Correcting Radio Astronomy Observations for Ionospheric Faraday Rotation

A. G. Willis

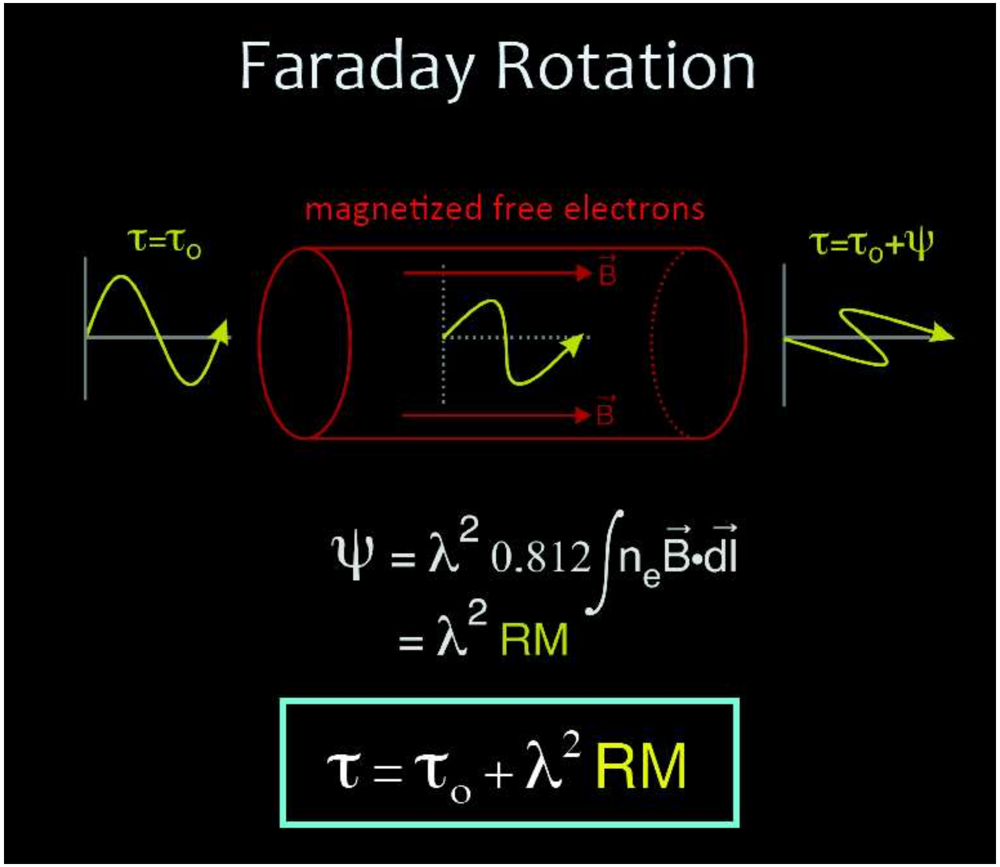
National Research Council of Canada
Dominion Radio Astrophysical Observatory

Nov 6, 2013

Collaborators

- Tom Landecker, DRAO
- Maaijke Mevius, RUG/ASTRON
- Shane O’Sullivan, CSIRO
- James Anderson, MPIFR
- Emil Lenc, Sydney
- Balwinder Singh Arora, Curtin

Faraday Rotation



- The ionosphere has a magnetic field going through it plus a bunch of free electrons so ...
  - it produces Faraday rotation on electromagnetic waves coming in from space
- Diagram courtesy Jo-Anne Brown

Jones Matrices and Transformations

- Jones matrices may be viewed as forming a transformation matrix between a Stokes coherency vector, or matrix, and the observed visibilities. If we assume that Faraday rotation is the only effect on the observed data, the visibility for an interferometer composed of *station* i and *station* j is then given by the following equation, where $\vec{V}_{\mathsf{ij}}$ is the observed visibility, $\vec{I}$ is the incoming electromagnetic coherency matrix, and $\mathsf{F}_{\mathsf{j}}^{*}$ is the transposed complex conjugate of F_{j}:

$$\vec{V}_{\mathsf{ij}} \equiv \begin{pmatrix} \mathsf{v}_{\mathsf{ip\,jp}} & \mathsf{v}_{\mathsf{ip\,jq}} \\ \mathsf{v}_{\mathsf{iq\,jp}} & \mathsf{v}_{\mathsf{iq\,jq}} \end{pmatrix} = \mathsf{F}_{\mathsf{i}}\, \vec{I}\, \mathsf{F}_{\mathsf{j}}^{*}$$

- The subscripts i and j are the labels of the two *feed*s that make up the *interferometer*. The subscripts p and q are the labels of the two output *IF-channel*s from each *feed*. For linear polarization

$$\vec{I} = \begin{pmatrix} I+Q & U+iV \\ U-iV & I-Q \end{pmatrix}$$

- and for circular polarization

$$\vec{I} = \begin{pmatrix} I+V & Q+iU \\ Q-iU & I-V \end{pmatrix}.$$

Correcting for Faraday Rotation

- We can then obtain visibilities corrected for ionospheric effects by performing the inverse transformation on the observed visibilities:

$$\vec{V}_{\mathsf{ij}} corr = \mathsf{F}_{\mathsf{i}}^{-1} \, \vec{V}_{\mathsf{ij}} \, \mathsf{F}_{\mathsf{j}}^{-1*}$$

- The inverse matrix for linear polarization is given by

$$\mathsf{F}_{\mathsf{i}}^{+}(\vec{\rho}, \vec{r}_{\mathsf{i}})^{-1} = \begin{pmatrix} \cos\chi_{\mathsf{i}} & \sin\chi_{\mathsf{i}} \\ -\sin\chi_{\mathsf{i}} & \cos\chi_{\mathsf{i}} \end{pmatrix}$$

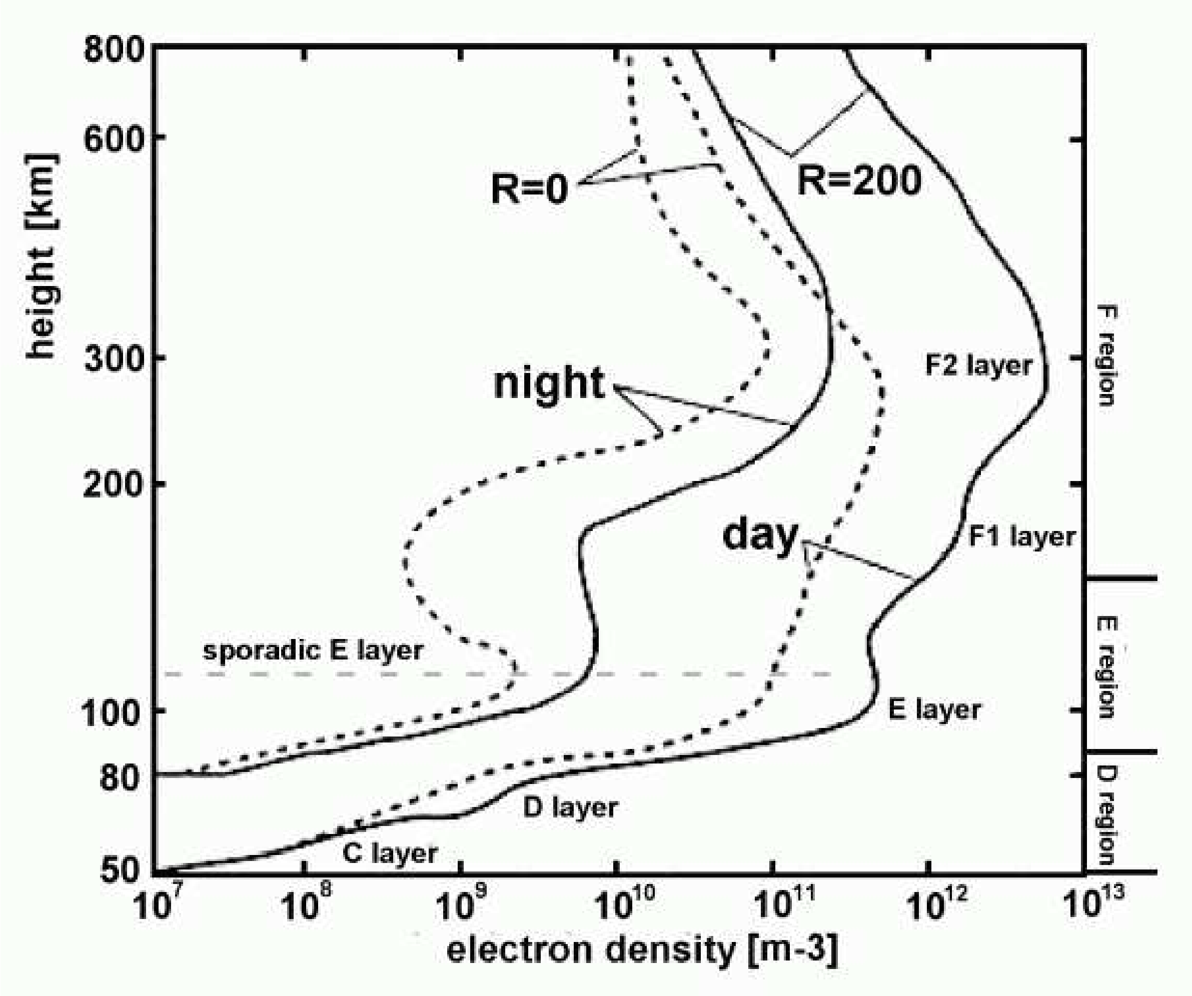
- the inverse matrix for circular polarization is given by

$$\mathsf{F}_{\mathsf{i}}^{\odot}(\vec{\rho}, \vec{r}_{\mathsf{i}})^{-1} = \mathsf{Diag}(\exp^{-i\chi_{\mathsf{i}}}, \exp^{i\chi_{\mathsf{i}}}) = \begin{pmatrix} \cos\chi_{\mathsf{i}} - i\sin\chi_{\mathsf{i}} & 0 \\ 0 & \cos\chi_{\mathsf{i}} + i\sin\chi_{\mathsf{i}} \end{pmatrix}$$

$$\chi = RM\lambda^2$$

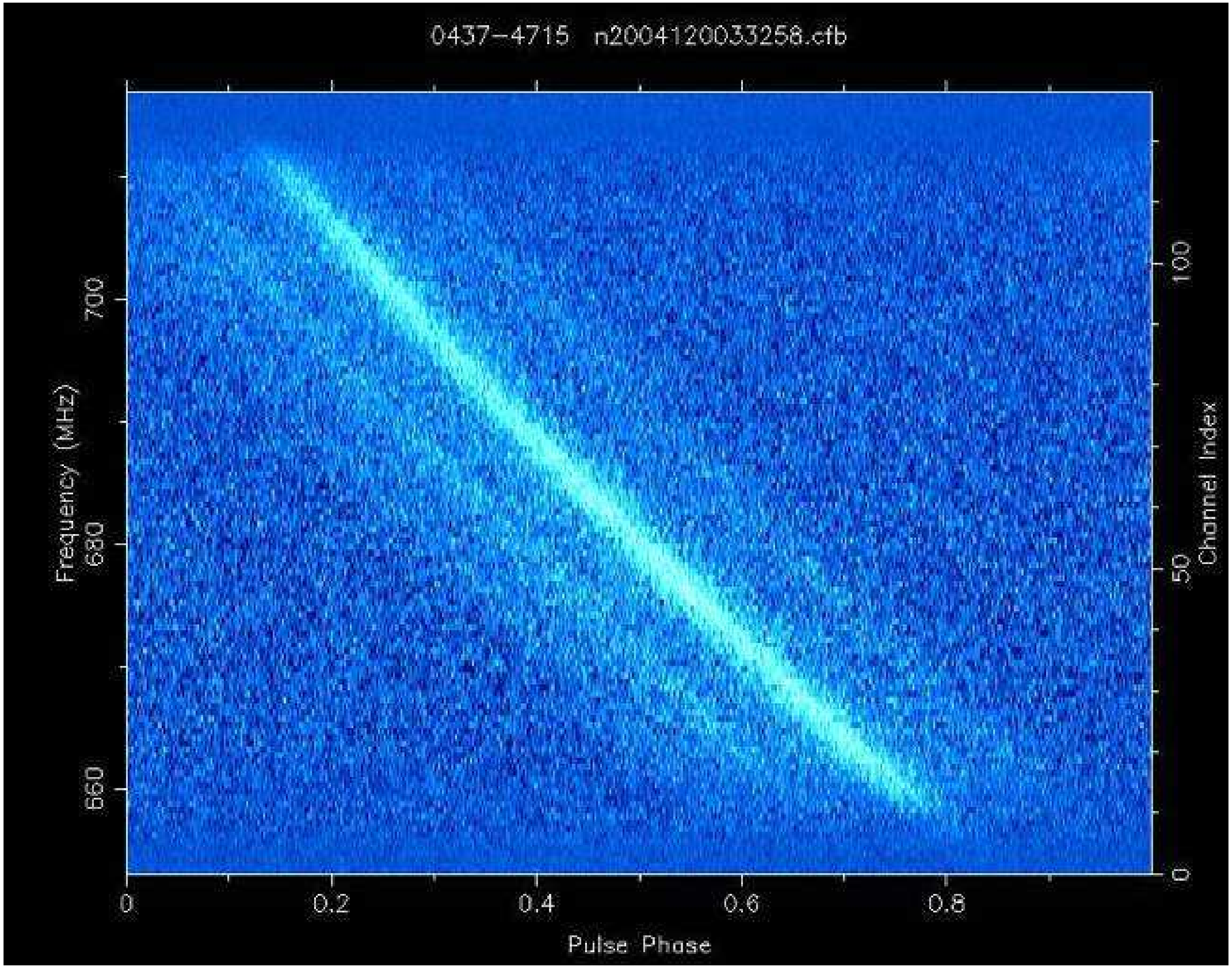
- Basic procedure
  - obtain ionosphere rotation measures as a function of time (ASCII file)
  - read this file into Oleg Smirnov's MeqTrees package by means of a PyNode
  - apply the inverse RM transformation given above to data (must be in CASA measurement set format)

Ionosphere Distribution of Free Electrons



HERZBERG INSTITUTE of ASTROPHYSICS

Example of Dispersion in an ionized medium



NRC · CNRC
HERZBERG INSTITUTE of ASTROPHYSICS

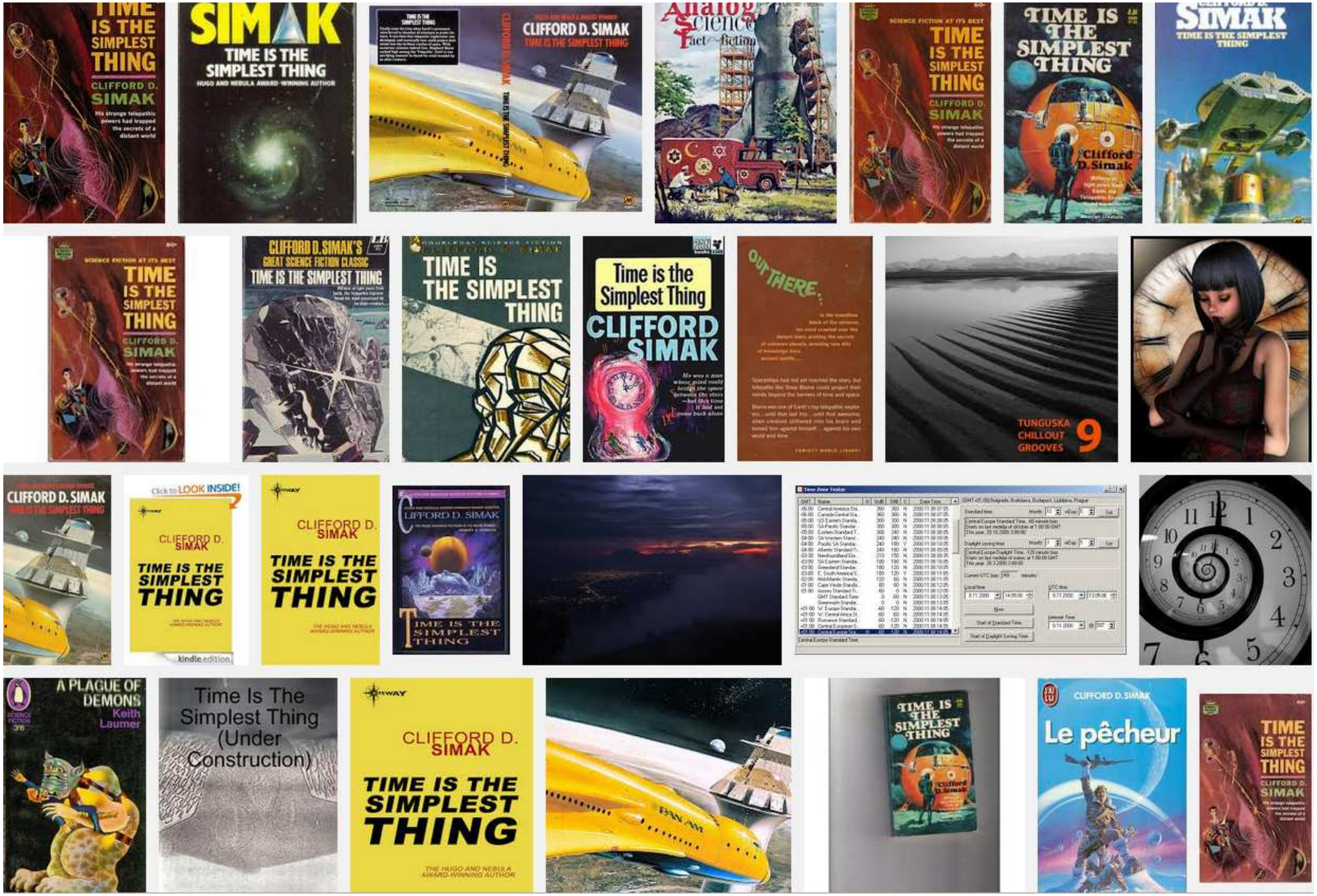
We can use GPS Receivers to Measure Delays due to Ionosphere

- Everybody is interested in GPS these days!

Really Really Really Basic GPS and Ionospheric Delay

- A GPS Satellite broadcasts at 2 Frequencies in L band
  - L1 = 1575.42 MHz = 19 cm wavelength
  - L2 = 1227.60 MHz = 24 cm wavelength (which is annoying for radio astronomers)
- ionosphere delay $\Delta r = (40.3 * TEC)/f^2$
  - Δr = delay in metres
  - TEC = column density of electrons measured in electrons m^{-2} (1 TECU = 10^{16} electrons m^{-2}) and the frequency is in Hz.
  - 1 TECU of electrons gives a delay of 0.163 metres for L1 and 0.267 metres for L2
  - So every excess of 0.104 metres on L2 - L1 delay corresponds to 1 TECU of electrons
- In an ideal world the only differences in (pseudo)range, P, measured between ground and satellite should be due to the ionosphere delay between L1 and L2
- So (in theory) electron column density in TECU = $(P_{L2} - P_{L1})/0.104m$
- In reality observed TECU = $(P_{L2} - P_{L1})/0.104m$ + instrumental delays + multipath + noise
- The BIG question - how to get rid of measurement errors?
- There's a bit more to this story, but this is the basic concept
- NOTE: Basic 'unit' of GPS = 1 nanosecond, or 30 cm - the distance electromagnetic radiation travels in that time

Is time the simplest thing?



Time is simple ... NOT!!

- Sorry Mr Simak, Time is (absolutely) NOT the simplest thing!!
- ‘Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.’ - Herman Minkowski at the 80th Assembly of German Natural Scientists and Physicians (September 21, 1908)
- GPS measurements are strongly affected by issues relating to space and time (clocks)!!!

NRC · CNRC HERZBERG INSTITUTE of ASTROPHYSICS

A ‘Typical’ Example of GPS Antenna

- GPS antenna at DRAO used for Geodetic GPS measurements
- Ionosphere TEC measurements a byproduct

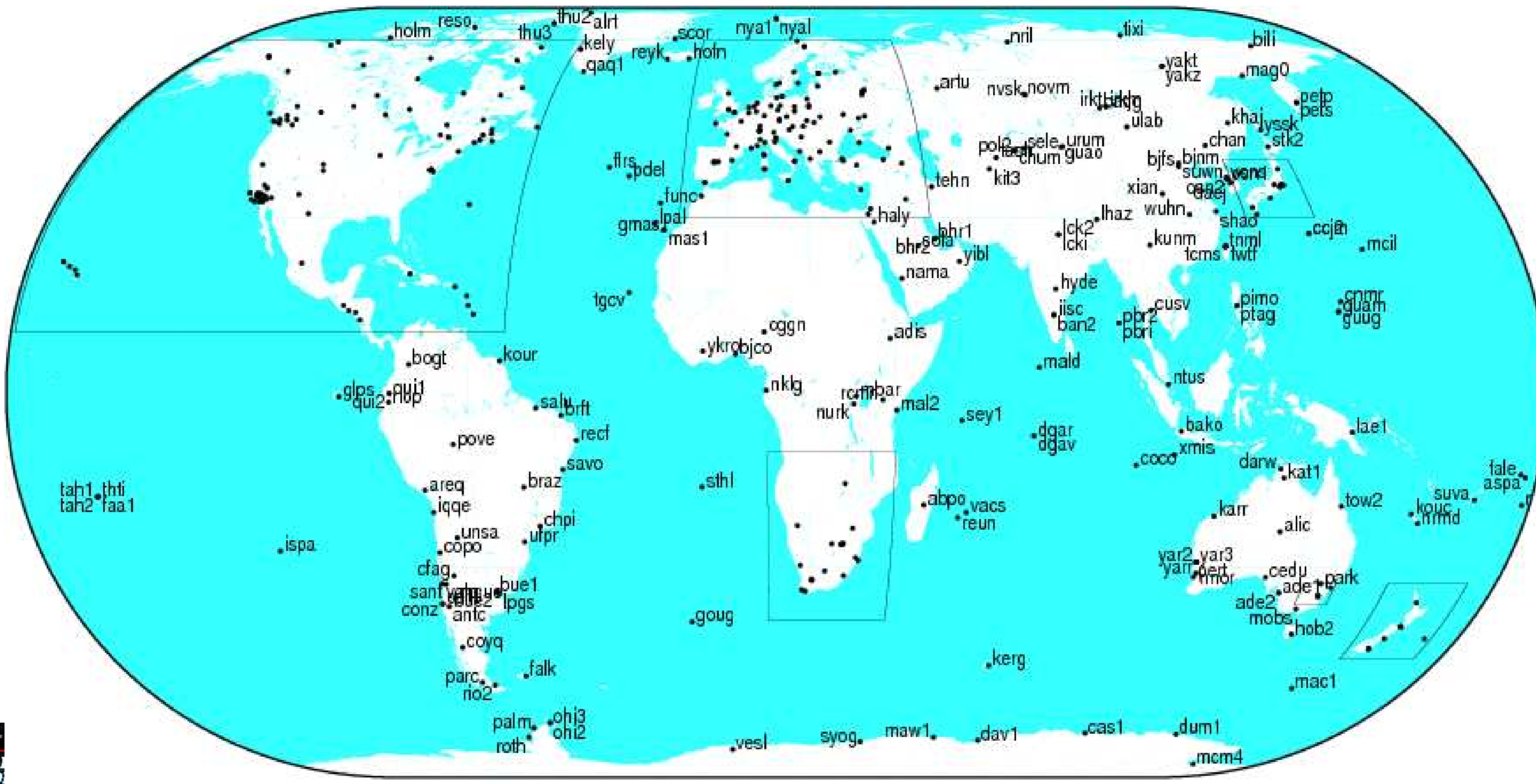
NRC · CNRC
HERZBERG INSTITUTE of ASTROPHYSICS

Location of DRAO GPS Antenna

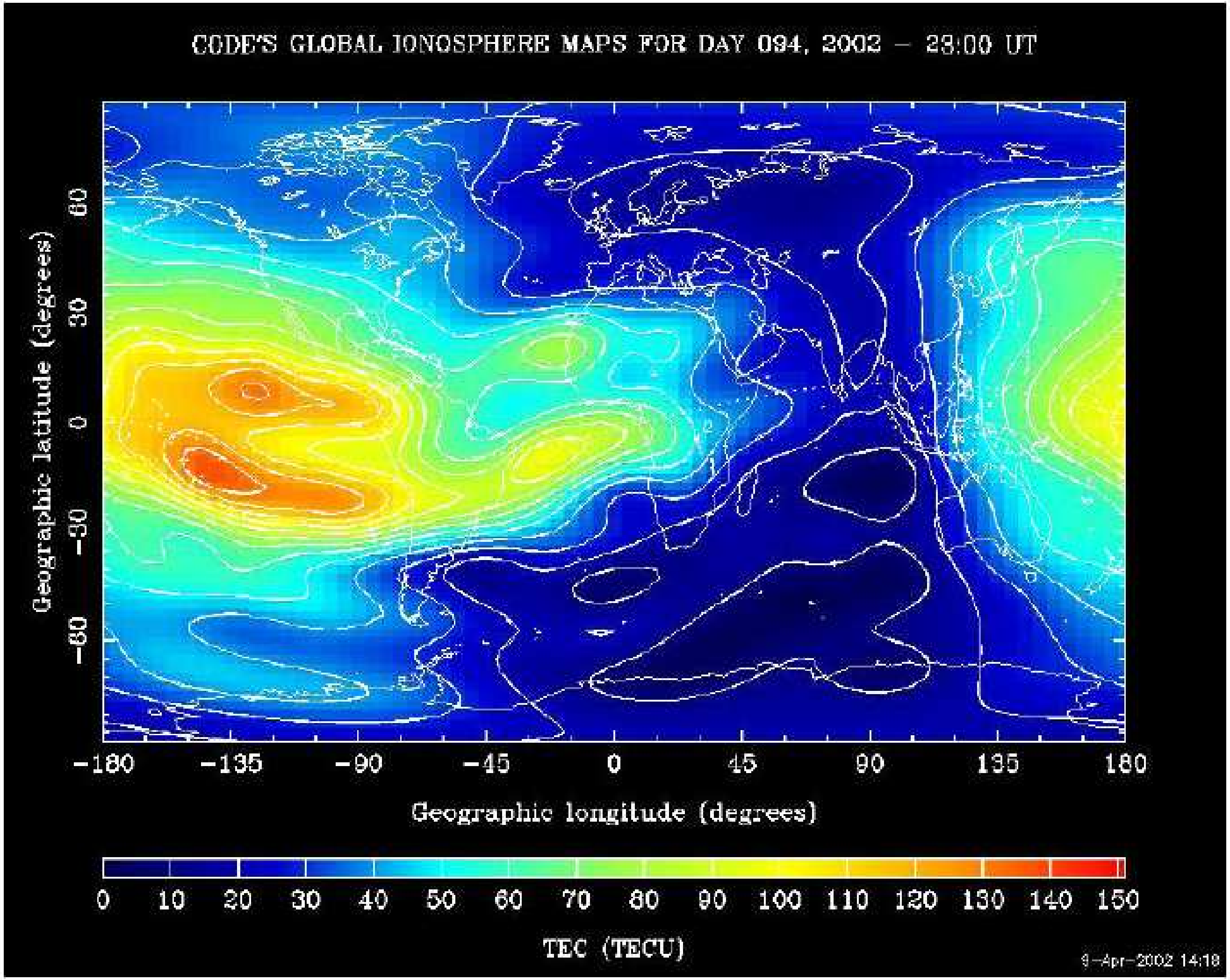
NRC·CNRC HERZBERG INSTITUTE of ASTROPHYSICS

Locations of GPS Stations Used by CODE

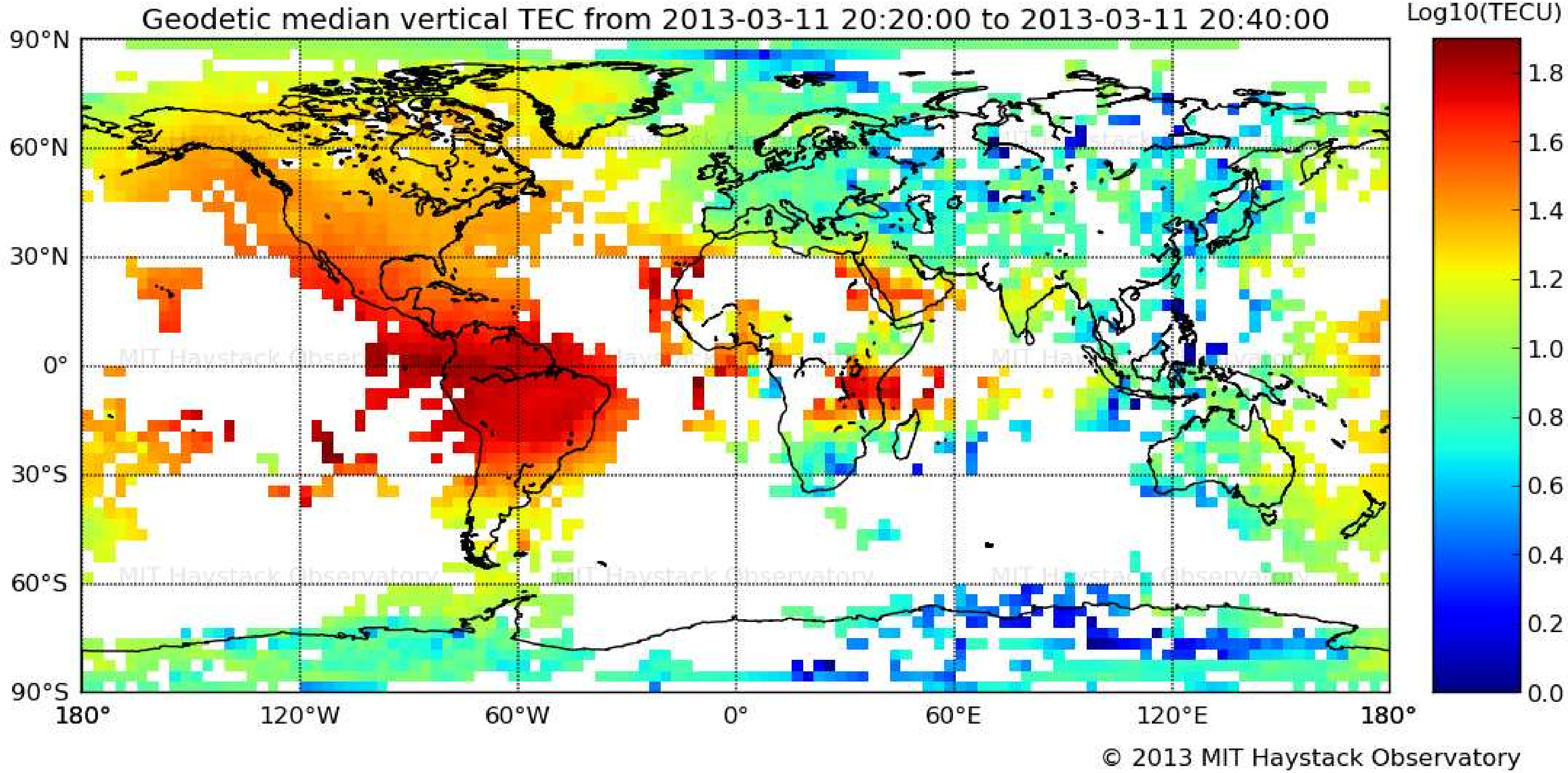
- CODE = Centre for Orbital Determination Europe, located at University of Berne Observatory, Switzerland
- Both DRAO and WSRT are reference stations in this network



A Typical CODE Map of VTEC



A Typical Haystack Map of VTEC



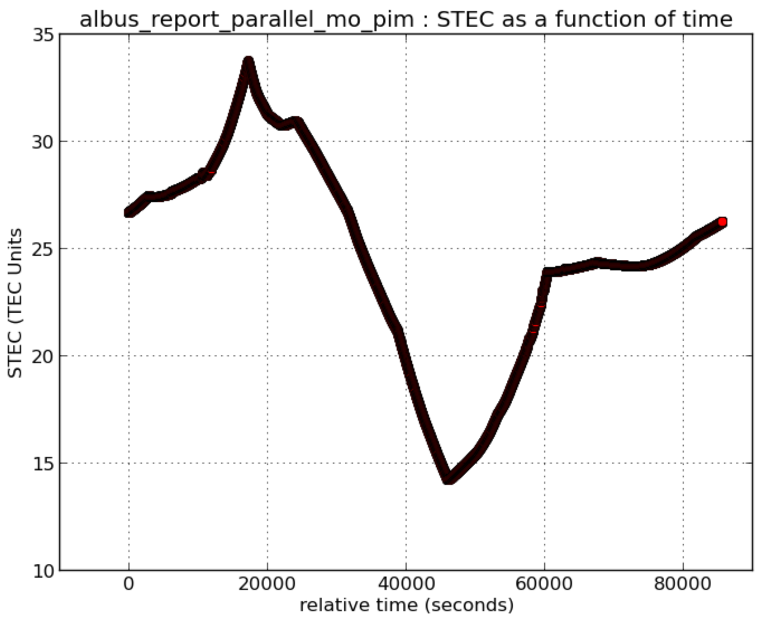
Background - The James Anderson Software Package

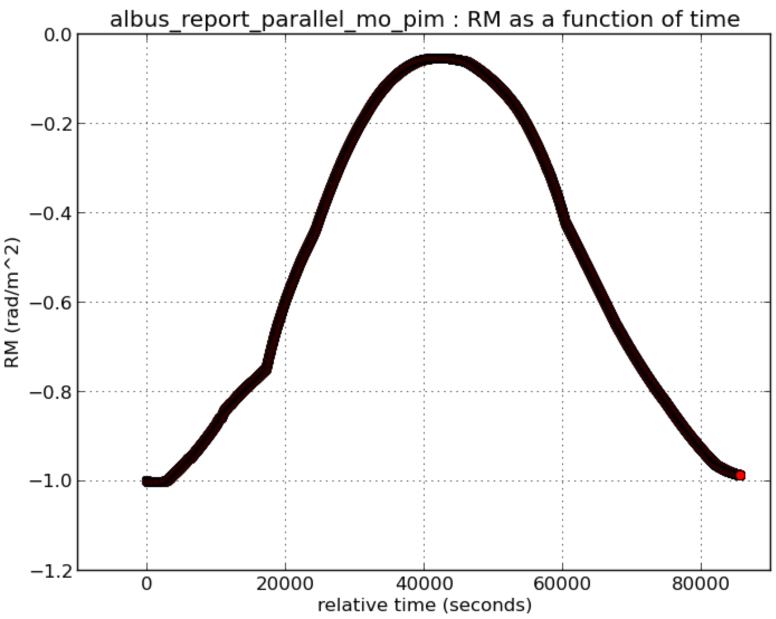
- Developed at ASTRON/JIVE by James Anderson as part of the ALBUS (Advanced Long Baseline User Software) project
- original goal - correct for ionospheric phase jitter in VLBI observations
- He offered to adapt this software for use by the ASPAP POSSUM polarization project
- Has a database of about 3500 GPS stations
- ASKAP will observe from 700 to 1800 MHz so ionosphere corrections are certainly necessary at the lower frequencies

Tests of IonFR and ALBUS packages

- ionFR (Sotomayor et al. 2013 - Ger is co-author) uses CODE maps + IGRF magnetic field to predict rotation measure contribution due to Ionosphere
- Which washing machine gets your clothes whiter?
- test observations
  - ATCA observations of PKS 1903-80 on Dec 12, 2012
  - DRAO observations of 3C286 on Dec 12, 2012
  - DRAO observations of 3C286 on May 15, 2013
  - MWA observations of J0636-2041, various dates
  - Various LOFAR Observations

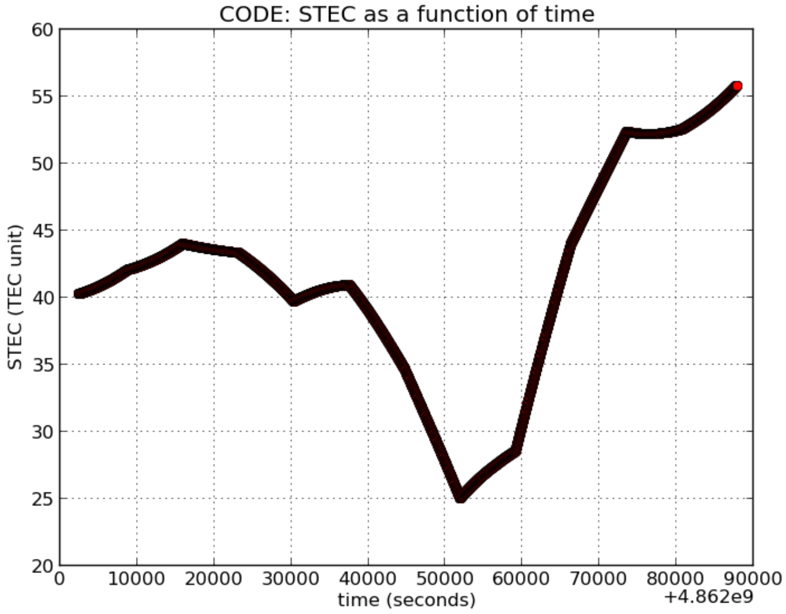
ATCA Observation of PKS 1903-80 Dec 12, 2012; PIM Predictions

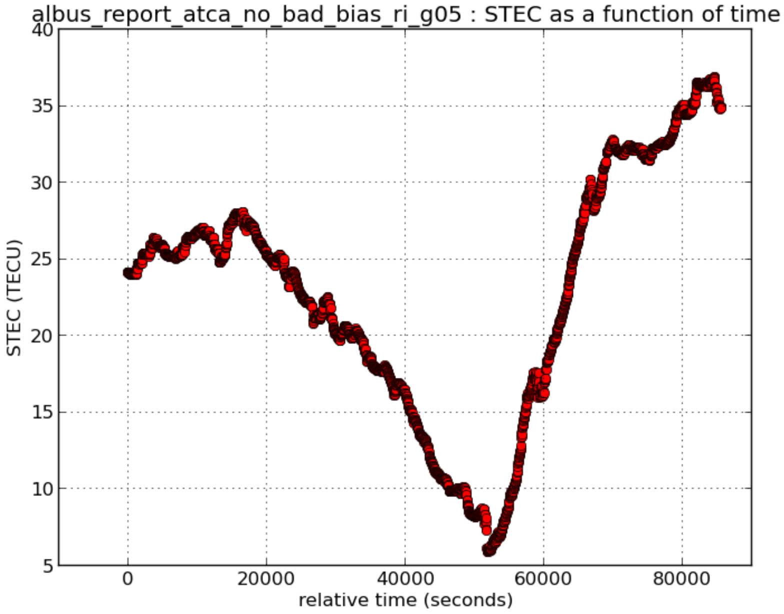




- Left PIM STEC prediction; Right PIM RM prediction

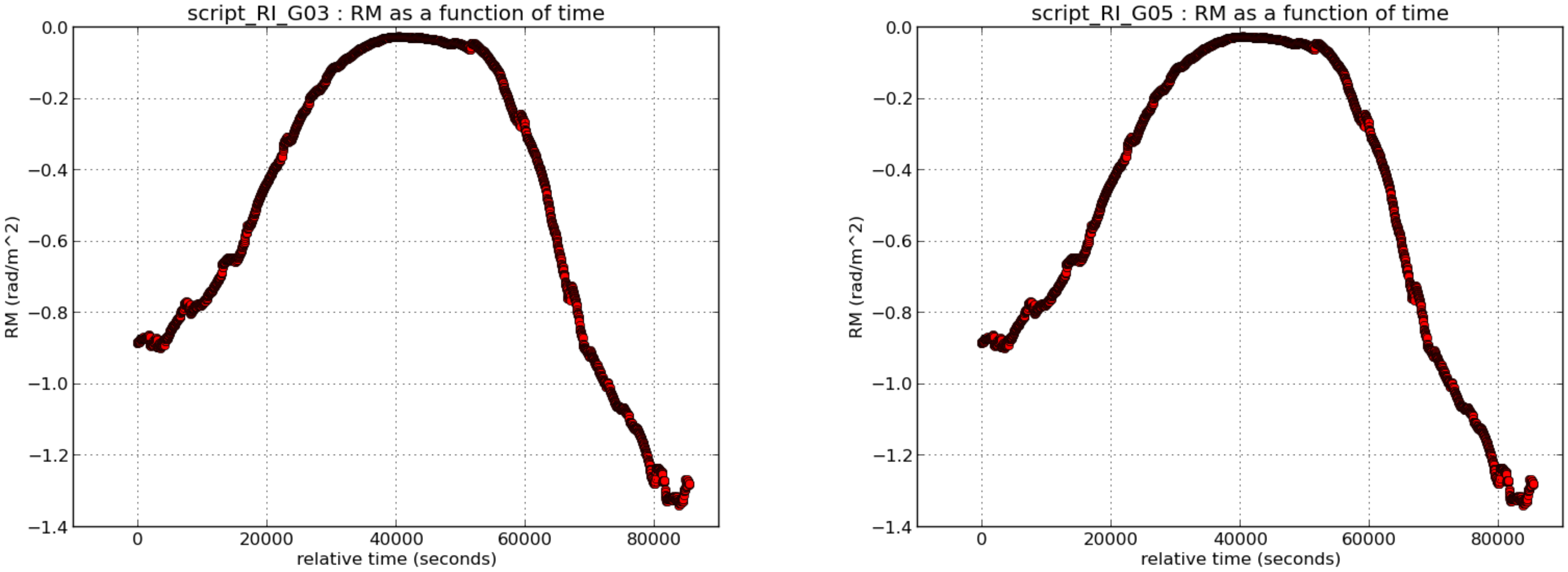
ATCA Observation of PKS 1903-80 Dec 12, 2012; more STECs





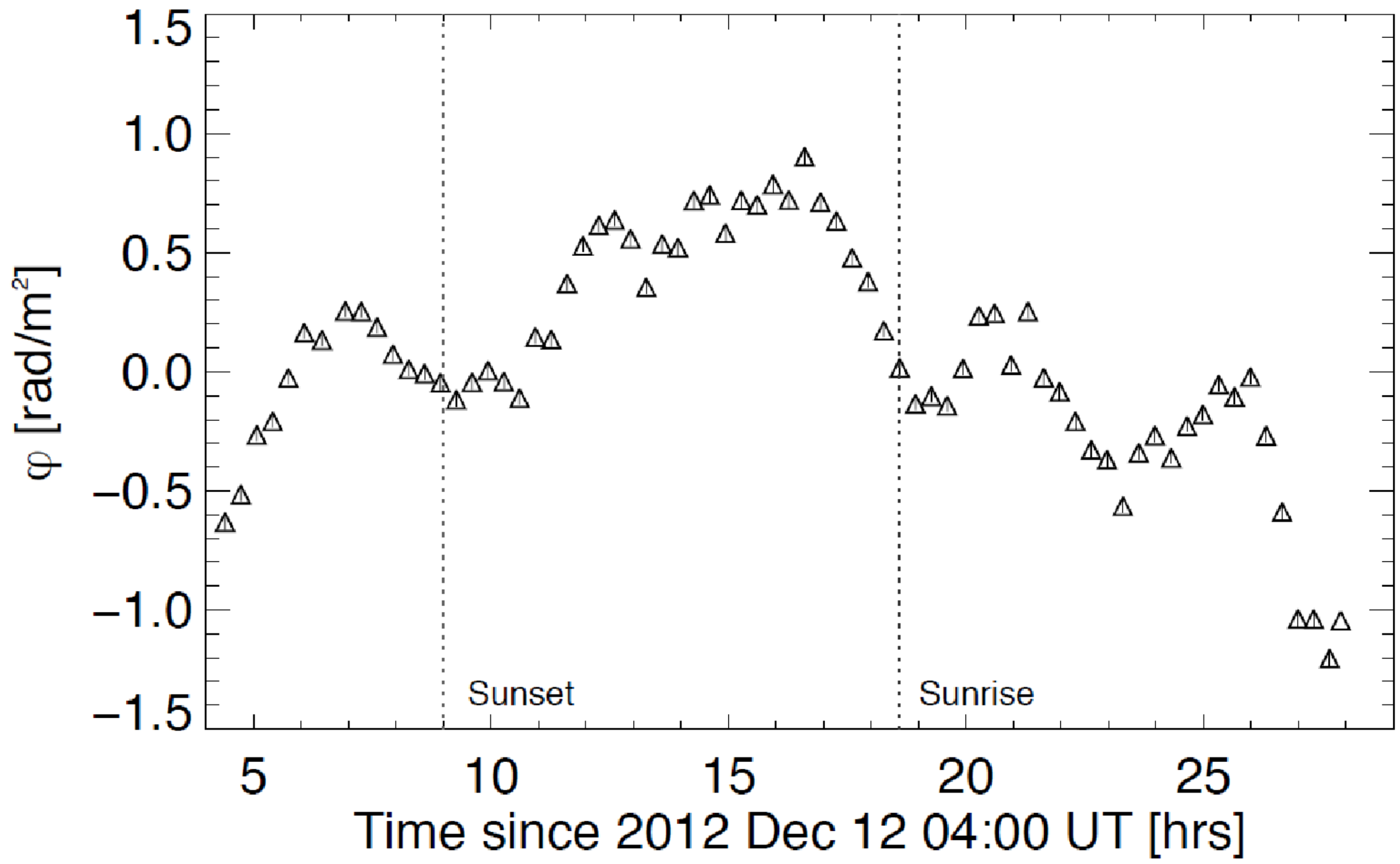
- Left STEC from 2 hr CODE Maps; Right STEC from ALBUS RI_G05 fit

ATCA Observation of PKS 1903-80 ALBUS RM Predictions

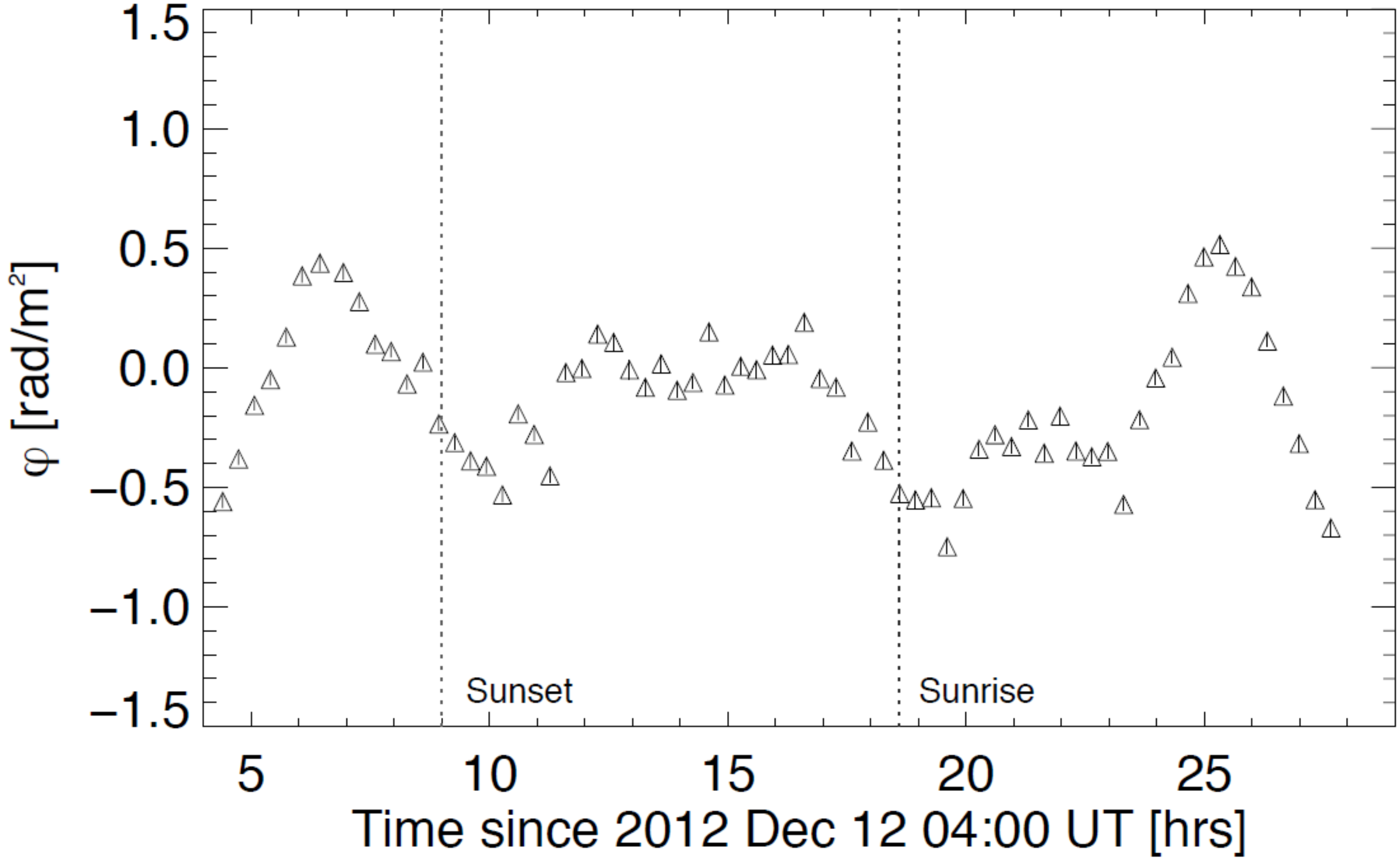


- Left RM from RI_G03 fit; Right RM from RI_G05 fit

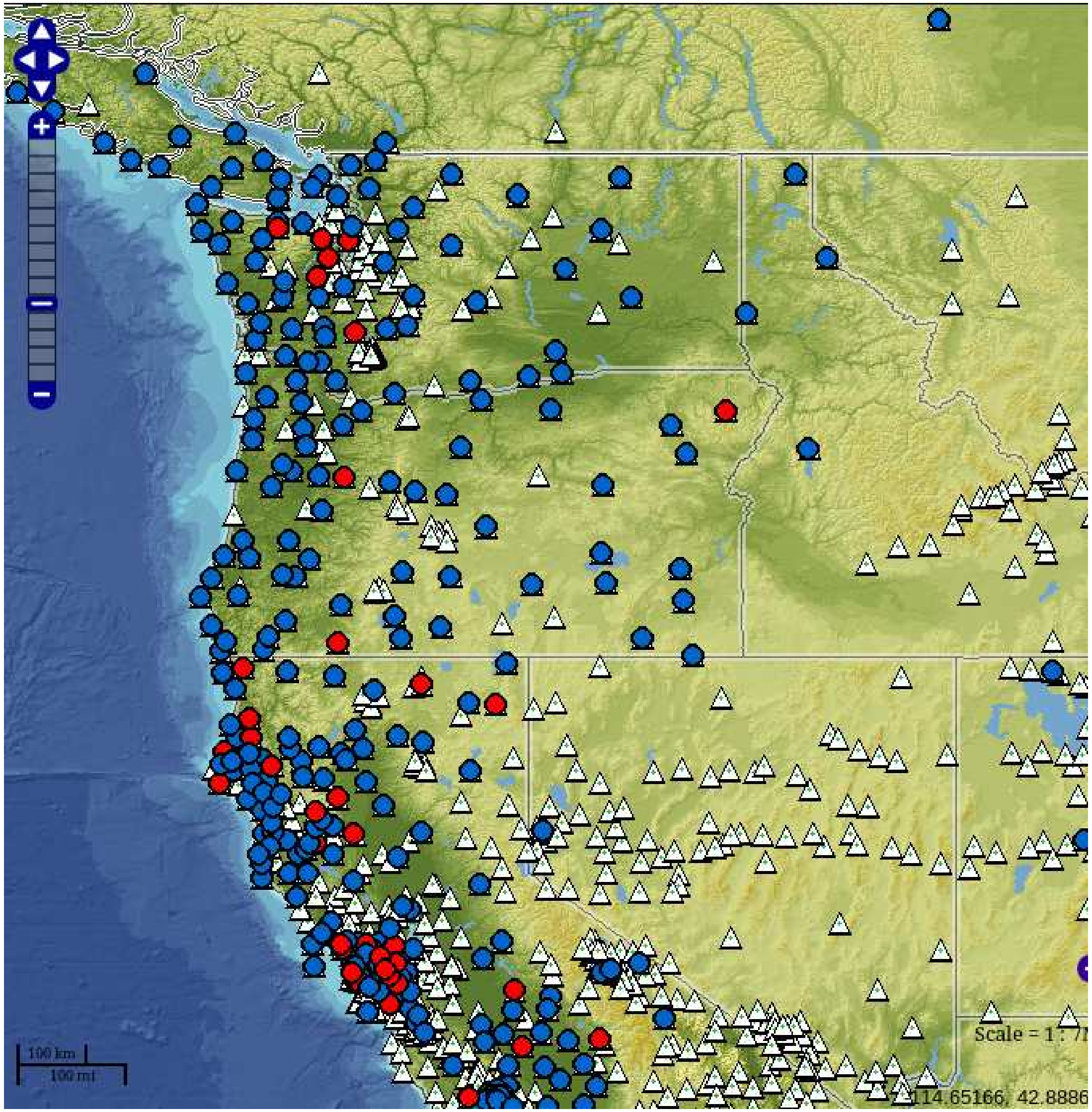
ATCA Observed Uncorrected RMs of PKS 1903-80



ATCA Corrected RMs PKS 1903-80

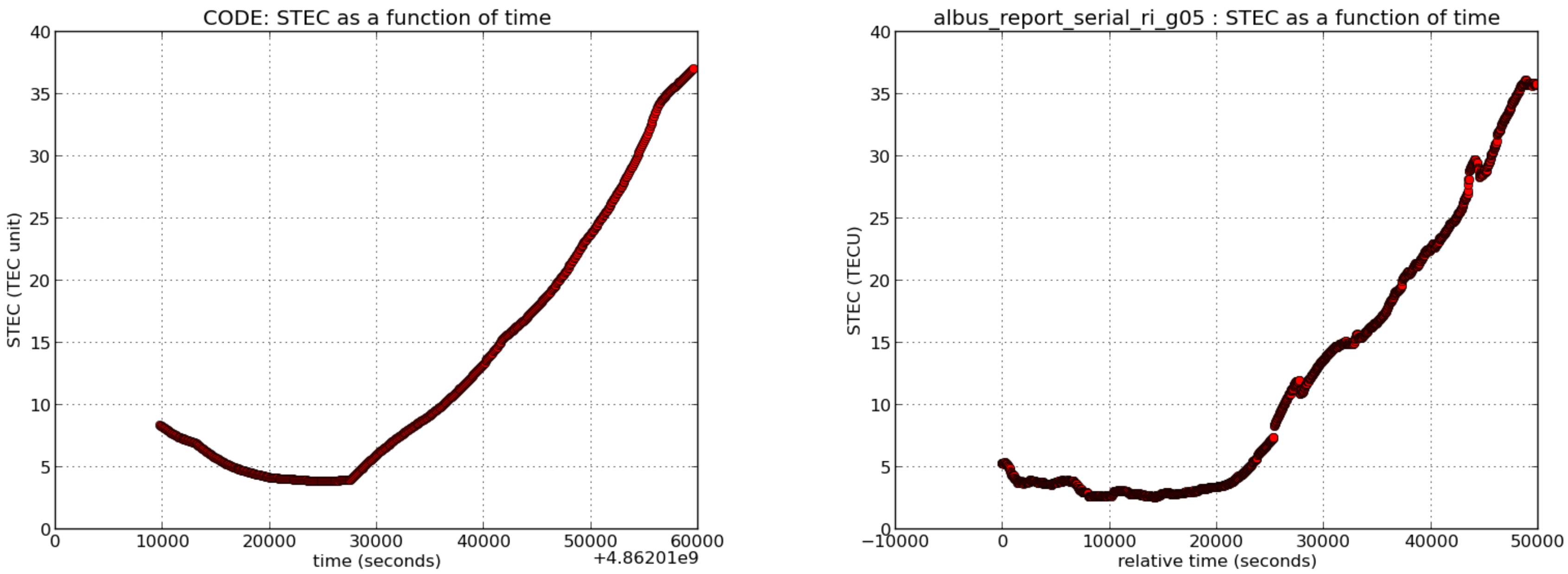


GPS Stations in Western North America



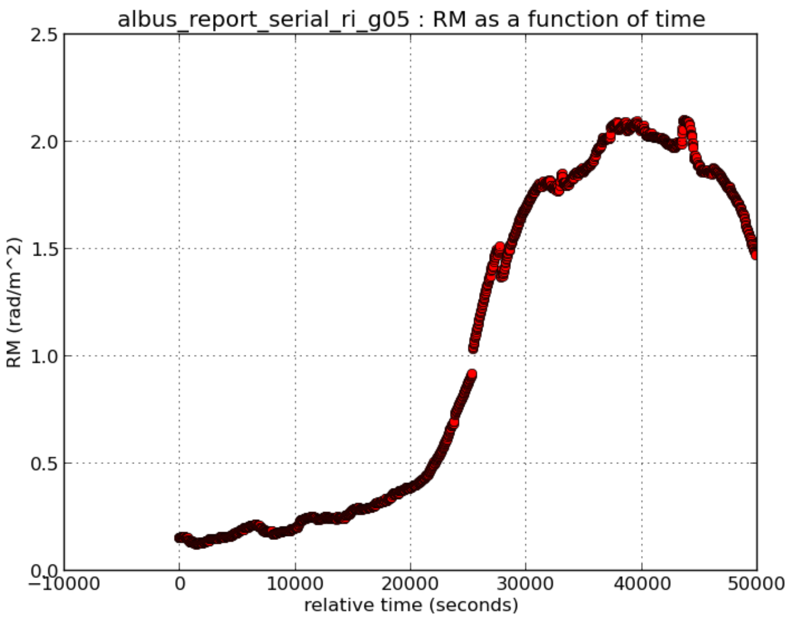
Map from SOPAC - Scripps Orbital and Permanent Array Center UCSD

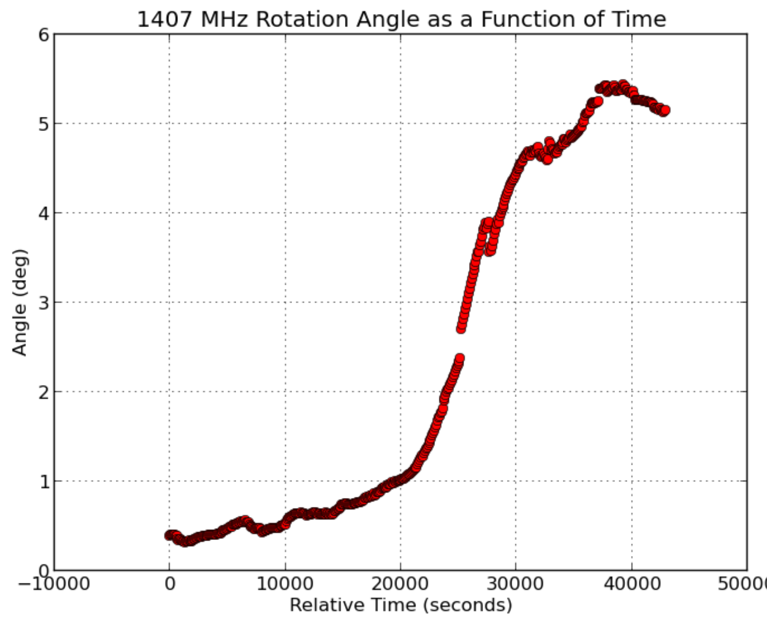
DRAO Observation of 3C286 Dec 12, 2012



- Left STEC from 2 hr CODE maps; Right STEC from JMA RI_G05 fit

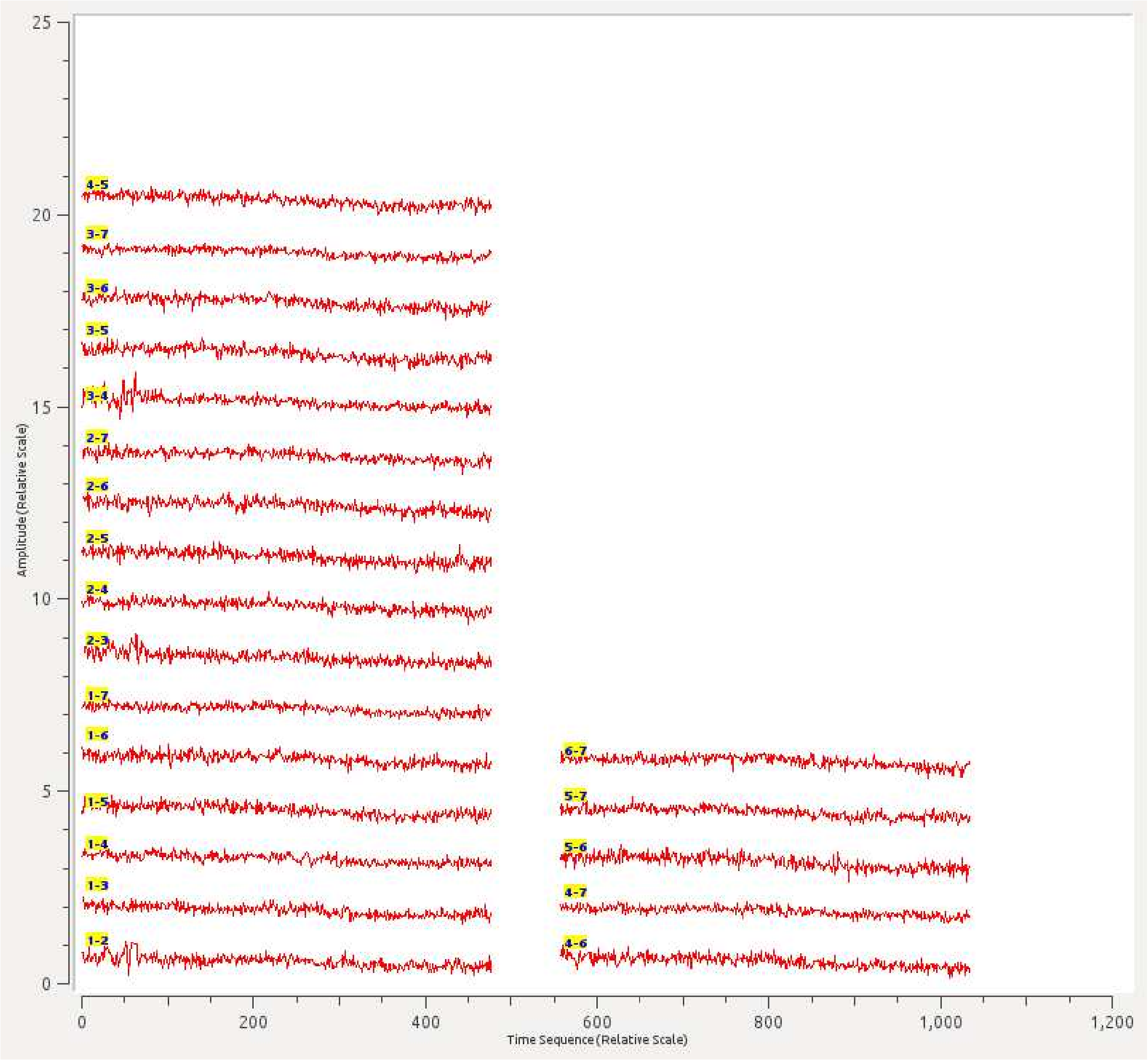
DRAO Observation of 3C286 Dec 12, 2012



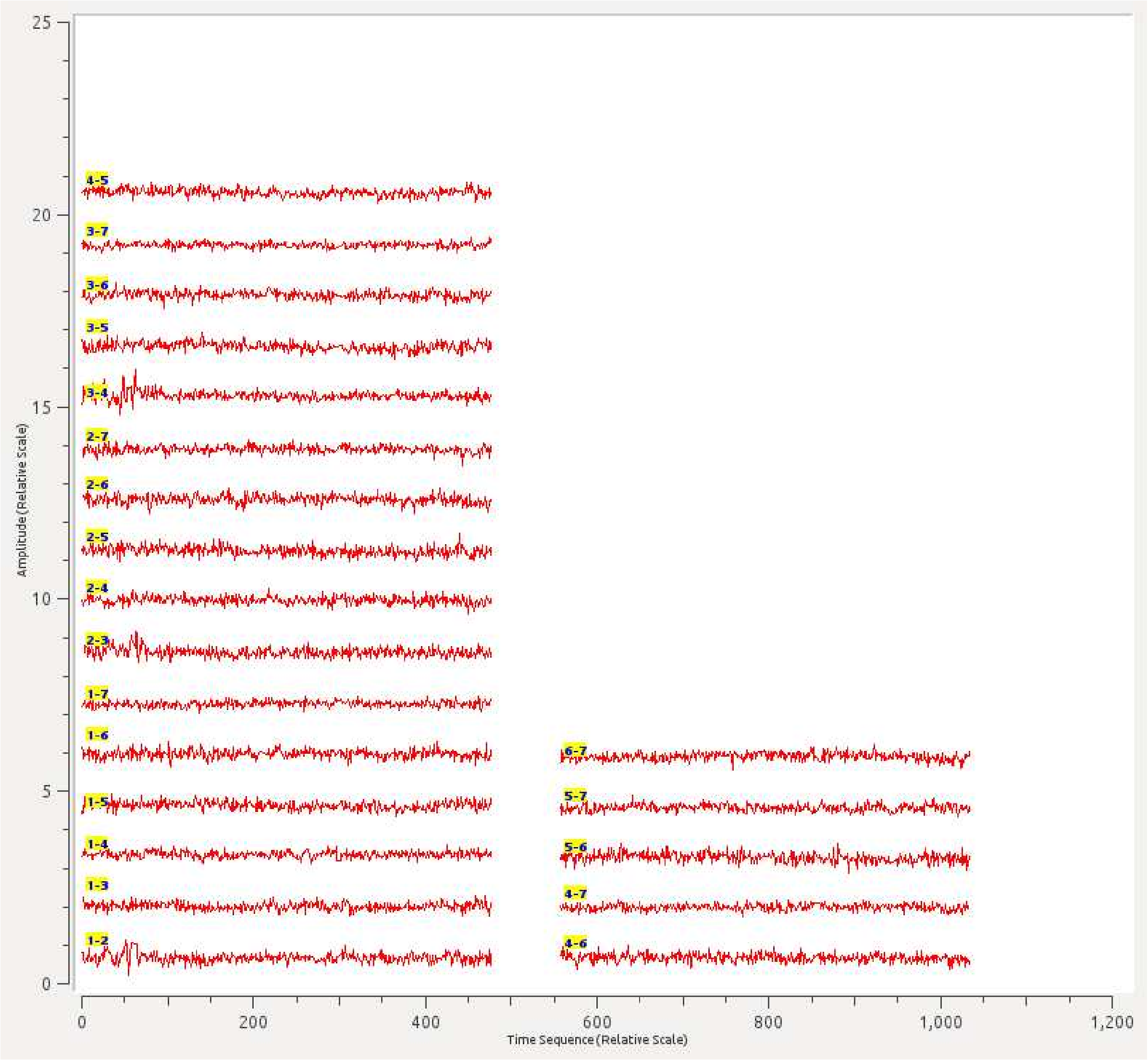


- Left RM from RI_G05 fit; Right resulting rotation angle at 1407 MHz

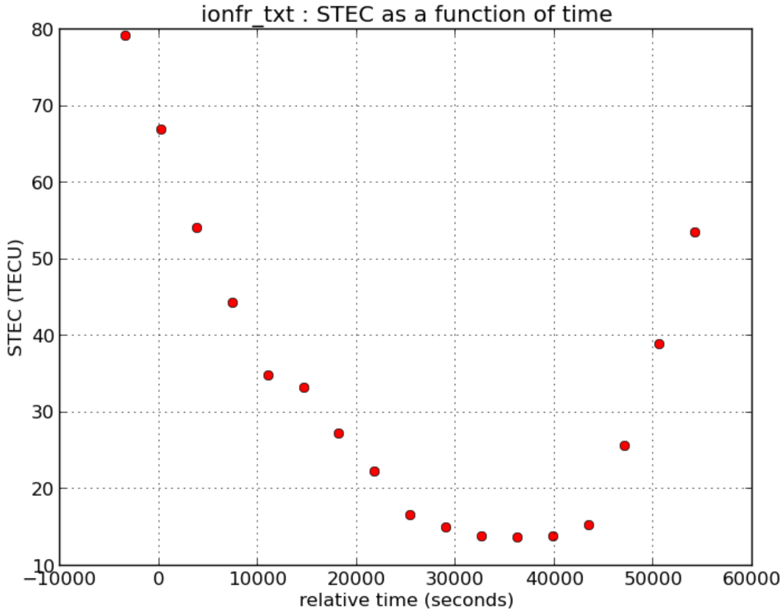
DRAO Uncorrected Stokes Q

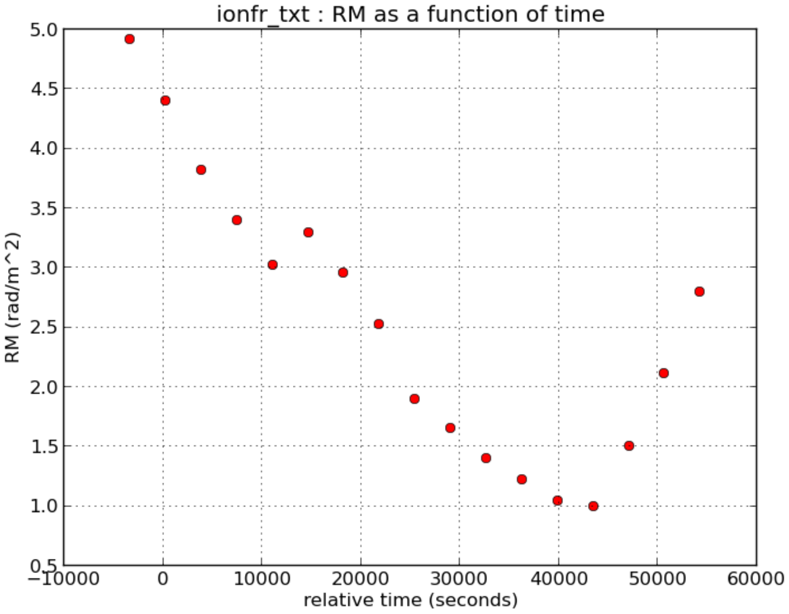


DRAO Corrected Stokes Q



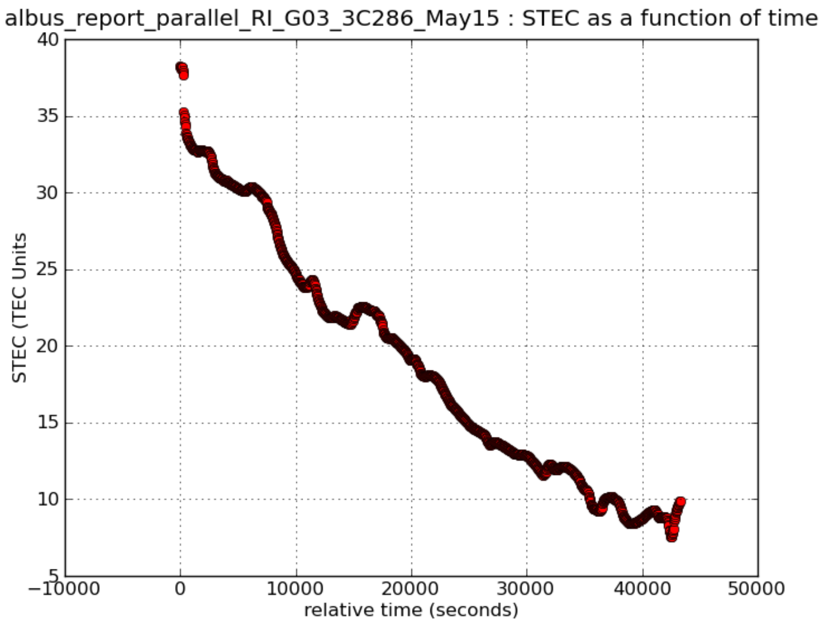
DRAO Observation of 3C286, May 15 2013

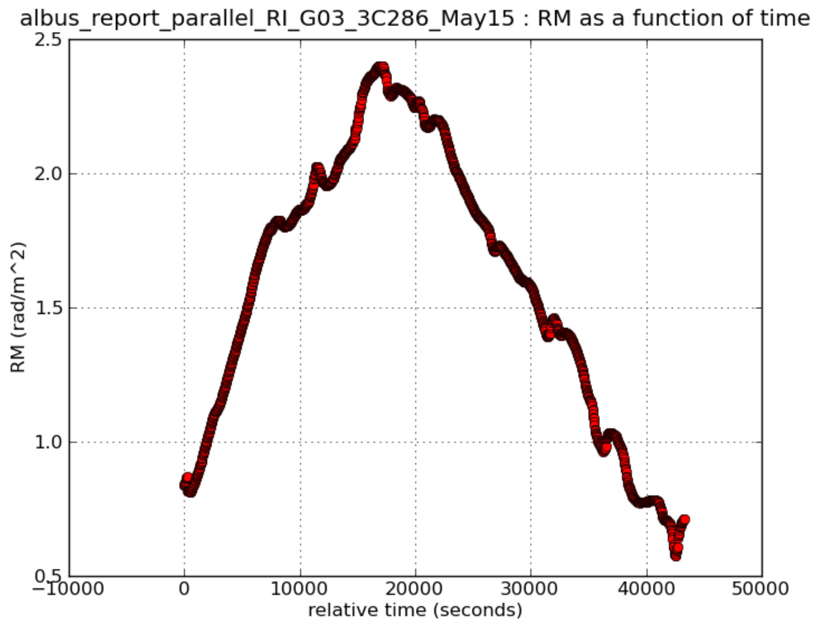




- Left ionFR prediction of STEC from CODE maps; Right ionFR prediction of RM from CODE maps and IGRF magnetic field

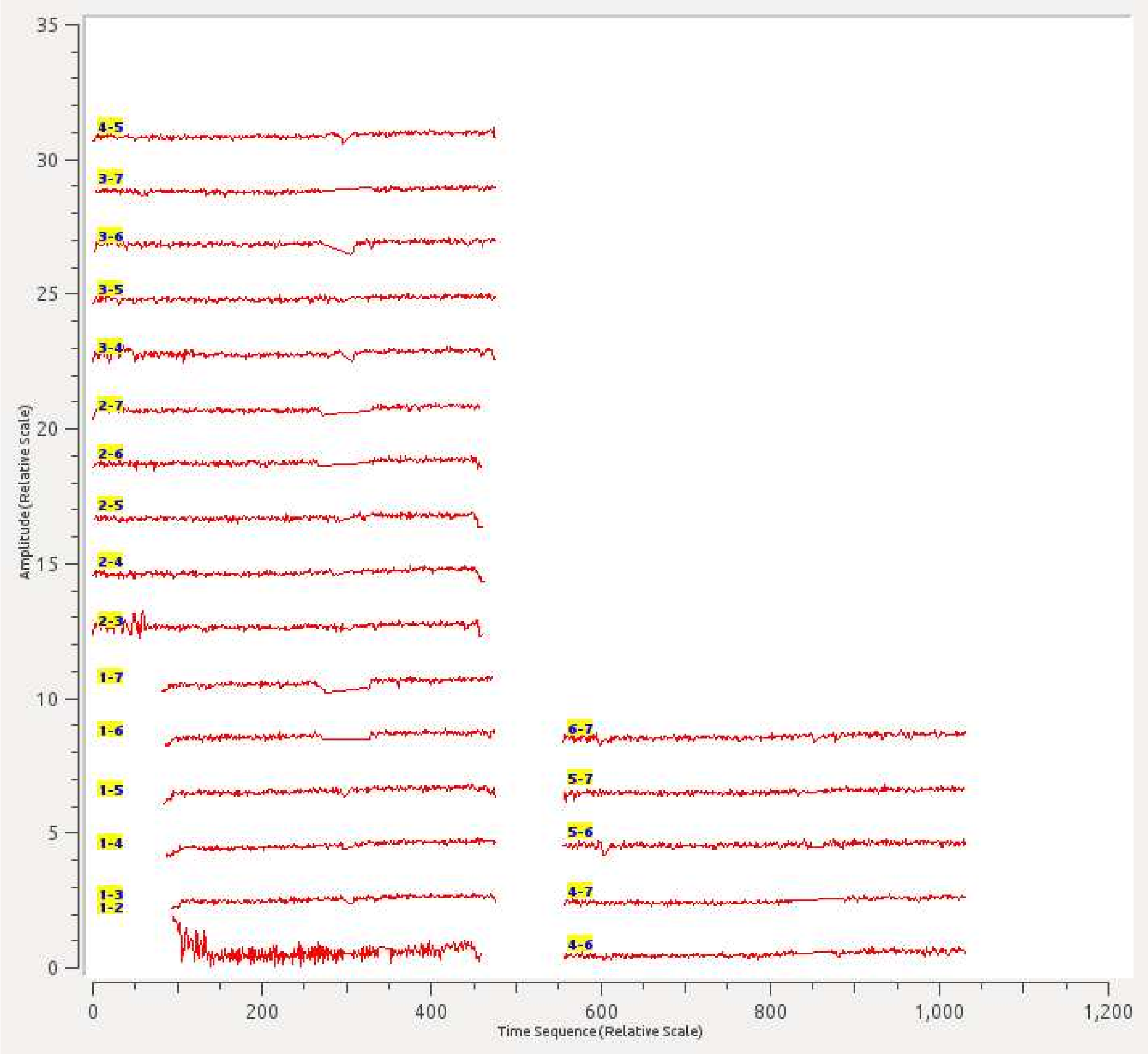
DRAO Observation of 3C286, May 15 2013





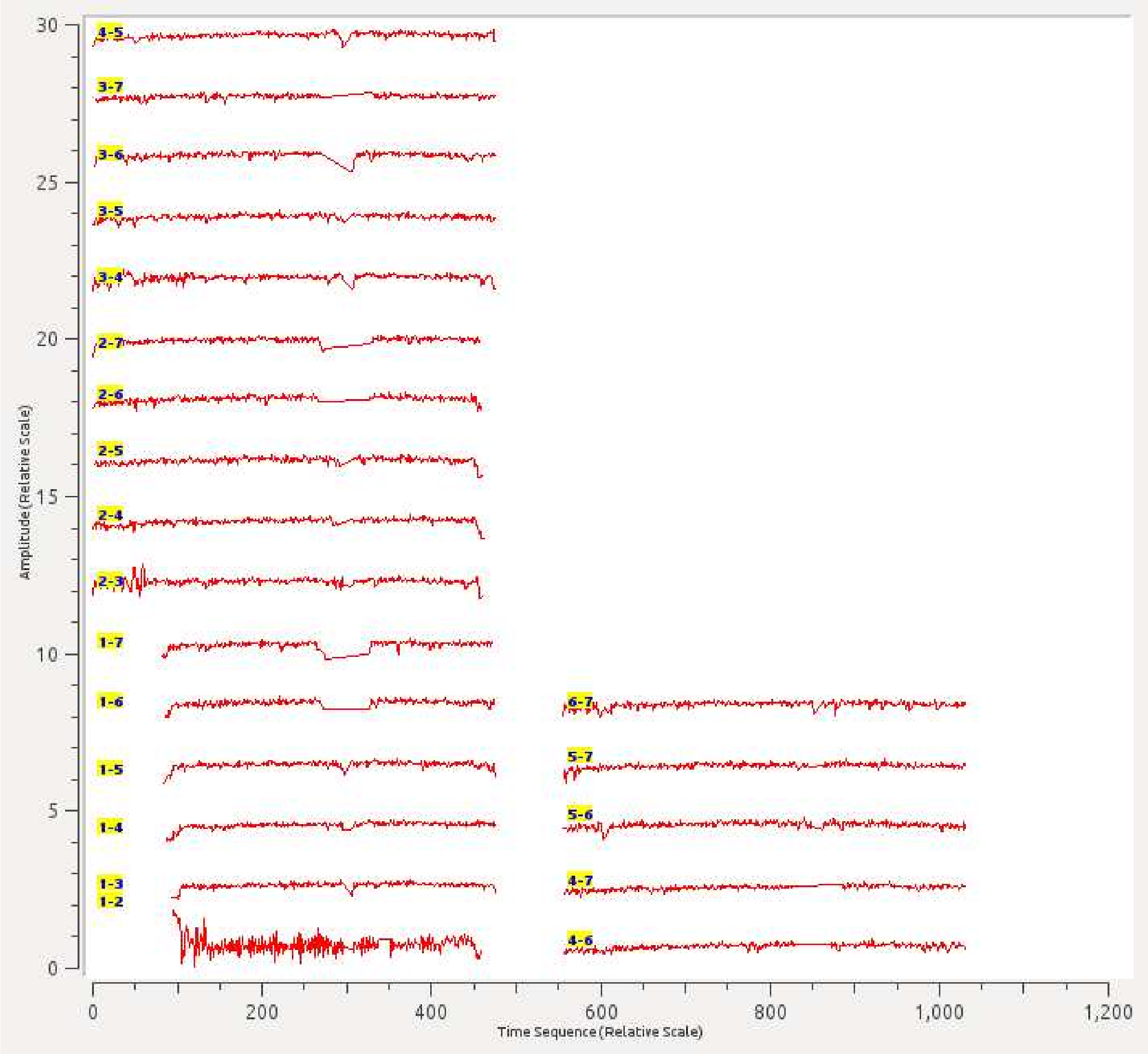
- Left ALBUS prediction of STEC; Right ALBUS prediction of RM

DRAO Uncorrected Stokes Q May 2013

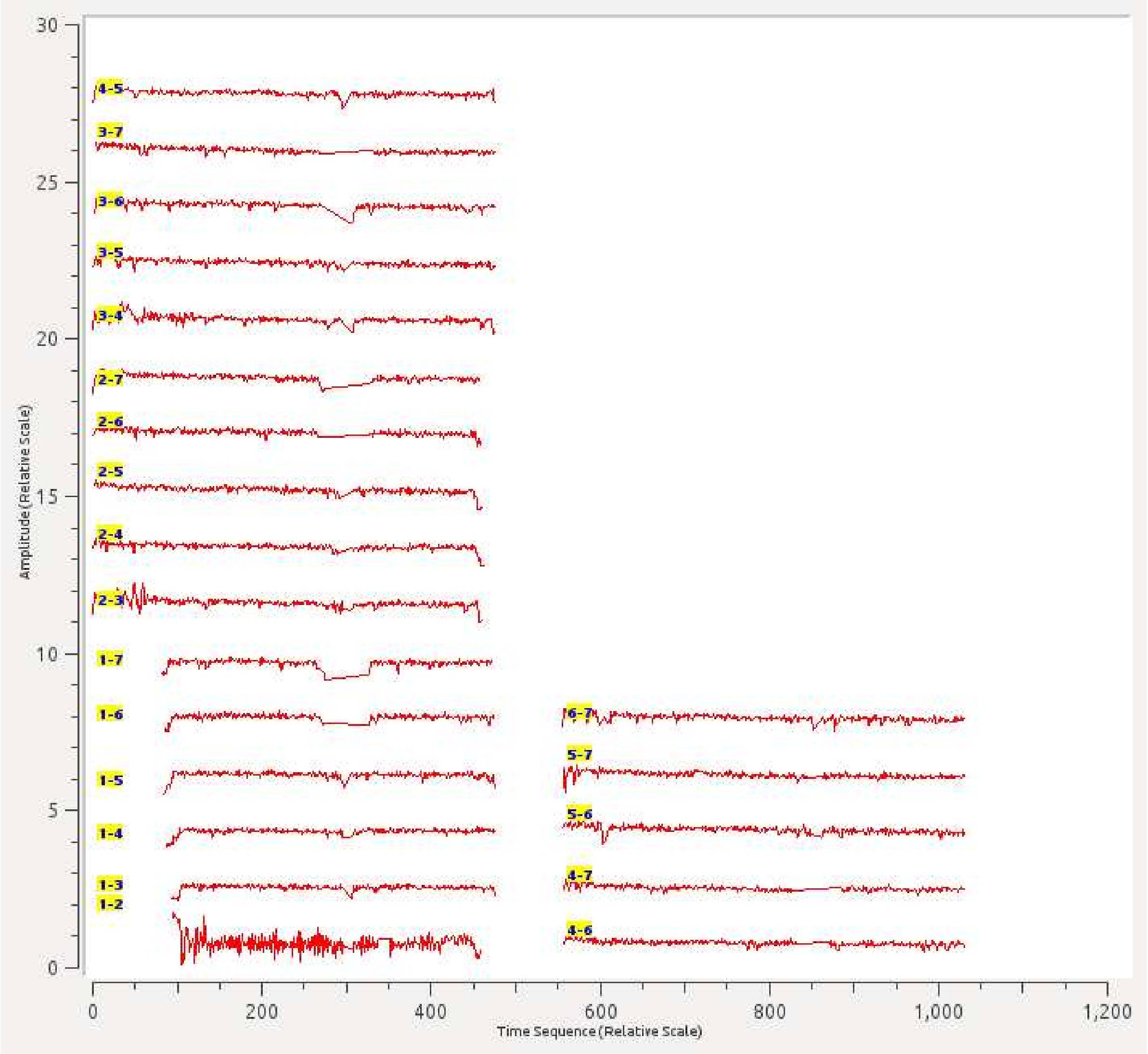


NRC · CNRC
HERZBERG INSTITUTE of ASTROPHYSICS

ALBUS DRAO Corrected Stokes Q

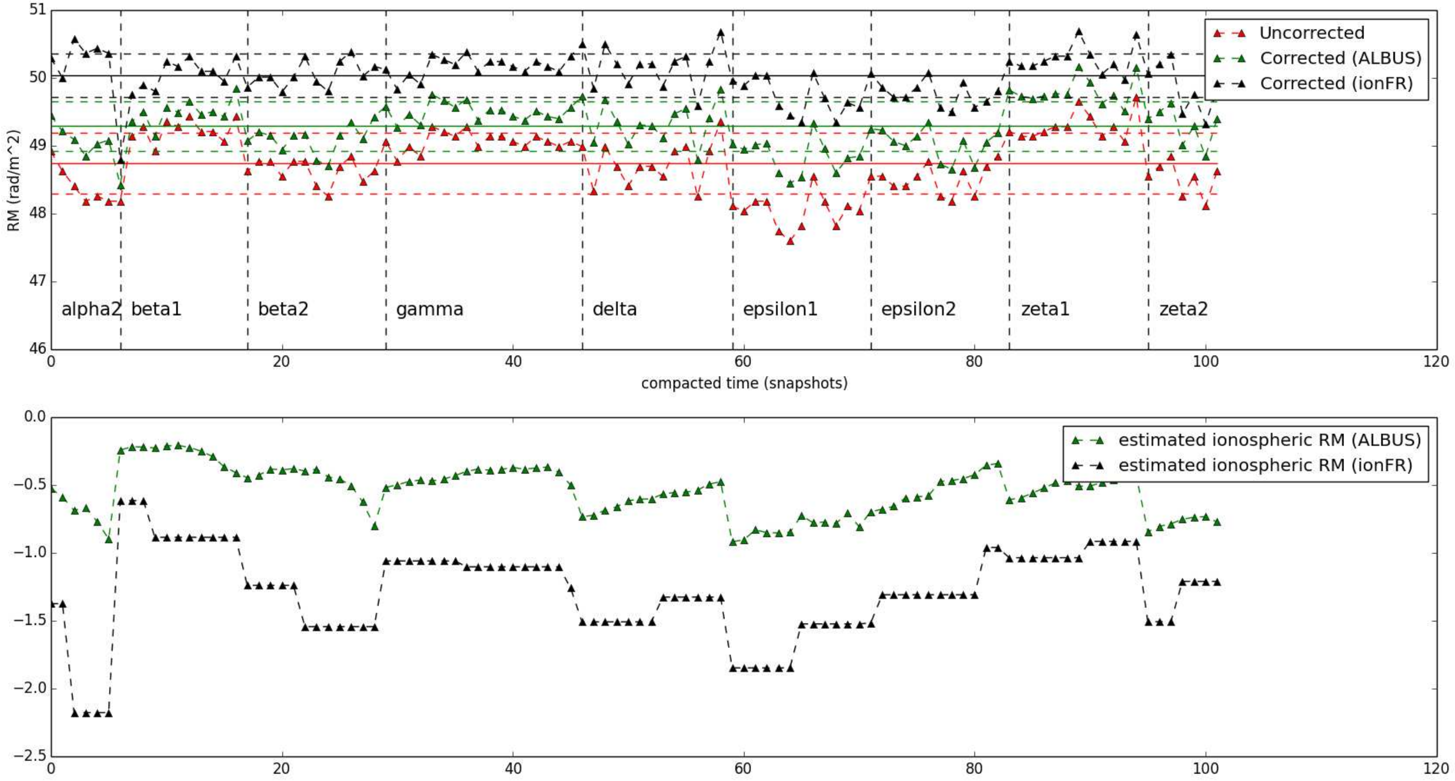


IonFR DRAO Corrected Stokes Q



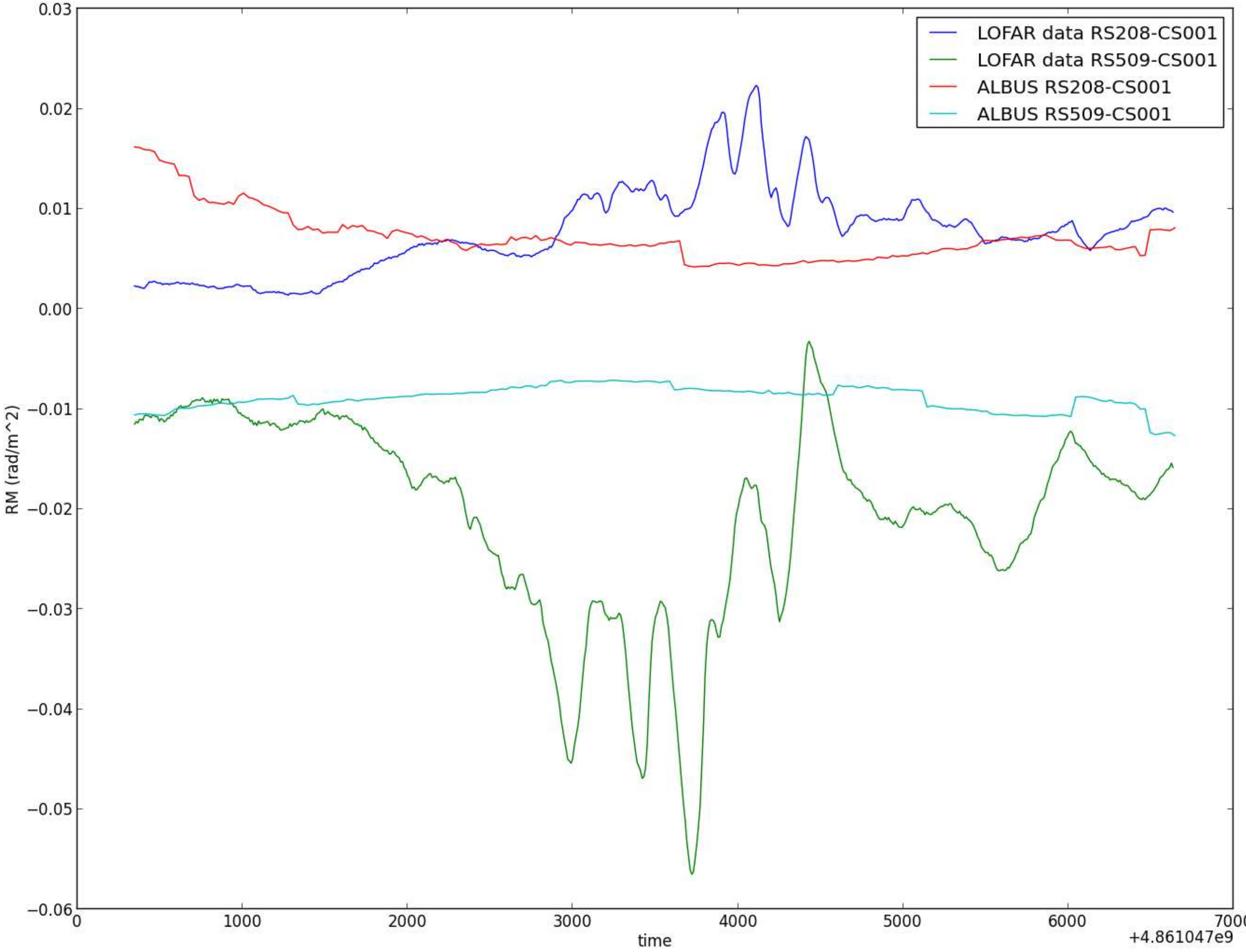
NRC · CNRC HERZBERG INSTITUTE of ASTROPHYSICS

Emil Lenc MWA Observations of J0636-2041

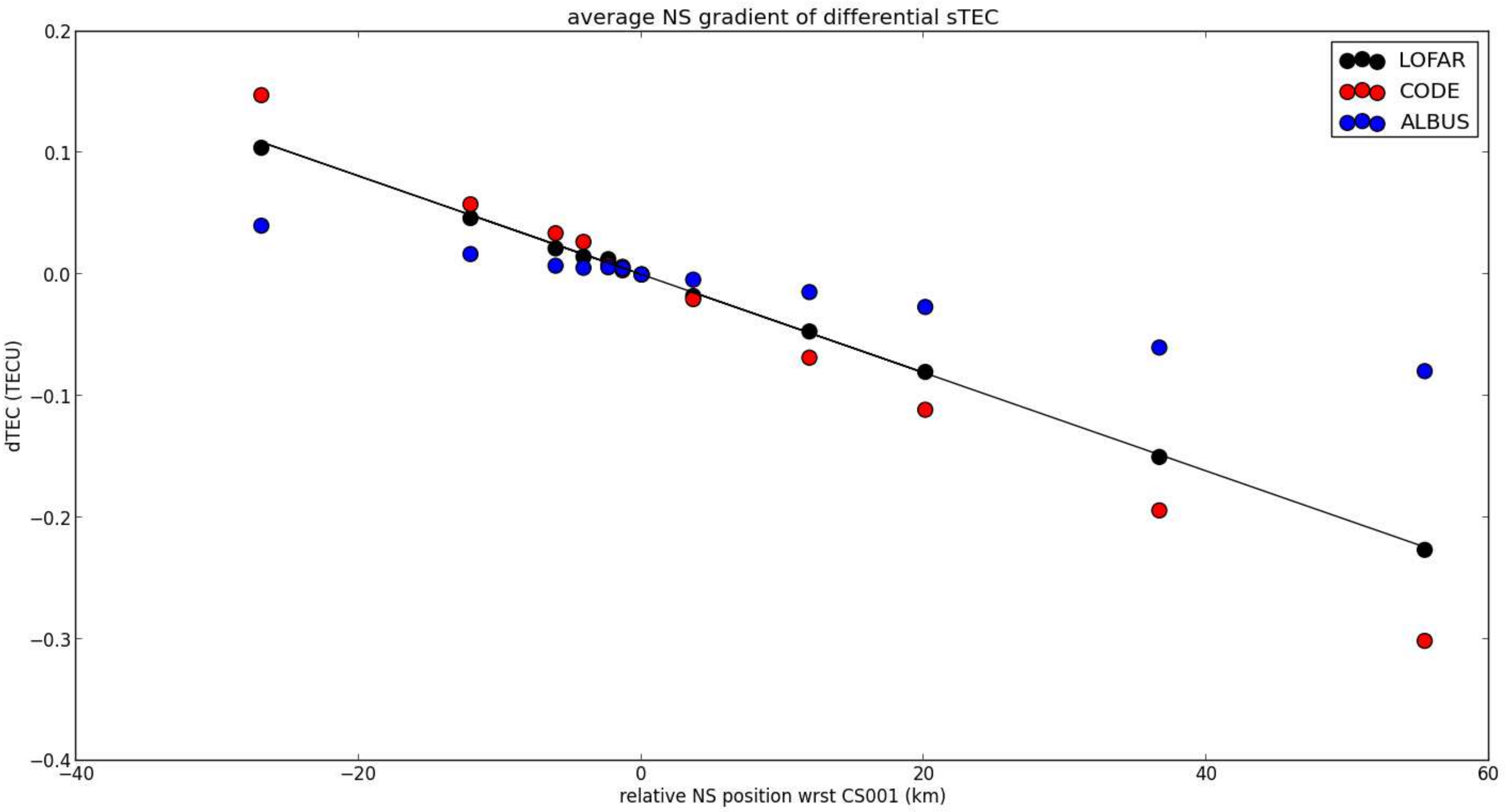


- Nominal RM expected to be 47.1 rad/m^2 from Taylor et al. (2009)
- MWA observations are in the range 164.735-194.975MHz (using 160 kHz channels)

ALBUS Differential RM vs LOFAR Observed RM



LOFAR Example of Changing TEC as a function of Station Position



Conclusions

- TEC determined by ionFR(CODE) is always greater than or equal to TEC determined by ALBUS
- CODE-based results seem to work better for LOFAR (Europe) than does ALBUS
- Elsewhere ALBUS seems as good or better than CODE
- Further Investigate of the inner workings of the ALBUS code is needed
- If you want to apply corrections for the ionosphere to CASA measurement sets, a procedure using MeqTrees is available right now. (Or you could wait xxx years for the CASA developers to implement something themselves.)

GPS Stations within 700 km of an Observatory

GPS Stations within 700 KM	
Observatory	GPS Stations with Data
ATCA	23 out of 112
MWA	12 out of 17
MEERCAT	7(?) out of 9(34)
LOFAR	77 out of 195
GMRT	1 out of 1
VLA	66 out of 95
DRAO	125 out of 146
Hat Creek	360 out of 445