the VOLPE center

Calibration of Ionospheric Observations from GNSS Reference Networks

U.S. Department of Transportation
Research and Innovative Technology Administration

Ionospheric Observation Reference Network Noise and Bias Calibration Techniques

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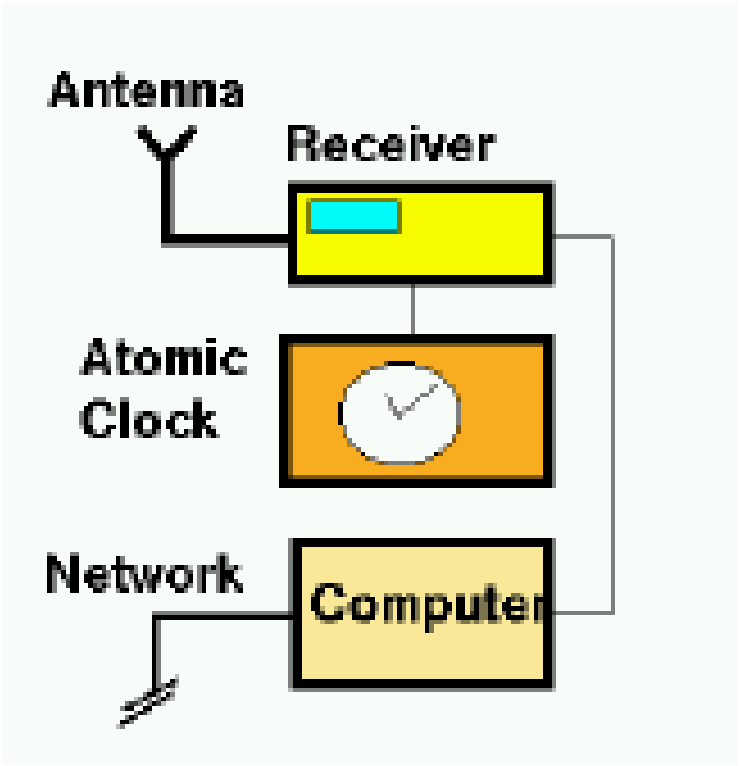
Overview

- Observation Equation
- Inter-frequency Bias Calibration
- Noise Calibration
- Reference Network Configuration
- Example Data Set from GPMS
- Summary and Recommendations

Reference Station Configuration



Receiver Measurement Equations

Code

$$\begin{aligned} \tilde{\mathrm{TEC}} &= \frac{pr_{\mathrm{L}_2} - pr_{\mathrm{L}_1}}{\gamma - 1} \\ &= \mathrm{TEC} + \frac{\gamma}{\gamma - 1}(IFB + \tau_{gd}) + \frac{1}{\gamma - 1}(M_{\mathrm{L}_2} - M_{\mathrm{L}_1} + \xi_{\mathrm{L}_2} - \xi_{\mathrm{L}_1}) \end{aligned}$$

Carrier

$$\begin{aligned} \tilde{\mathrm{TEC}}_{\phi} &= -\frac{\phi_{\mathrm{L}_2} - \phi_{\mathrm{L}_1}}{\gamma - 1} \\ &= \mathrm{TEC} + \frac{\gamma}{\gamma - 1}(IFB + \tau_{gd}) - \frac{1}{\gamma - 1}(N_2\lambda_{\mathrm{L}_2} - N_1\lambda_{\mathrm{L}_1}) \end{aligned}$$

Noise Calibration Equations

Carrier a posteriori

$$\widehat{\mathrm{TEC}} = \tilde{\mathrm{TEC}}_\phi - \frac{\sum_{m=0}^{M} \frac{\mathrm{TEC}_\phi - \tilde{\mathrm{TEC}}_m}{\sigma_m^2}}{\sum_{m=0}^{M} \sigma_m^{-2}}$$

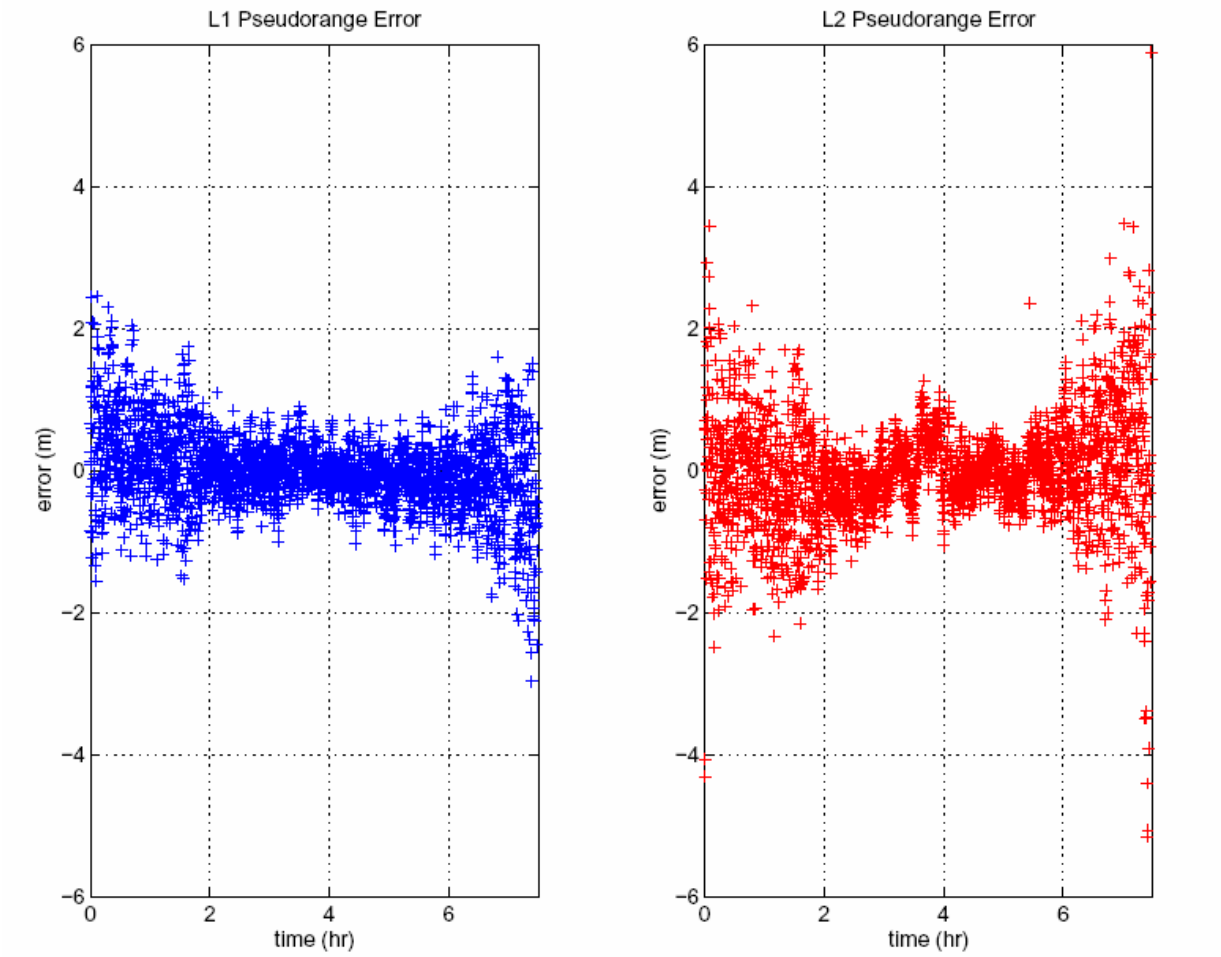
Carrier Phase Residual

$$\begin{aligned} e_i &= pr_{\mathsf{L}_i} - \phi_{\mathsf{L}_i} - 2\widehat{\mathrm{TEC}} \\ &= M_{\mathsf{L}_i} + \xi_{\mathsf{L}_i} - N_i \lambda_{\mathsf{L}_i} \end{aligned}$$

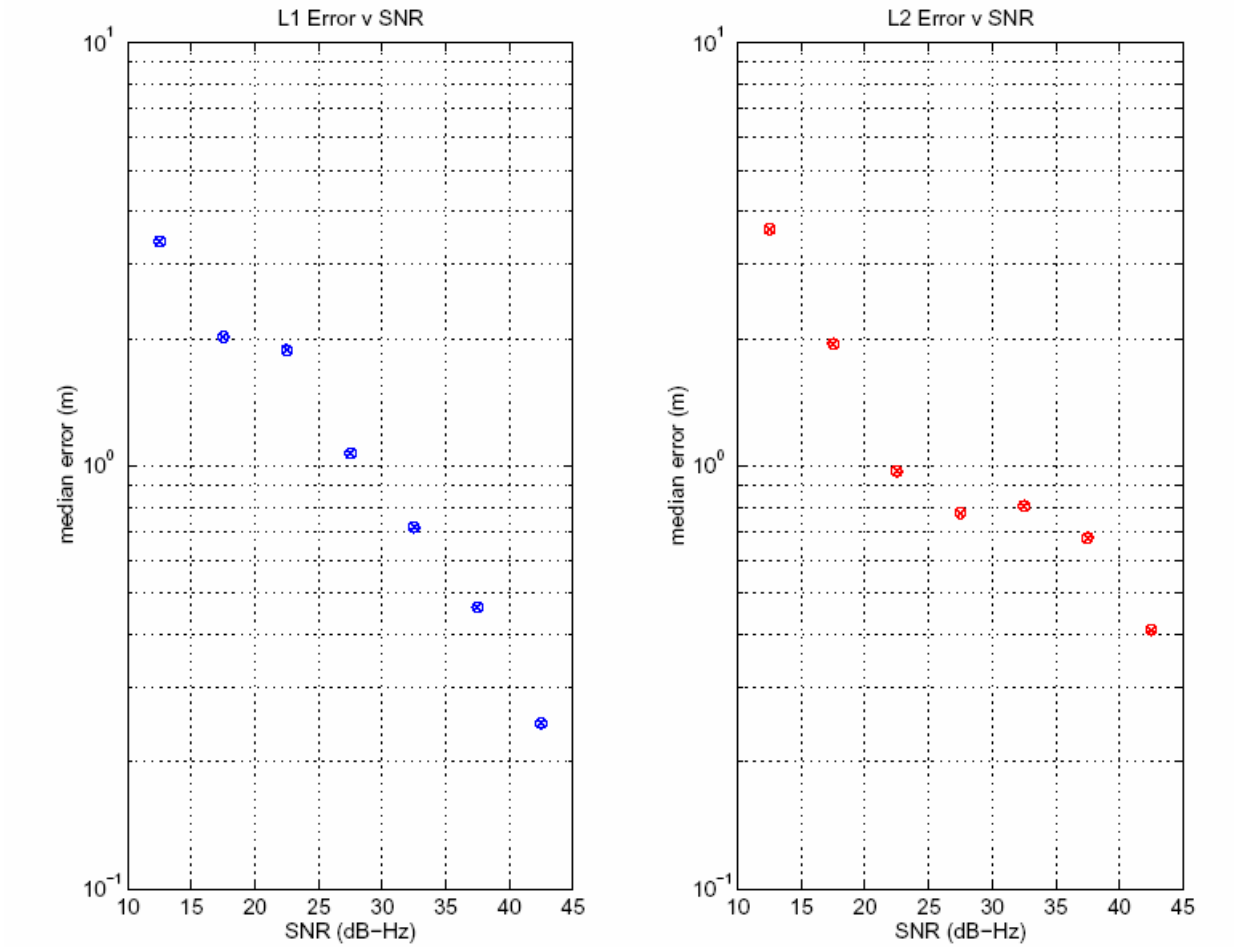
Carrier Phase Residual Bias

$$\hat{e}_i = e_i - \frac{\sum_{m}^{M} \frac{e_i - e_m}{\sigma_m^2}}{\sum_{m}^{M} \sigma_m^{-2}}$$

Residual Error in Carrier Ionosphere



Residual Error as Function of C/No



Identify Receiver Noise Performance

Instantaneous Residual Error as a Function of SNR (C/No)

$$\sigma_e = A\exp(-SNR/\tau) + C$$

Error Function Characterization of Receiver

$$A\begin{bmatrix}\exp(-SNR_0/\tau_t)\\ \vdots \\ \exp(-SNR_M/\tau_t)\end{bmatrix} = \begin{bmatrix}\hat{e}_{i0}\\ \vdots \\ \hat{e}_{iM}\end{bmatrix} - C_t$$

	L_1		L_2	
Receiver	τ (dB-Hz)	C (m)	τ (dB-Hz)	C (m)
Type A	-0.1179	0.0025	-0.1121	0.0027
Type B	-0.1132	0.0041	-0.0934	0.0035
Type C	-0.1049	0.0028	-0.1021	0.0030

Interfrequency Bias Calibration Equations

Software Calibration Requires an Ionospheric Model (A) to Separate Ionosphere from IFB & Tgd

$$\mathbf{A}\,x = \tilde{\mathrm{TEC}}$$

Measurement Epoch

$$\mathbf{A} = \begin{bmatrix} A_{00} & \cdots & A_{0N} & \left| \right. & \frac{\gamma}{\gamma-1} & 0 & 0 & \cdots & \frac{\gamma}{\gamma-1} & 0 & \cdots & 0 \\ A_{10} & \cdots & A_{1N} & \left| \right. & \frac{\gamma}{\gamma-1} & 0 & 0 & \cdots & 0 & \frac{\gamma}{\gamma-1} & \cdots & 0 \\ \vdots & & & & & & & & & & & \\ A_{M0} & \cdots & A_{MN} & \left| \right. & 0 & 0 & \frac{\gamma}{\gamma-1} & \cdots & 0 & 0 & \cdots & \frac{\gamma}{\gamma-1} \end{bmatrix}$$

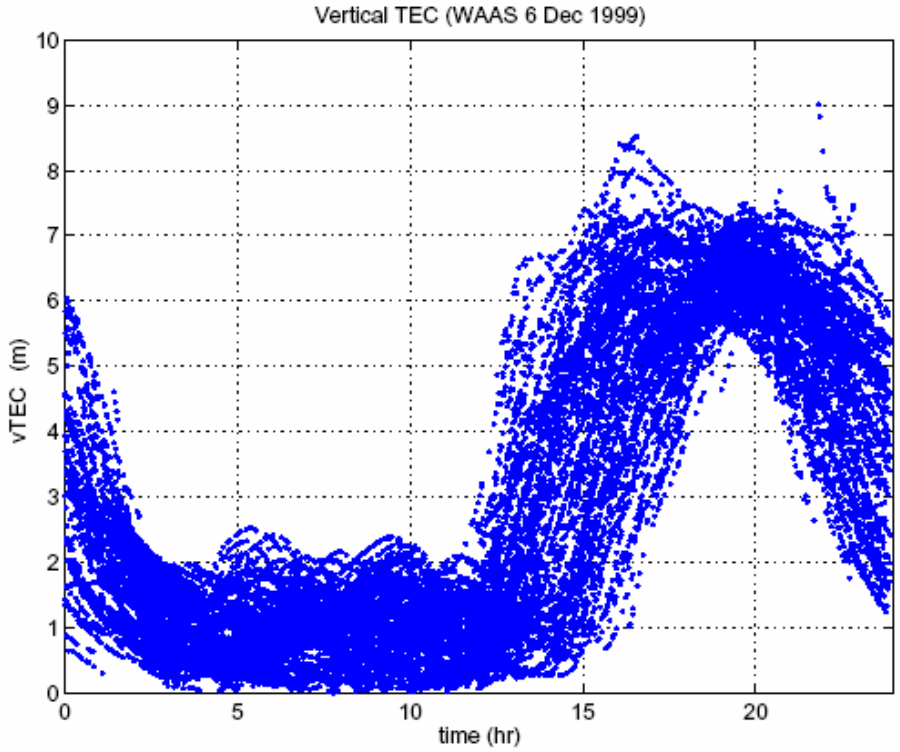
$$\tilde{x} = \left[Ne_0 \cdots Ne_N \mid IFB_0 \cdots IFB_R \mid \tau_{gd}^0 \cdots \tau_{gd}^S \right]^T$$

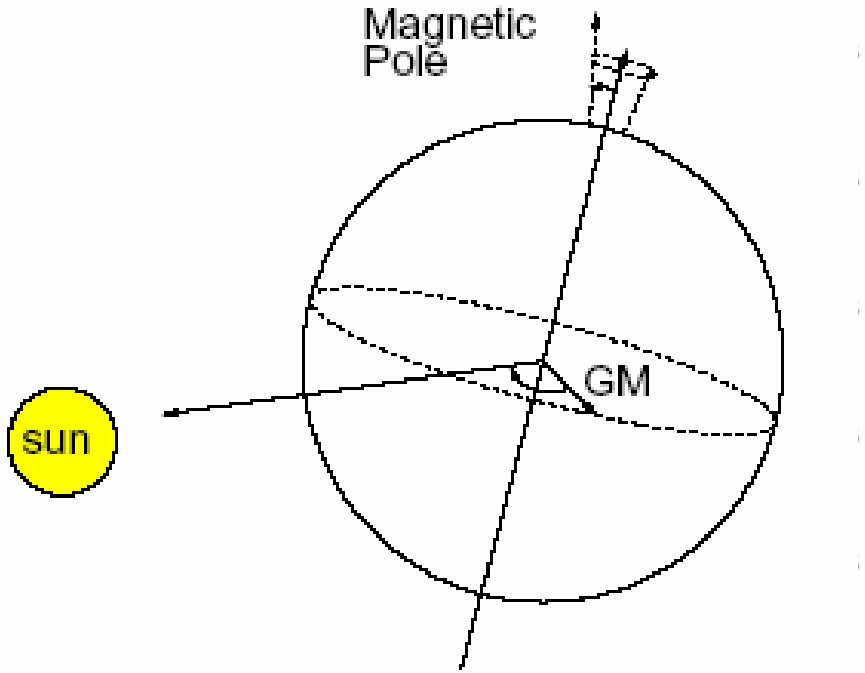
Stack Epochs (multi-day)

$$\hat{\mathbf{A}} = \left[\mathbf{A}_0\ \mathbf{A}_1 \cdots \mathbf{A}_T \right]^T$$

$$\bar{\mathrm{TEC}} = \left[\widehat{\mathrm{TEC}}_0\ \widehat{\mathrm{TEC}}_1 \cdots \widehat{\mathrm{TEC}}_T \right]^T$$

Transform Measurements to Solar-Magnetic Coordinates





Solution of Bias Calibration Equation

Batch Solution

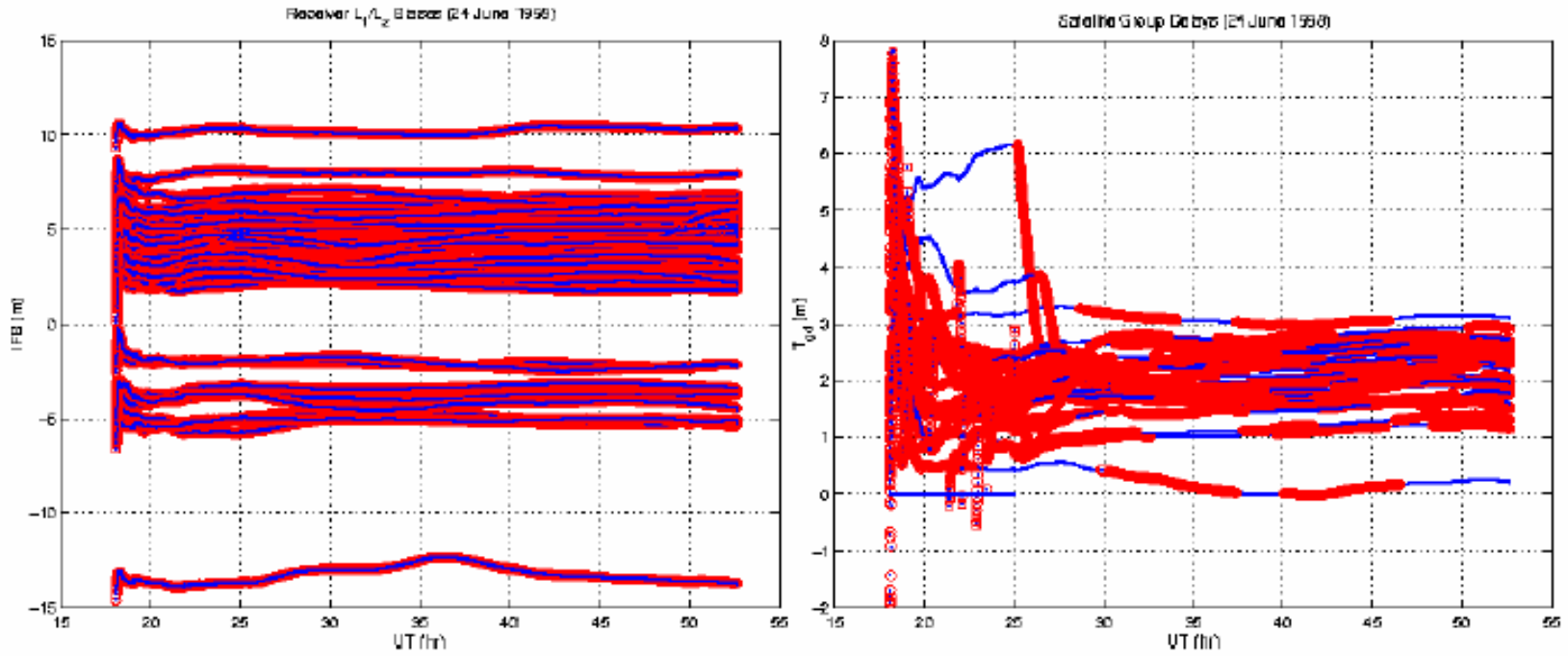
$$\bar{x} = \tilde{\mathbf{A}}^{+}\mathrm{T}\bar{\mathrm{E}}\mathrm{C}$$

$$\Sigma_{\bar{x}} = \tilde{\mathbf{A}}^{+}\Sigma_{\mathrm{TEC}}\tilde{\mathbf{A}}^{+T}$$

Sequential Solution

$$x_{i+1} = \mathbf{F}_i x_i + \eta_i, \quad x_0 = \bar{x},$$

$$\mathrm{TEC}_i = \mathbf{A}_i x_i + \xi_i$$



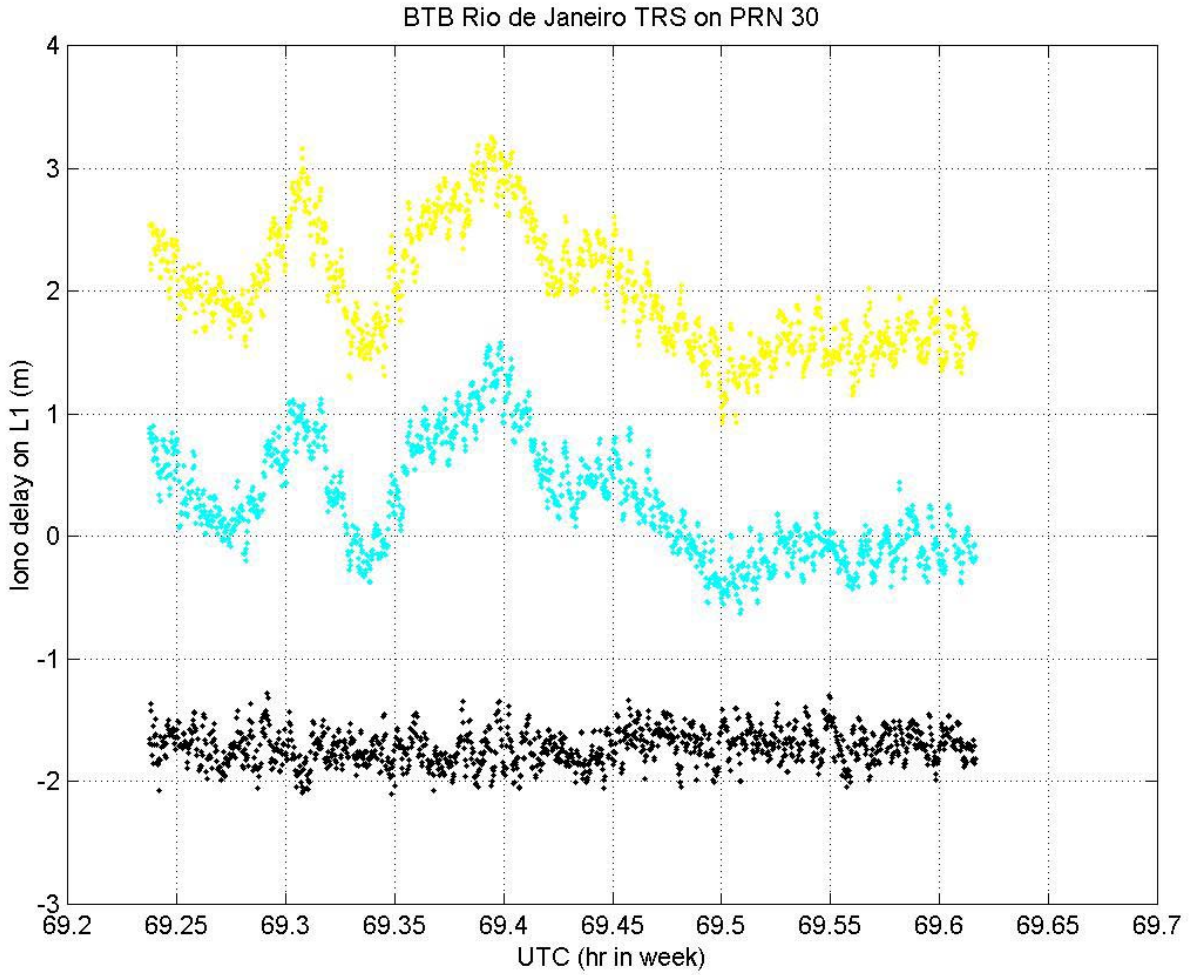
Example Data Collection & Tools

- *Central Data Repositories*
  - *FAA Technical Center—GBAS and NSTB services*
  - *DECEA GPMS Server—SQL services*
  - *Flight tests of secondary technical importance*
- *Pre-processing of observations*
  - *Reference Receiver and Satellite L1-L2 calibration*
  - *Correlate observations with geomagnetic & seasonal conditions*
  - *Filters for noise/anomalies from ionospheric conditions*
- *Construction of verification and validation data sets*
  - *Threat model truth sources needed to establish a standard*
  - *Stakeholder acceptance heavily influenced by quality of data sets and their coverage of stressful operating conditions*
  - *Transparency and documentation of the data will be key*

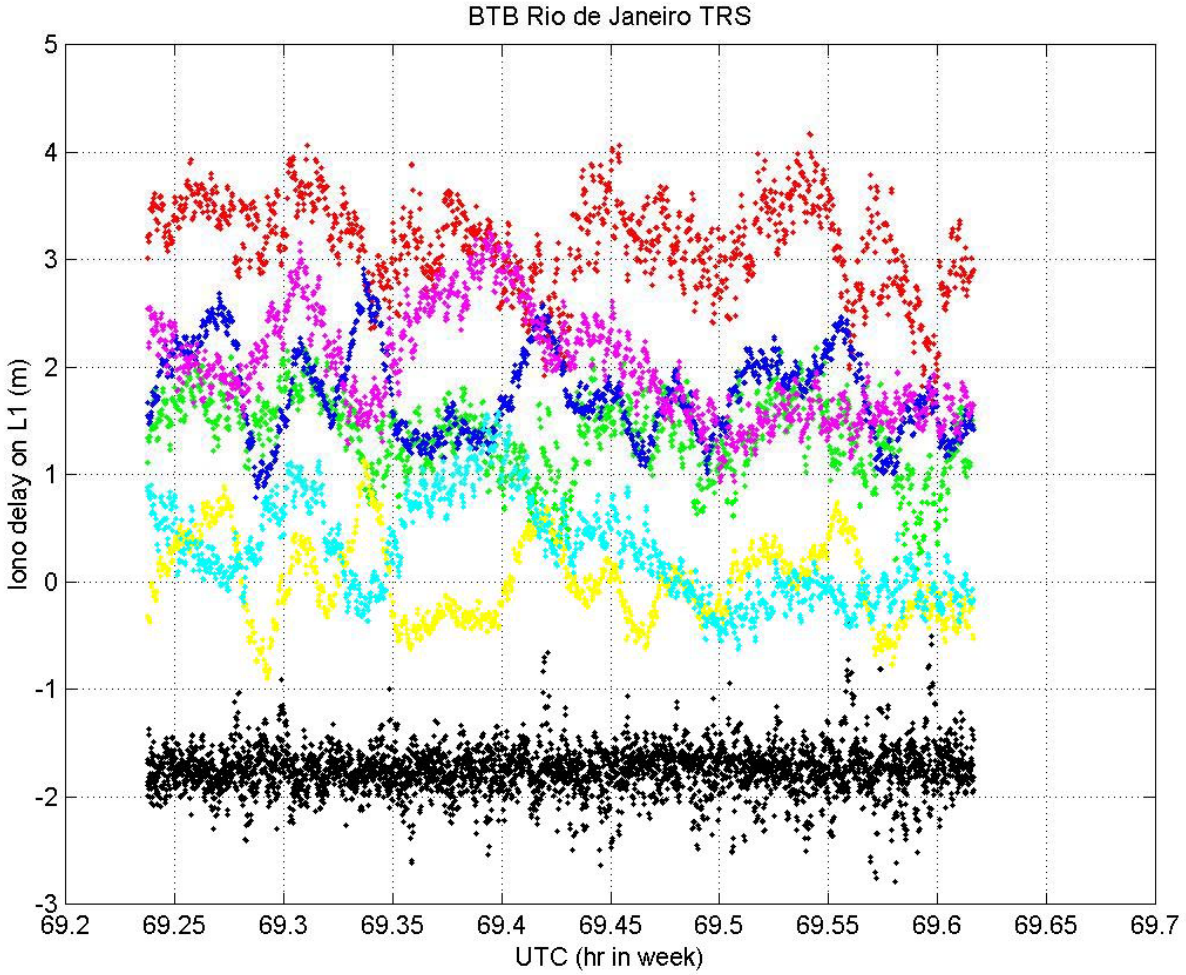
Initial Observation Data Survey

- *Combination of script and Matlab software*
- *Measurements retrieved from FAA-TC BTB archives*
- *Carrier phase ionospheric estimates*
  - *Semi-automated cycle ambiguity (bias) resolution*
  - *Bias break detection/patch (rely on Doppler & C/No)*
  - *Split ionospheric phase (wide-lane) tracks*
  - *No correction yet for reference receiver Inter-frequency bias (IFB) or satellite group delay (Tgd)*

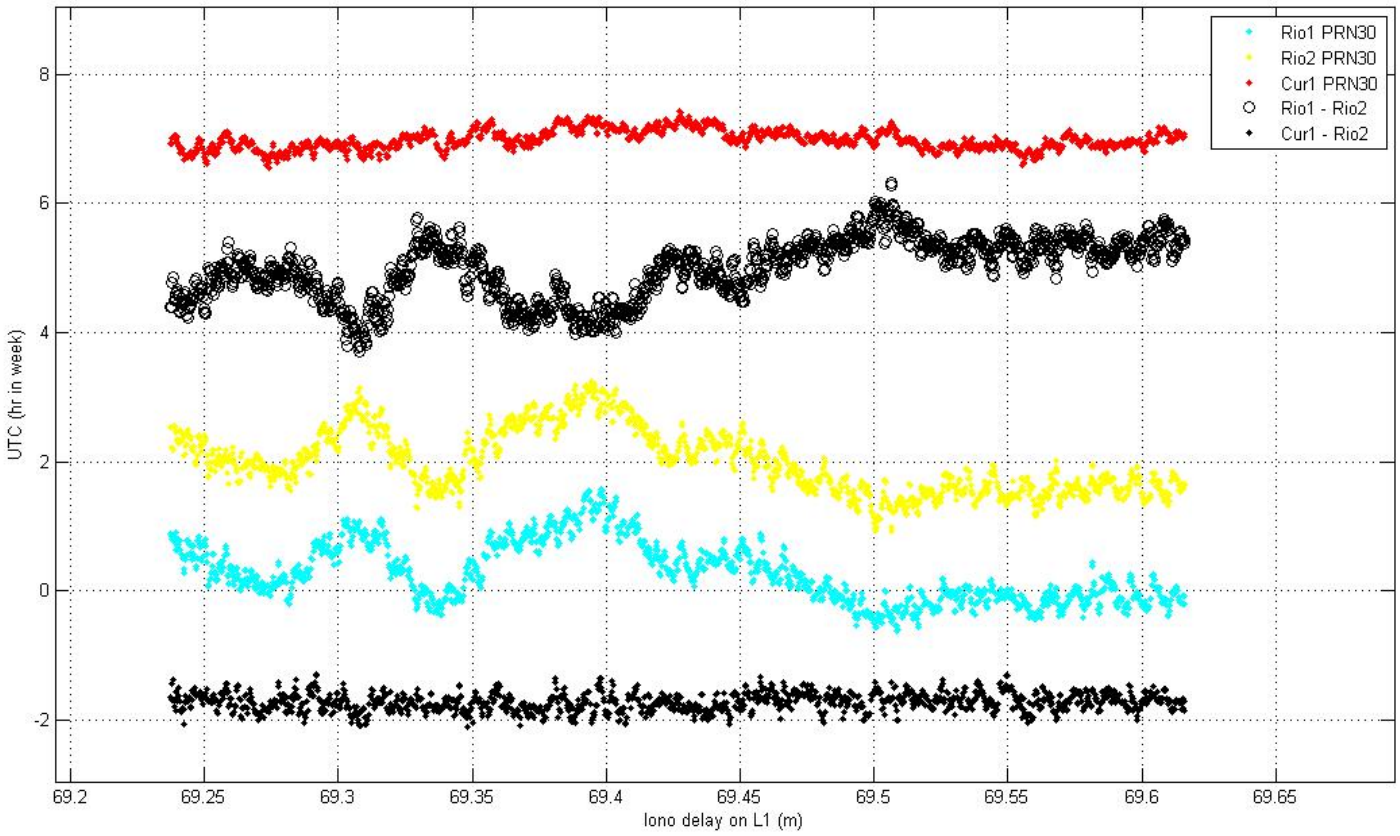
Progression of Bias Calibration Concept



Progression of Bias Calibration Concept



Progression of Bias Calibration Concept



Summary and Recommendations

- *Calibration of Residual Error as Function is Noise is Recommended*
  - *Improves carrier cycle slip correction*
  - *Improves confidence in ionospheric measurement*
- *Calibration of Interfrequency Bias is Necessary in Development and Operation*
  - *Use of hardware for IFB calibration is expensive and time consuming*
  - *Hardware calibration of Tgd is not possible*
  - *Software calibration requires ionospheric model to separate ionosphere from biases*