Canadian High Arctic Ionospheric Network

Effect of scintillation on GNSS-based TEC metrology

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"There is Physics behind every measurement technique"

Anonymous

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NBIF INNOVATION
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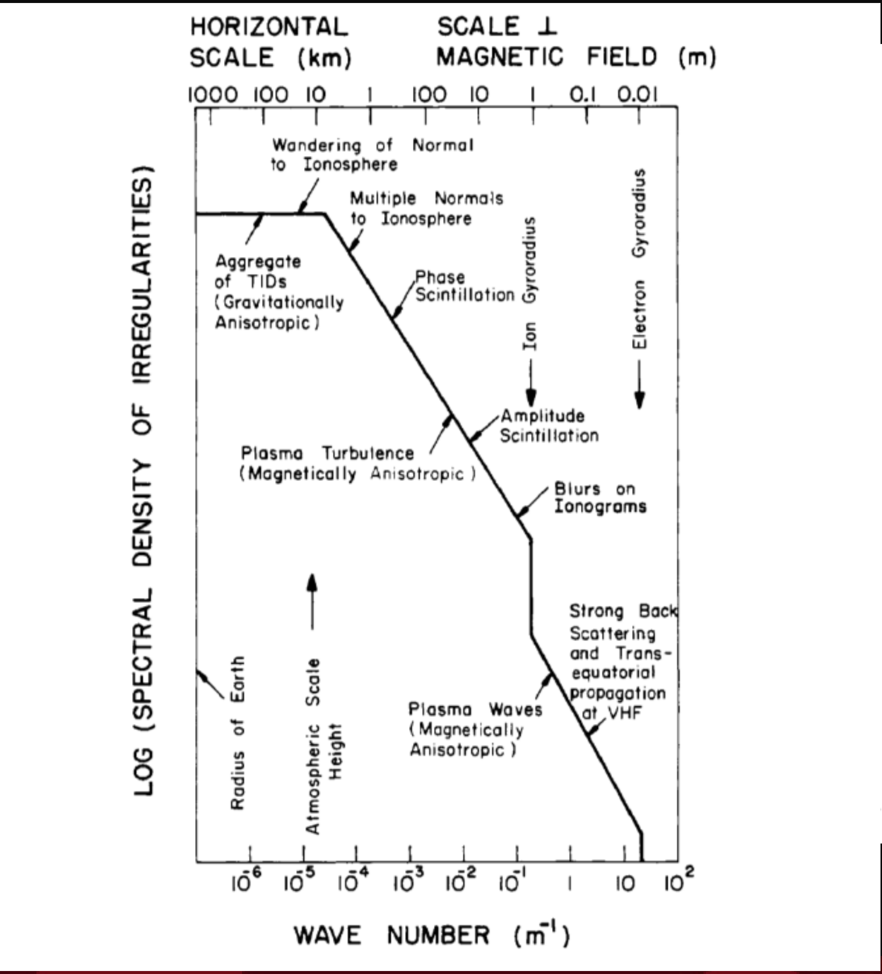
Outline

- Introduction and background
- GNSS metrology pertaining to TEC estimation
- The issue
- Concluding remarks

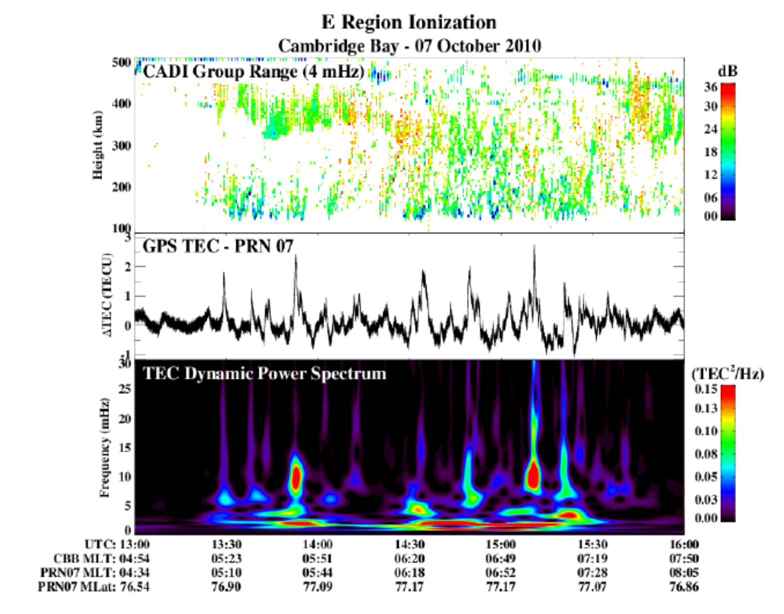
The ionosphere

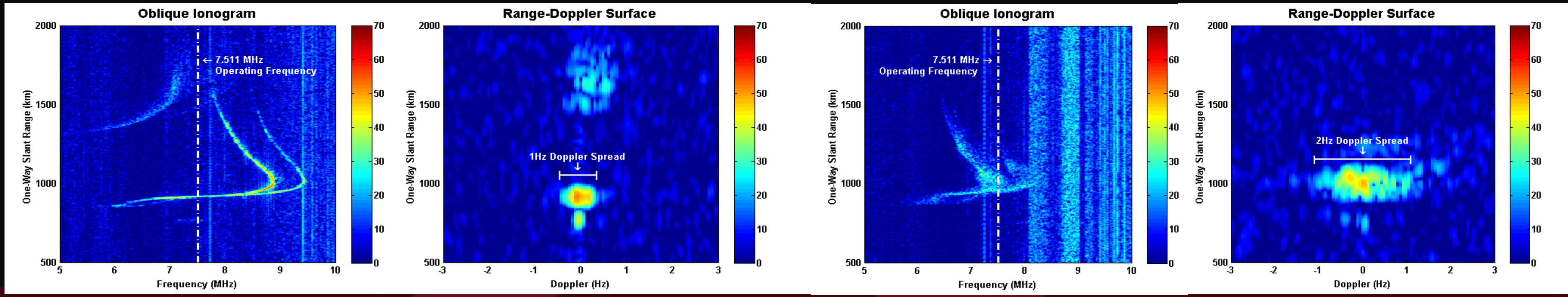
- Region of ionized plasma above 60 km from the Earth's surface
- Primarily produced by the solar EUV and particle precipitation
- Temporal variation scales from "milliseconds" to solar cycle
- Spatial variations from cm to few thousand km
- Affects the propagation of radio waves
- Significant impact on navigation and communication systems



The ionosphere

- Refraction and dispersion-Deterministic
  - TEC variations
  - HF Propagation
- Diffraction and scattering-Stochastic
  - Scintillation
  - Coherent backscatter





Sources or errors in GNSS-Correctable/Manageable

- satellite:
  - orbit ~5 m
  - clock
  - instrumental delays
- signal path
  - ionosphere 5-40 m
  - troposphere 50 cm – 2 m
  - multipath 1-2 m
- receiver
  - clock 1-2 m
  - instrumental delays
- other
  - spoofing 1-2 m
  - interference

Total : 14 – 55 m

Range Delay

TEC	S-Band	L-Band	UHF	VHF	Elev	Mapping Function
50	2.4 m	12 m	104 m	787 m	90 °	x 1
110	5.1 m	26 m	223 m	1.7 km	20 °	x 2.12

A world of applications

Safety of life

- Transportation (air, rail, and water)
- Public safety (Police, fire, ambulance….)
- Traffic
- ADAS
- SatCom
- Military
- ………..

Integrity (error-free)
Standards, regulation, continuity, availability, accuracy

Mass market

- Personal communication and navigation
- Recreation
- LCVs
- Trucks and buses
- IoT and LBS
- ……

Low cost,
User friendly
Best perf. available

Professional

High precision
High accuracy
High reliability

- Oil and natural Gas
- Mining
- Timing
- Surveying
- Geodesy
- Agriculture
- SatCom
- IoT and LBS
- Vehicle control and robotics
- Construction
- Meteorology and weather forecast
- Fisheries
- Environmental monitoring
- ……………

Scintillation

- Rapid random fluctuations of the amplitude and phase of a trans-ionospheric radio signal
- Caused by Fresnel scale irregularities in the ionosphere
- Earlier observation using signal from radio stars
- Early studies using geo-stationary satellite signals
- Morphological characteristics are well known
- Two regions of *intense* scintillations – Polar and equatorial regions (just stating this for historical reasons). This is outdated as ‘scintillation’ is not intense in the high-latitudes
- Produce stochastic errors in PNT applications

Disclaimer-Scintillation

Fluctuations in the amplitude of the signal

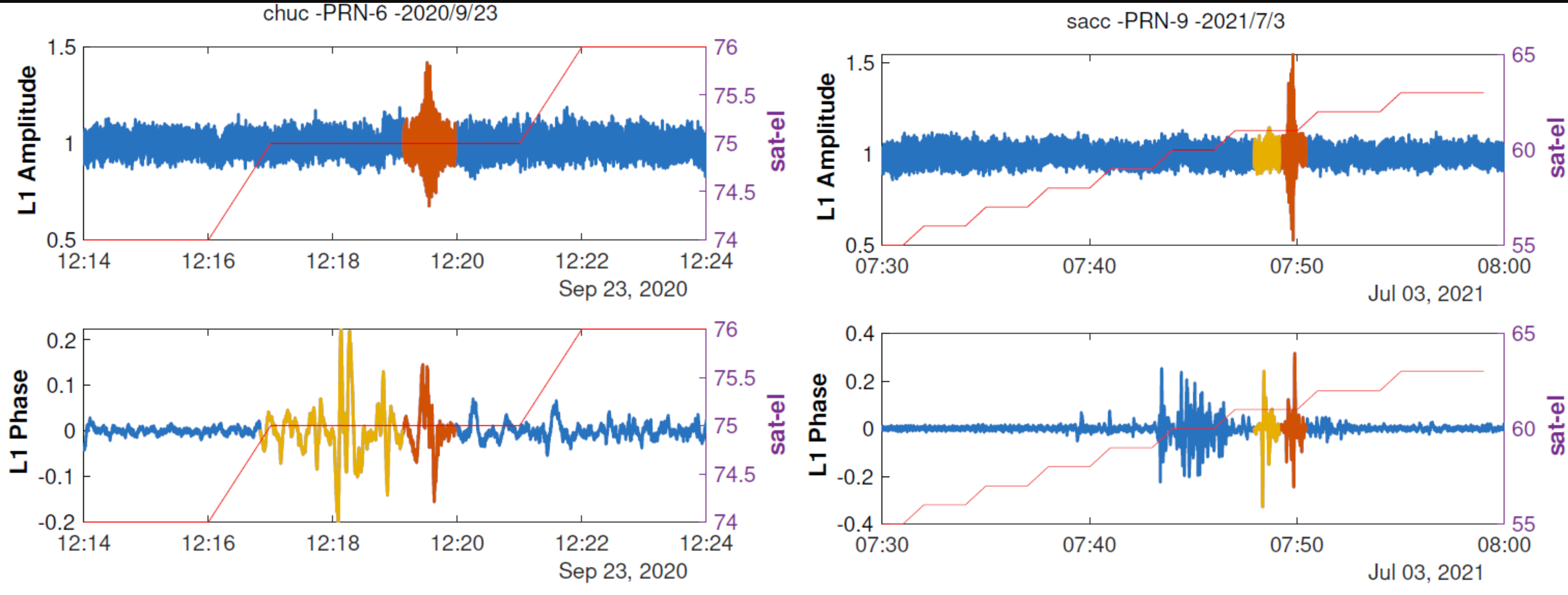
↓

Variations in phase that does not follow $1/f^2$ dependence (if it does, it is called TEC)

↓

Fresnel scale irregularities

Scintillation



Song, et al., 2022

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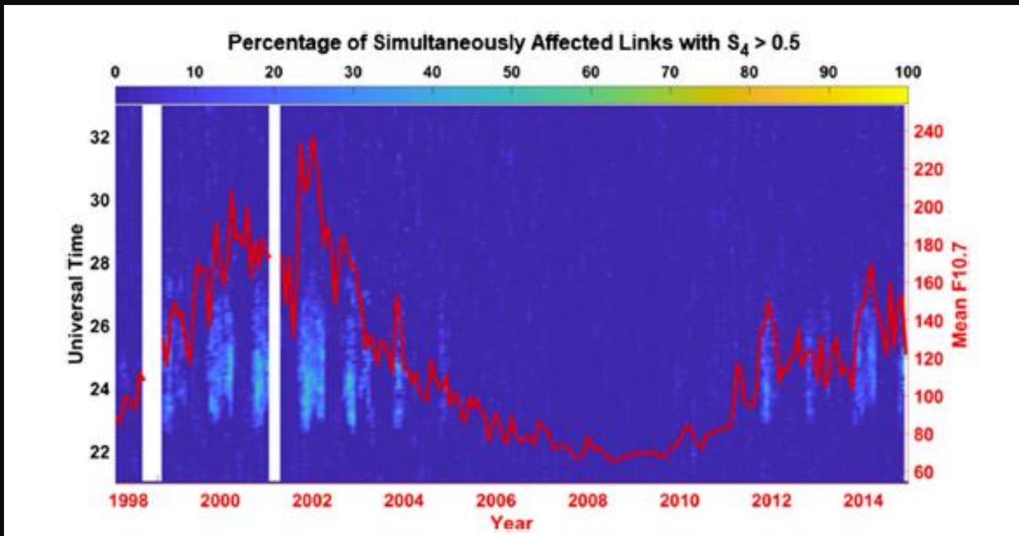
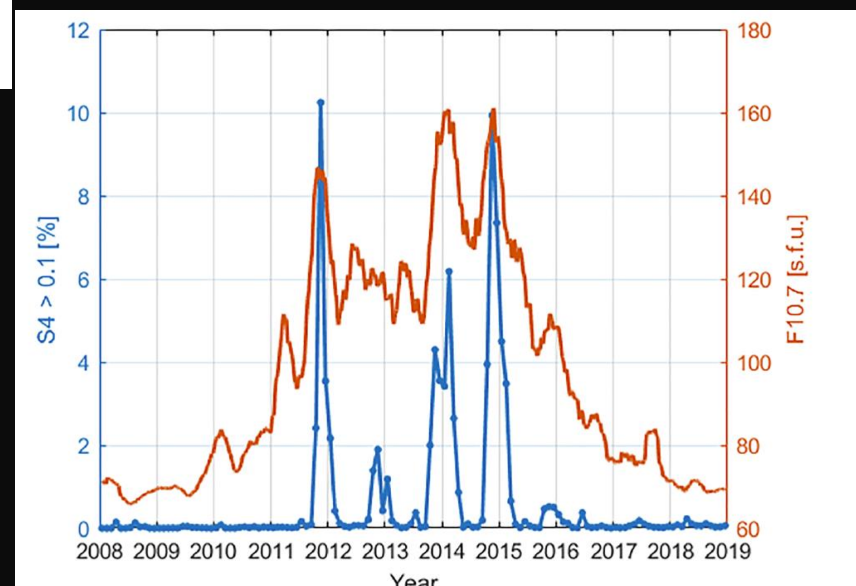
Scintillation occurrence – Tale of two regions



Equatorial region – Salles, et al., 2021

In term of probability of occurrence, Scintillation is not a major concern for the polar region



Polar region – Meziane, et al., 2019

Probability Distribution Function (PDF) - Moments

- **Zero moment – Normalization**

$$1 = \int_{-\infty}^{+\infty} f(u)\,du$$

- **First moment – Mean μ**

$$\mu = \int_{-\infty}^{+\infty} u f(u)\,du$$

- **Second moment – Variance σ^2**

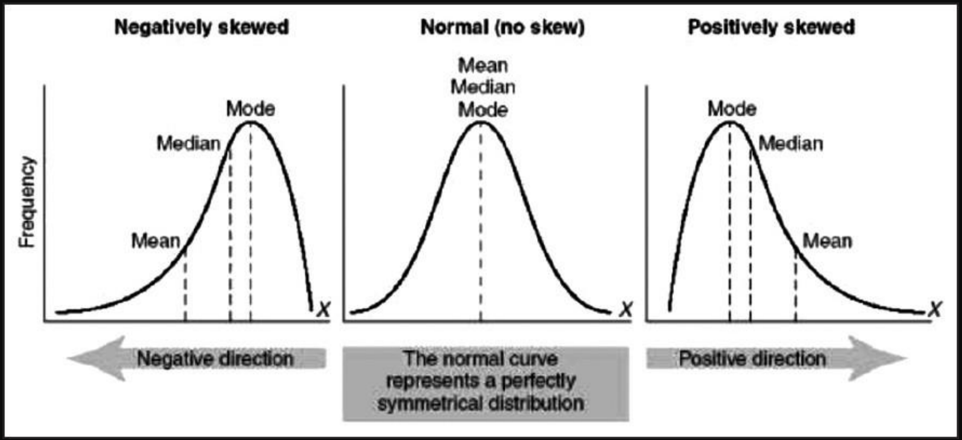
$$\sigma^2 = \int_{-\infty}^{+\infty} (u-\mu)^2 f(u)\,du$$

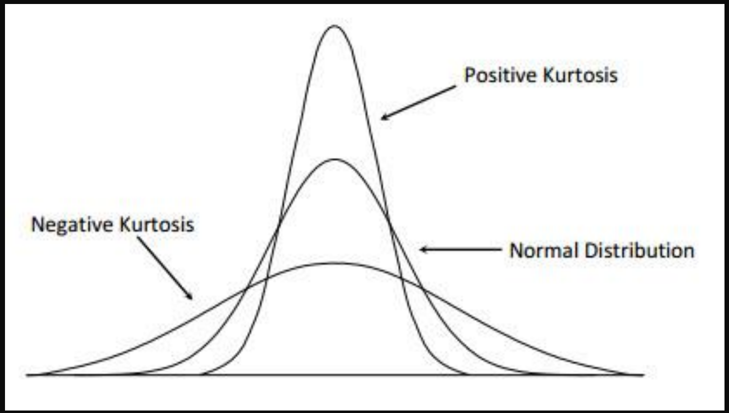
- **[Standard] Third moment – Skewness S**

$$S = \frac{1}{\sigma^3}\int_{-\infty}^{+\infty} (u-\mu)^3 f(u)\,du \quad [S_G = 0]$$

- **[Standard] Fourth moment – Kurtosis K**

$$K = \frac{1}{\sigma^4}\int_{-\infty}^{+\infty} (u-\mu)^4 f(u)\,du \quad [K_G = 3]$$

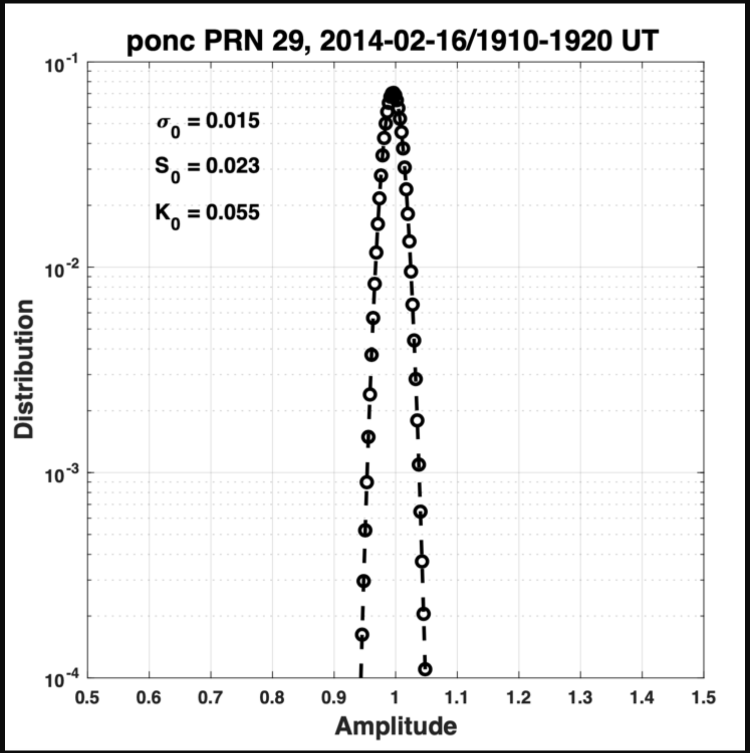




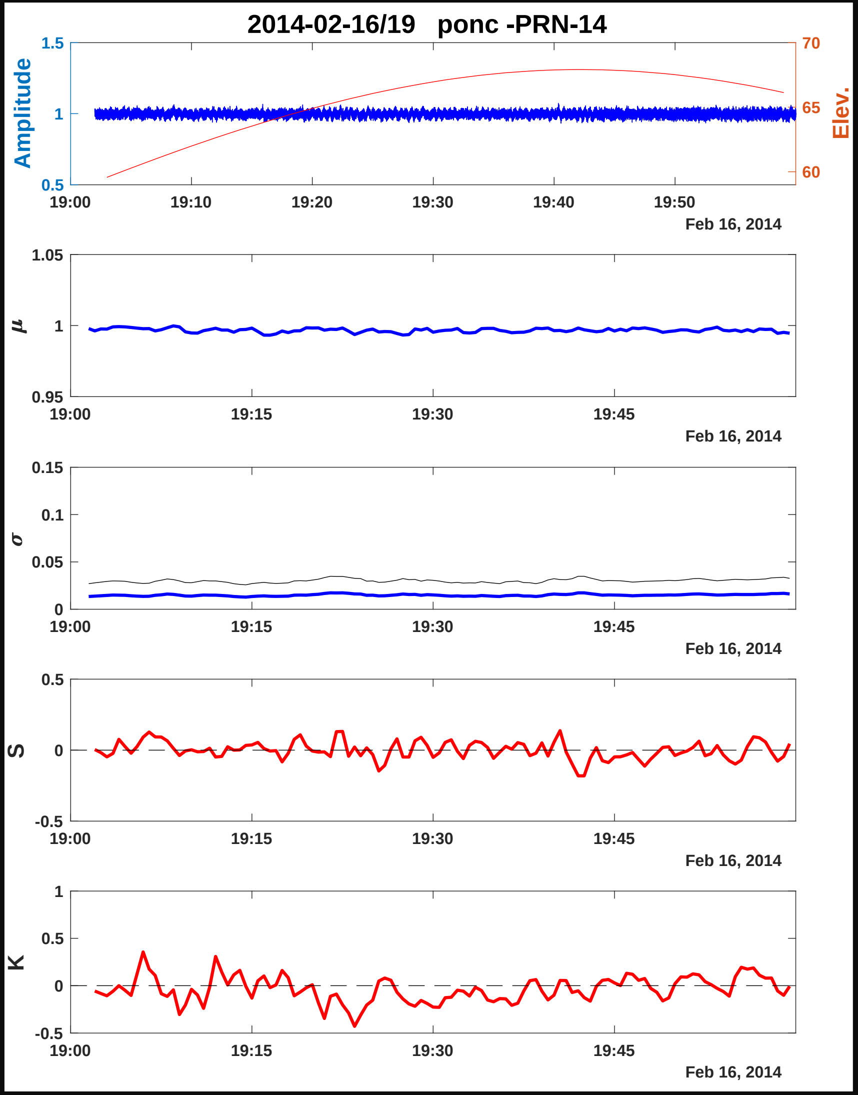
Which distribution?

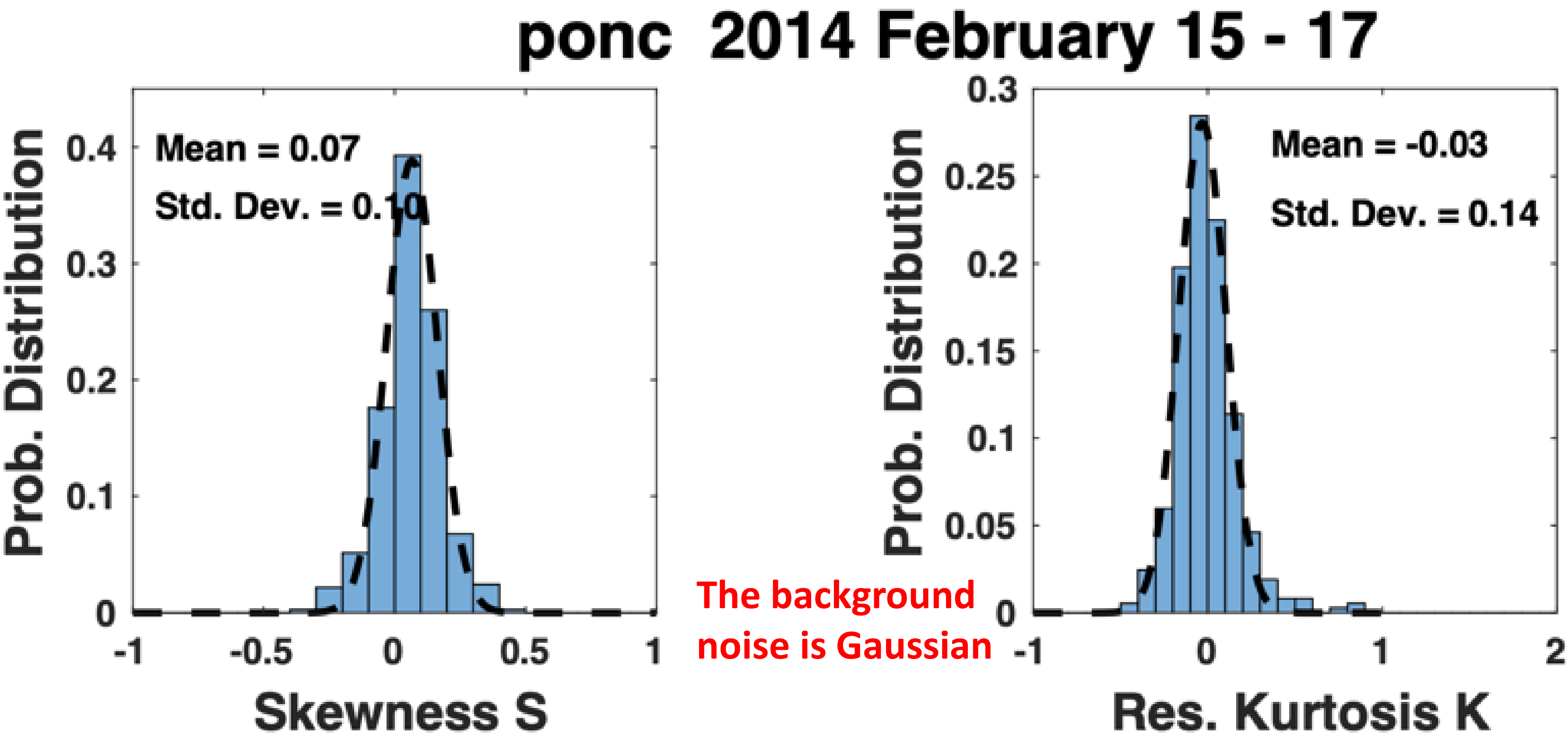
- **Normal [Rino *et al*., 1976; …]**
- **Log-normal [Wheelon, 2003; …]**
- **Nakagami [Fremouv *et al*., 1980]**
- **Rician [Mercer, 1962]**
- **α-μ distribution [Moraes *et al*., 2014]**
- **Generalized Gaussian [?]**

An example - Noise



Best Gaussian fit

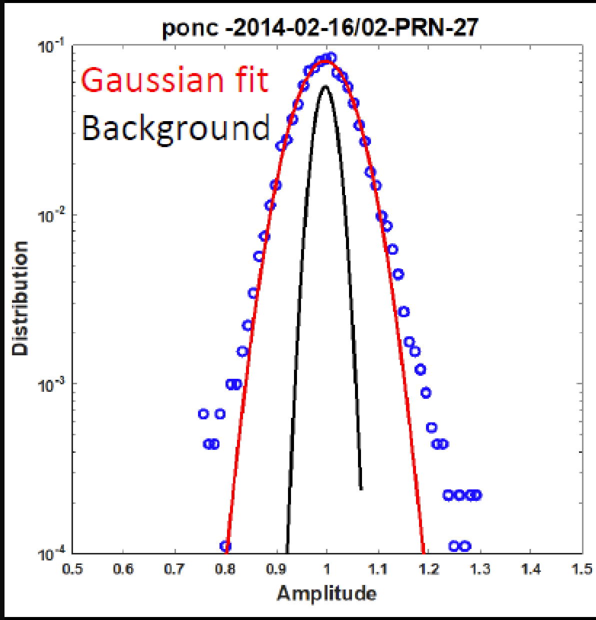


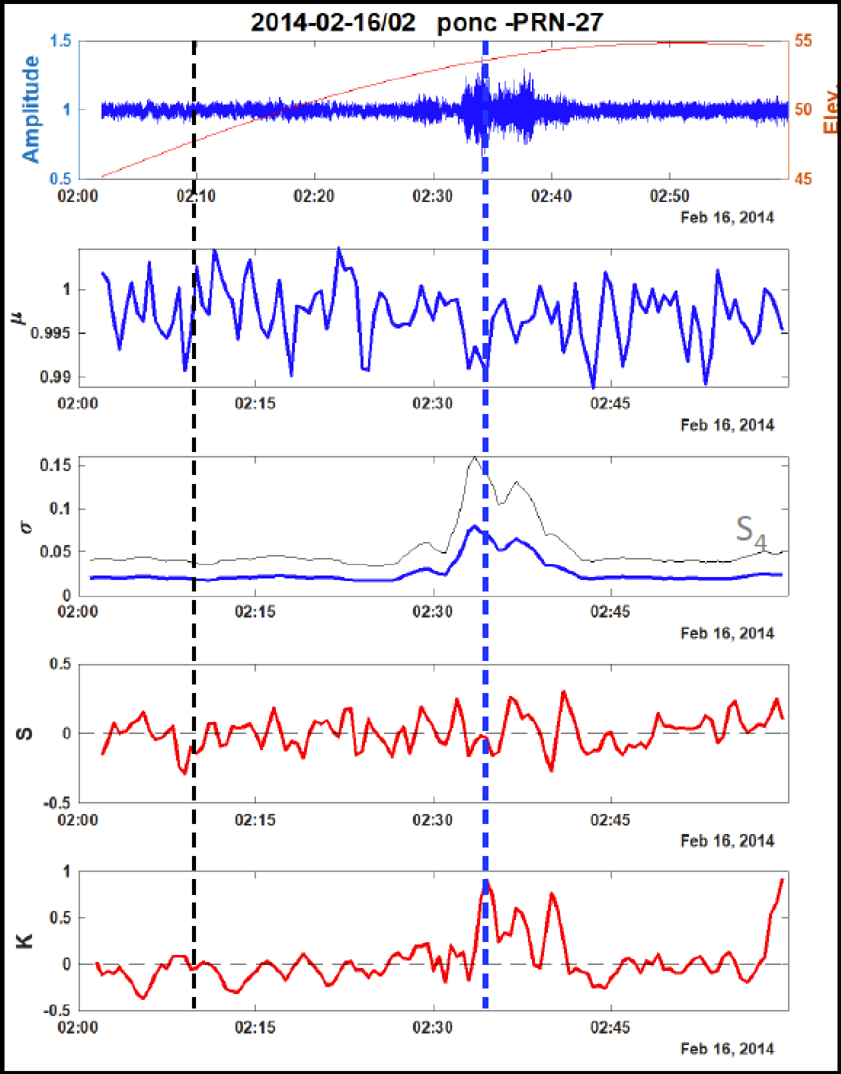


The background noise is Gaussian

$S_{Rayleigh} = 0.63$ $K_{Rayleigh} = 0.25$

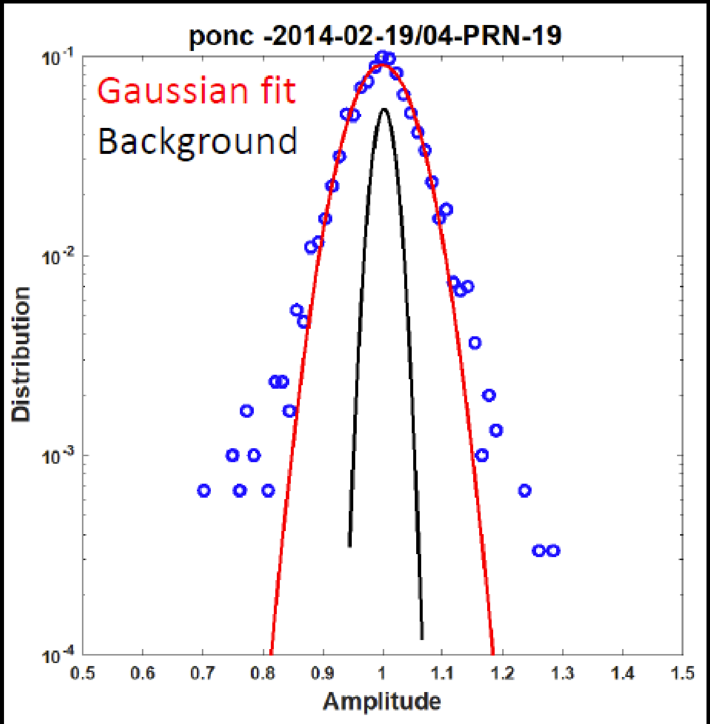
An Example - Scintillation

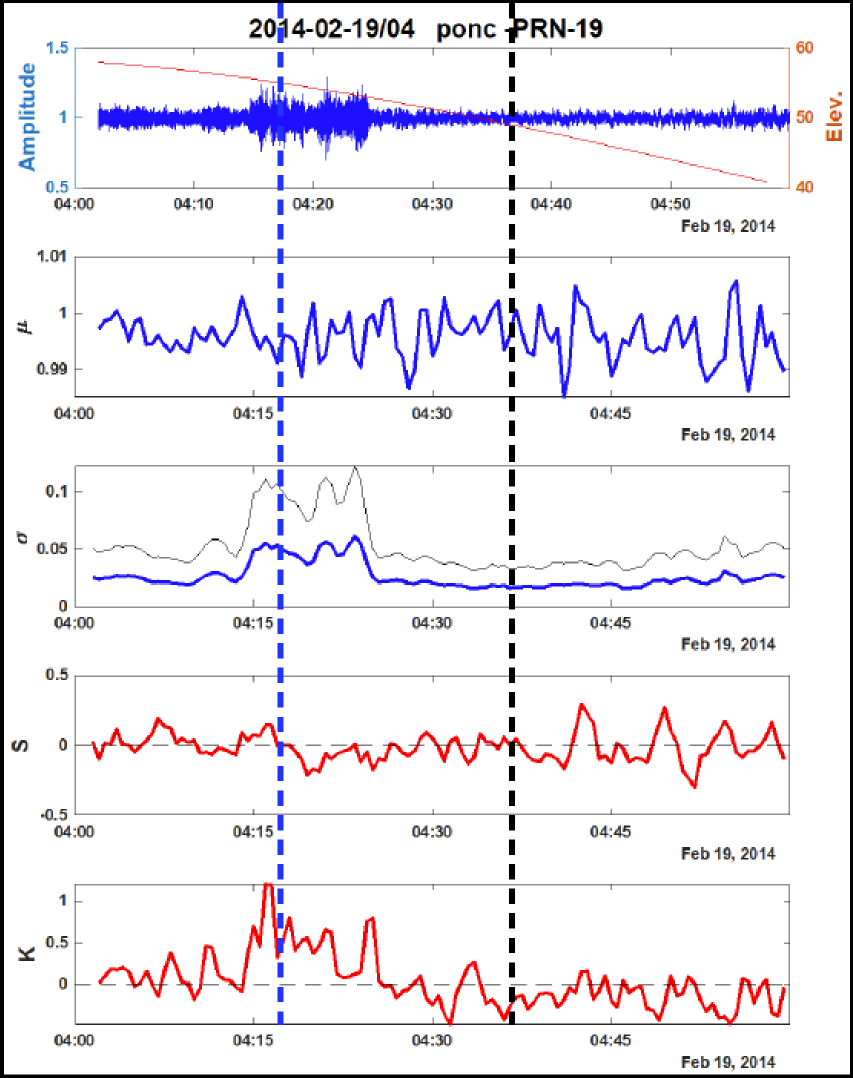




Skewness S ≈ 0
Kurtosis K > 0

Another example

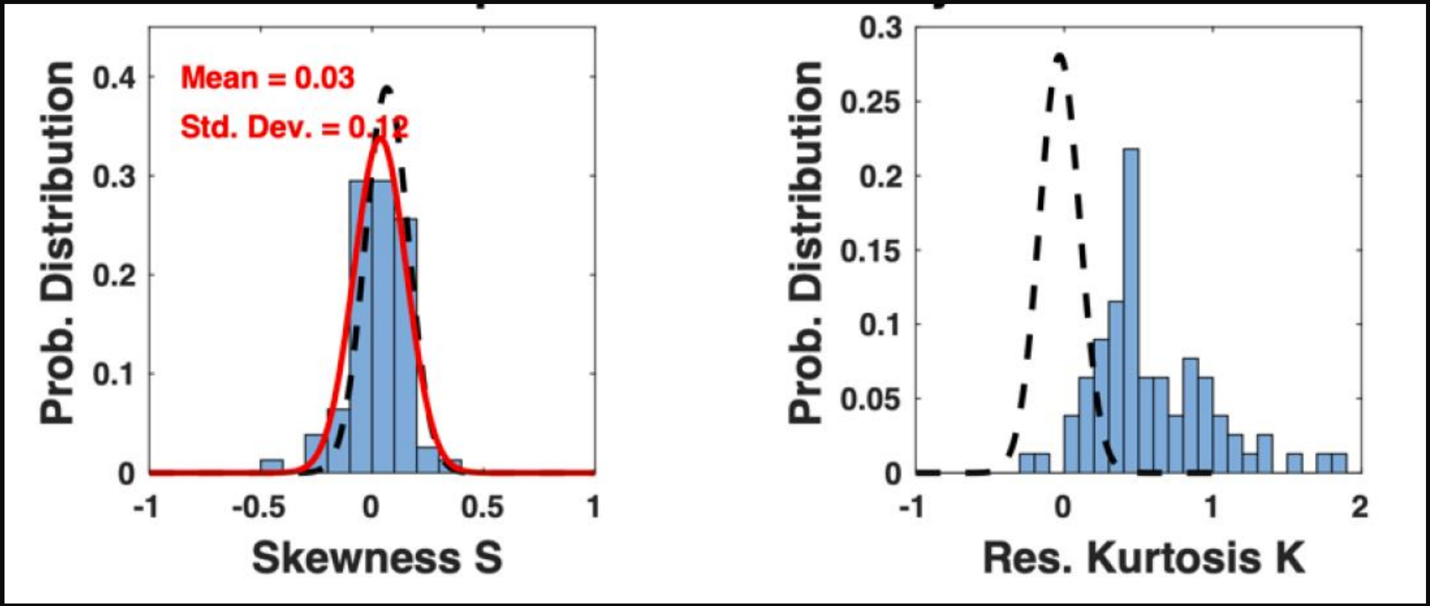




Skewness S ≈ 0

Kurtosis K > 0

Statistics

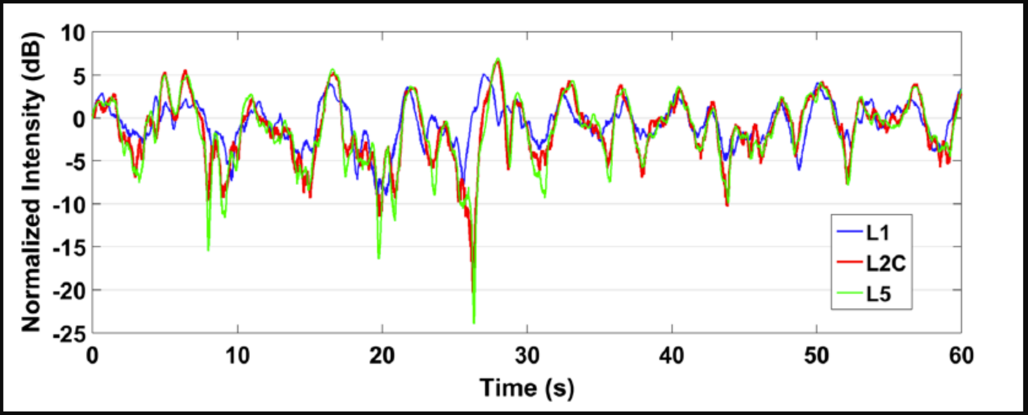


- Absence of scintillation [background]
  - Gaussian distribution.
  - Weakly scattered signal.

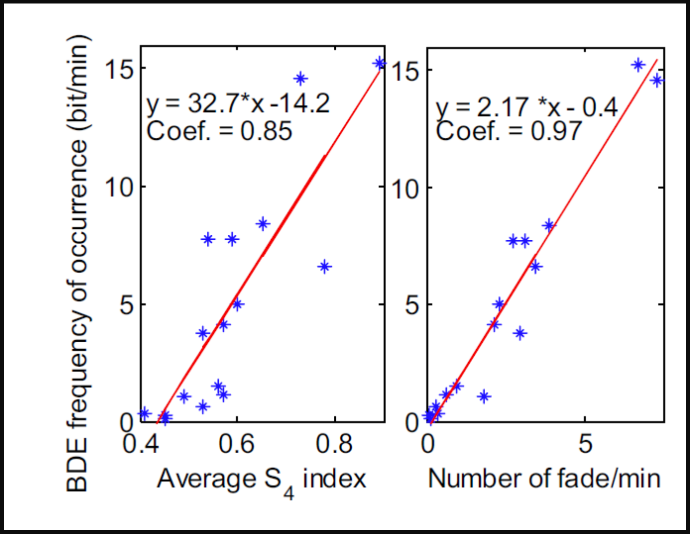
- Presence of scintillation
  - Symmetric (S = 0), Leptokurtic (K > 0) distribution.
  - Best fit: Generalized Gaussian distribution with $\beta < 2$.
  - Familiar distributions (Log-normal, Rician, Nakagami) not satisfactory.

Effects on systems and measurements

- Decrease positioning accuracy and precision
    - Range errors
    - Cycle slips
    - Loss of lock
- Communications
    - Information or bit loss
    - Navigation message BDE
- Estimation of TEC using GNSS observables
- In the worst case scenario, GNSS based applications will not function



An example scintillation at Eureka, NU, Canada



Xu and Morton, 2018

Indices derived using GNSS observables

- Scintillation indices (amplitude and phase)
- Rate of change of TEC (ROT) - Pi et al., 1997

$$\mathrm{ROT} = \frac{\mathrm{TEC}_i - \mathrm{TEC}_{i-1}}{\tau_t - \tau_{t-1}}$$

- ROT (ROTI) index – Pi et al., 1997

$$\mathrm{ROTI}(i) = \sqrt{\frac{1}{N}\sum_{j=i-N}^{i}\left(\mathrm{ROT}(j) - \overline{\mathrm{ROT}}\right)^2}$$

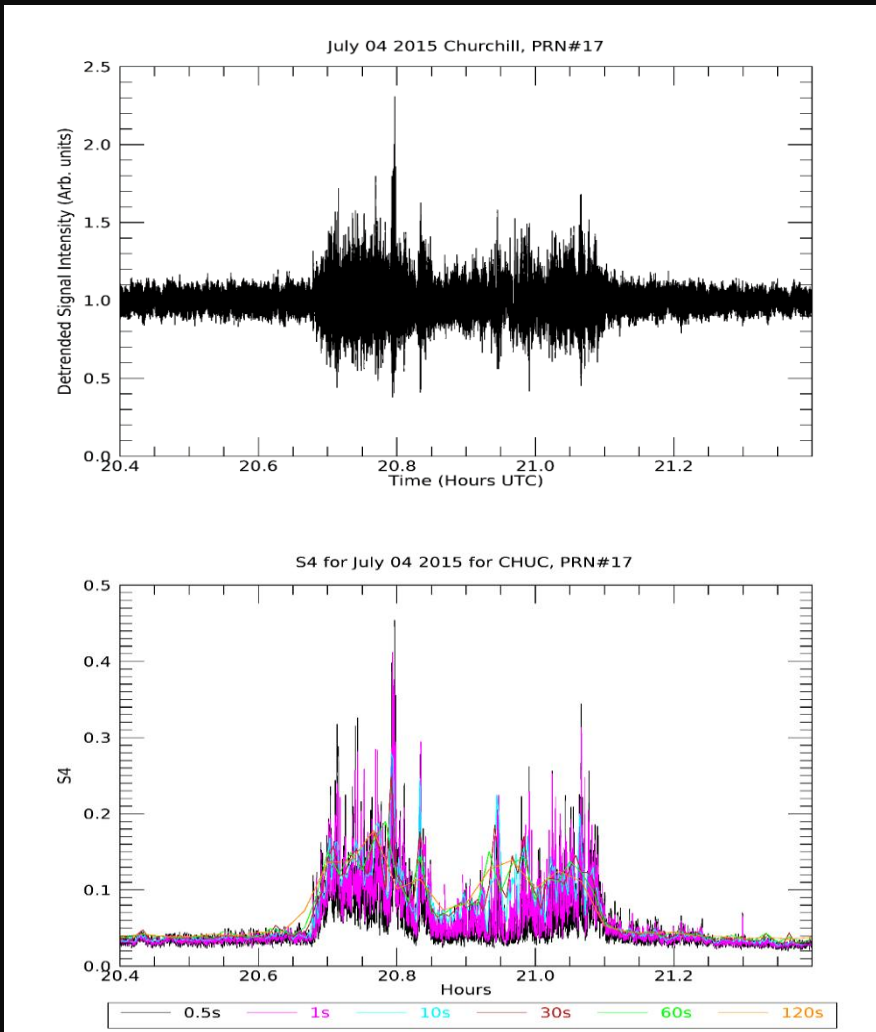
- Disturbance ionosphere index (DIX) – Jakowski et al., 2012
- Gradient ionospheric index (GIX) – Jakowski and Hoque, 2018
- Delta phase rate (DPR) - Ghoddousi-Fard and Lahaye, 2012) -

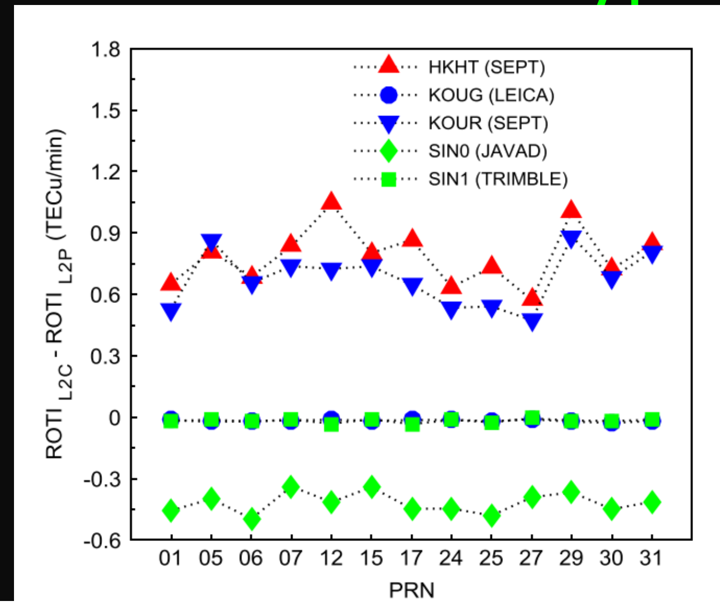
$$\mathrm{DPR} = \frac{\sum_{i=0}^{n} \psi_i}{n}$$

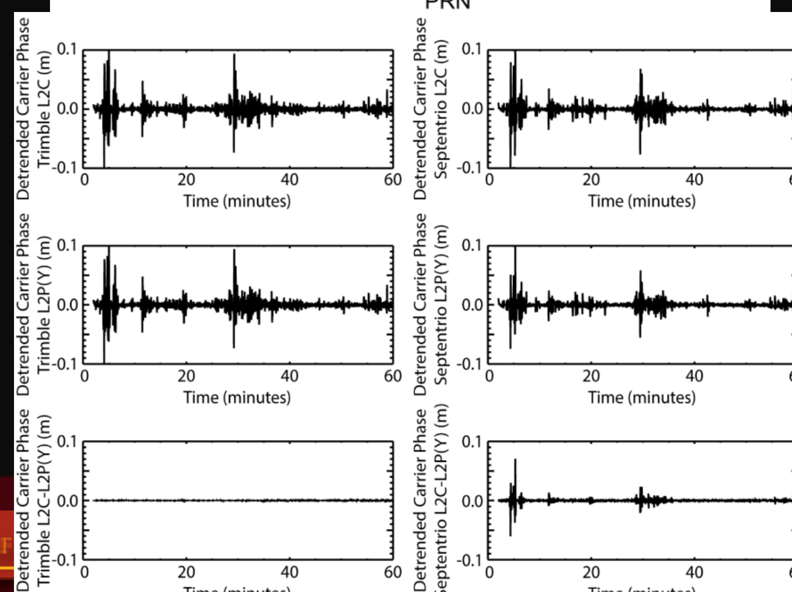
$$\psi_i = \frac{\varphi_g^{t_{i+1}} - \varphi_g^{t_i}}{t_{i+1} - t_i}$$

$$\varphi_g = \lambda_1 L_1 - \lambda_2 L_2$$

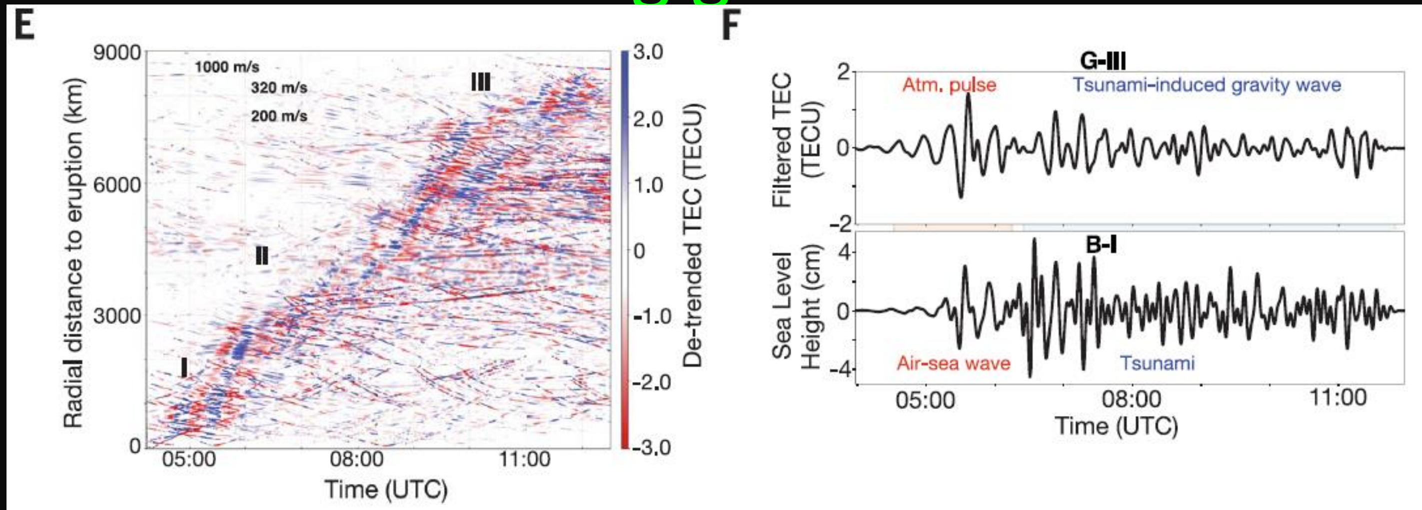
These indices depend on the sampling rate, receiver type etc.





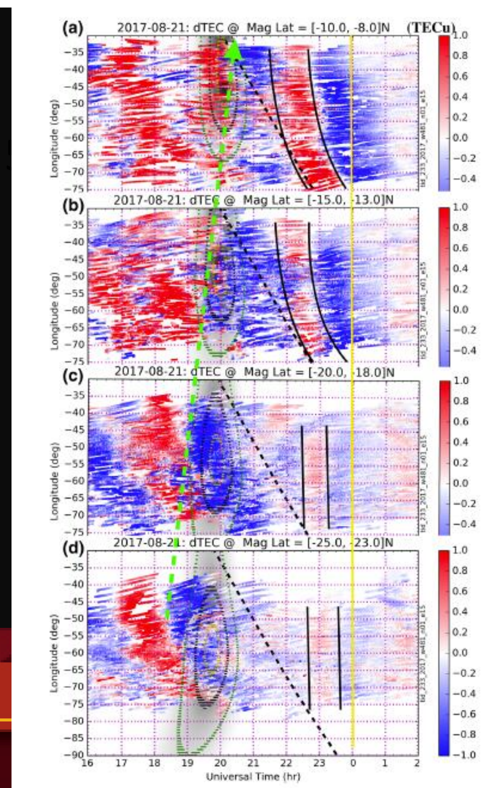


Recent studies using global GNSS observations



Matoza et al., 2022

1-2 m



Zhang et al., 2020

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GNSS Metrology-TEC

$$\Phi_L^{s,r}(t) = \rho^{s,r}(t) + c\left(dt^s(t) - dt^r(t)\right) + T^{s,r}(t) - I_L^{s,r}(t) + \lambda_L N_L^{s,r} + \epsilon_L^{s,r}(t)$$

Ionosphere is dispersive

$$n(h) = 1 - \frac{40.3 N_e(h)}{f^2}, \quad n_g(h) = \frac{c}{v_g} = 1 + \frac{40.3 N_e(h)}{f^2}$$

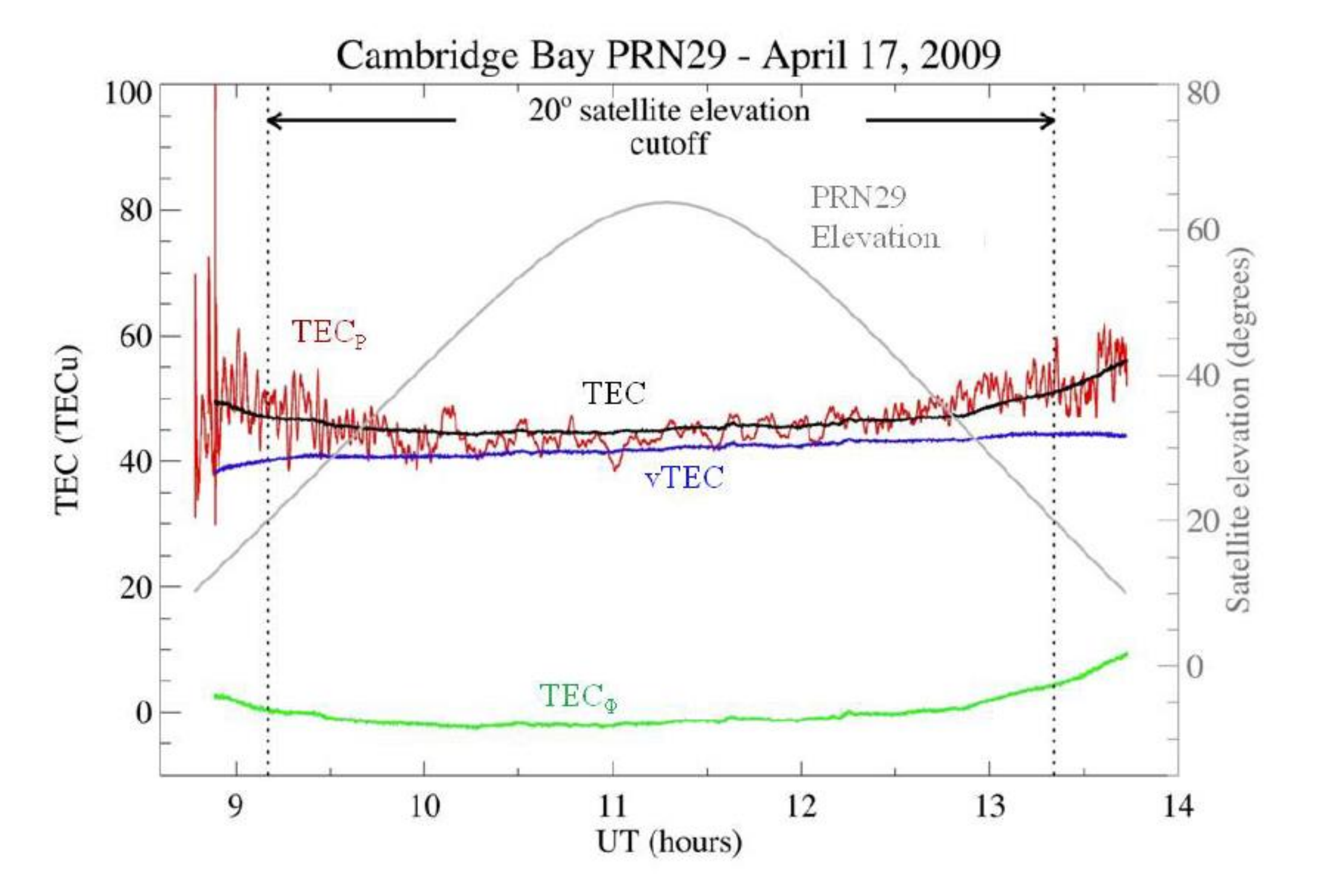
Change in Phase or Code

$$\Delta\Phi = -\Delta P = -\frac{40.3}{f^2}\int N_e dl$$

Total electron content (TEC)

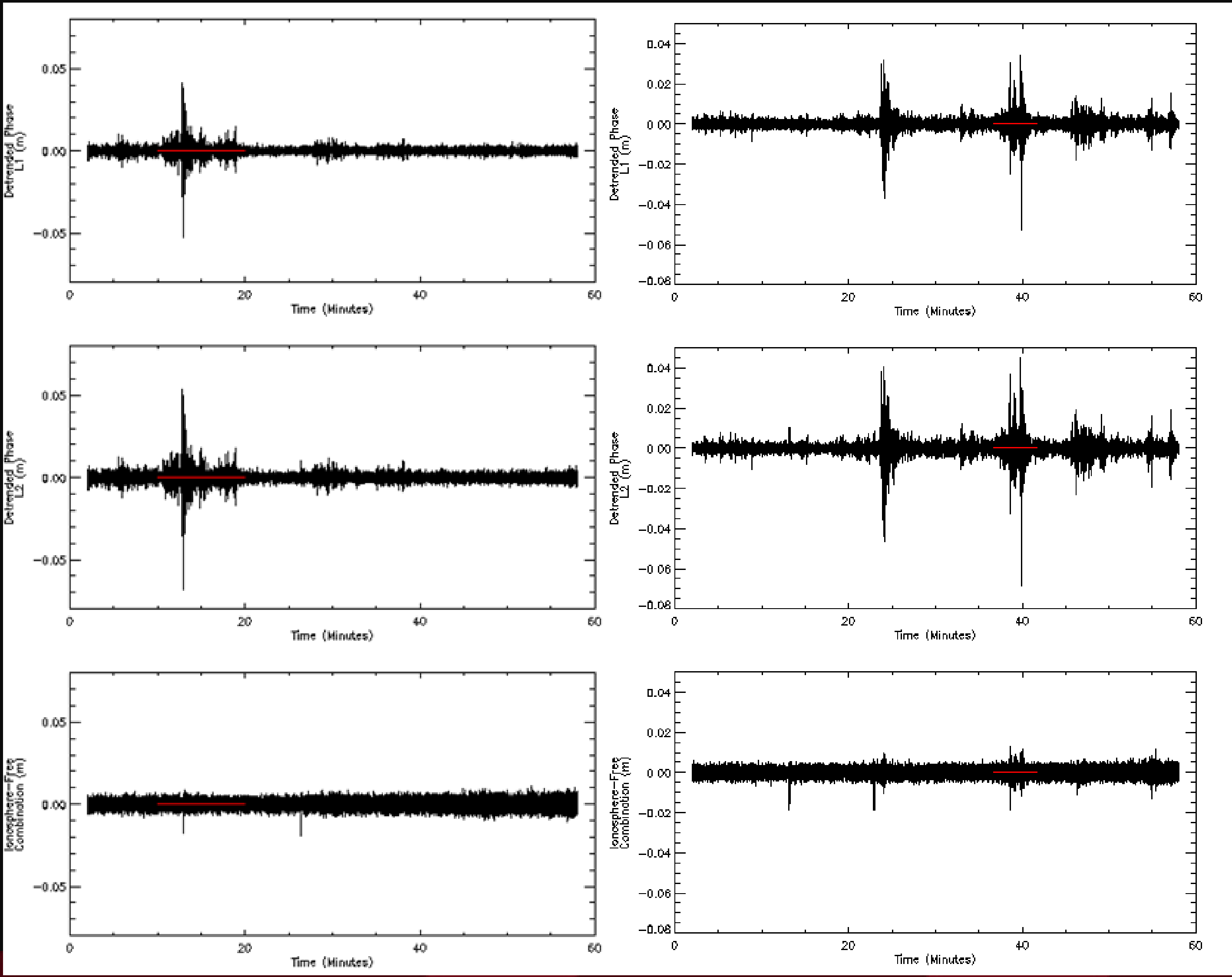
$$TEC = \frac{f_{L1}^2 f_{L2}^2}{40.3(f_{L1}^2 - f_{L2}^2)}\Delta\Phi$$

TEC



Cambridge Bay PRN29 - April 17, 2009
20° satellite elevation cutoff
PRN29 Elevation
TEC_P
TEC
vTEC
TEC_Φ
TEC (TECu)
Satellite elevation (degrees)
UT (hours)
100
80
60
40
20
0
9
10
11
12
13
14

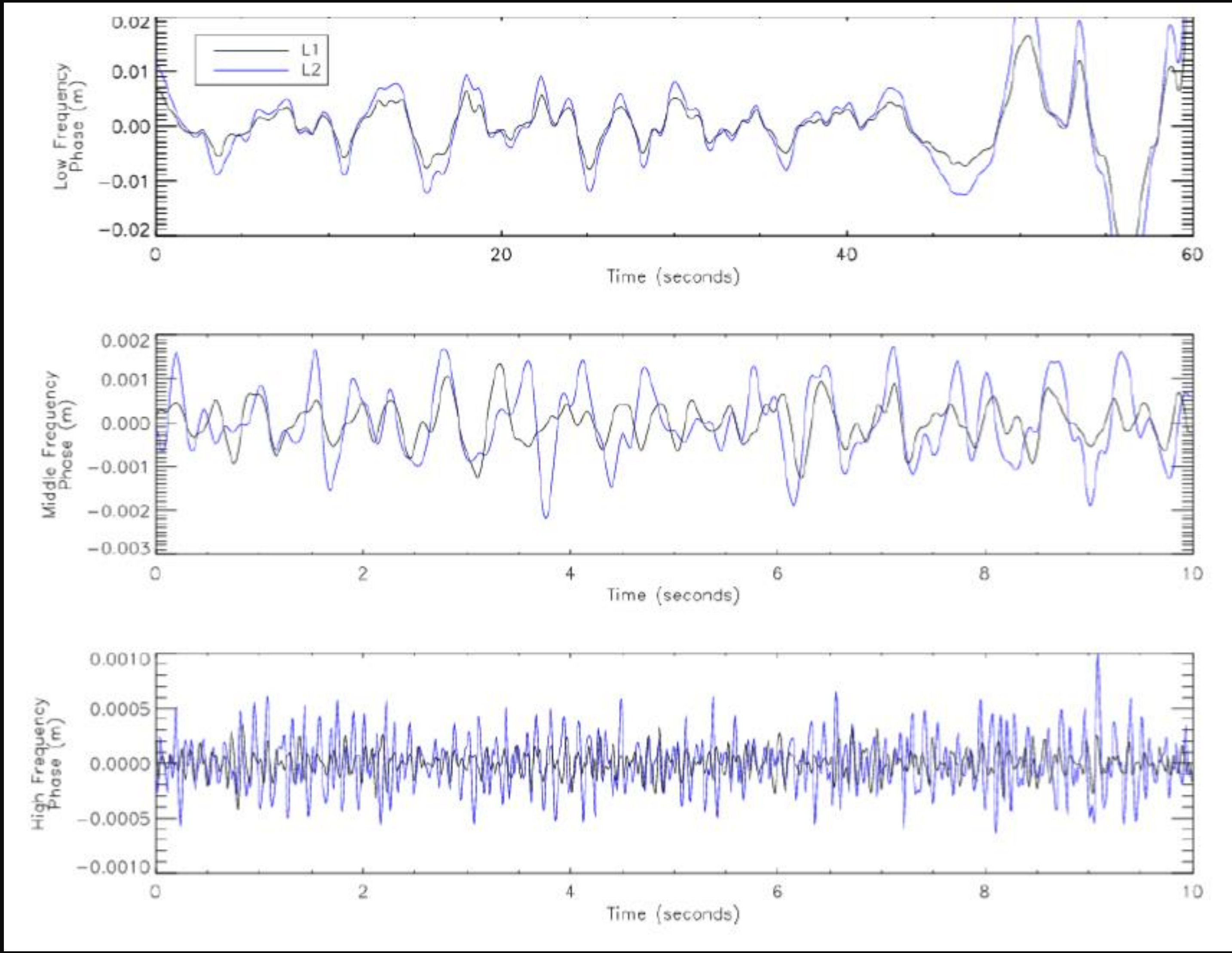
Ionosphere free linear combination (IFLC)



$$\Phi_{IFLC} = \frac{\Phi_1 f_1^2 - \Phi_2 f_2^2}{f_1^2 - f_2^2}$$

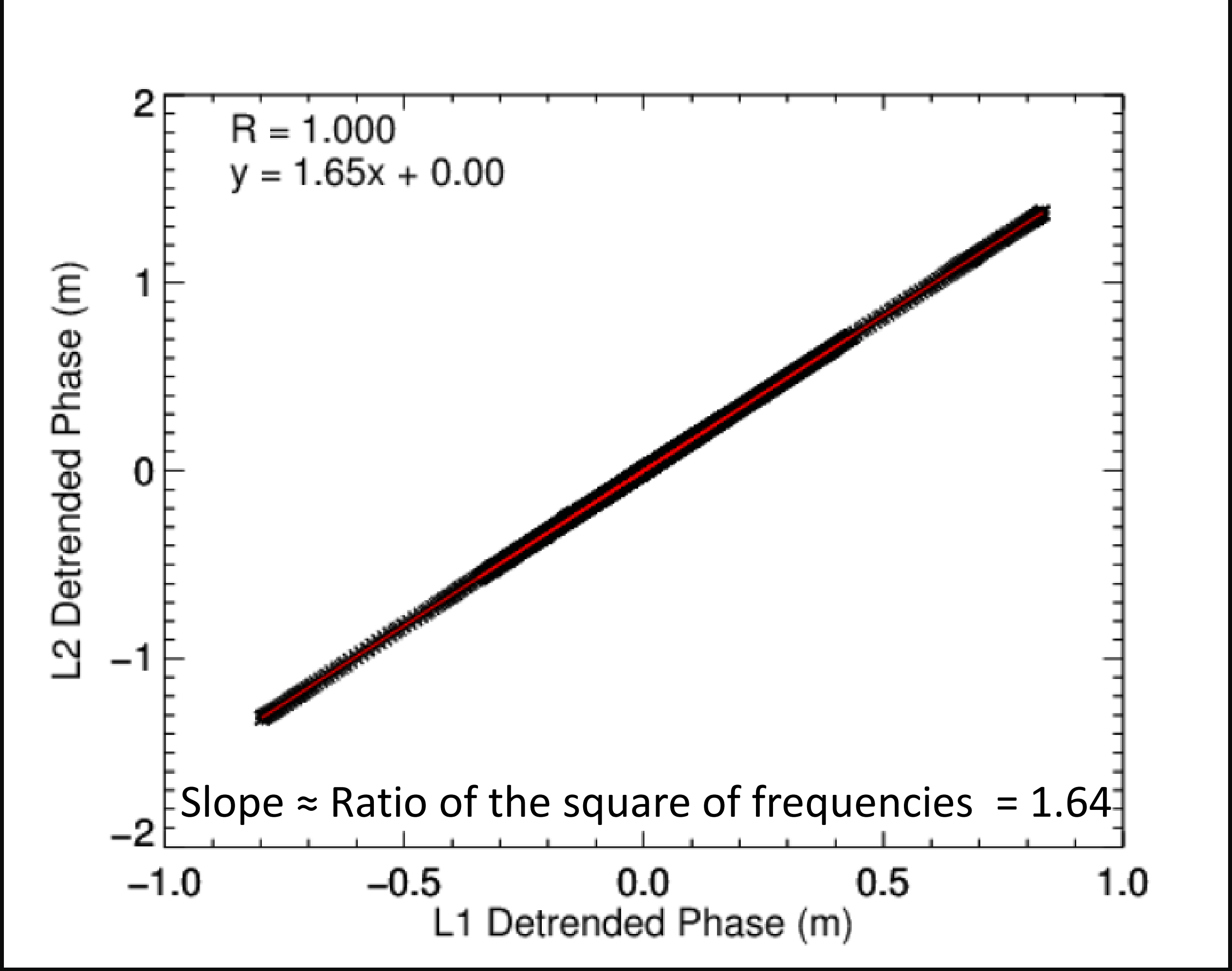
McCaffrey and Jayachandran, 2019

Variation of phase at two frequencies

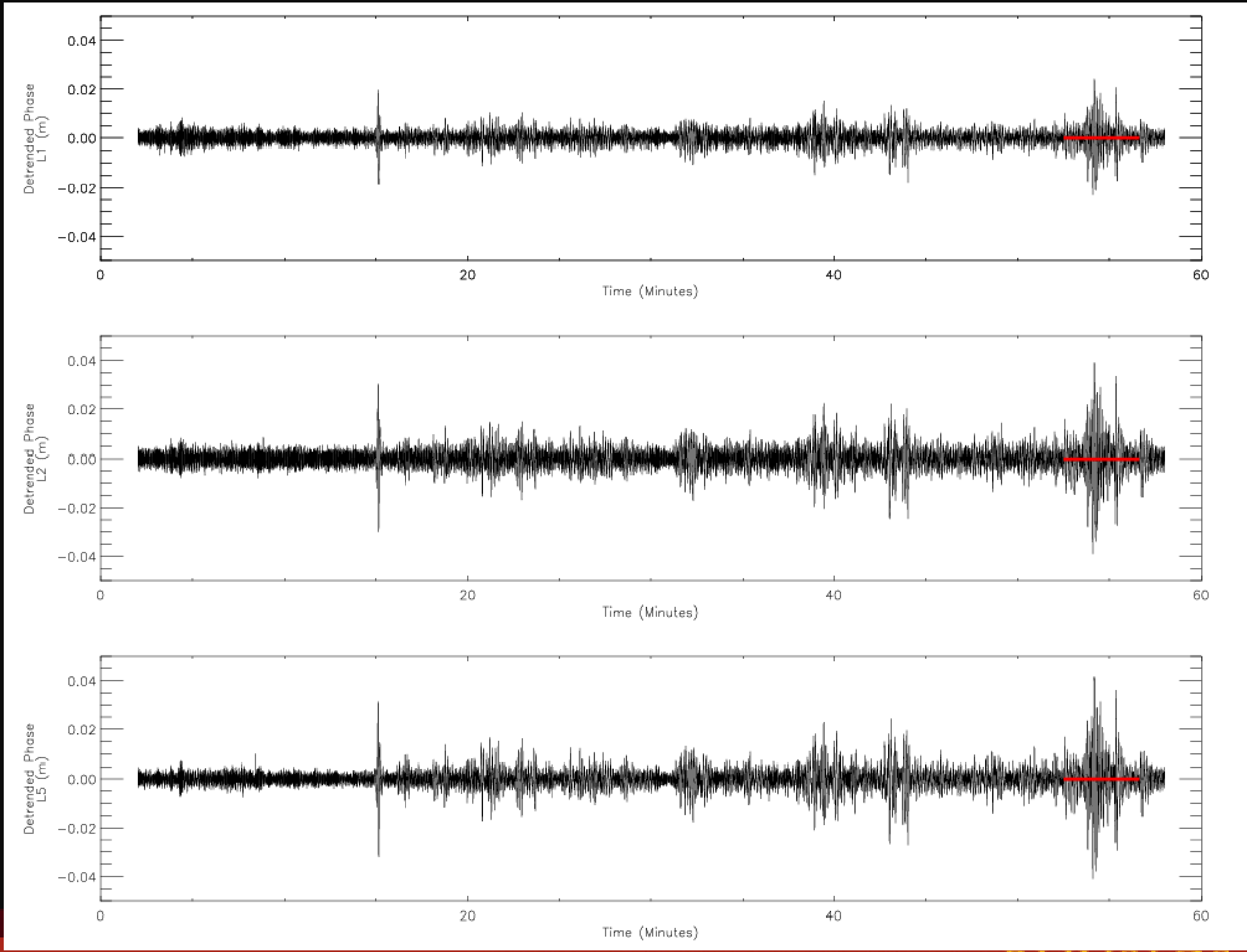


McCaffrey and Jayachandran, 2019

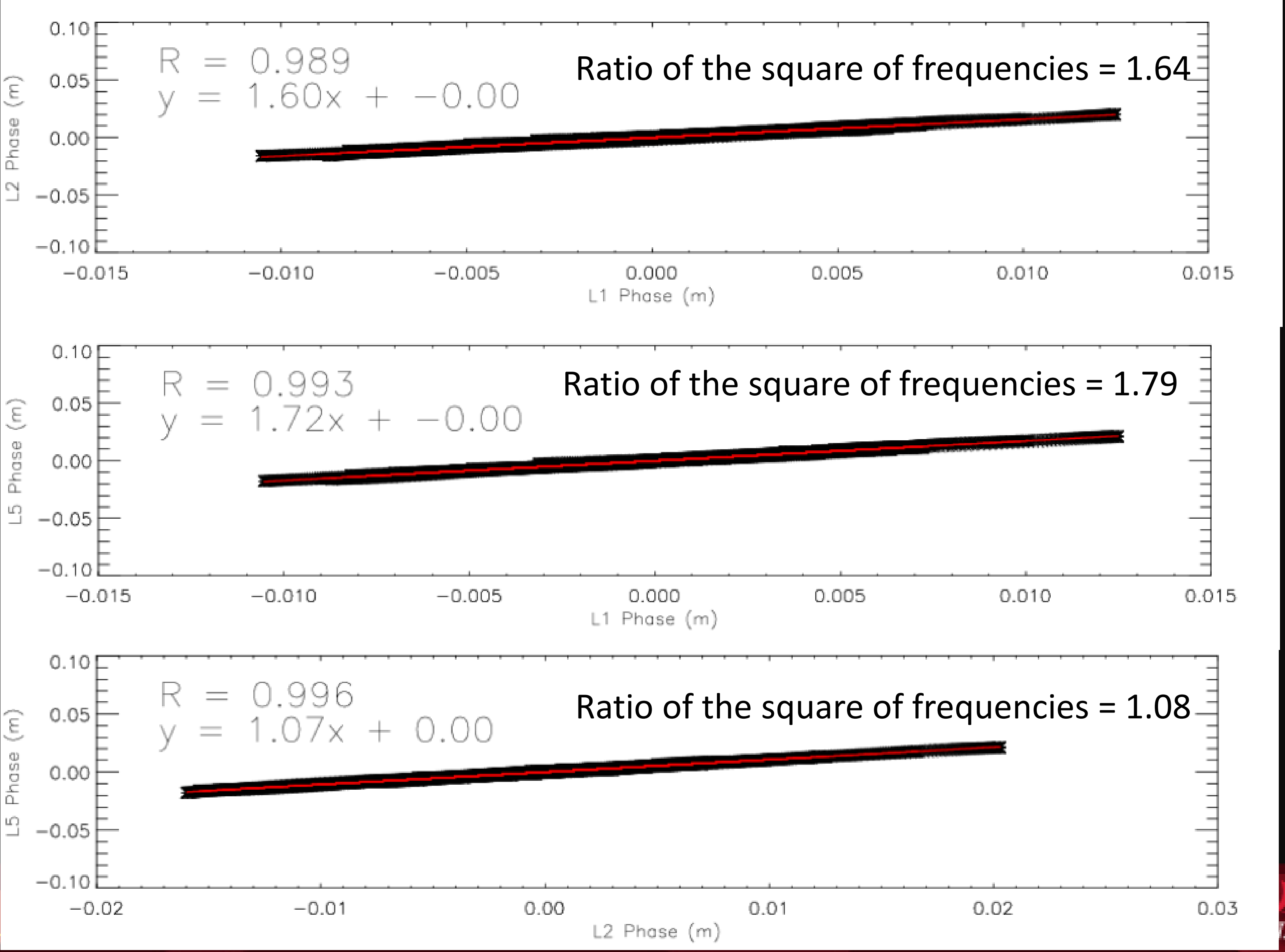
It works most of the time



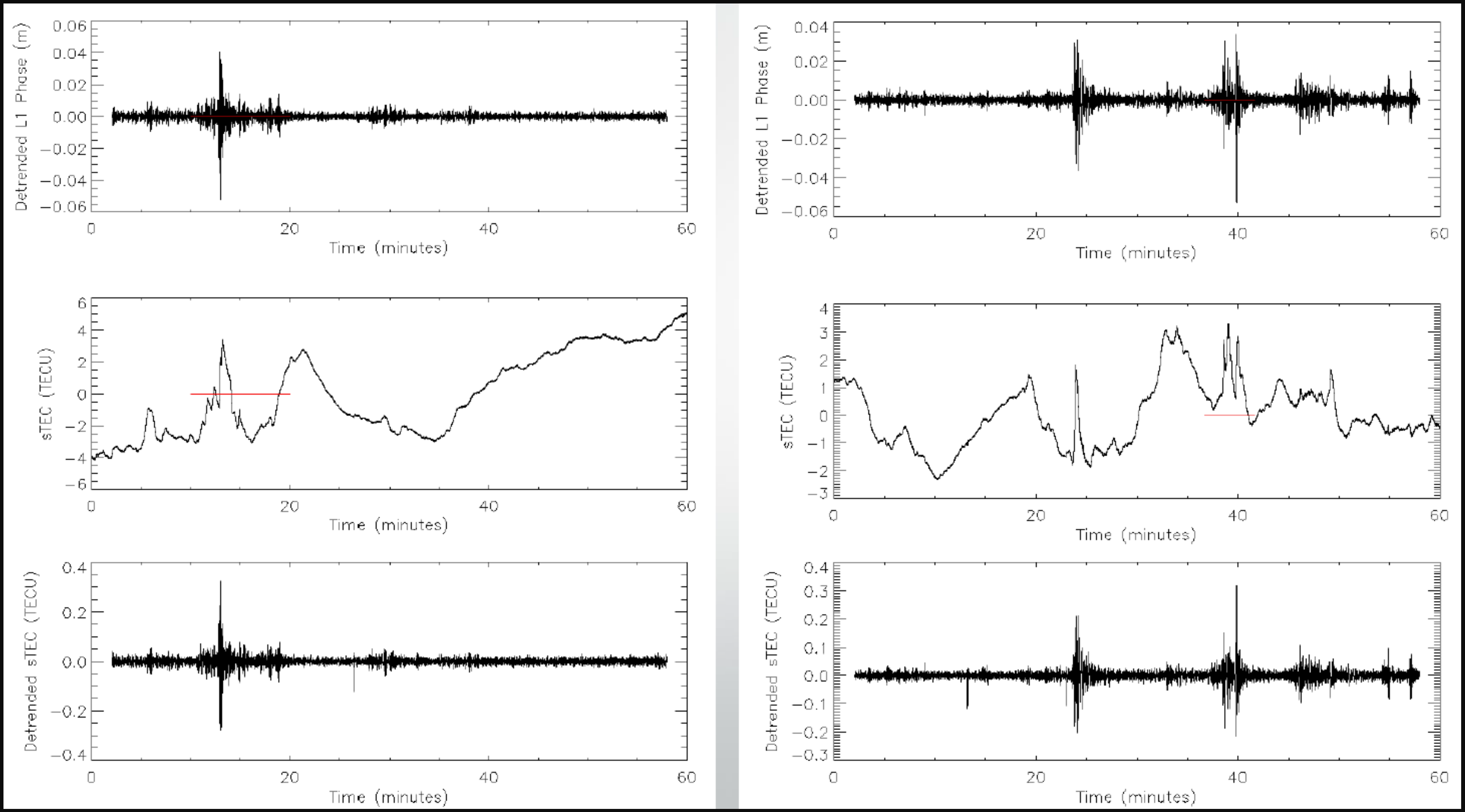
Three frequencies



Three frequencies

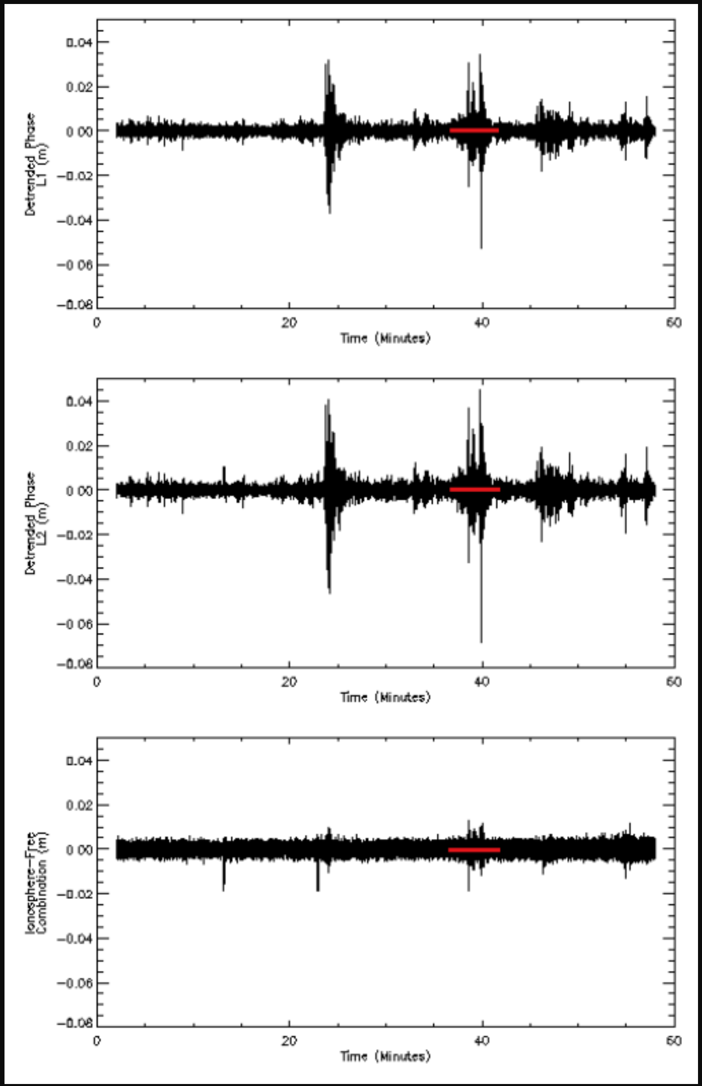


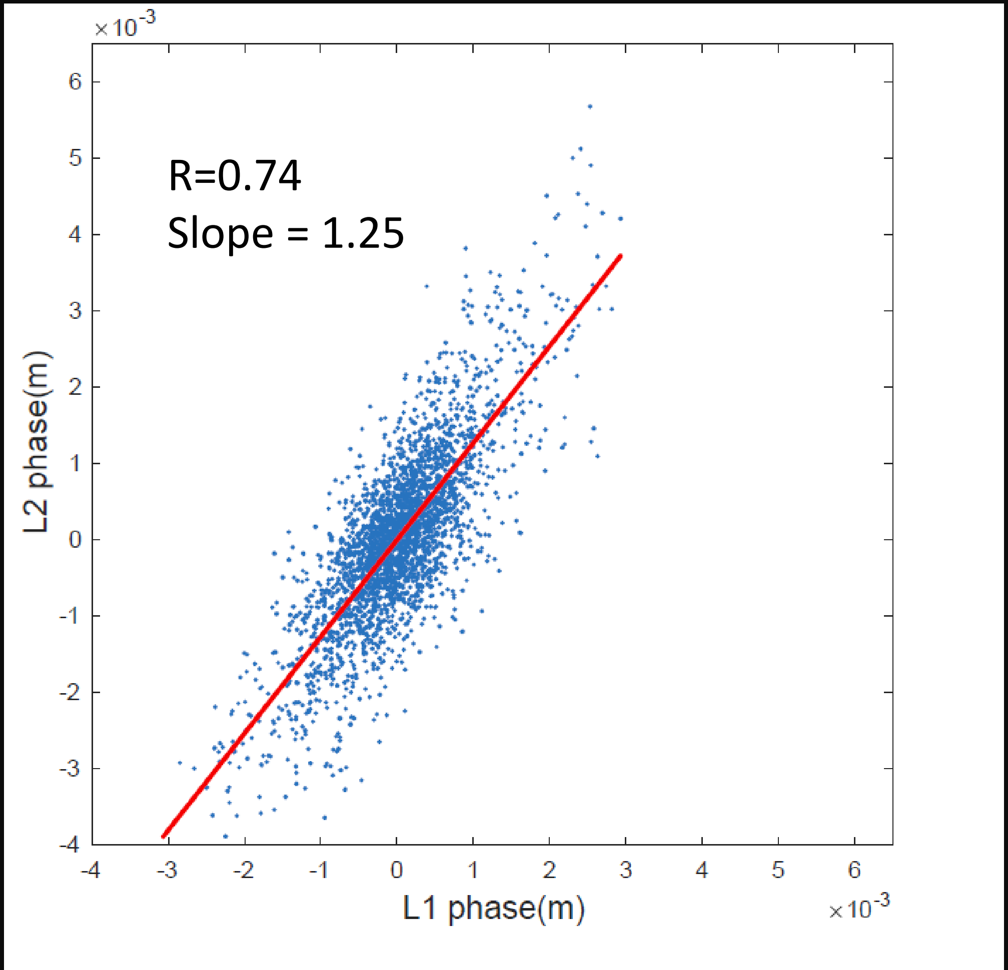
TEC and phase variations



McCaffrey and Jayachandran, 2018

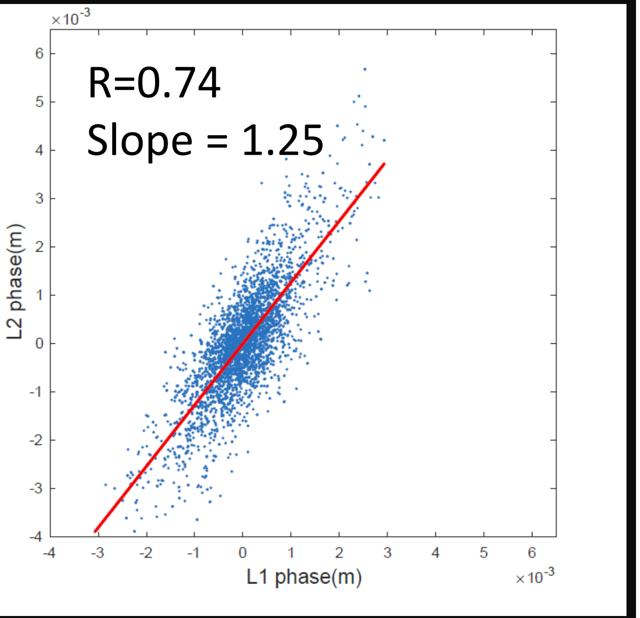
Under real scintillation

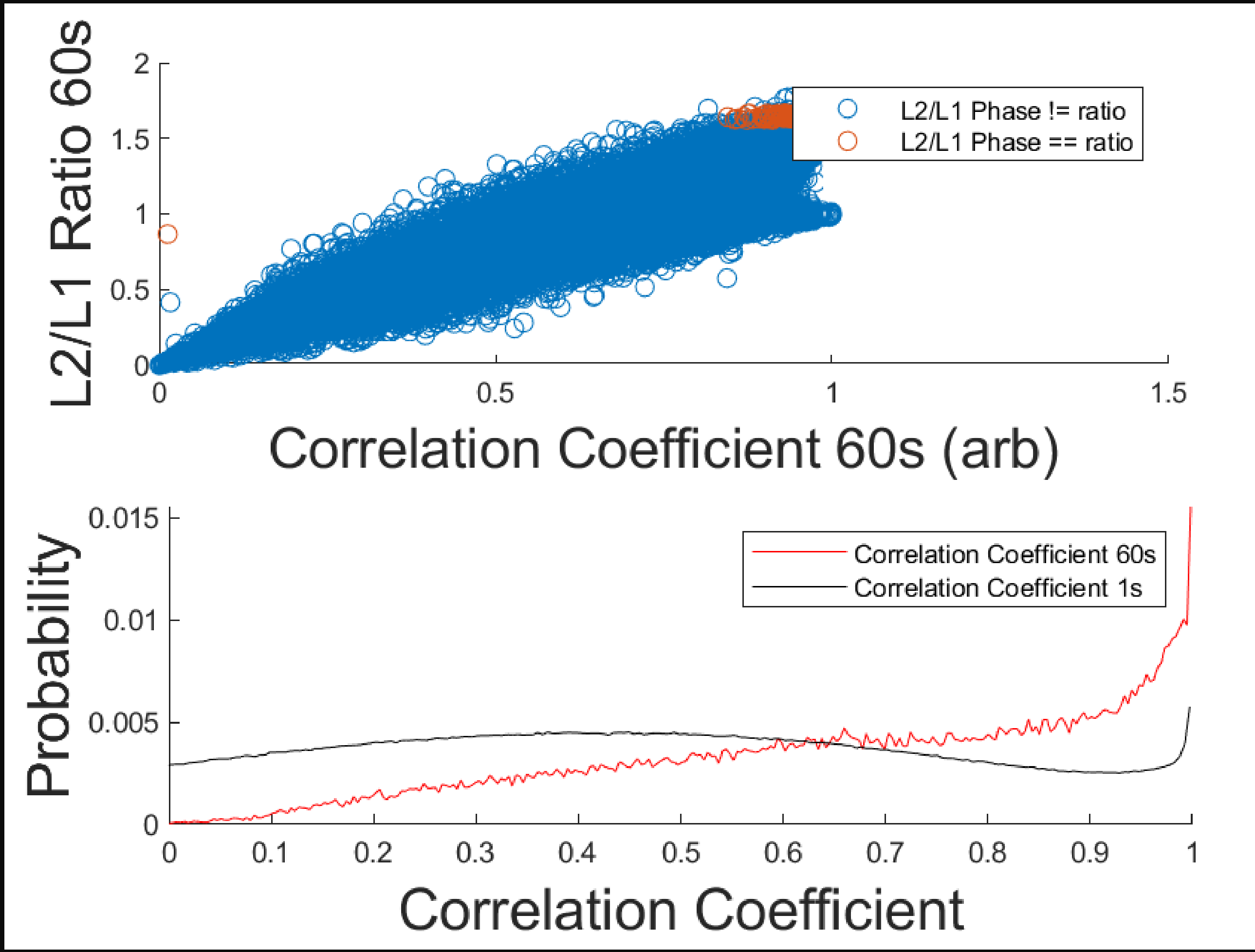




TEC estimate under scintillation is not accurate because $1/f^2$ dependence is violated

Under scintillation

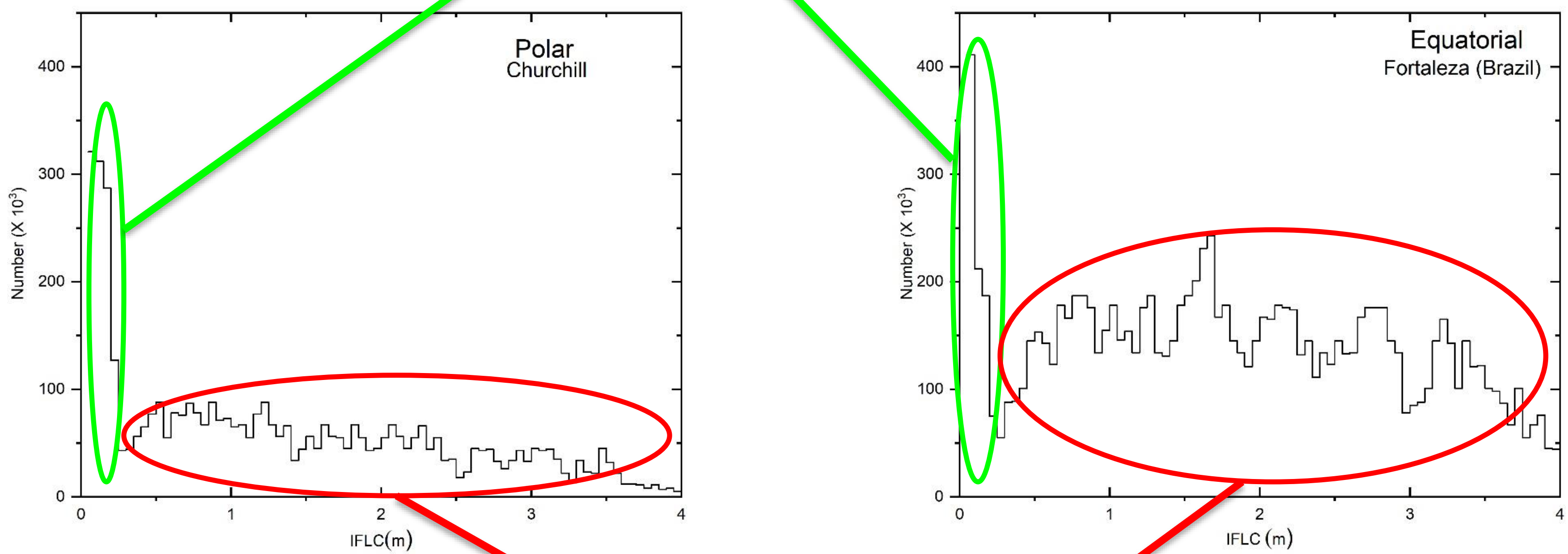




TEC estimate under scintillation is not accurate because $1/f^2$ dependence is violated

In a nutshell

Good/accurate within the limit



Bad/significant error in TEC estimate or not TEC at all

Conclusions

- Scintillation is a major issue in estimating accurate TEC based on GNSS observables
- Under "actual scintillation", this $1/f^2$ dependence is violated. Ergo the TEC estimated will not be accurate and will be nonphysical
- Any Space weather indices (e.g. ROTI) is derived using the estimated TEC will not represent the actual situation
- We need to develop a method to flag or provide an error estimate for the TEC derived using GNSS observables
- This can be based on the correlation value of phase at multiple frequencies.