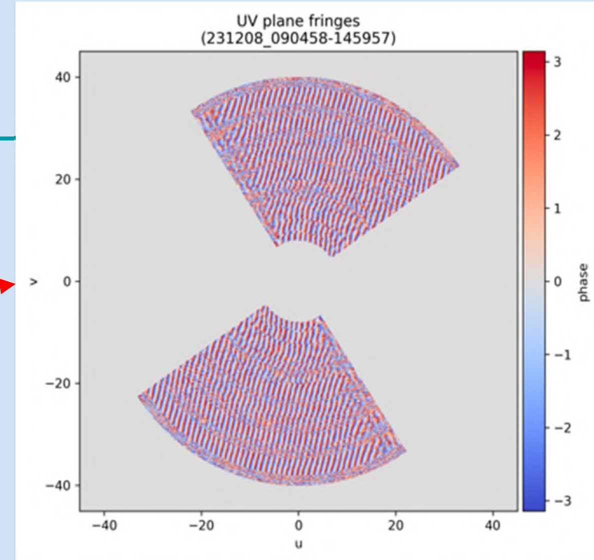
$$\text{coeff} = \frac{\text{xc}}{\sqrt{\text{ac}_1\text{ac}_2}} = \frac{f_{\text{src}} + \text{RFI}}{\text{SEFD} + f_{\text{src}} + \text{RFI}}$$

$$\text{SEFD} = \frac{f_{\text{src}}}{\text{coeff}}(1 - \text{coeff})$$

- Need characterization with another (weaker) radio source
- B0329+54 single pulse:
  - GMRT 400-500MHz peak ~10xSEFD in any minute (central square SEFD 40Jy)
  - brightest pulses estimate 200 - 400 Jy
  - Fushan 256 peak ~ 0.022xSEFD → SEFD = 9-18kJy
  - Expected ~ 6kJy

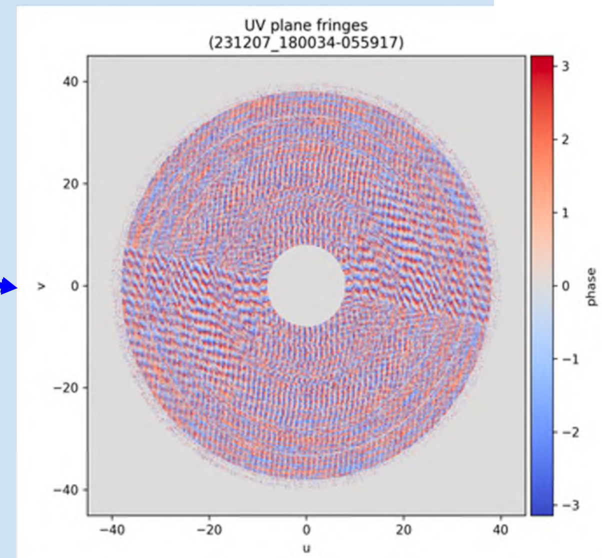
All-Sky Visibility





Sujin Eie

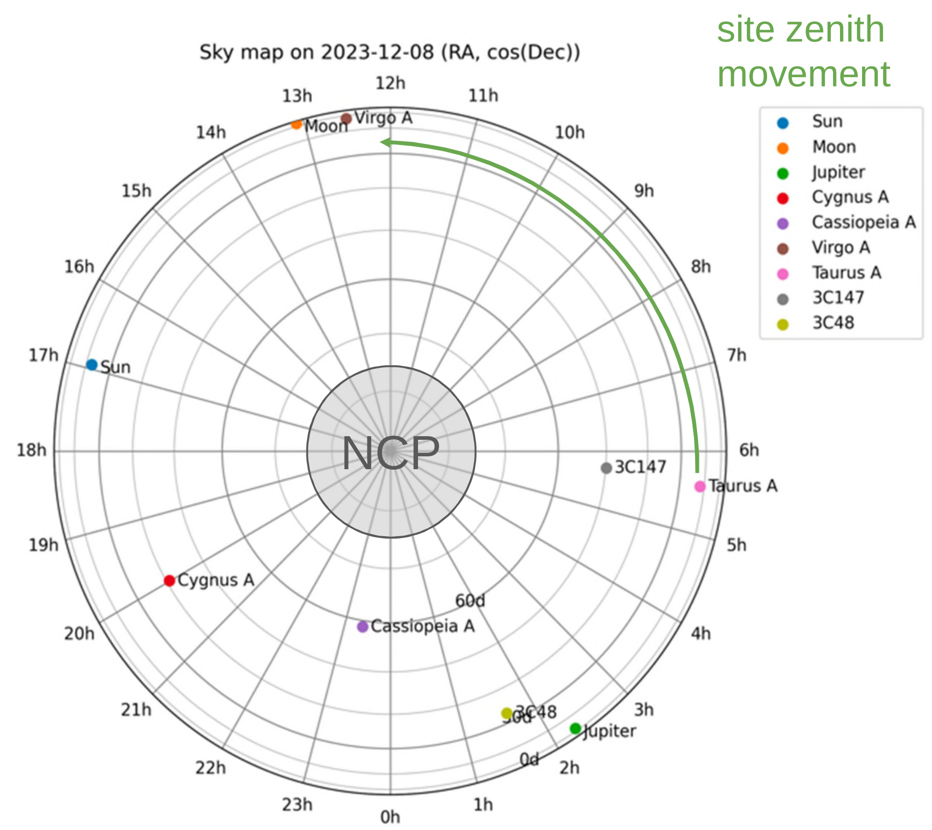
phase on uv-plane

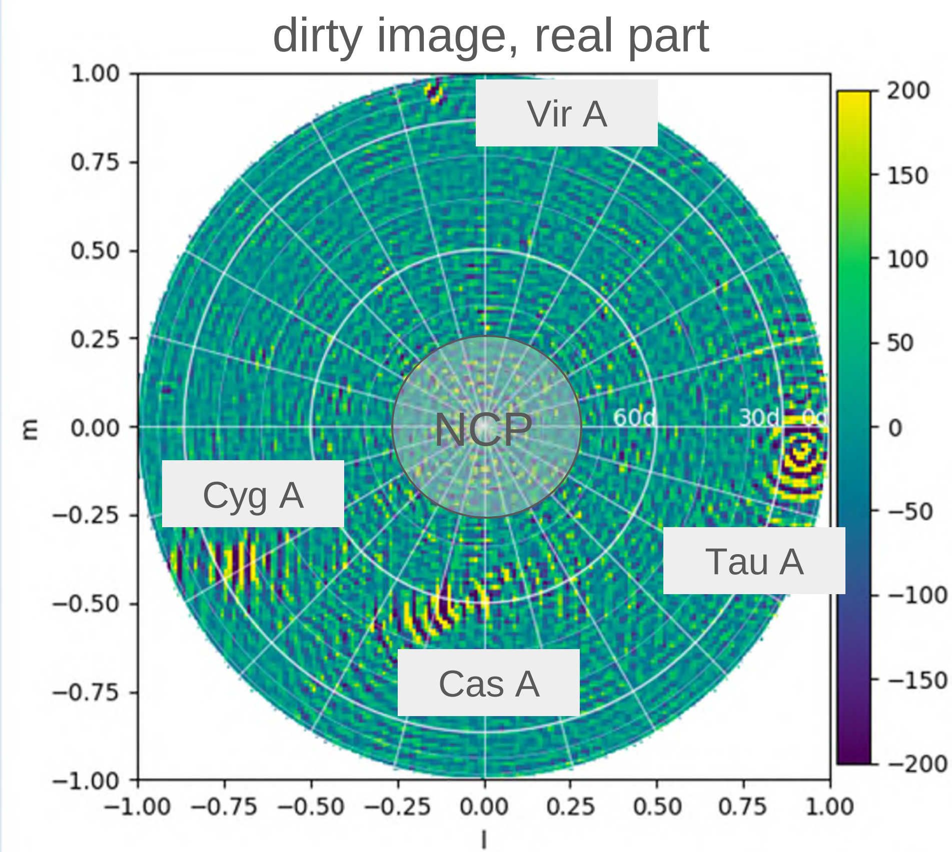


All-Sky Imaging

credit:
Sujin Eie

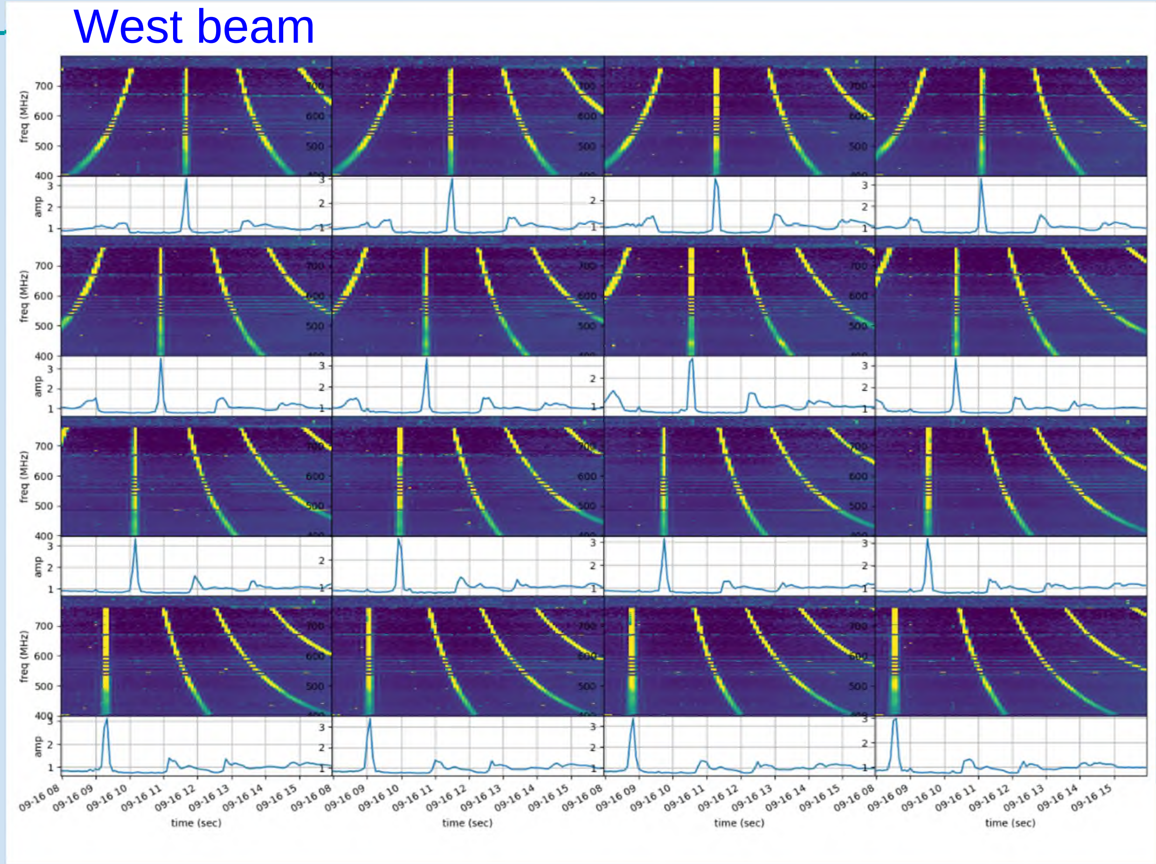
continuous recording of
visibility between 4 antennas





1D Beamform (bf16)

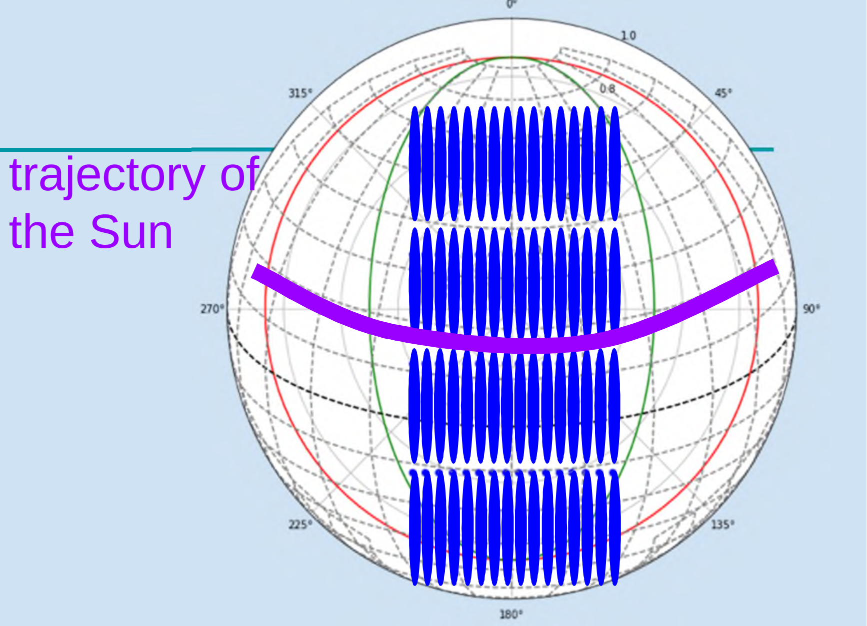
- 16 antennas → 16 beams
- Bandpass calibration done
- Use the Sun to map out the main and side lobes
- Proof of concept for front-end, back-end, and site



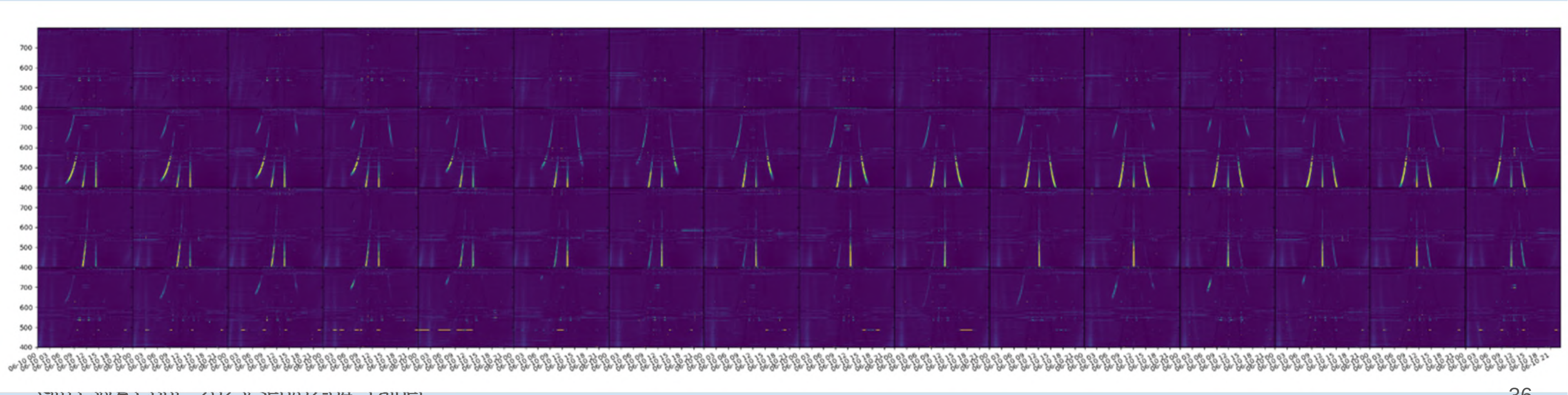
East beam

2D beamform (bf64)

- 4 rows of 16-beam each
  - typically: [-34, -10, +10, +34] deg
- Calibration of delay between FPGAs



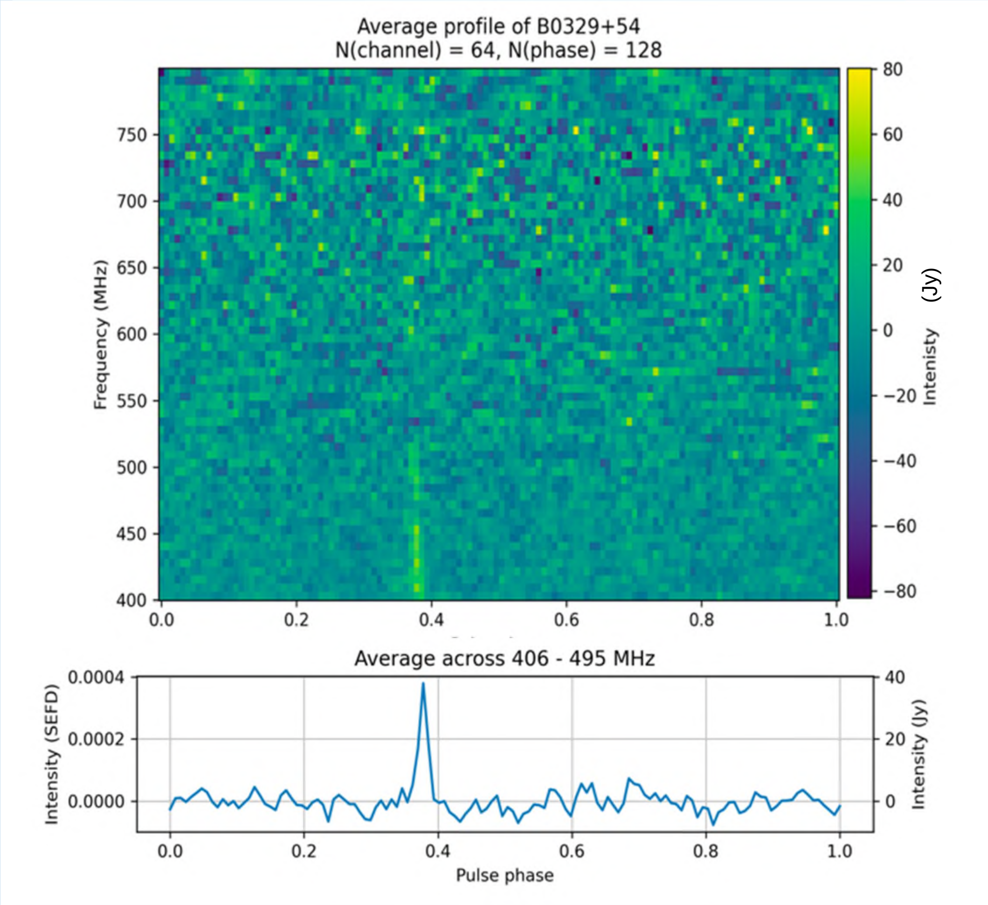
local time 00h -- 24h recording



First light: Pulsar B0329+54

bf16

- period ~ 714ms
- peak flux ~ 105Jy @ 450MHz
- DM = 26.76 pc/cm^3
- Stacking for ~ 10min
    - timing correction: TEMPO2
- measured at ~40Jy
    - up to ~ 500MHz
- detected both in Fushan and Nantou independently

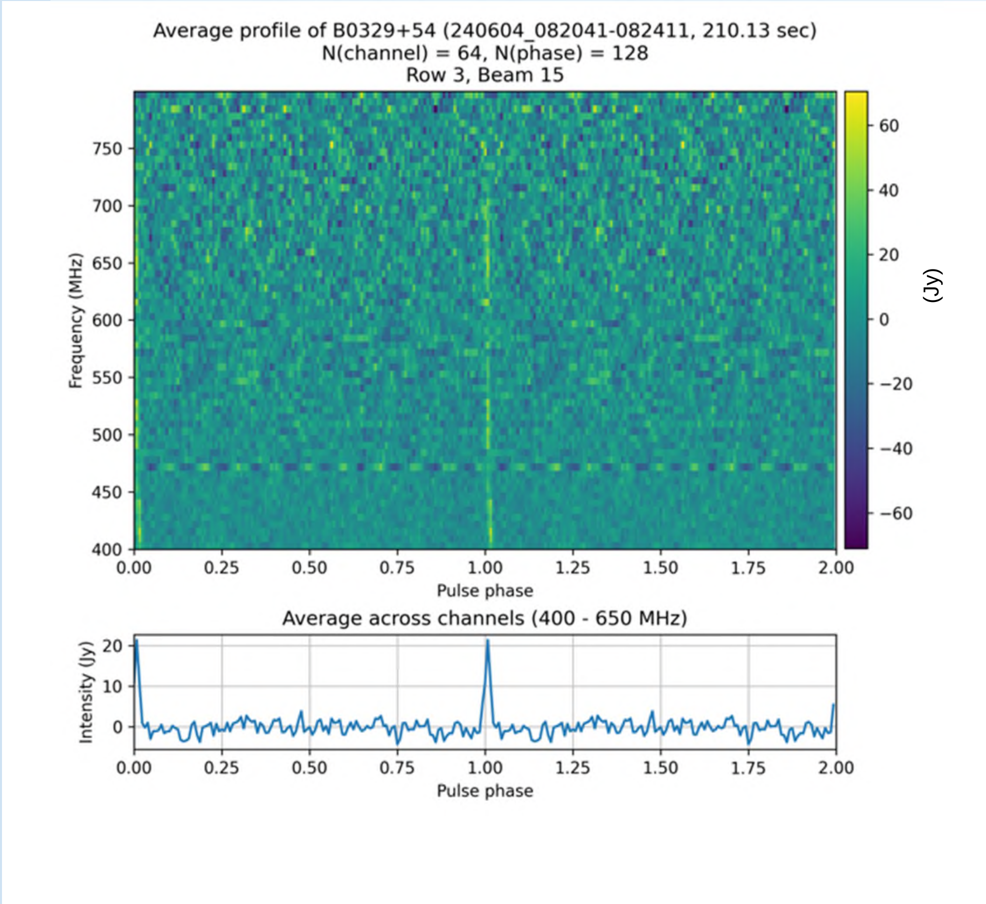


credit: Sujin Eie

First light: Pulsar B0329+54

bf64

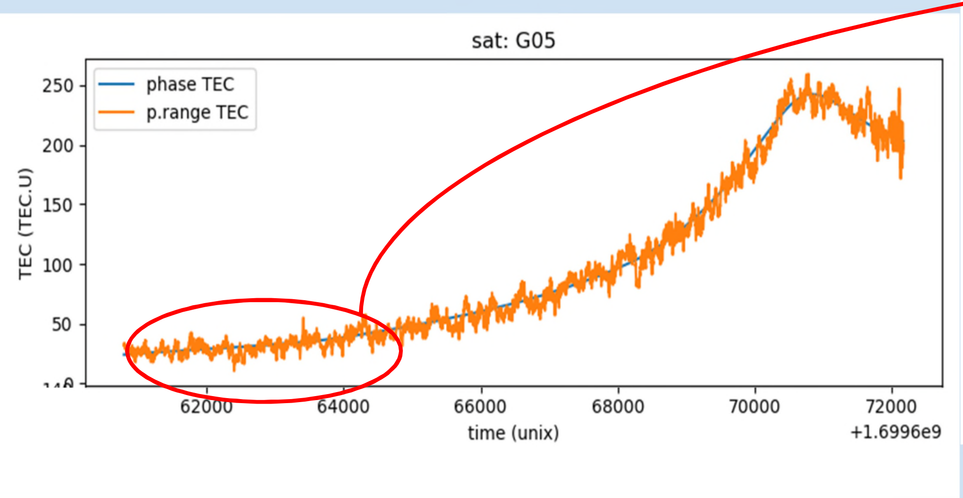
- stacking: 2min
- clear detection of pulse up ot 700MHz
- measured at ~25Jy (prelim.)
  - vs. 40Jy from bf16
  - antenna attenuation
  - beam-center offset attenuation
  - under-estimated SEFD

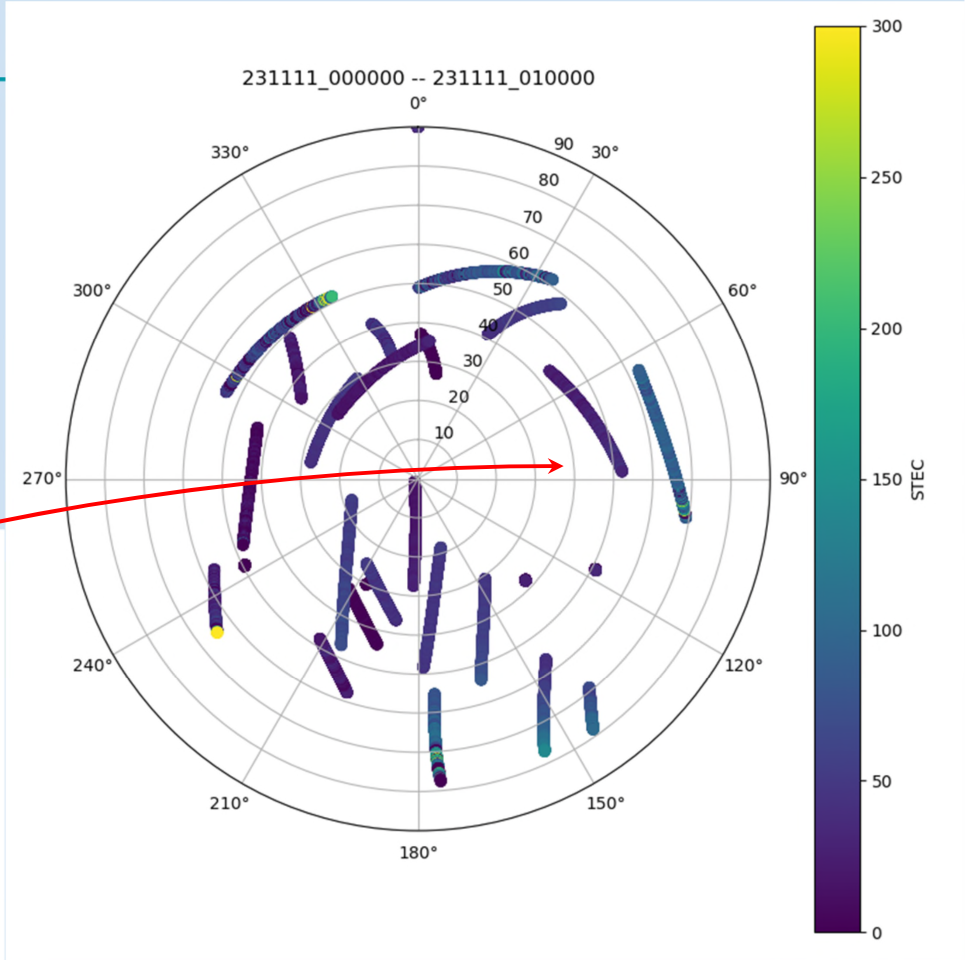


credit: Sujin Eie

Slant TEC vs. pointing

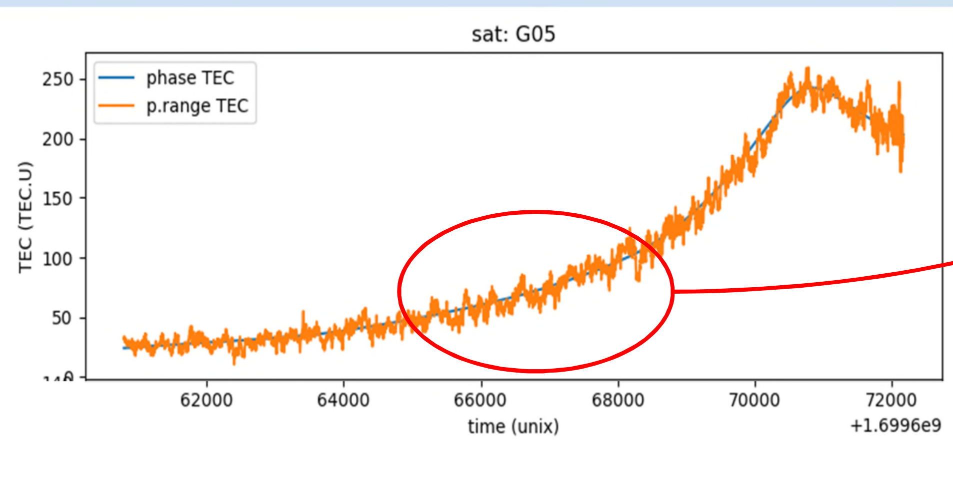
8:00--9:00

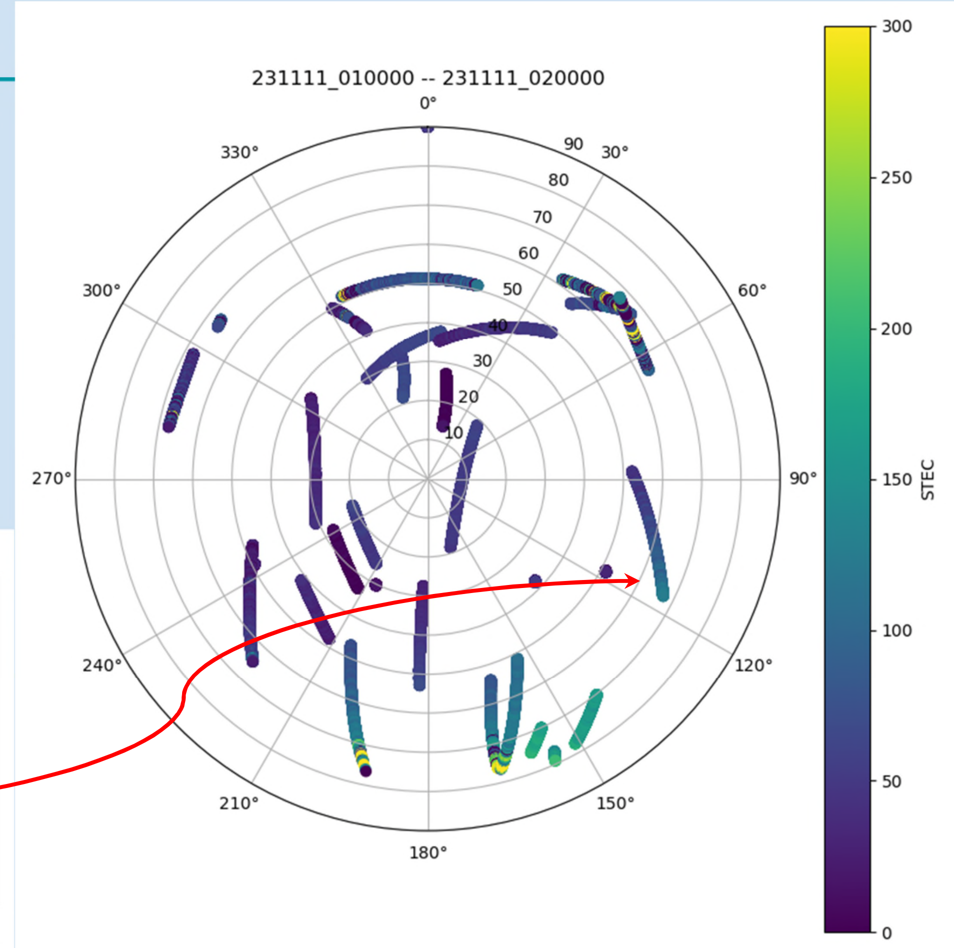




Slant TEC vs. pointing

9:00--10:00





Slant TEC vs. pointing

10:00--11:00