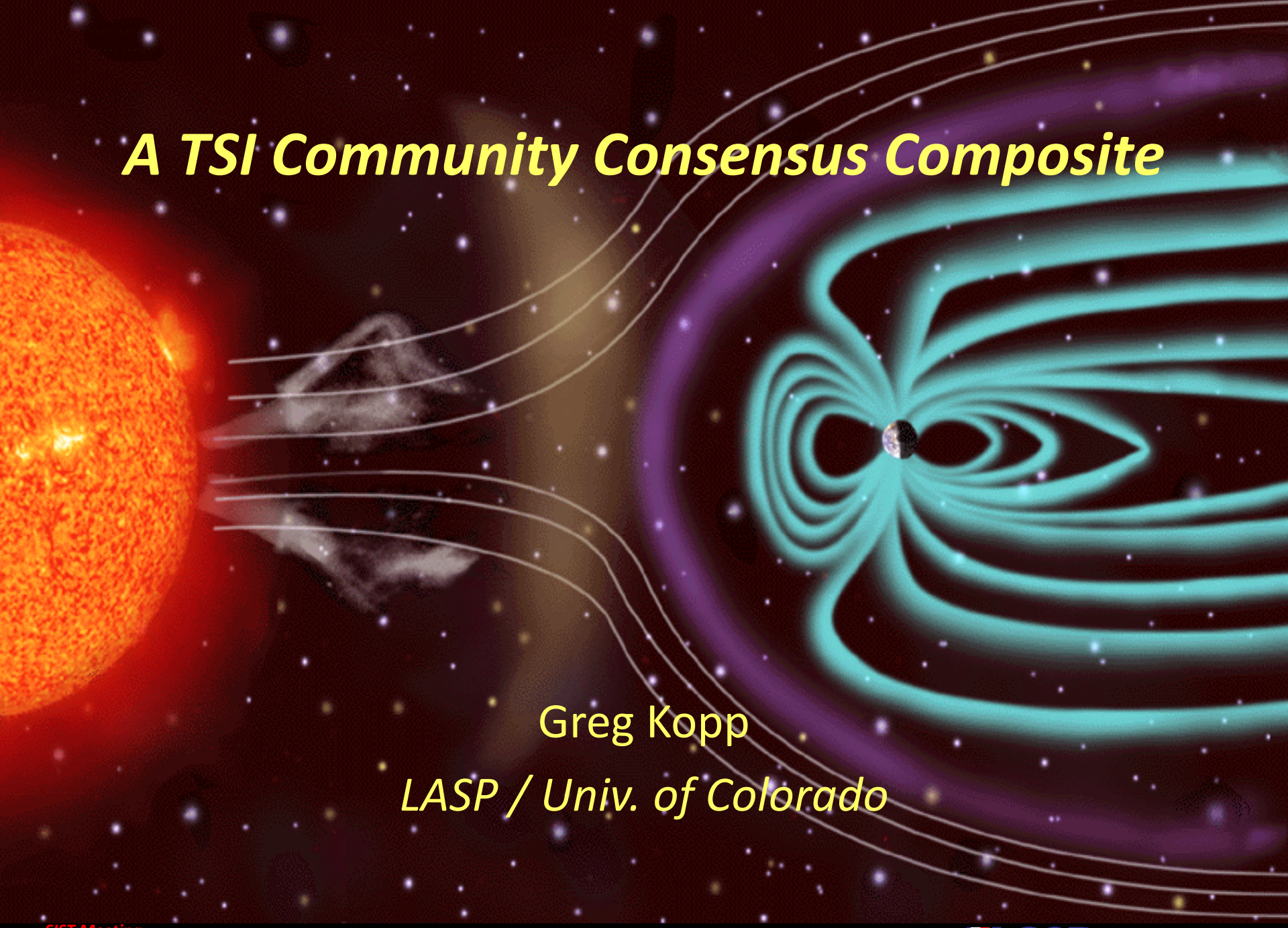
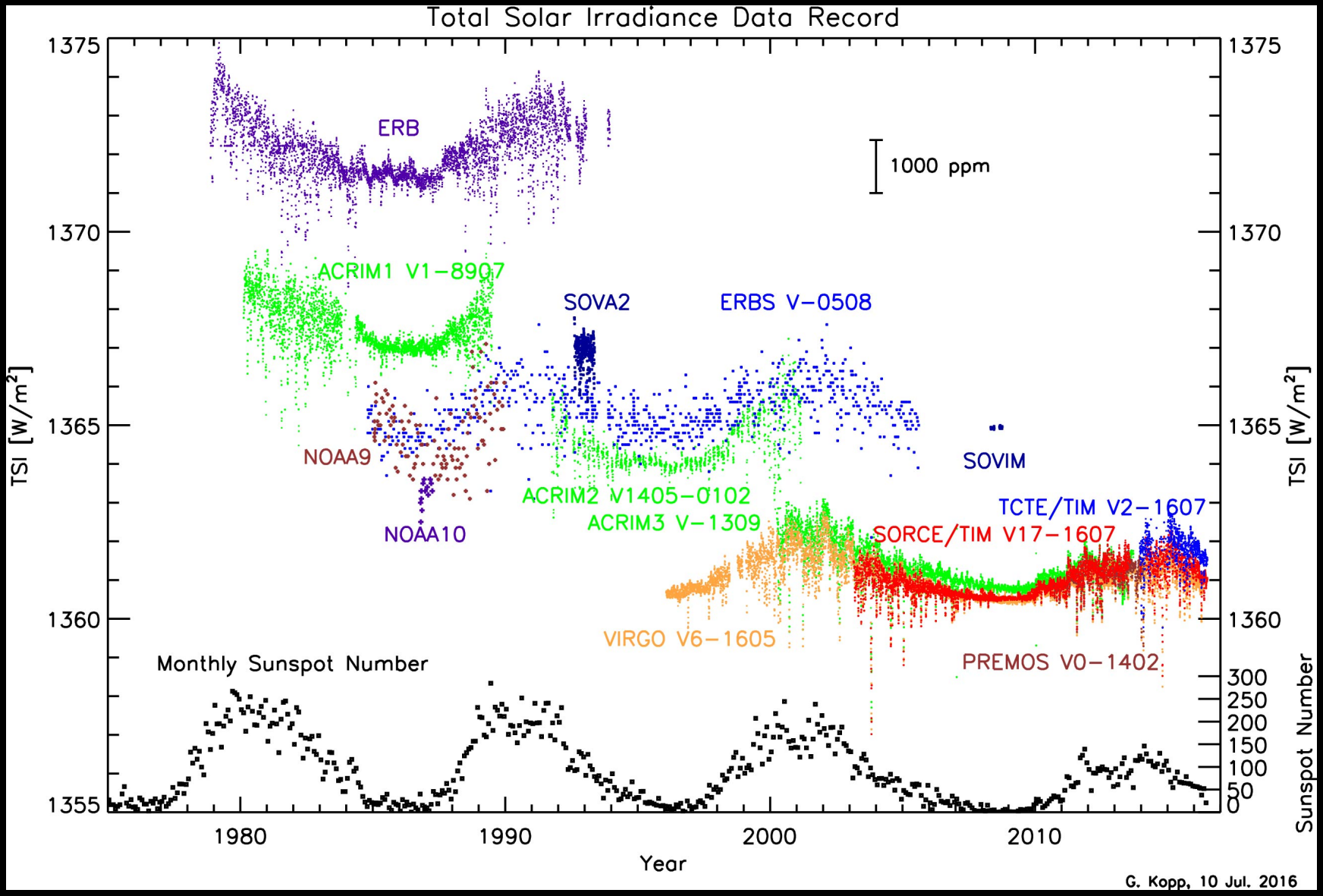
A TSI Community Consensus Composite



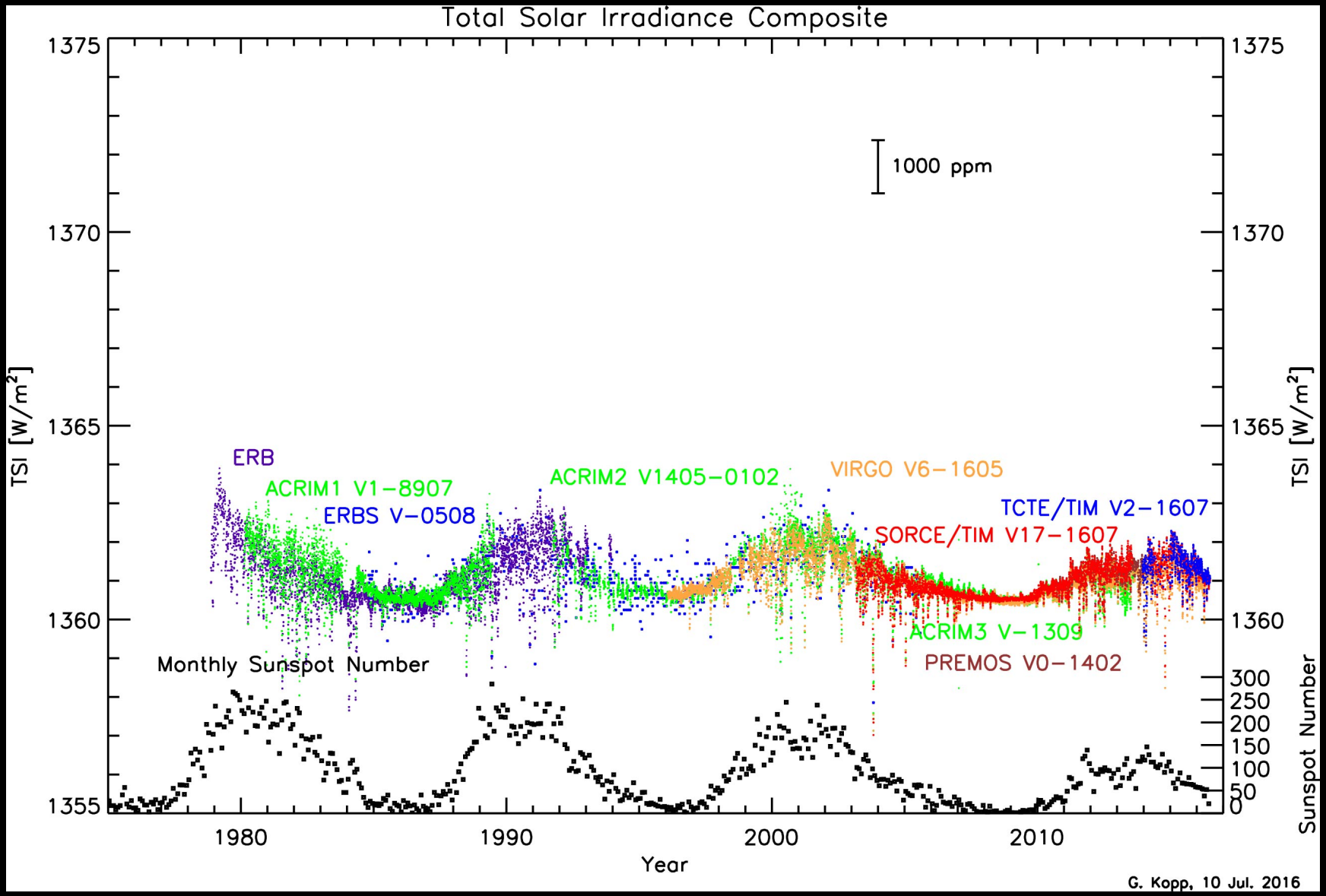
Greg Kopp

LASP / Univ. of Colorado

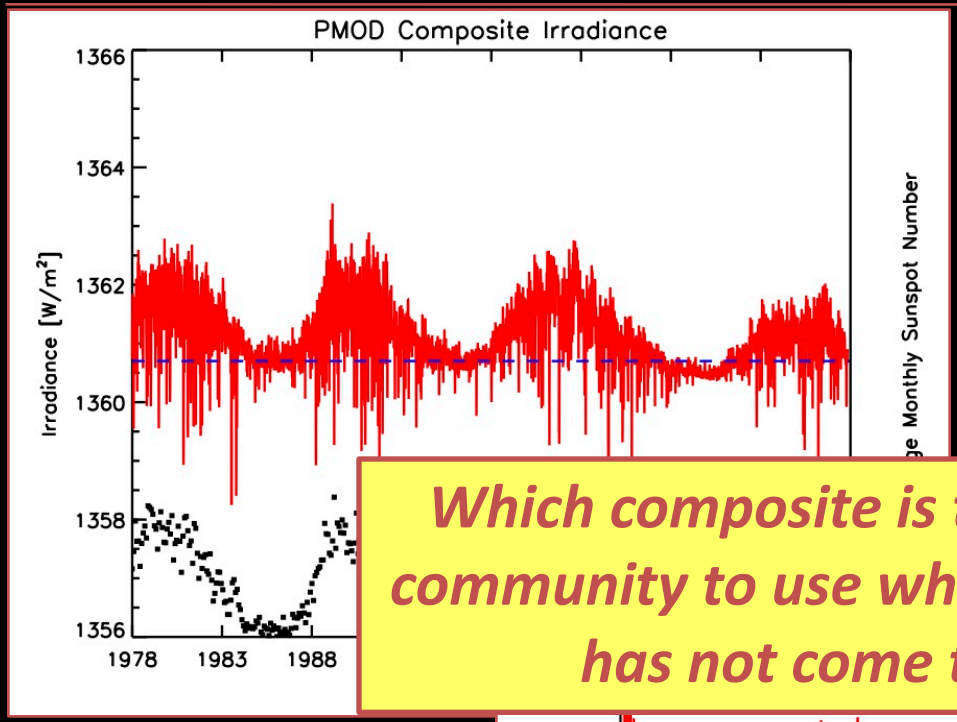
Spacecraft-Era TSI Measurements

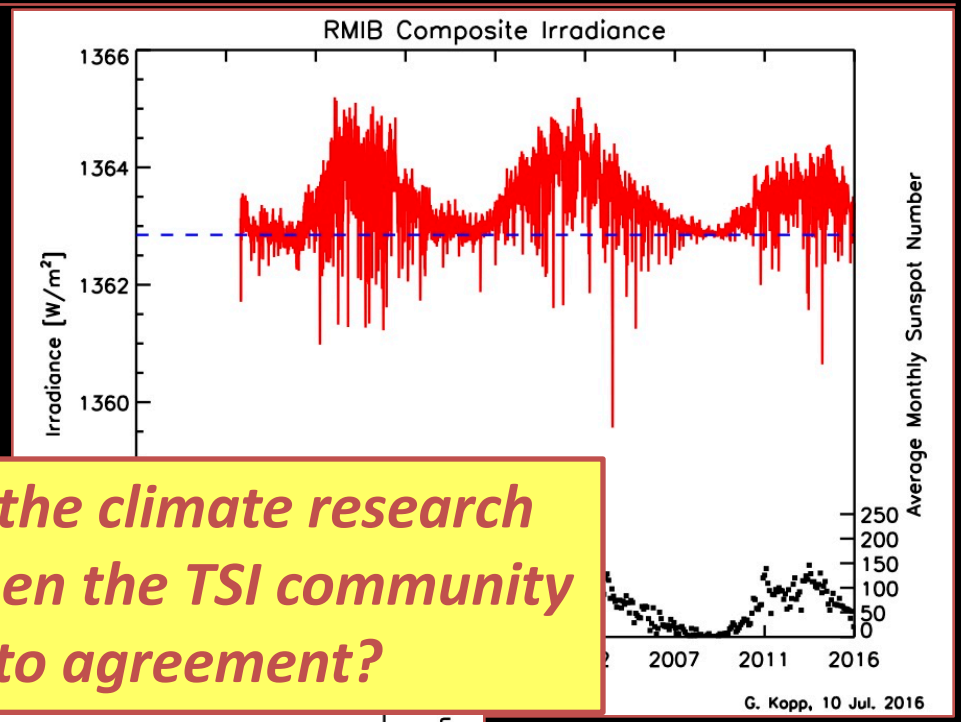


Community Needs a Composite Record...

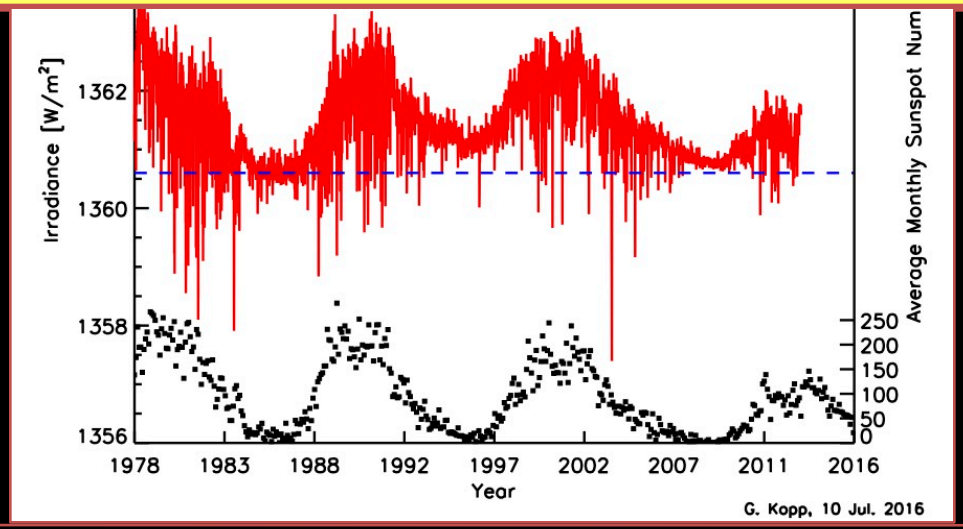


...But Instead Has Three Composites





Which composite is the climate research community to use when the TSI community has not come to agreement?



ISSI Team Laid Groundwork

1. Agreed upon the absolute value to use for the composite TSI record
2. Agreed upon an unbiased computational methodology to create this new composite

Team: Greg Kopp (PI), Will Ball, Steven Dewitte, Thierry Dudok de Wit, André Fehlmann, Wolfgang Finsterle, Claus Fröhlich, Sabri Mekaoui, Werner Schmutz, Richard Willson, Pia Zacharias

ISSI Team Laid Groundwork

- Consolidated data from all space-borne TSI instruments
- Discussed accuracies and stabilities with instrument PIs
- Reviewed ground-based calibrations/validations for instruments
- Refined uncertainties of some instruments
- *Agreed on the absolute value to which a new TSI composite would be normalized and weightings of each contributing instrument*
- Reviewed knowledge of known artifacts affecting data and time-dependent corrections potentially needed for some flight data
- Compared flight data to the SATIRE TSI proxy model to identify short-term time- and frequency-dependent measurement artifacts
- *Agreed upon Bayesian-based computational methodology to create a TSI composite*
- Considered methods of estimating initial uncertainties and the time ranges over which they are applicable

SIST Effort

1. Improve and implement the computational methodology to create this new community consensus TSI composite including time-dependent uncertainties with (partial) continued involvement from ISSI team
2. Distribute the composite to public via a website and produce a publication detailing the methodology
3. Establish a system to update this TSI composite regularly as new data are available

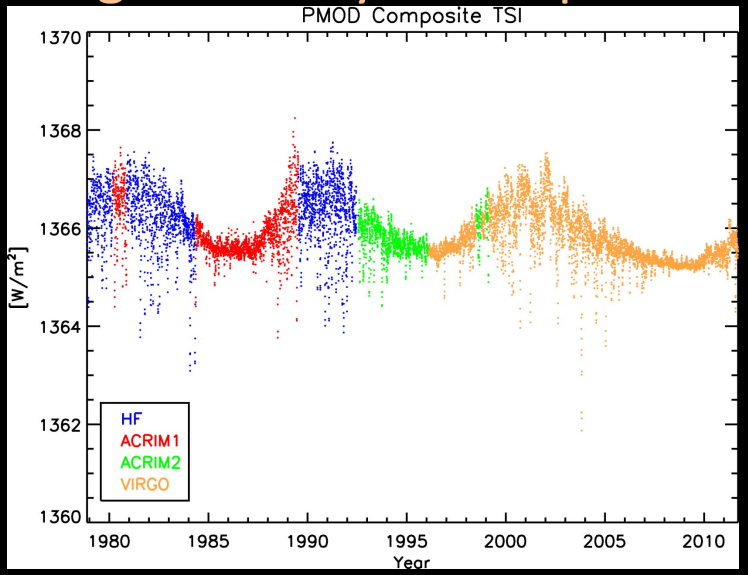
Summary: *Provide data users with a single TSI composite including, for the first time, time-dependent uncertainties, a non-binary selection of contributing instruments, and an unbiased weighting of those instruments*

SIST Team Collaborators

Collaborator	Expertise & Responsibility
Dr. Will Ball	Modeler for the SATIRE TSI proxy model. Comparisons to this model provide insight into individual data record accuracies and realism of resulting composite.
Dr. Thierry Dudok de Wit	Scientist and mathematician with expertise in statistical analyses methods, PCA, and Bayesian techniques applied to creating composite records. Dr. Dudok de Wit has demonstrated a proof-of-concept TSI composite using the described and agreed upon methodology. He will help tune the Bayesian approach during the initial, more experimental, stages of the proposed effort.
Dr. Wolfgang Finsterle	Instrument Scientist for Picard/PREMOS provides updated PREMOS TSI data and knowledge about that instrument's uncertainties due to on-orbit operations influences
Dr. Claus Fröhlich	PI for SoHO/VIRGO who is responsible for VIRGO TSI and creation of PMOD TSI composite. Dr. Fröhlich provides knowledge not only about the VIRGO but also the oldest TSI instrument, the NIMBUS-7/ERB. He also shares his experience from having created the most prominent TSI composite, that of PMOD.
Dr. Werner Schmutz	PI for Picard/PREMOS provides the absolute value of the PREMOS TSI measurements and insight into the World Radiometric Reference maintained by his organization at PMOD
Dr. Richard Willson	PI for ACRIM-1, -2, and -3, spanning 30 years of TSI measurements. Dr. Willson has knowledge of the older TSI instruments including the NIMBUS-7/ERB as well as experience in creating the ACRIM TSI composite

Improvements in Planned Composite

- Recent improvements to *absolute accuracy* in the newer TSI measurements have not yet been reflected in TSI composites
  - Picard/PREMOS and TCTE help transfer the ground-based TRF reference standard to space
- Weight data from *all available instruments*
- Use *unbiased approach* rather than favored instrument
- Include *time-dependent uncertainties* to indicate temporal regions where the contributing data may be suspect



Specific Results from SIST Effort

- A *single TSI composite* having daily values over space-borne measurement era *with consensus from experts* representing the TSI instruments
  - Current composites are from individual researchers, not groups representing all instruments, so show bias in selection of instrument data
- *Time-dependent uncertainties* for values in the composite
  - No current composite includes uncertainties (let alone time-dependent ones)
- Consolidated estimates of time-dependent uncertainties in the current and historical individual TSI instrument records
  - Proposed approach provides an unbiased assessment of all data records
- Establishment of computational algorithms to enable regular updates as new data and new instruments become available
- Creation of a website providing the resulting composite to users
- A publication detailing the methodology

Methodology

- Assess trends and individual instrument uncertainties
  - Use historical knowledge from instrument team members
  - Use comparisons between instruments and/or models
  - Use data-driven estimates of frequency-dependent uncertainties
- Use temporal commonalities to determine most likely correct values
  - Maximum-likelihood and Bayesian methods
- Results
  - Composite with time-dependent uncertainties
    - Update regularly
  - Papers (one was proposed but now intend two separate ones)
    - TSI absolute value
    - Composite

Absolute Value Determined at Solar Minimum

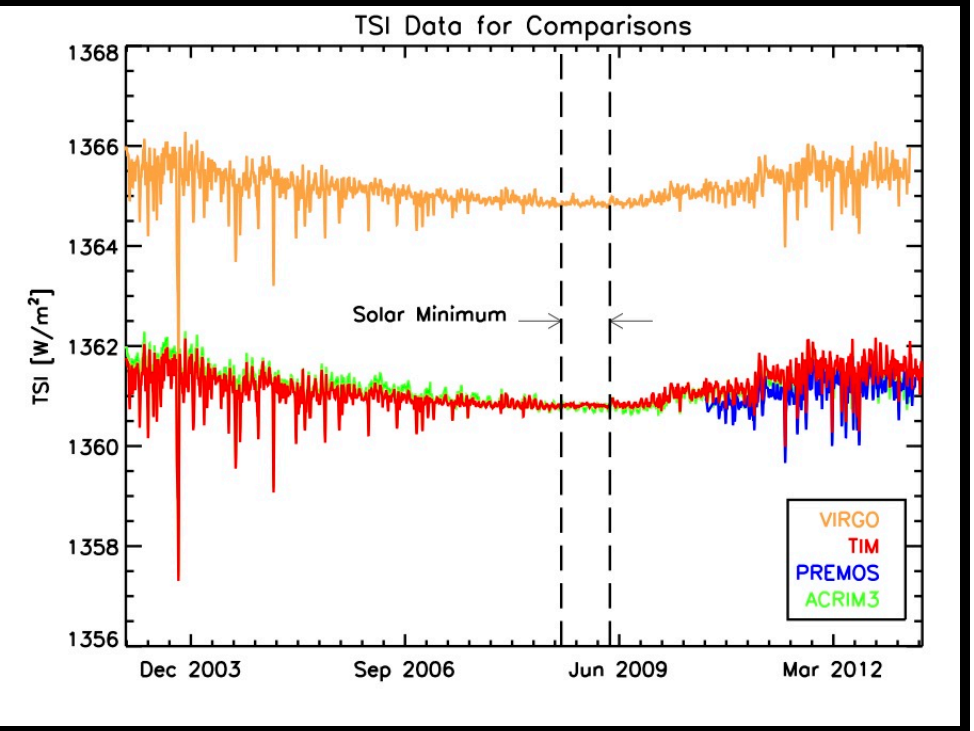
- Determined absolute value based on latest measurements
  - Used data from ACRIM3, PREMOS, TIM, VIRGO (incl. DIARAD)
  - Selected temporal region of overlap
    - 2008 solar minimum
  - Computed mean over region weighted by estimated instrument uncertainties
- Normalize composite to resulting 1360.54 W/m^2
  - Using solar minimum period from 20 Sept. 2008 through 5 May 2009
- Include TCTE/TIM via comparisons similar to those for PREMOS

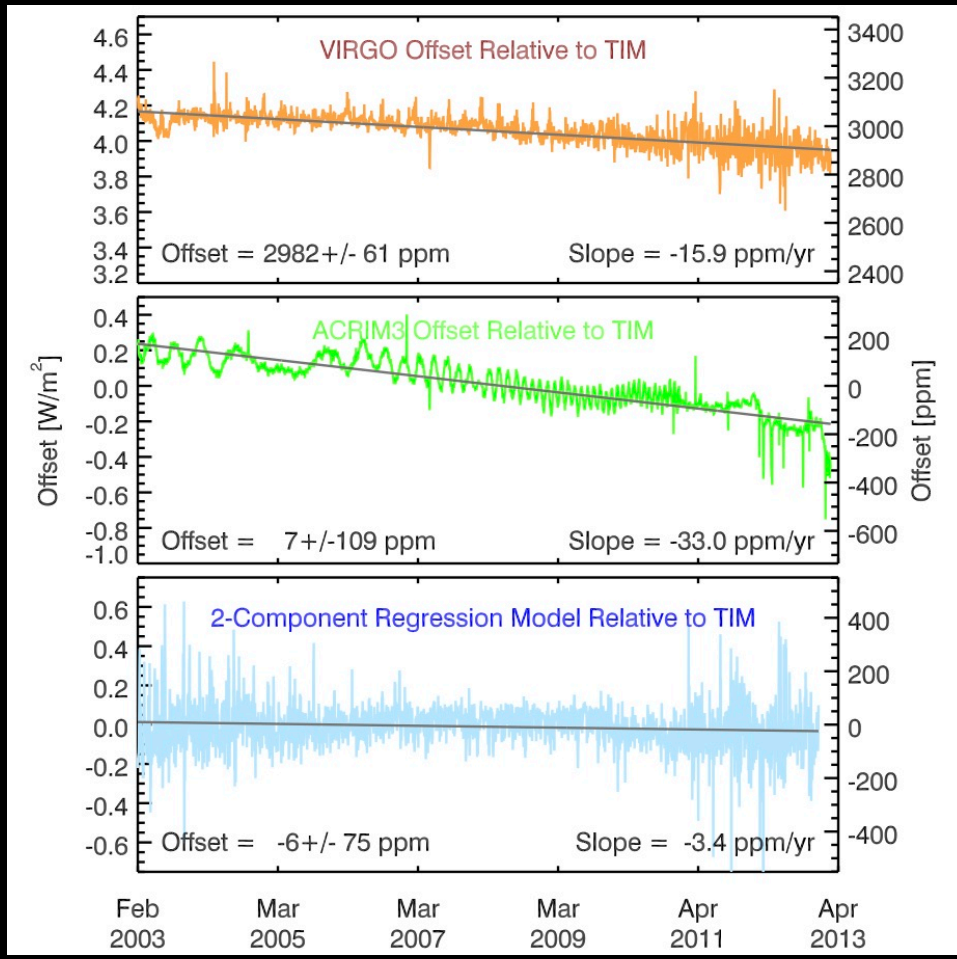
Uncertainty Considerations

- Time-dependent uncertainties
  - Causes (degradation, power measurement stability, operations changes)
  - Means of estimating uncertainties for relative differences between two times
- Means of estimating uncertainties
  - Consider different frequency domains separately
  - Short-term / high-frequency
    - White noise autocorrelations and power-spectral analyses?
    - Reconstructions from bootstrapping?
    - Estimate future values based on recent values?
  - Long-term / low-frequency
    - Relative instrument comparisons?
    - Magnitude of degradation corrections?
    - Correlations with sunspot record?
    - Extend short-term uncertainties with $1/f$ scaling?

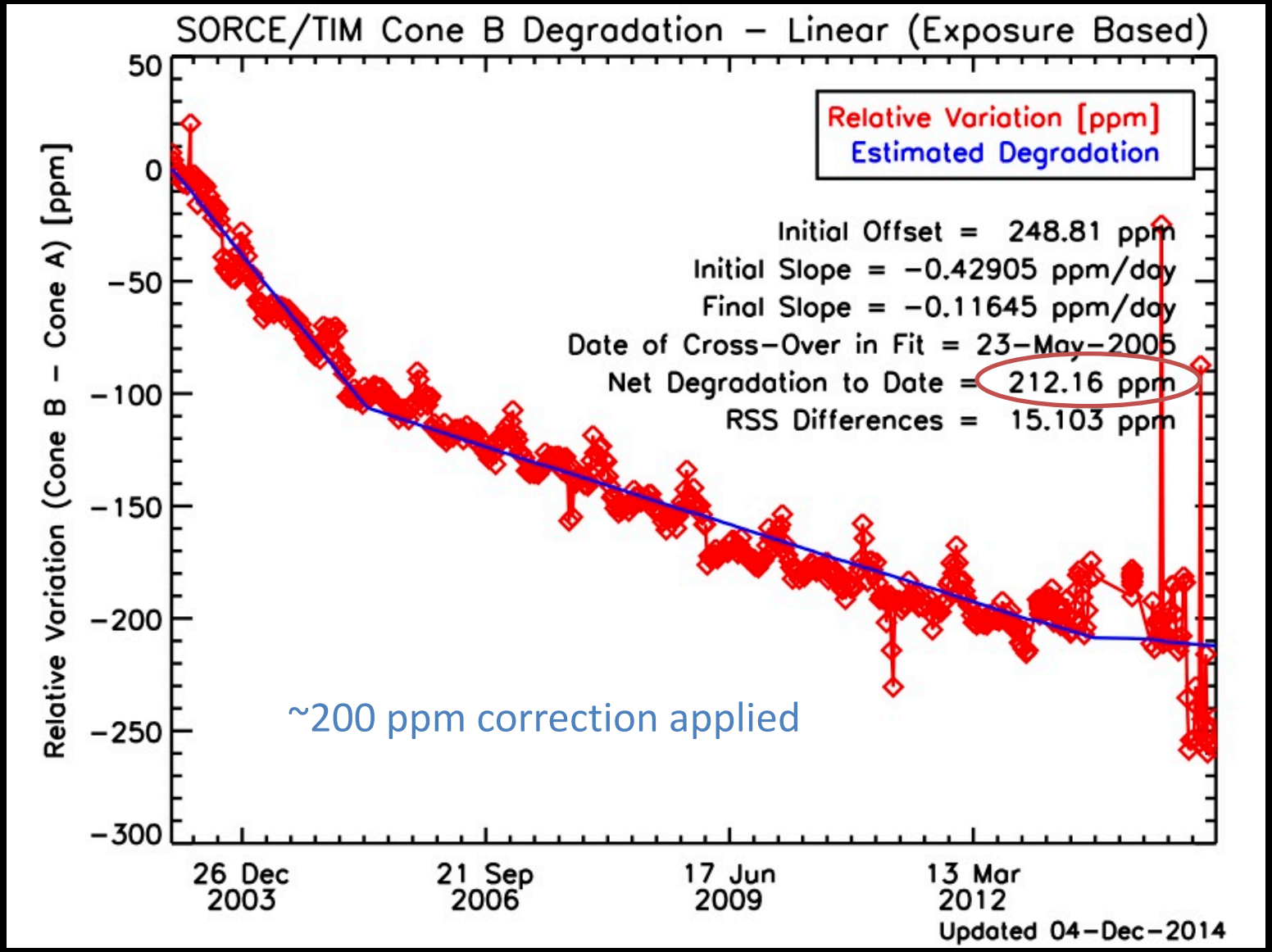
Instrument Data Comparisons Indicate Artifacts

- There remain significant differences between existing instruments
  - ACRIM3 oscillations and VIRGO Keyhole spikes are known problems





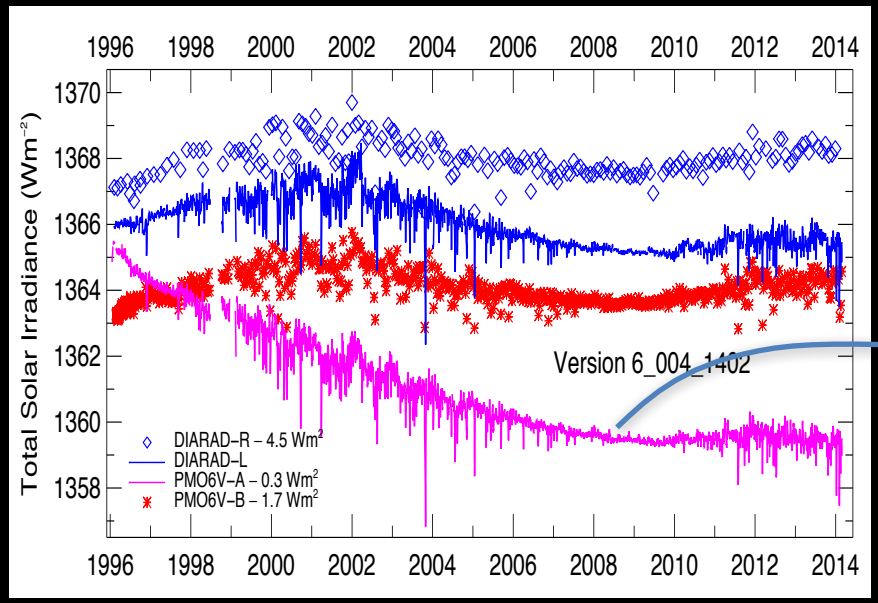
Stability May Indicate Long-Term Uncertainties



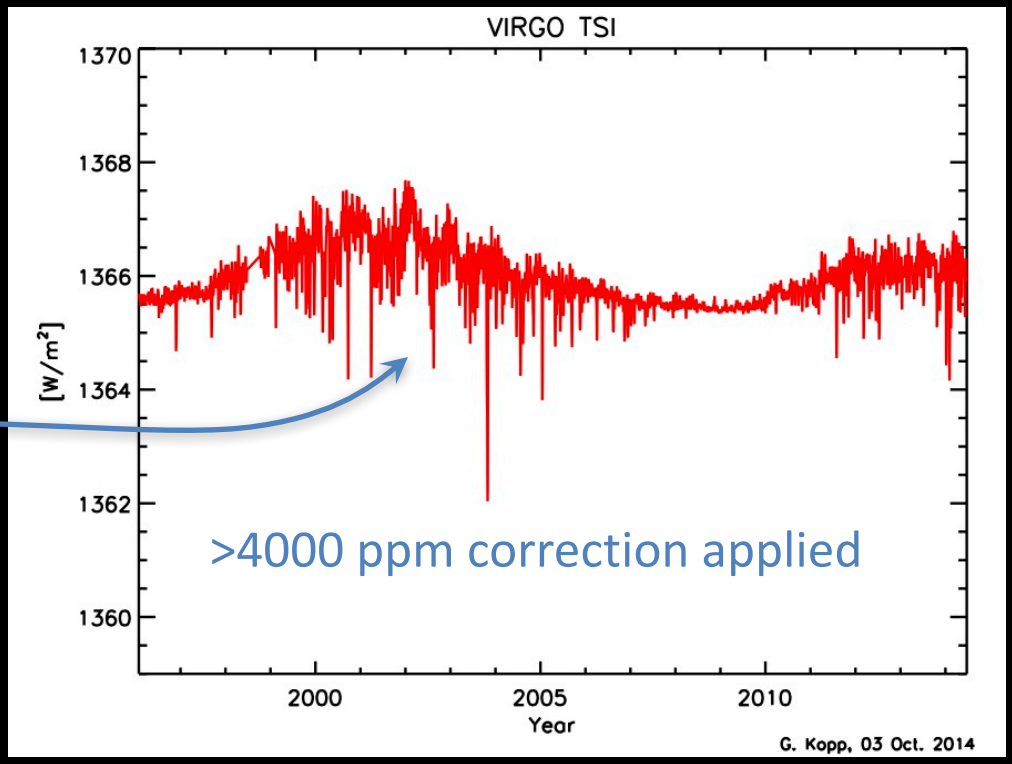
Stability May Indicate Long-Term Uncertainties

- Level 1 VIRGO data demonstrate level of variations of individual channels

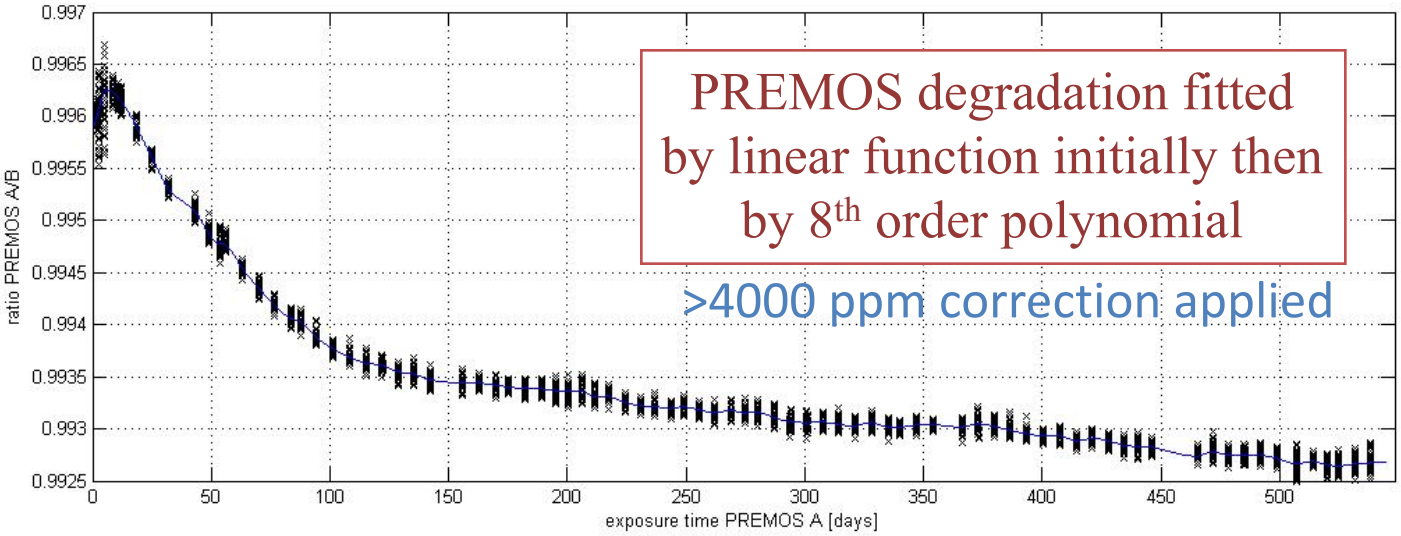
Level 1 Data (all 4 channels)

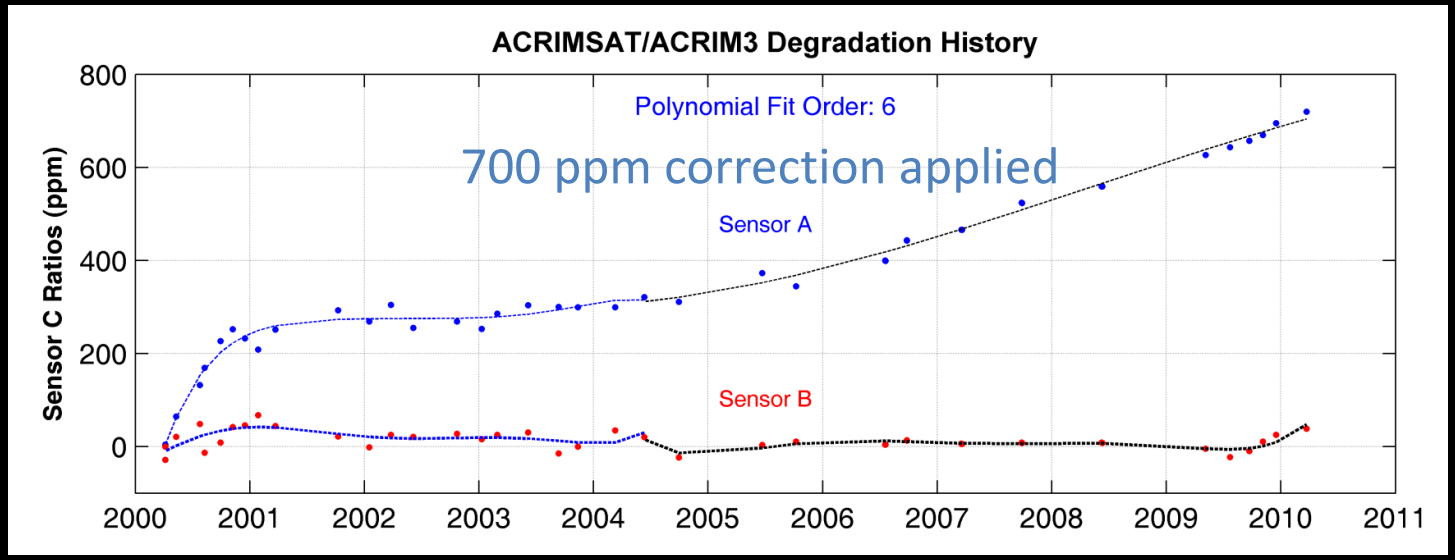


Level 2 Data (VIRGO)



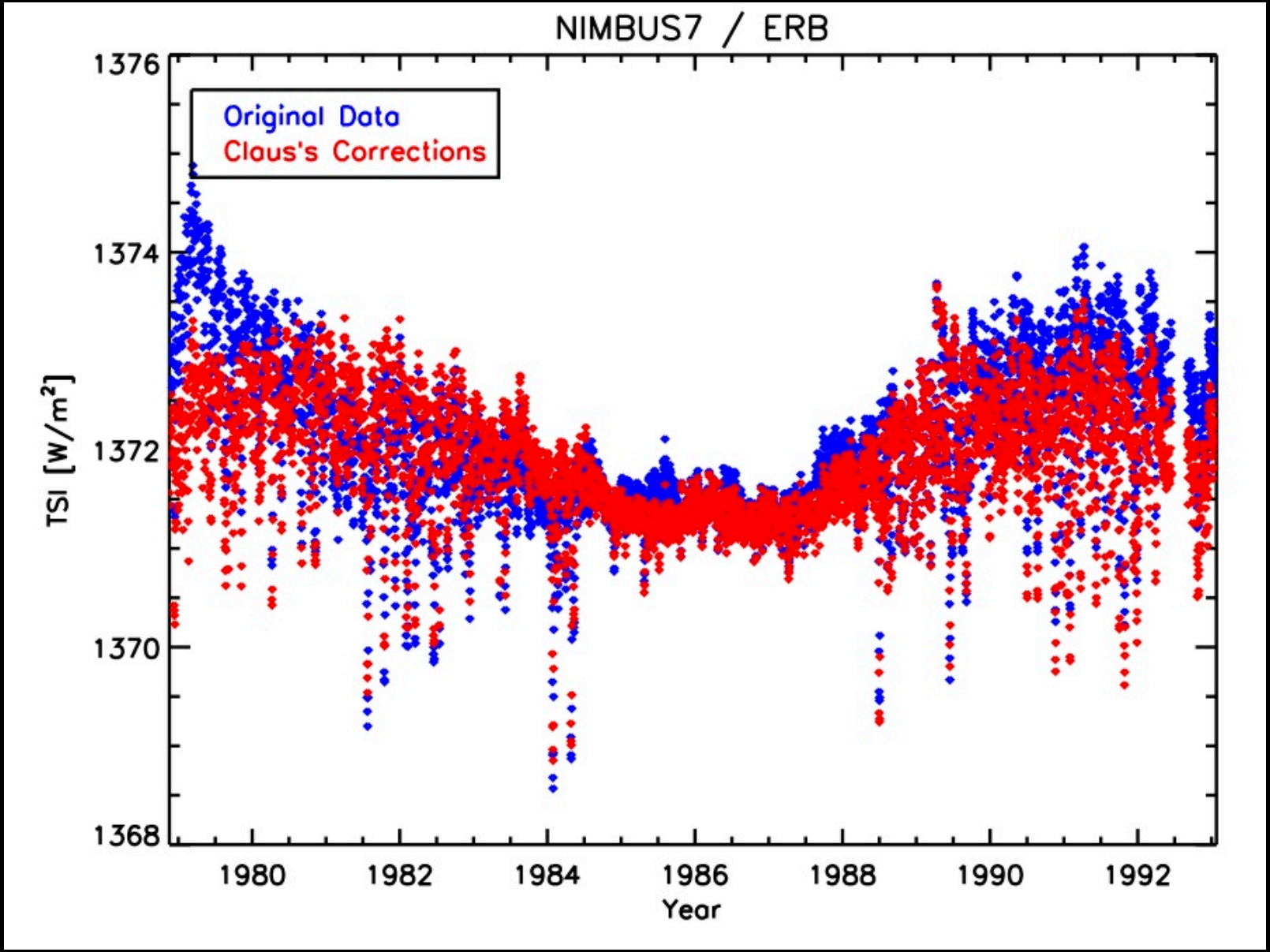
Stability May Indicate Long-Term Uncertainties



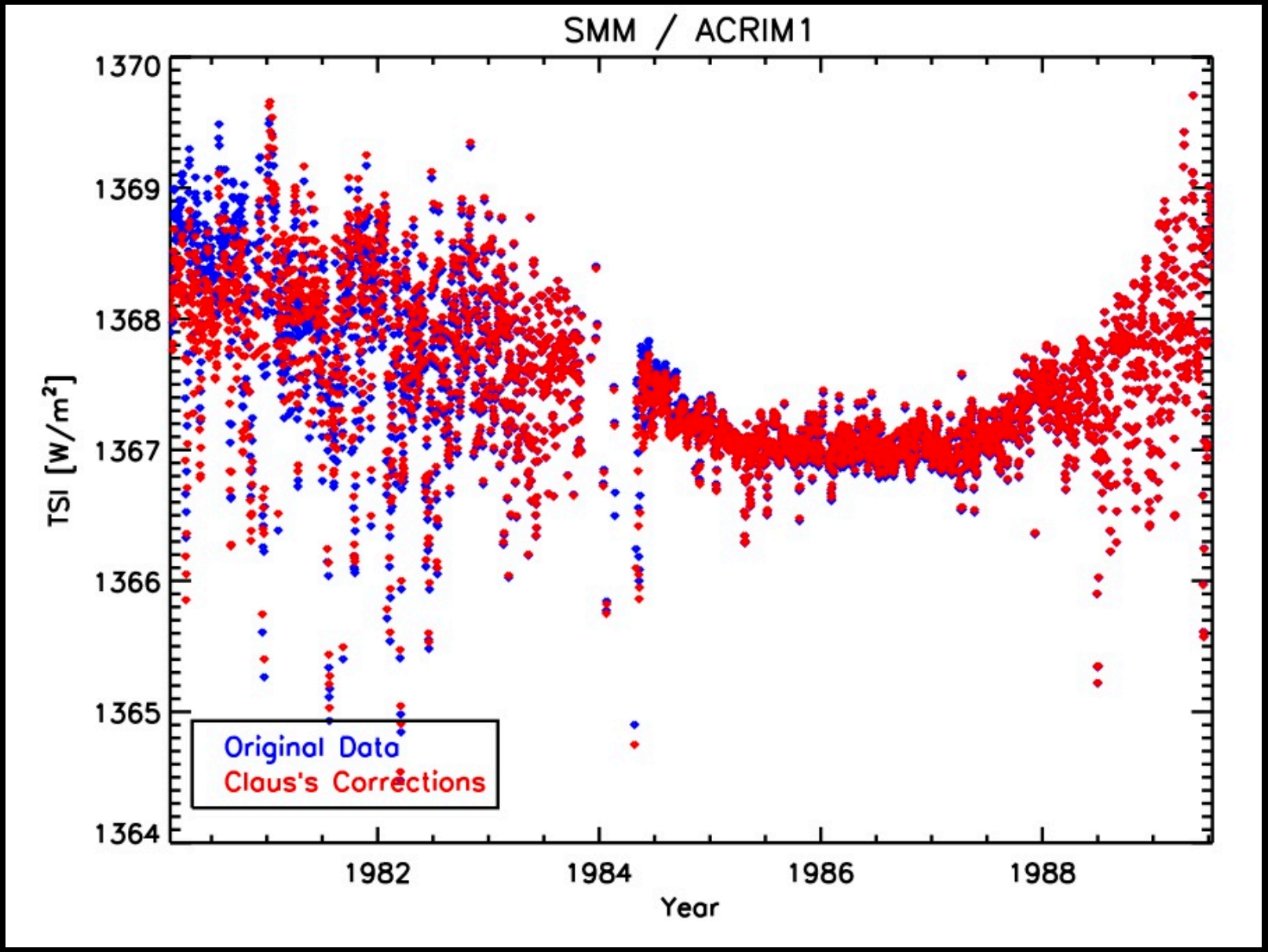


ACRIM3 degradation fitted by 6th order polynomial

What About NIMBUS7 / ERB Corrections?



Or ACRIM1 Corrections?

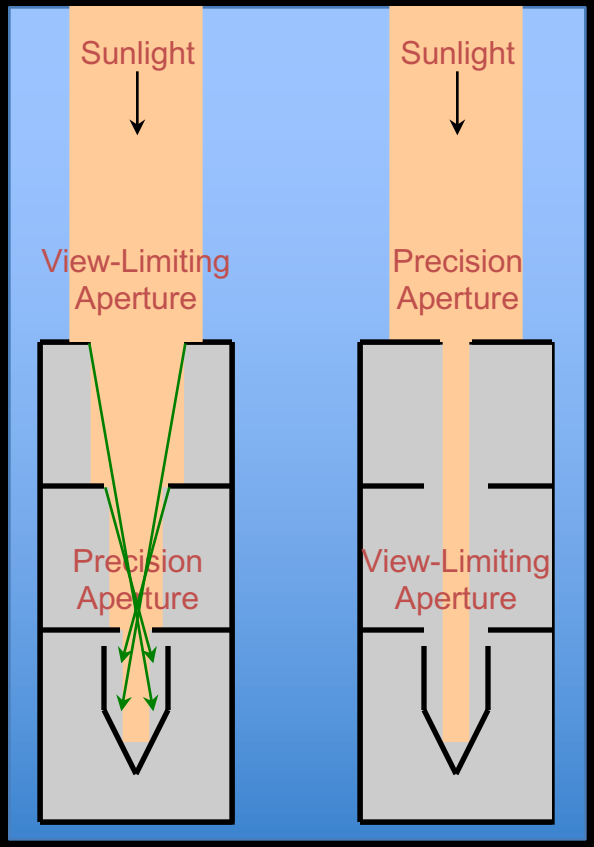


Diffraction & Scatter Erroneously Increase Signal

All instruments except the TIM put primary aperture close to the cavity

Expanding TRF beam from filling precision aperture while underfilling view-limiting aperture to overfilling view-limiting aperture causes increase in signal due to scatter and diffraction from front and interior sections of instrument

all other TSI instrument geometries



Additional light allowed into instrument can scatter into cavity

Majority of light is blocked before entering instrument

TIM geometry

Kopp and Lean, *GRL*, 2011

Measured increases due to uncorrected scatter/diffraction are surprisingly large

Instrument	Increase
PREMOS-1	0.10%
PREMOS-3	0.04%
VIRGO2	0.15%
ACRIM-3	0.51%
SOVAR	0.20%

This affects the World Radiometric Reference too

Fehlmann *et al.*, *Metrologia*, 2012 report the WRR measures TSI 0.34% higher than the true SI scale

Composite-Creation Methodology

- Use all available measurement data from every day
  - Weight by instrument uncertainties determined from power-spectral density
- Compute discrete wavelet transform for each record
  - Expectation-maximization fills gaps (do not contribute to final composite)
- Scale-wise average the weighted wavelets
  - Avoid discontinuities in composite by low-frequency scale-wise averaging discrete wavelet transform
- Invert averaged wavelet transform to create composite time-series
- Estimate time-dependent uncertainties
  - Monte-Carlo or bootstrapping

Dudok de Wit, Kopp, Fröhlich, and Schöll, GRL, 2016 (in preparation)

Future Efforts

- Improvements to composite itself
  - Modify initial weightings based on known instrument artifacts
  - Consider appropriateness of applying 1/*f* spectral variation to all instruments
  - Improve method of adding/losing instruments
  - Consider Bayesian approach rather than maximum-likelihood
- Implement computational methodology to provide regular updates as new data or instruments become available
- Publish and serve resulting composite to research community