

# Calibration of Ionosphere Faraday Rotation for Low Frequency Arrays

Balwinder Singh Arora

◦ Ph.D. Candidate, Curtin Institute of Radio Astronomy,  
Curtin University

# Overview

- ▶ Introduction to IFR
- ▶ Computation of RM
- ▶ Calibration regime of MWA 128
- ▶ Overview of calibration challenges of future telescopes

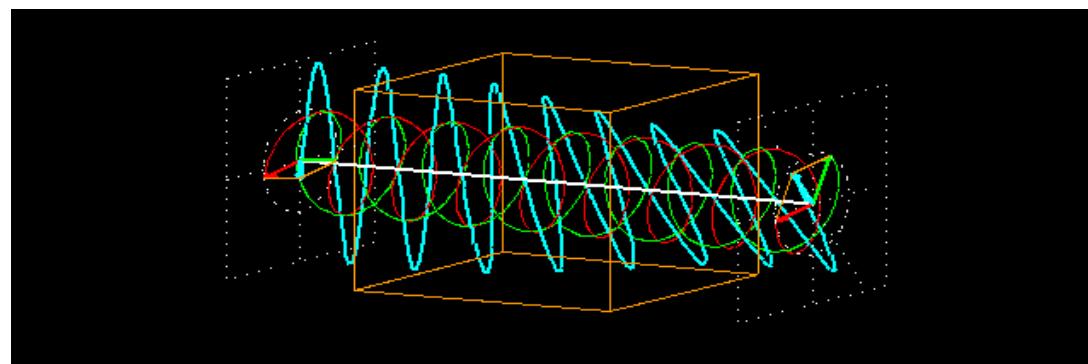
# Faraday Rotation

- ▶ A Linearly Polarised wave  $A \cos(\omega t) \hat{x}$ 
  - Right-hand and Left-Hand Circular Polarisations

$$A_{RHCP} = \frac{A}{2} \cos(\omega t) \hat{x} - \frac{A}{2} \sin(\omega t) \hat{y} \quad A_{LHCP} = \frac{A}{2} \cos(\omega t) \hat{x} + \frac{A}{2} \sin(\omega t) \hat{y}$$

- anisotropic magnetic plasma, travel at different speeds and pick up net phase difference

$$A_{RHCP} = \frac{A}{2} \cos(\omega t - \varphi) \hat{x} - \frac{A}{2} \sin(\omega t - \varphi) \hat{y} \quad A_{LHCP} = \frac{A}{2} \cos(\omega t + \varphi) \hat{x} + \frac{A}{2} \sin(\omega t + \varphi) \hat{y}$$



$$A_{RHCP} + A_{LHCP} = A \cos(\omega t) [\cos(\varphi) \hat{x} + \sin(\varphi) \hat{y}]$$

# Faraday rotation

- ▶ Polarisation angle

$$\chi = \chi_0 + (\phi_{ion} + \phi_{ISM} + \phi_{IGM}) \lambda^2$$

- ▶ Rotation Measure due to ionosphere

$$\begin{aligned}\phi_{ion} &= 0.81 \int_{telescope}^{source} n_e B \cdot dl \quad rad \quad m^{-2} \\ &= 0.81 \quad TEC_{LOS} \quad B_{LOS}\end{aligned}$$

$B_{LOS}$  = magnetic field  $\mu G$

$TEC_{LOS}$  = electron density  $cm^{-3}$

1TECU =  $10^{16}$  electrons /  $m^2$

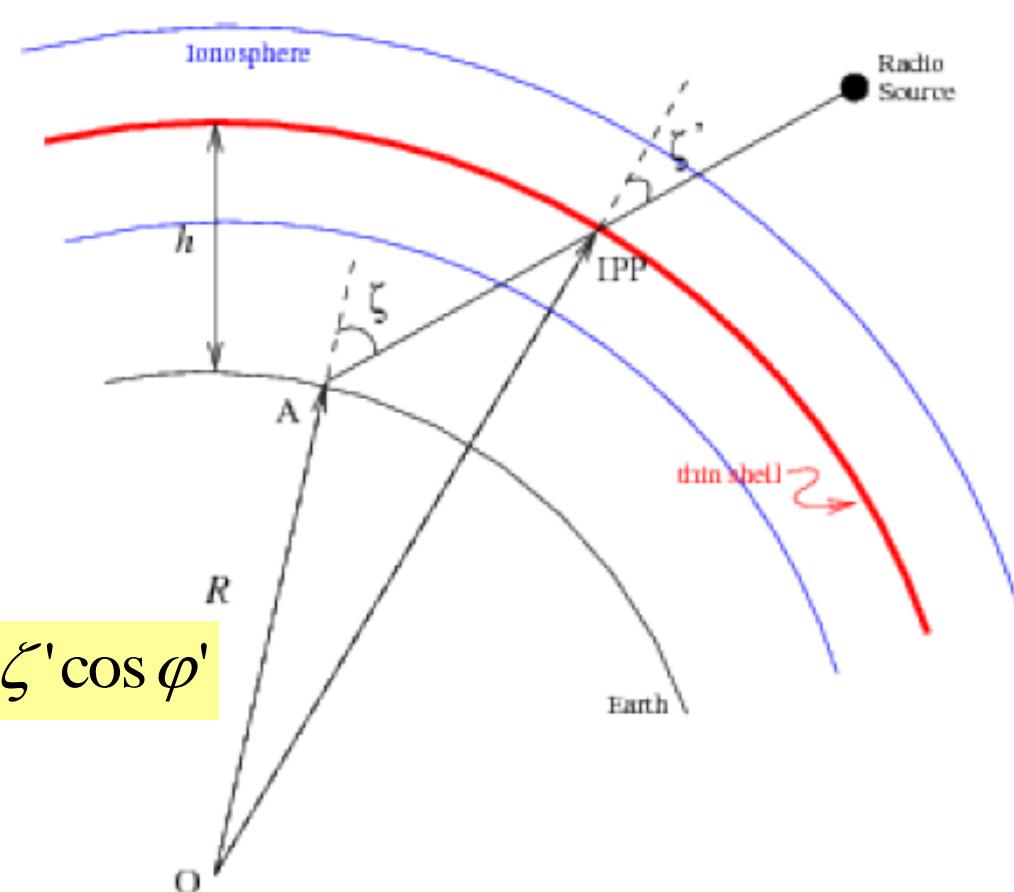
# Ionosphere and magnetic field data

## ▶ LOS ionosphere

$$TEC_{LOS} = \frac{VTEC}{\cos \zeta'}$$

## ▶ LOS Magnetic field

$$B_{LOS} = Z \cos \zeta' + Y \sin \zeta' \sin \varphi' + X \sin \zeta' \cos \varphi'$$



azimuth ( $\varphi'$ ) of the IPP.

zenith angle ( $\zeta'$ ) at the IPP

# Accuracy of data sets

- ▶ Ionosphere from CODE – VTEC, 2 hr time resolution,  $5^\circ \times 2.5^\circ$  spatial resolution
  - 1-sigma uncertainty in RMS is  $2 - 5 \text{ TECU} = 0.81$  to  $2 \text{ rad m}^{-2} = 185.8^\circ$  to  $464.6^\circ$  rotation in PA at 150 MHz ( $B = 50,000 \text{ nT}$ )
- ▶ International Geomagnetic Reference Field (IGRF11; Finlay et al. 2010)
  - 5, 5 and 7 nT in X, Y, and Z directions respectively

# Using GPS/GNSS data for ionosphere

- Global Positioning System (GPS)– US Military, currently 31 operational satellites
- GLObal Navigation Satellite System (GLONASS)
  - Russia, 24 operational satellites
- Galileo – European Union, 4 satellites in orbit
- BeiDou – China, 15 satellites in orbit

## Benefits of using GNSS:

- Dual Frequency, 24/7 all weather operable

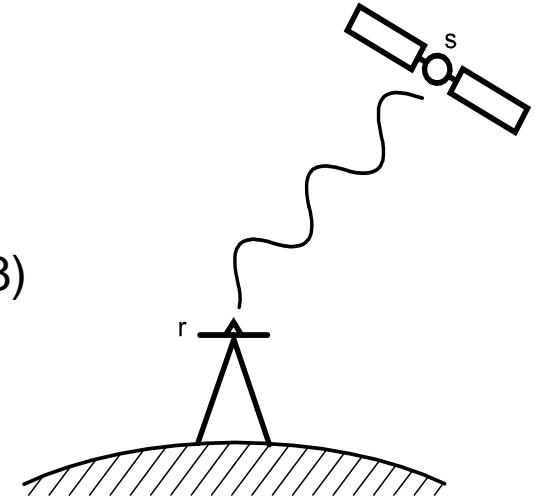
# Ionosphere estimation using GNSS data

- Code (range) observables

$$p_{r,j}^s = \rho_r^s + \mu_j \dot{i}_r^s + DCB_r + DCB^s + \varepsilon_{r,j}^s$$

↑      ↑      ↑      ↑      ↑  
range    iono delay    Receiver bias    Satellite bias    other errors

(Teunissen and Kleusberg, 1998)



$c$  = speed of light

$j$  = frequency (1,2,...)

$\mu$  = frequency-dependent ionospheric coefficient

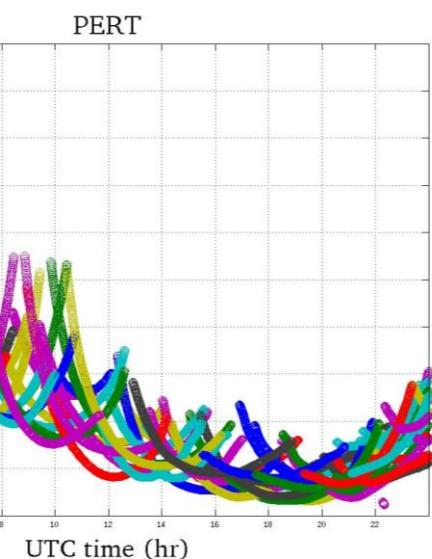
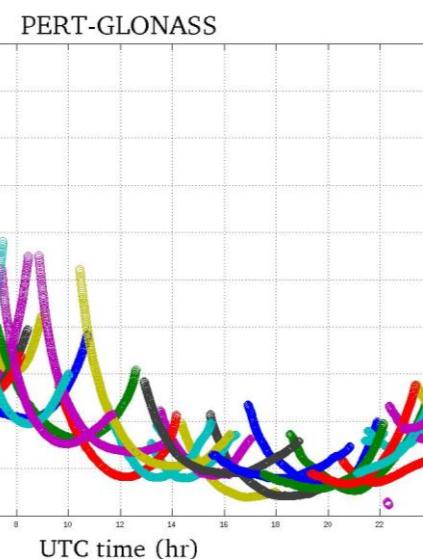
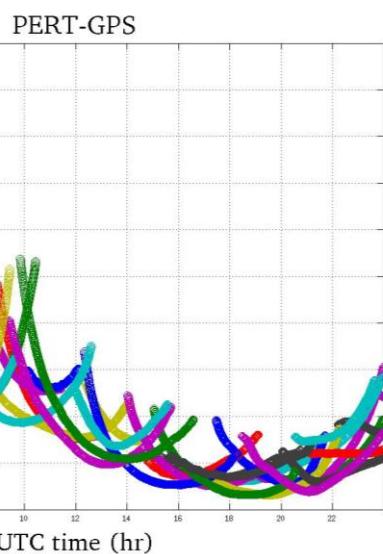
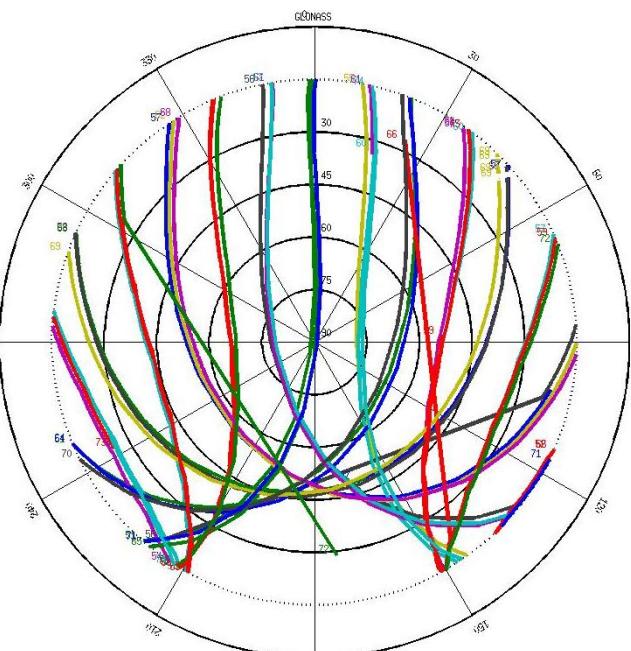
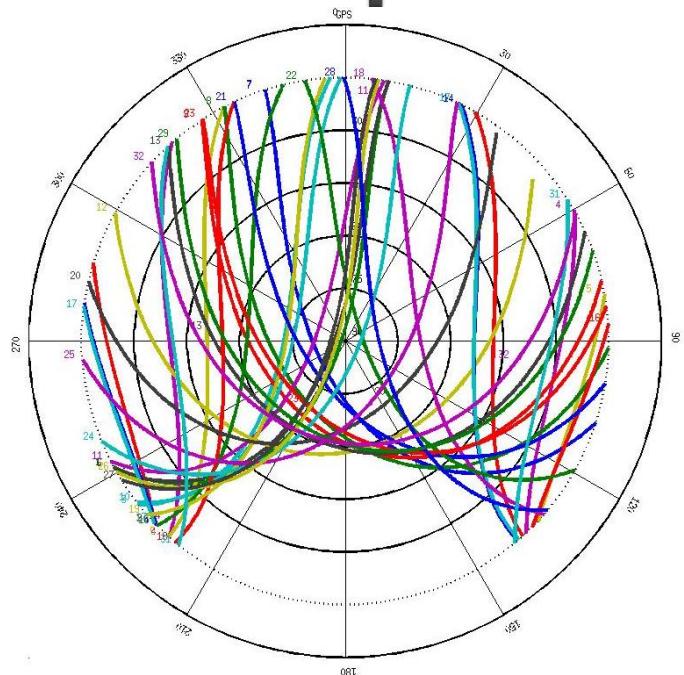
ionospheric delay:

frequency-dispersive:

(scaled w.r.t. 1<sup>st</sup> frequency)  $\mu_j = \left( \frac{\lambda_j}{\lambda_1} \right)^2$

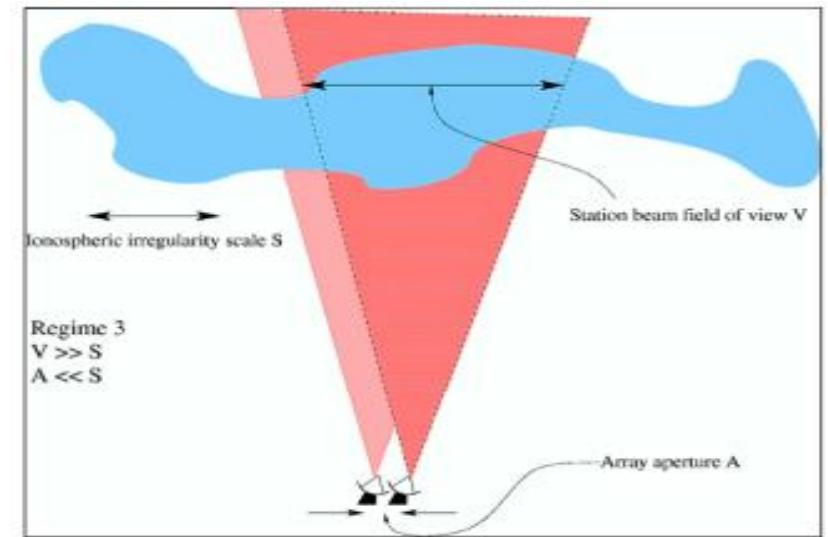
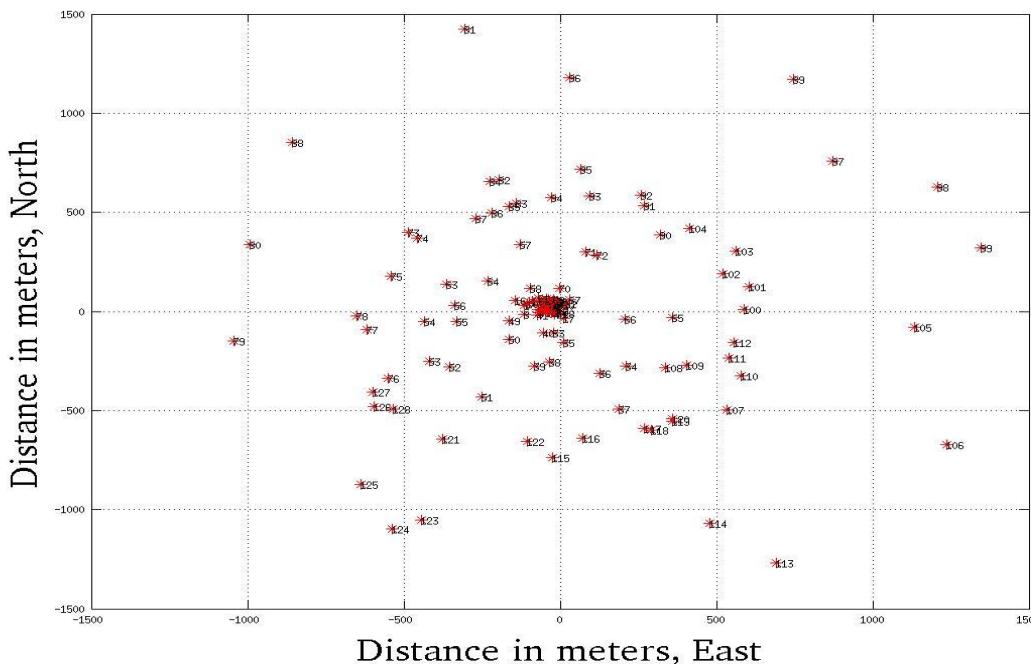
$$p_{r,12}^s = p_{r,2}^s - p_{r,1}^s = \mu_{12} \dot{i}_r^s + DCB_{r,12} + DCB_{12}^s + \varepsilon_{r,12}^s$$

# Ionosphere -GPS & GLONASS



# Calibration of MWA 128

- Frequency range – 80 to 300 MHz
- Baseline lengths – 7.7 m to 2864 m
- Field of View – 25 degrees (half power beamwidth) at 150 MHz



Regime 3 scenario, Wijnholds  
(2009) et al.

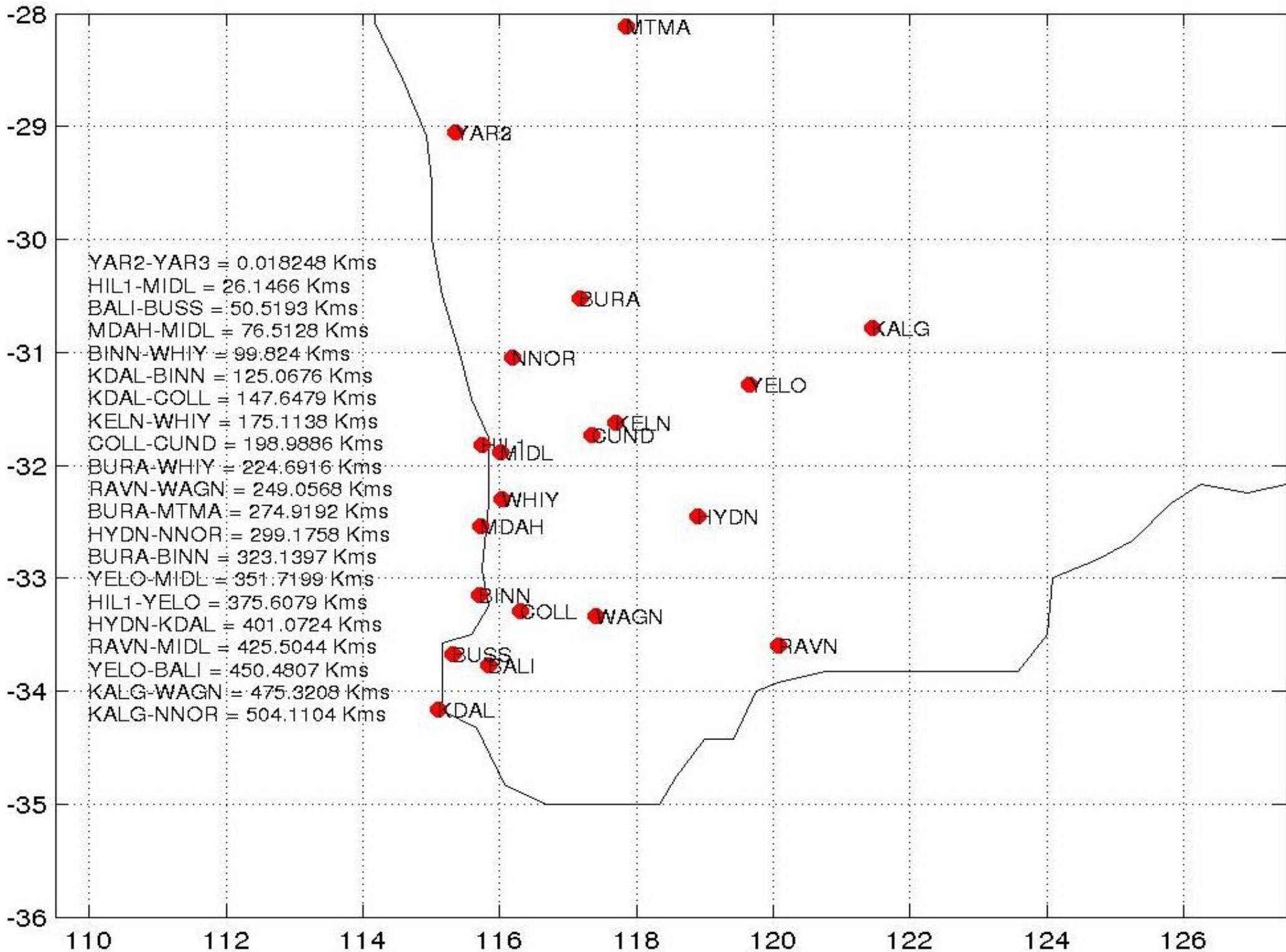
- Calibration considerations
  - Ionosphere difference between the two antennas

$$\Delta I_{ij}(t) \leq I_{tol}$$

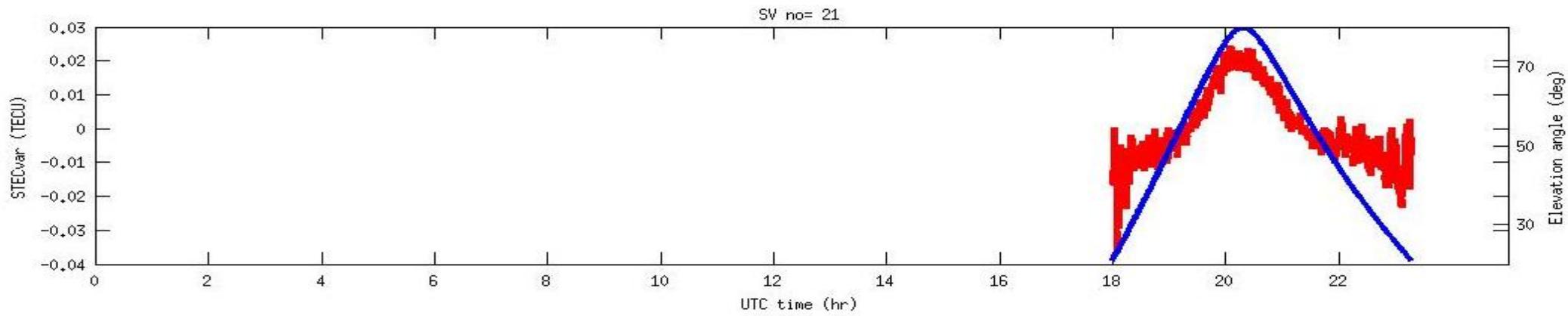
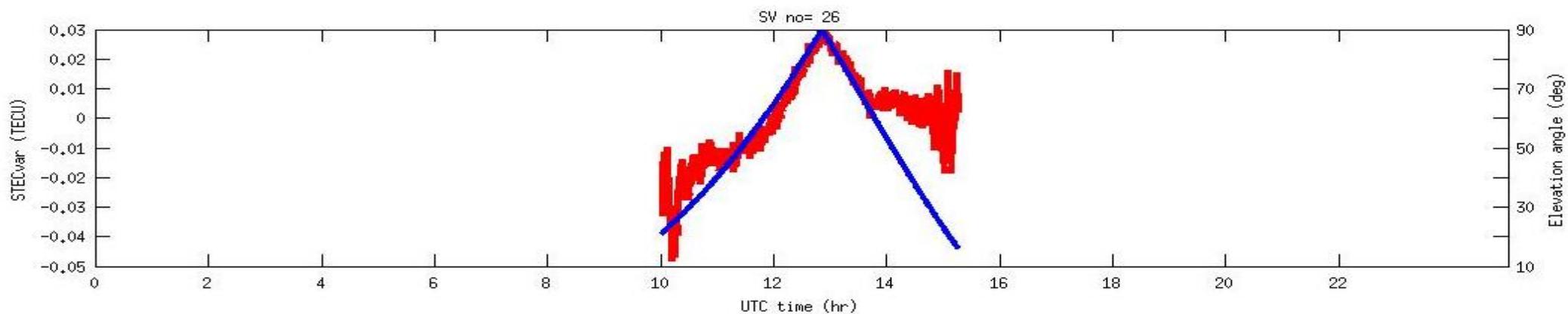
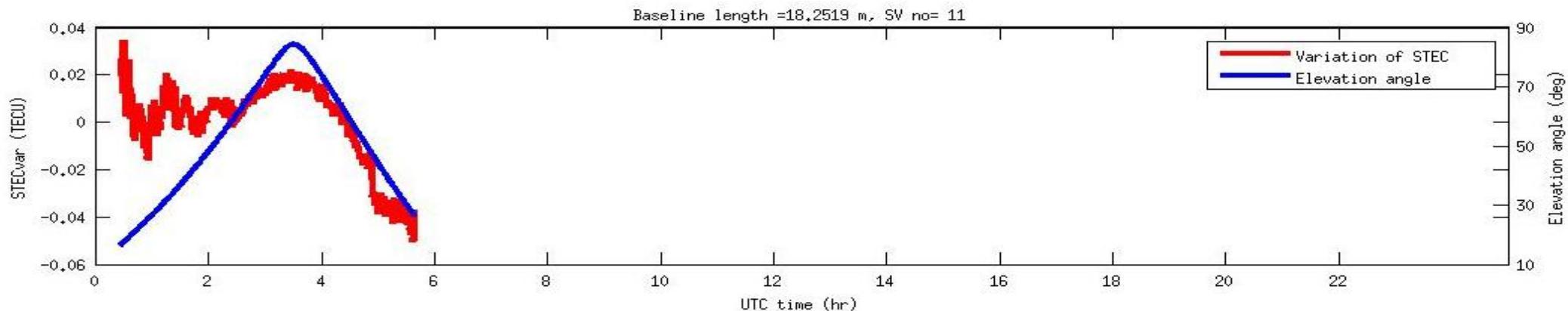
- Batch length for averaging visibilities

$$\Delta I_i(t - t_k) \leq I_{th} \quad I_{tol} = I_{th} \quad \begin{aligned} &\cong 0.1 \quad \text{TECU} \\ &\cong 10^\circ \text{ PA} \quad 150 \text{ MHz} \end{aligned}$$

- Ionosphere data source
  - GNSS
  - ALBUS

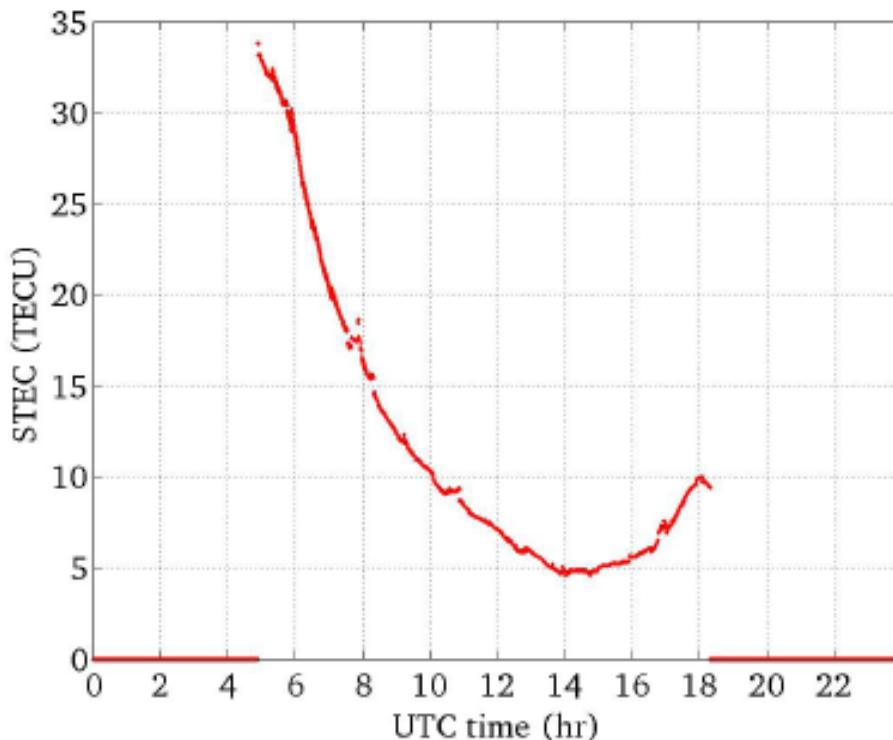


# $\Delta I_{ij}(t)$ using GPS - 18 m baseline

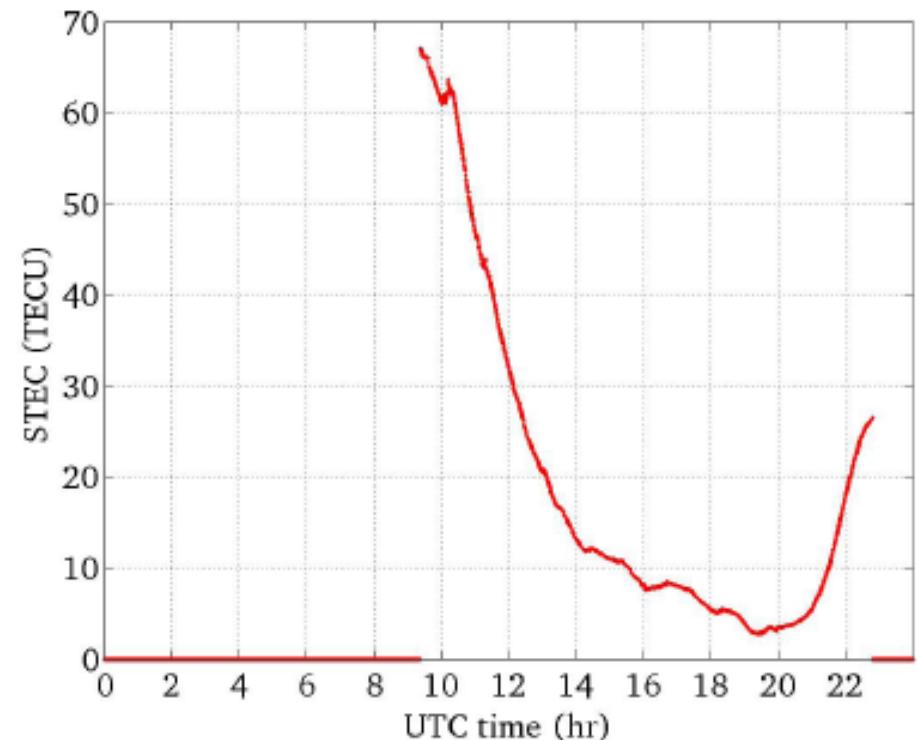


# ALBUS, J0636-2041

- ▶ MWA 128, 8128 baseline combinations
- ▶ Two scenarios – Normal & Active Ionosphere



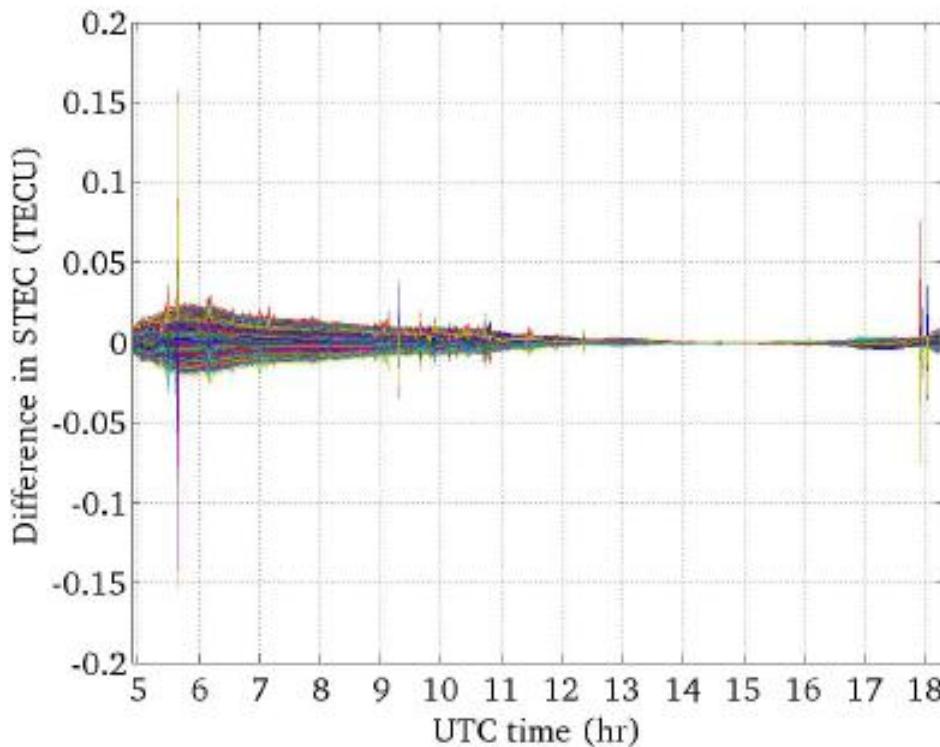
(a) STEC for MWA tiles on 11 March 2007



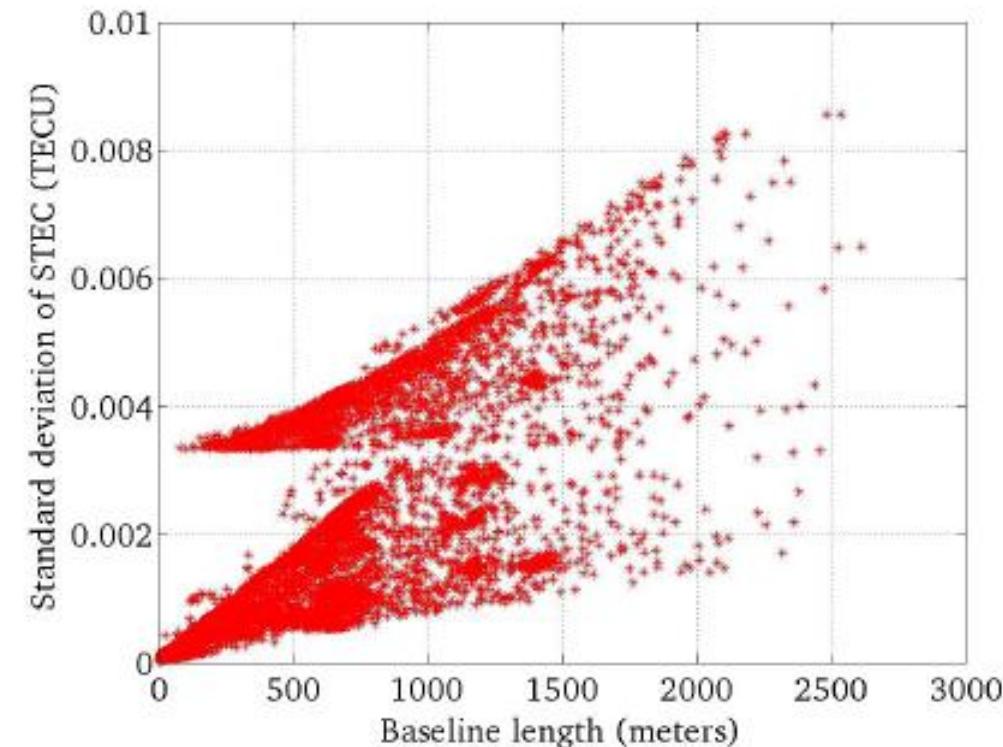
(b) STEC for MWA tiles on 1st January 2013

# Normal ionosphere scenario

- ▶ 99% baselines – Max Relative STEC of 0.025  
 $\text{TECU} = 2.32^\circ \text{ change in PA}$



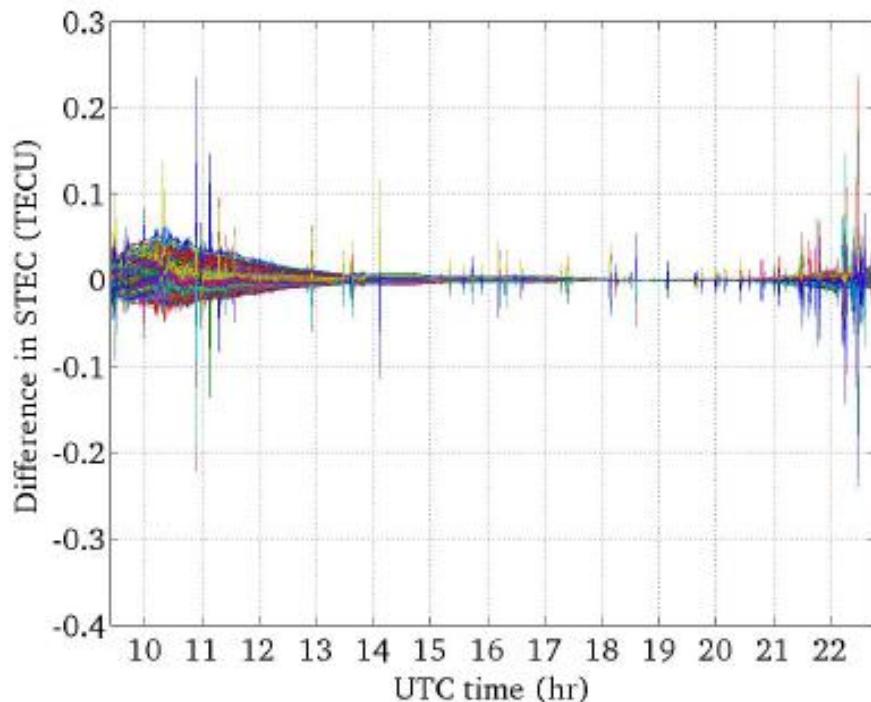
(a) Relative STEC



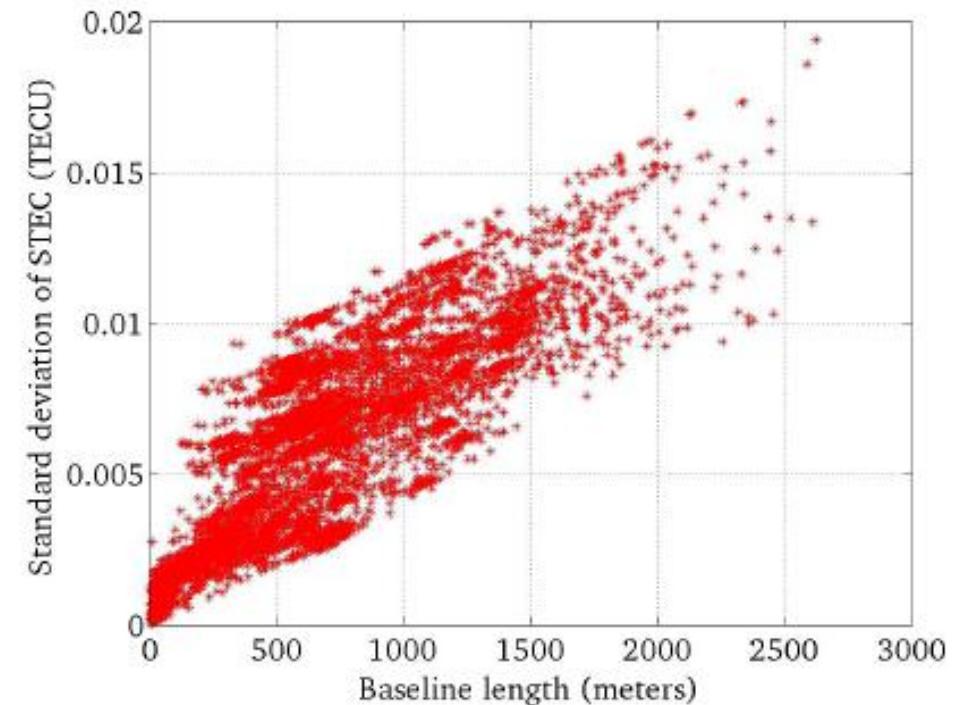
(b) Standard deviation in STEC

# Active ionosphere scenario

- ▶ 97% baselines – Max Relative STEC of 0.05  
 $\text{TECU} = 4.64^\circ$  change in PA



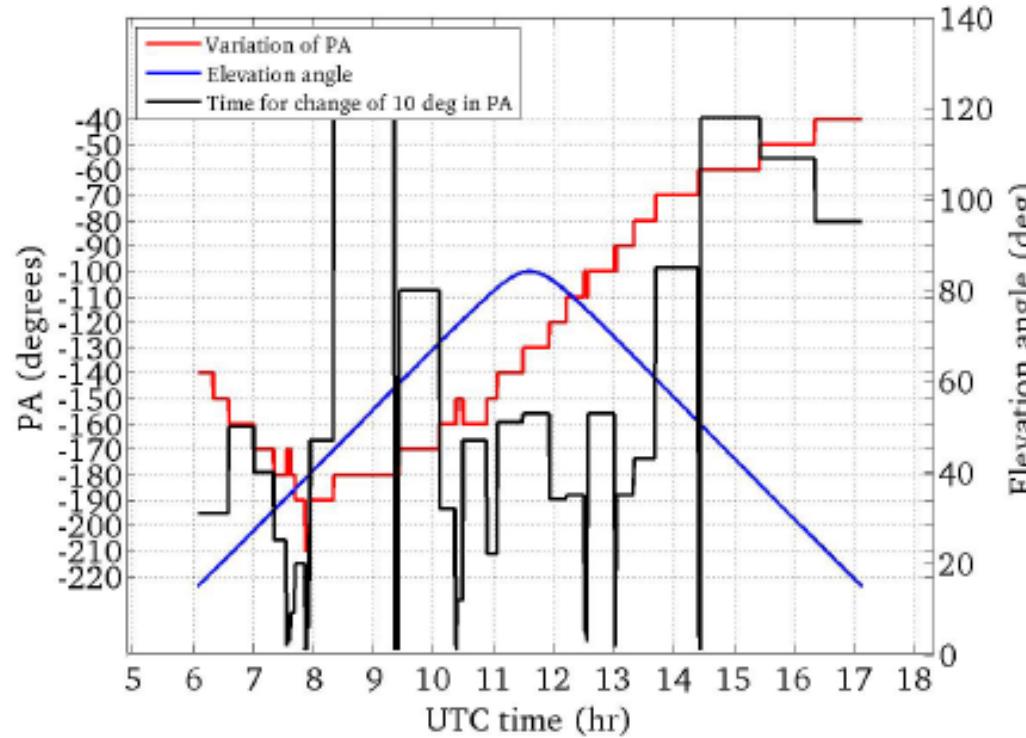
(a) Relative STEC



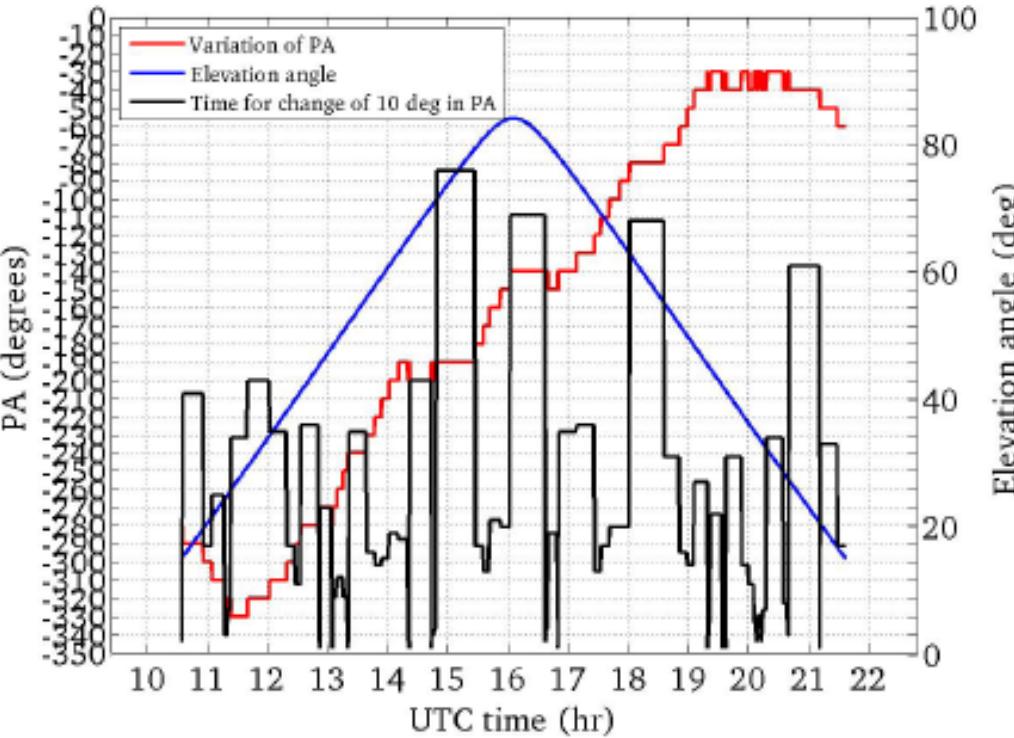
(b) Standard deviation in STEC

# Batch length – averaging visibilities

- ▶ PA at center of array – absolute STEC, RM
- ▶ Optimal elevation cutoff
- ▶ Normal ionosphere = ~ 25 mins
- ▶ Active ionosphere = ~ 10–15 mins



(a) Normal ionosphere activity

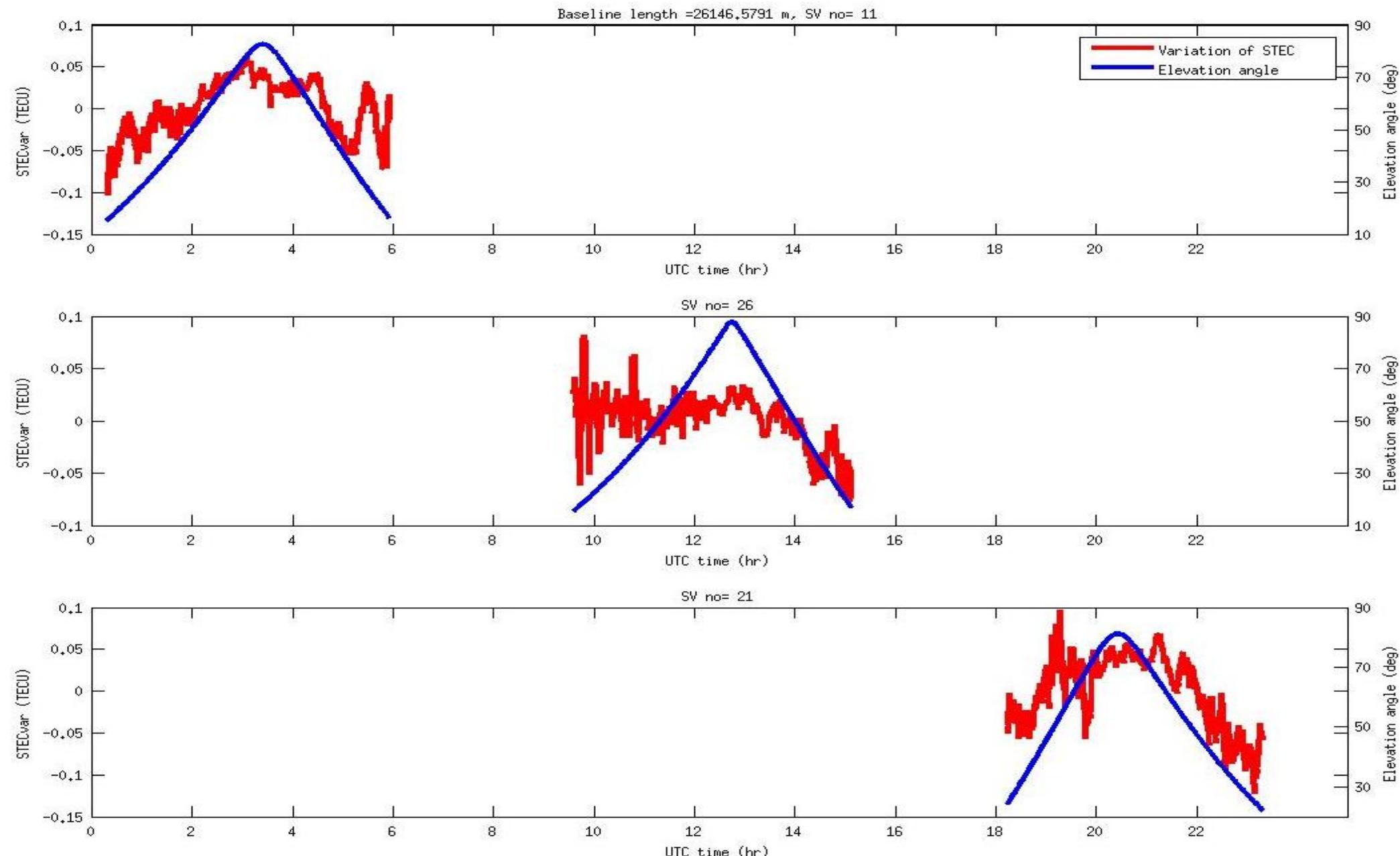


(b) High ionosphere activity

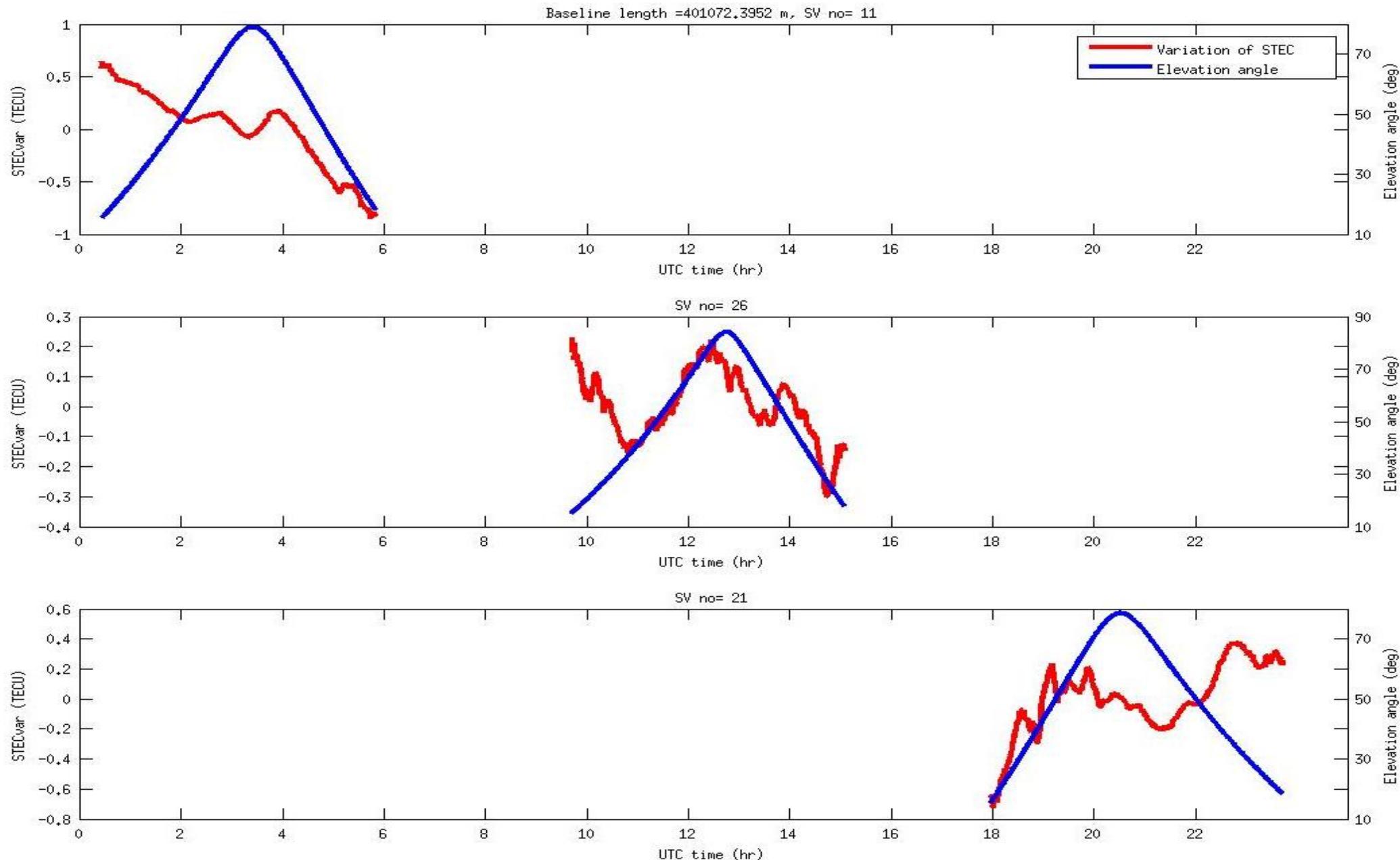
# Future Low frequency Arrays

- FR calibration for future arrays
  - ASKAP ->
    - 700 MHz to 1.8 GHz, @ 0.1 TECU, PA = 0.53°
    - Max baseline 6 Km -
    - FoV = 30 sq deg
  - SKA-low ->
    - 70 to 450 MHz - @ 0.1 TECU, PA = 25.7°
    - ~ 50 Km baseline
    - FoV=27 sq deg

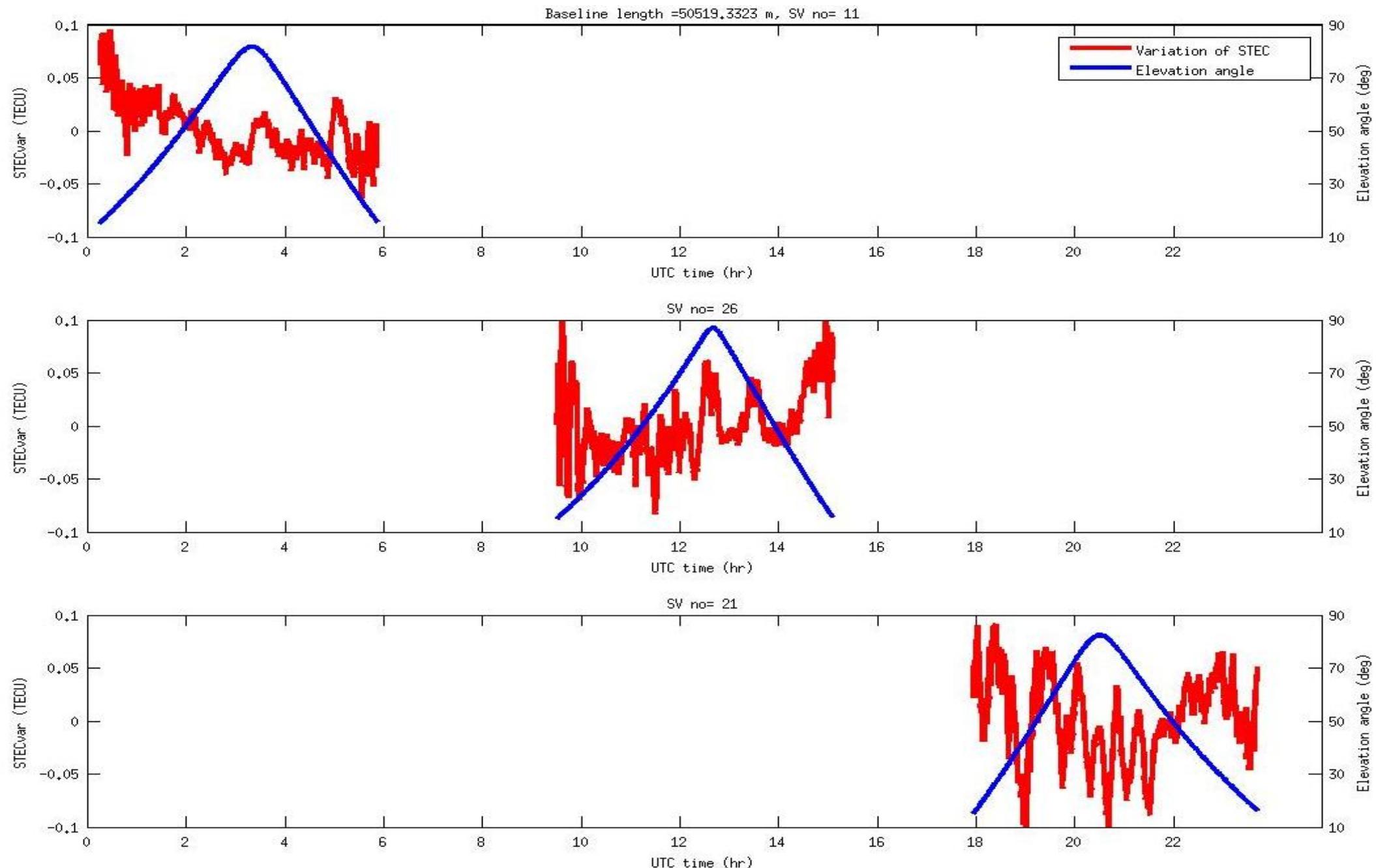
# 26 Km baseline



# 40 Km baseline - $I_i \neq I_j$ , $\Delta I_{ij} = \text{high}$



# 50 Km baseline - $I_i = I_j$ , $\Delta I_{ij} = noise$



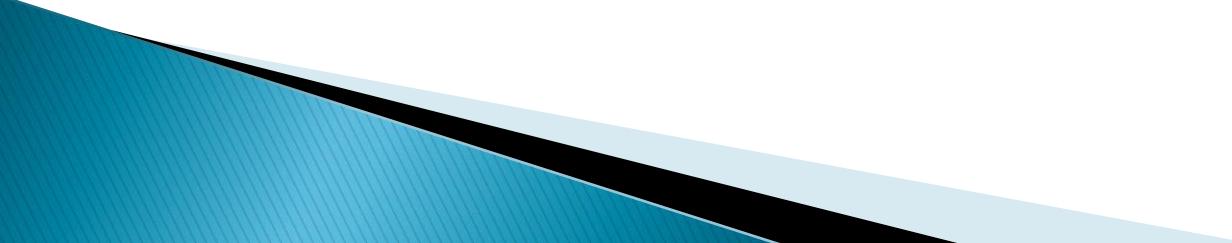
# Future Low frequency Arrays

- FR calibration for future arrays
  - ASKAP ->
    - 700 MHz to 1.8 GHz, @ 0.1 TECU, PA = 0.53°
    - Max baseline 6 Km -  $\Delta I_{ij}(t) \cong 0.1$  TECU
    - FoV = 30 sq deg
  - SKA-low ->
    - 70 to 450 MHz - @ 0.1 TECU, PA = 25.7°
    - ~ 50 Km baseline  $\Delta I_{ij}(t) \cong 0.7$  TECU
    - FoV=27 sq deg  $\Delta I_i(t - t_k) \cong 0.1$  TECU

# Possible Calibration schemes

- ▶ 3D ionosphere model
- ▶ Calibration challenges
  - FR correction for individual tiles/telescopes
  - Time for averaging visibilities

# Questions....?



Thank you for your kind  
attention!