Estimating the Precision of TSI Measured from VIRGO, SORCE, TCTE, and TSIS-1

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Acknowledgements

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  - Total Solar Irradiance (TSI) Instruments and algorithms

- Goddard Earth Sciences Data and Information Services Center (**GES DISC**)
  - TSIS-1, SORCE, and TCTE L3 6-hr TSI

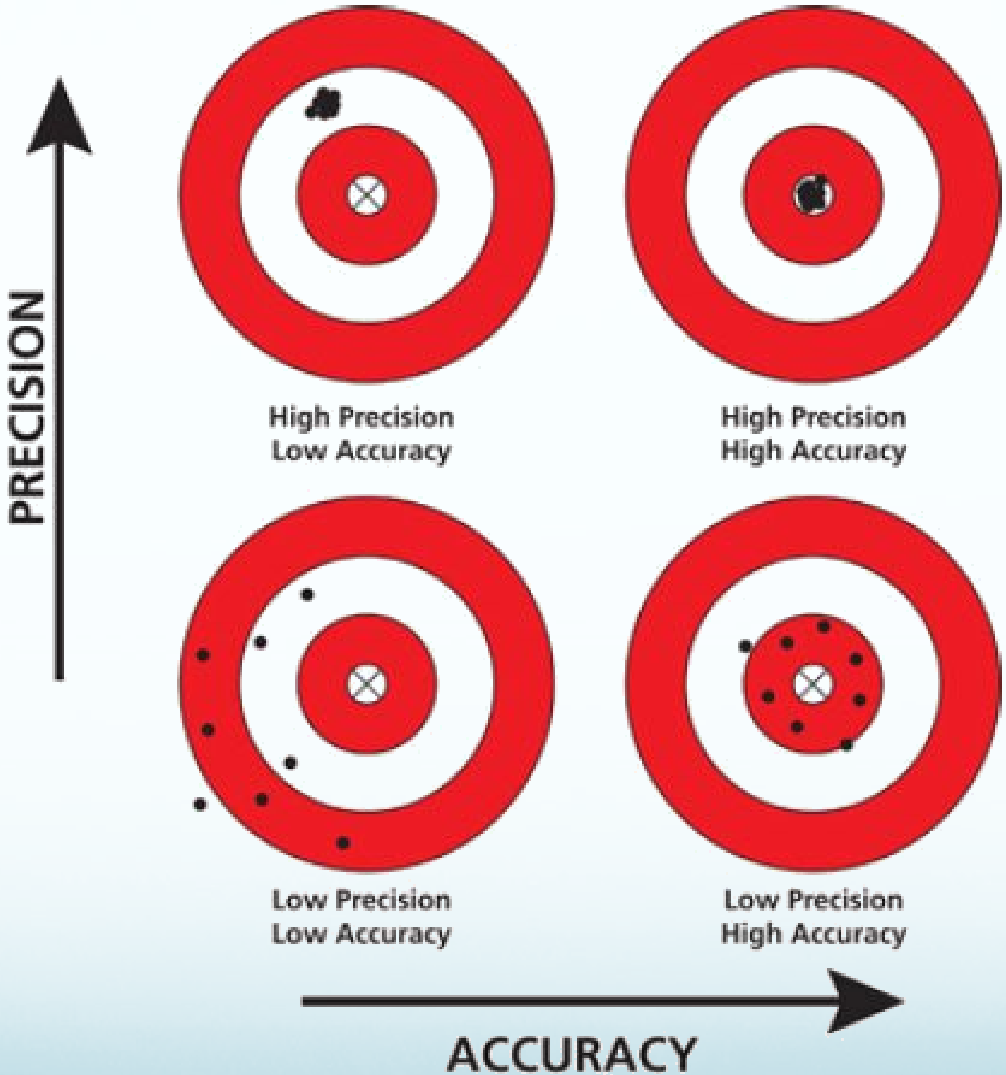
- Cooperative ESA/NASA Mission SoHO from VIRGO Team through PMOD/WRC, Davos, Switzerland
  - Version 6.5 VIRGO 1-hr TSI
    - Gridded to TSIS-1, SORCE, and TCTE 6-hr intervals.

- This work replicates a small portion of the research published by **Frank Grubbs (1948)**

Motivation: Why Precision?

- Some may use as a proxy for stability or accuracy
  - Not necessarily correct
- Useful for identifying sensitivity to specific events (e.g. Mercury Transit)
- Useful for identifying timescales of solar variability (assuming that one can pull out the precision)
- We can use the precision to more appropriately piece together a continuous TSI composite.

Precision vs Accuracy



Courtesy of https://blog.forecast.it/the-difference-between-accuracy-and-precision

Triple Differencing: Concept

$$X_C(t) = \bar{X} + \acute{X}(t) - \overline{\varepsilon_X} - \acute{\varepsilon}_X(t)$$

$$\langle \acute{X}(t) \rangle \equiv 0$$

$$\langle \acute{\varepsilon}_X(t) \rangle \equiv 0$$

$\langle\ \ \rangle$ Denotes Time-Averaging

- X_C, represents the true value of TSI at time t from instrument X (TSIS-1, VIRGO, TCTE, SORCE)
- $\bar{X} + \acute{X}(t)$ represent the mean + time-varying observed TSI for X
- $\overline{\varepsilon_X}$ represents the mean error in observed TSI for X
  - Absolute calibration error (e.g. 400 PPM error in TSI)
  - Stability related errors (e.g. 10 PPM yr^{-1}) if large averaging time
- $\acute{\varepsilon}_X(t)$ represents the time-varying error in observed TSI for X
  - Temporal gridding/averaging error (hopefully small)
    - This will include a solar variability component
  - Instrument noise

Triple Differencing: Concept

$$X_C(t) = \bar{X} + \acute{X}(t) - \overline{\varepsilon_X} - \acute{\varepsilon}_X(t)$$
$$Y_C(t) = \bar{Y} + \acute{Y}(t) - \overline{\varepsilon_Y} - \acute{\varepsilon}_Y(t)$$
$$Z_C(t) = \bar{Z} + \acute{Z}(t) - \overline{\varepsilon_Z} - \acute{\varepsilon}_Z(t)$$

$\langle\ \rangle$ Denotes Time-Averaging

$$\boldsymbol{X_C(t) \equiv Y_C(t) \equiv Z_C\ (t)}$$
$$\left\langle \acute{X}(t) \right\rangle \equiv \left\langle \acute{Y}(t) \right\rangle \equiv \left\langle \acute{Z}(t) \right\rangle \equiv 0$$
$$\langle \acute{\varepsilon}_X(t) \rangle \equiv \langle \acute{\varepsilon}_Y(t) \rangle \equiv \langle \acute{\varepsilon}_Z(t) \rangle \equiv 0$$

- $\boldsymbol{X_C}$, $\boldsymbol{Y_C}$, and $\boldsymbol{Z_C}$ represent the true value of TSI at time t for instruments X, Y, and Z

Triple Differencing: Concept

$$X_C(t) - Y_C(t) = 0$$

$$\boldsymbol{D_{XY}} = \bar{X} + \acute{X} - \bar{Y} - \acute{Y} = \overline{\varepsilon_X} + \acute{\varepsilon}_X - \overline{\varepsilon_Y} - \acute{\varepsilon}_Y$$

$$\langle\overline{\boldsymbol{D_{XY}}}\rangle = \left\langle \bar{X} + \acute{X} - \bar{Y} - \acute{Y} \right\rangle = \langle \overline{\varepsilon_X} + \acute{\varepsilon}_X - \overline{\varepsilon_Y} - \acute{\varepsilon}_Y \rangle$$

$$\overline{\boldsymbol{D_{XY}}} = \bar{X} - \bar{Y} = \overline{\varepsilon_X} - \overline{\varepsilon_Y}$$

⟨ ⟩ Denotes Time-Averaging

$$\acute{D}_{XY} = D_{XY} - \overline{D_{XY}} = \acute{\varepsilon}_X - \acute{\varepsilon}_Y$$

$$\acute{D}_{XY}{}^2 = \acute{\varepsilon}_X{}^2 + \acute{\varepsilon}_Y{}^2 - 2\acute{\varepsilon}_X\acute{\varepsilon}_Y$$

$$\left\langle \acute{D}_{XY}{}^2 \right\rangle = \left\langle \acute{\varepsilon}_X{}^2 \right\rangle + \left\langle \acute{\varepsilon}_Y{}^2 \right\rangle - \cancelto{0}{2\langle \acute{\varepsilon}_X\acute{\varepsilon}_Y \rangle}$$

Assume that the time-varying errors are not correlated!

Triple Differencing: Concept

$\langle \ \rangle$ Denotes Time-Averaging

$$\left\langle \acute{D}_{XY}{}^{2} \right\rangle = \left\langle \acute{\varepsilon}_X{}^{2} \right\rangle + \left\langle \acute{\varepsilon}_Y{}^{2} \right\rangle - \underbrace{2\left\langle \acute{\varepsilon}_X \acute{\varepsilon}_Y \right\rangle}_{0}$$

$$\sigma_{X-Y}^2 = \sigma_{\varepsilon_X}^2 + \sigma_{\varepsilon_Y}^2$$
$$\sigma_{X-Z}^2 = \sigma_{\varepsilon_X}^2 + \sigma_{\varepsilon_Z}^2$$
$$\sigma_{Y-Z}^2 = \sigma_{\varepsilon_Y}^2 + \sigma_{\varepsilon_Z}^2$$

Solving via substitution yields:

$$\sigma_{\varepsilon_X} = \sqrt{\frac{\sigma_{X-Y}^2 + \sigma_{X-Z}^2 - \sigma_{Y-Z}^2}{2}}$$

$$\sigma_{\varepsilon_Y} = \sqrt{\frac{\sigma_{X-Y}^2 - \sigma_{X-Z}^2 + \sigma_{Y-Z}^2}{2}}$$

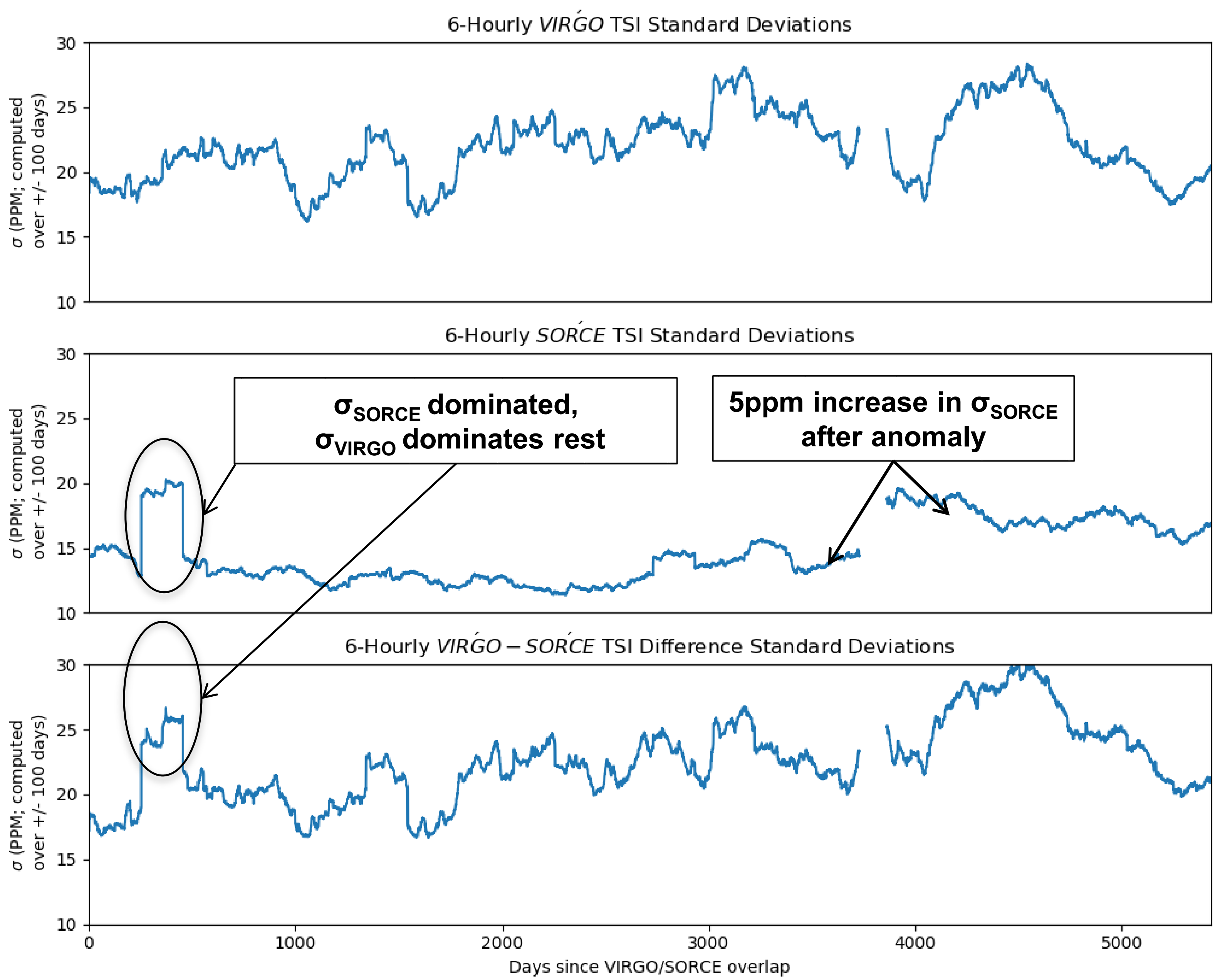
$$\sigma_{\varepsilon_Z} = \sqrt{\frac{-\sigma_{X-Y}^2 + \sigma_{X-Z}^2 + \sigma_{Y-Z}^2}{2}}$$

Triple Differencing: Caveats

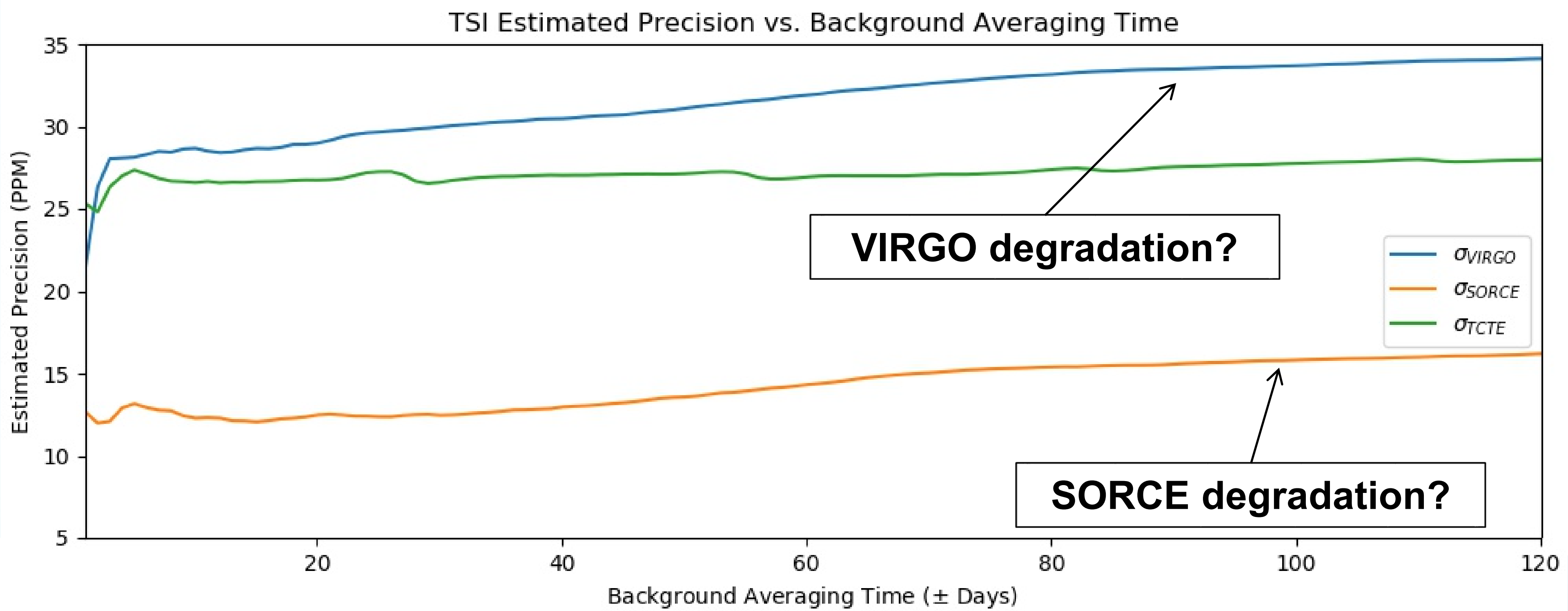
$$\acute{D}_{XY} = D_{XY} - \overline{D_{XY}} = \acute{\varepsilon}_X - \acute{\varepsilon}_Y$$

- Time-averaging of background means $\bar{X}$, $\bar{Y}$, and $\bar{Z}$
  - ∝ precision time-scale
- Time-averaging of $\acute{D}_{XY}{}^2$, $\acute{D}_{XZ}{}^2$, $\acute{D}_{YZ}{}^2$
  - Should be large enough to ensure that error covariances (e.g. $2\langle \acute{\varepsilon}_X \acute{\varepsilon}_Y \rangle$) are small relative to the smallest error variance.
  - Ideally, should be large enough to ensure that error distributions are adequately sampled.
  - Should be small enough to avoid washing out interesting error patterns.

VIRGO and SORCE TSI Perturbations

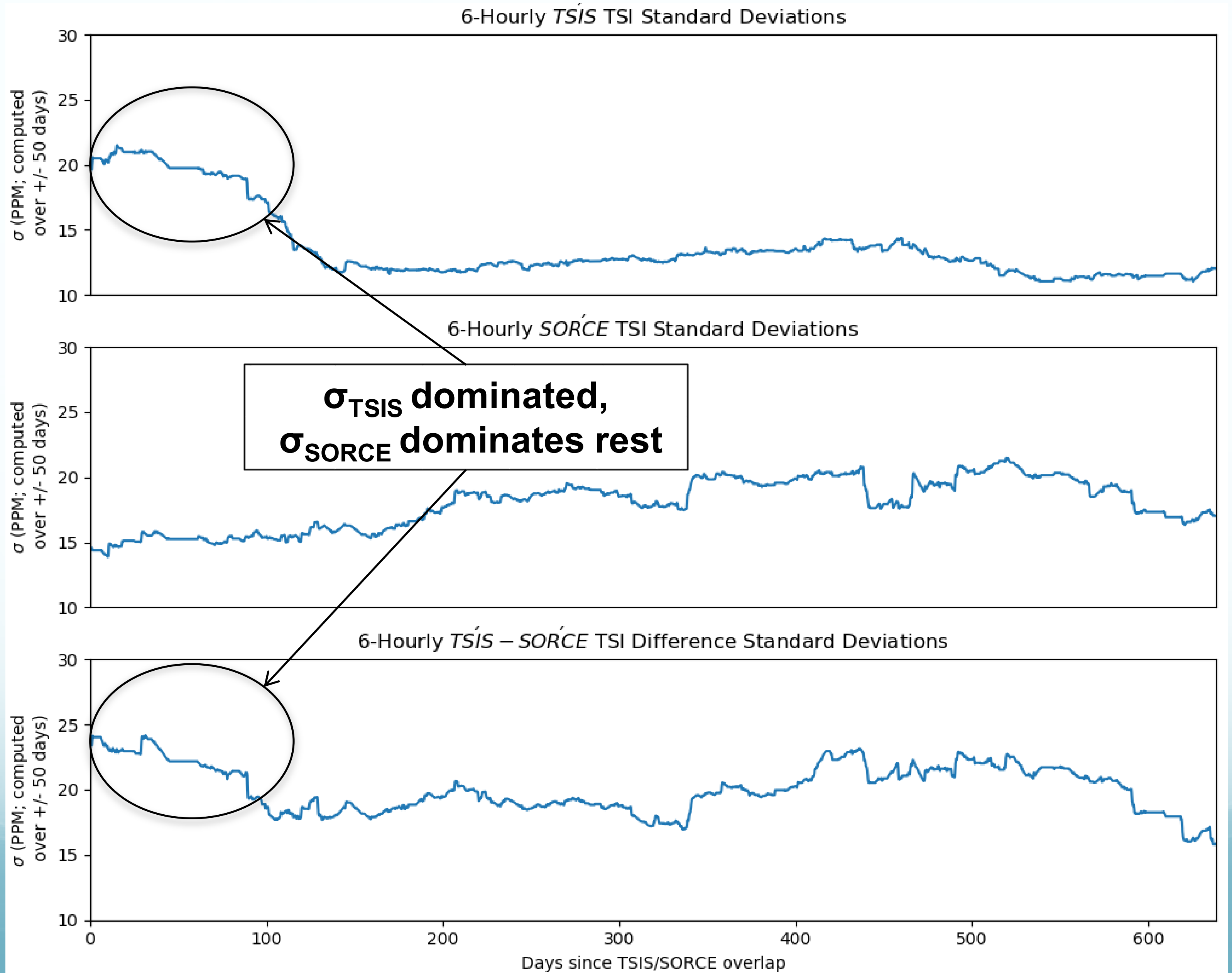


VIRGO, SORCE and TCTE Precisions

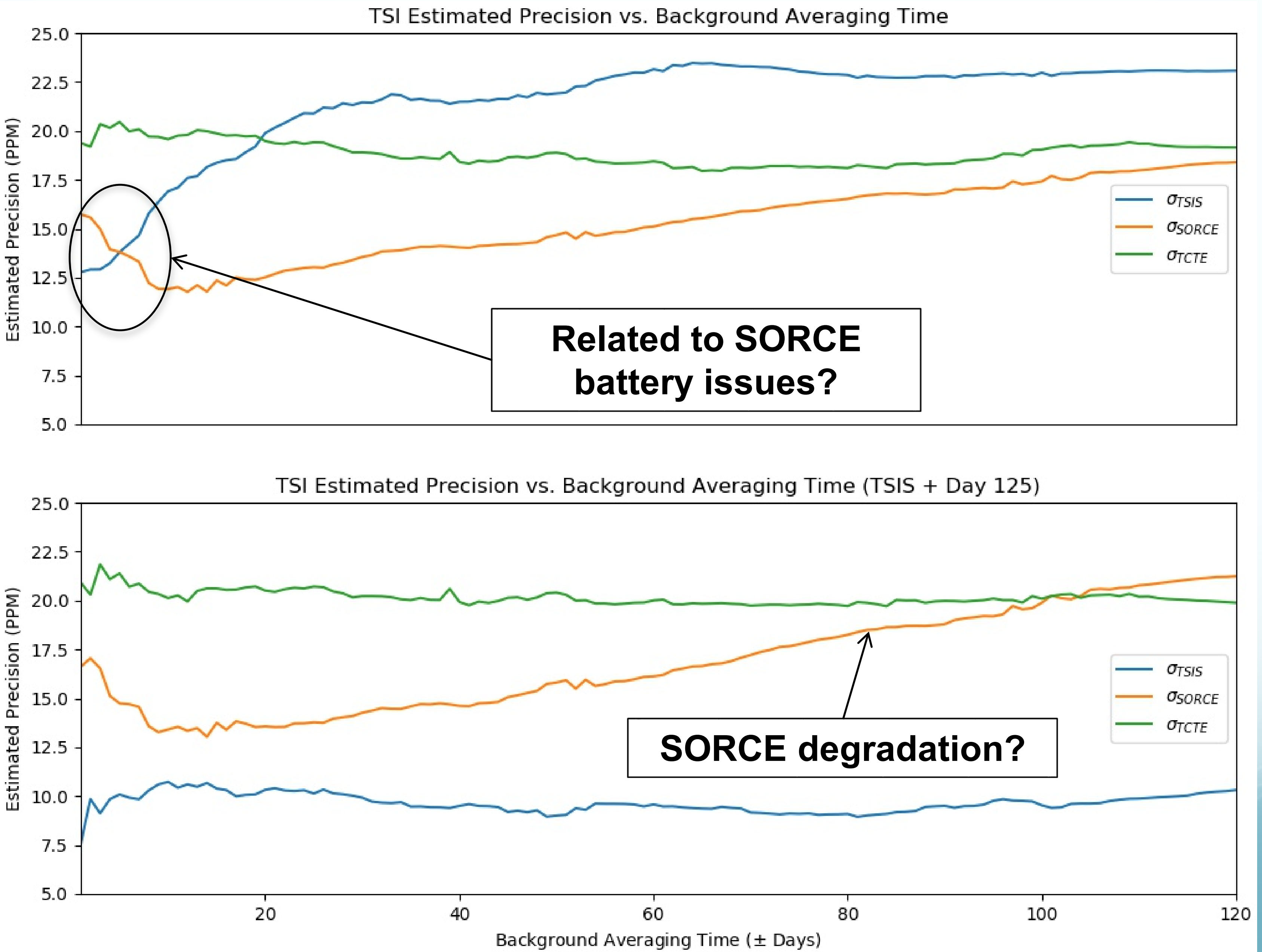


Not a time-series, these data represent precision (+ solar variability) at different time-scales

TSIS-1 and SORCE TSI Perturbations



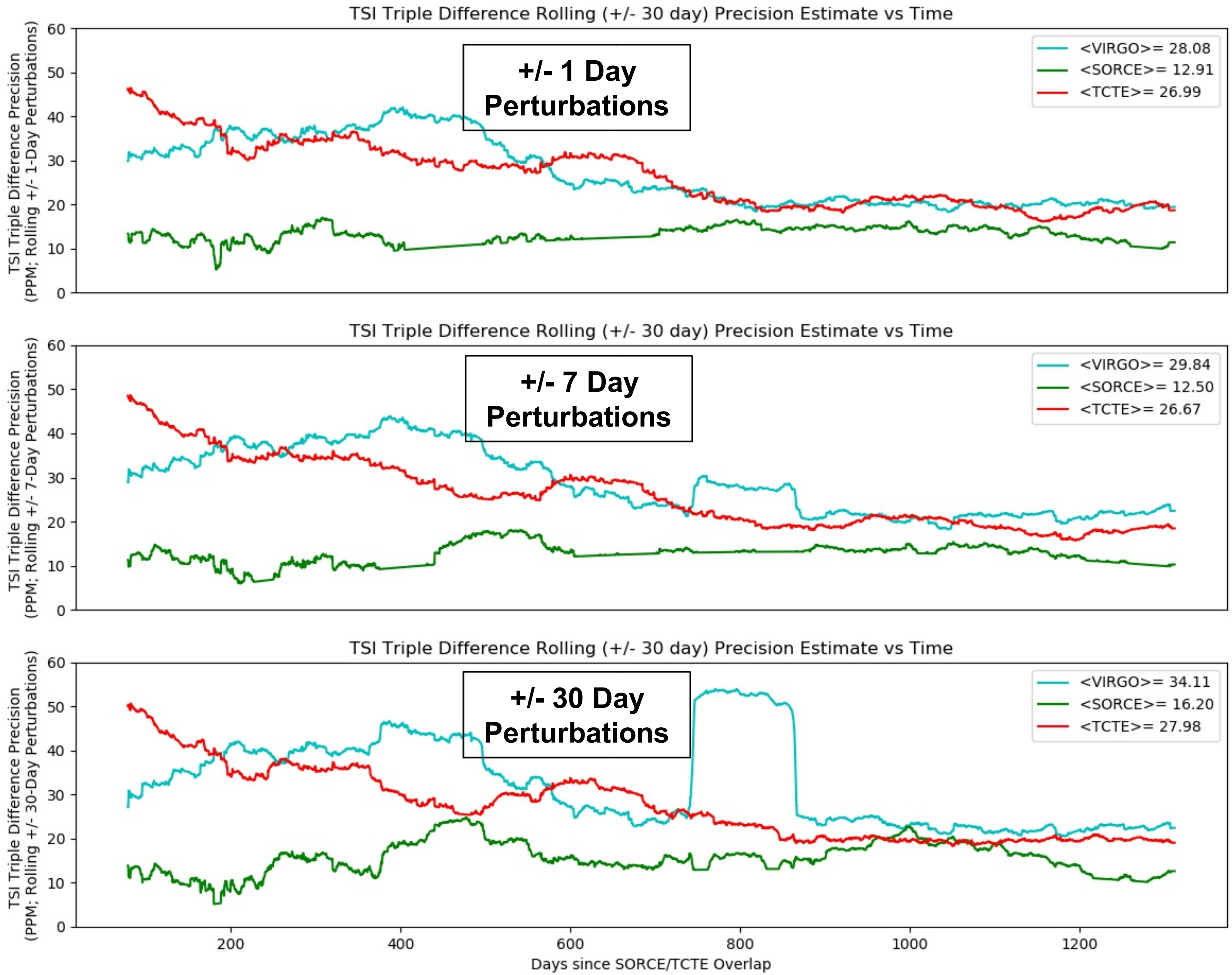
TSIS-1, SORCE, and TCTE precisions



Summary

- Shorter time-scales
  - **These precisions include short-term solar variability!**
    - **As such, these numbers probably an upper bound estimate of precision**
  - Difference variances tend to be dominated by TSI perturbations from the instrument with lower (higher value) precision.
  - Low $\boldsymbol{\sigma}_{\mathbf{VIRGO\text{-}SORCE}}$ correlation ($r<0.5$; not shown) with longer-scale mean TSI indicates that the 11-year solar cycle can only **minimally** (<0.25) account for the changes we see in precision (which includes short term variability).
- Longer time-scales
  - Precisions will include short-scale error (and variability) + long-term features such as degradation

Next Steps: Precisions vs. Time



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Additional

Triple Differencing: Concept

$\langle\ \rangle$ Denotes Time-Averaging

$$\left\langle \acute{D}_{XY}{}^{2} \right\rangle = \left\langle \acute{\varepsilon}_{X}{}^{2} \right\rangle + \left\langle \acute{\varepsilon}_{Y}{}^{2} \right\rangle - \cancel{2\left\langle \acute{\varepsilon}_{X} \acute{\varepsilon}_{Y} \right\rangle}$$

0

Algorithmically, this can be expressed as:

$$\overline{D_{XY}} = \frac{1}{2\Delta t} \sum_{t_1 = t - \Delta t}^{t + \Delta t} D_{XY}(t_1 | t_1 \neq 0)$$

$$\acute{D}_{XY} = D_{XY} - \overline{D_{XY}} = \acute{\varepsilon}_X - \acute{\varepsilon}_Y$$

$$\left\langle \acute{D}_{XY}{}^{2} \right\rangle = \frac{1}{2\Delta n + 1} \sum_{t = -\Delta n}^{\Delta n} \acute{D}_{XY}(t)^2$$

Here, Δt represents the window for computation of the rolling background mean, and Δn represents the window for computation of the difference variance.