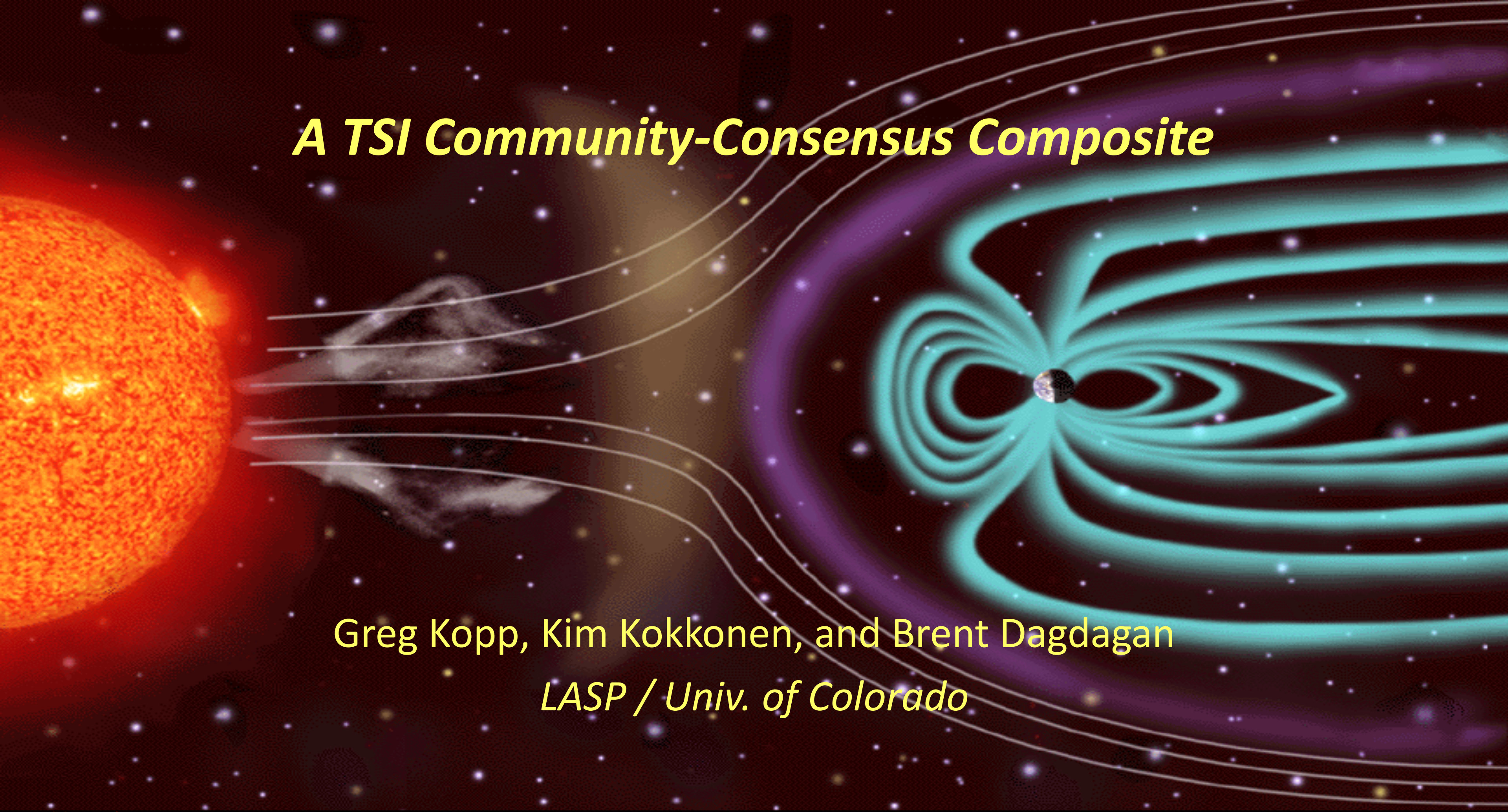
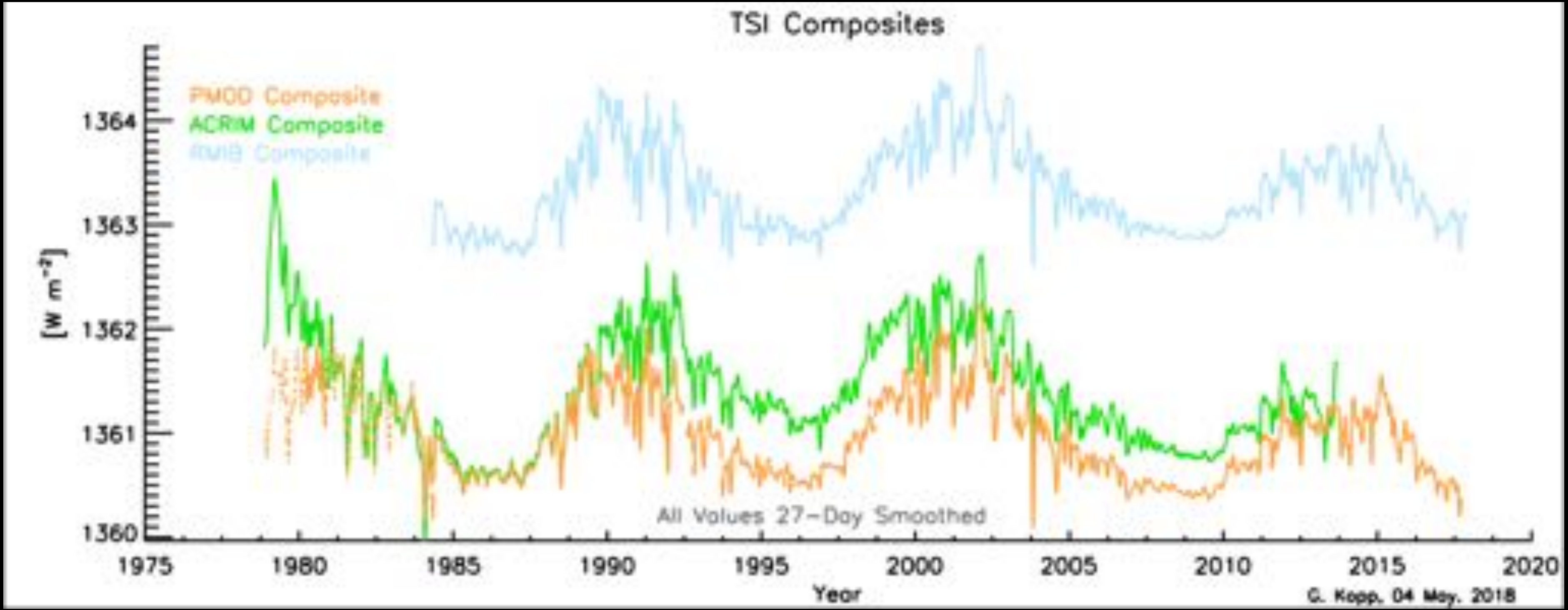


A TSI Community-Consensus Composite

Greg Kopp, Kim Kokkonen, and Brent Dagdagan

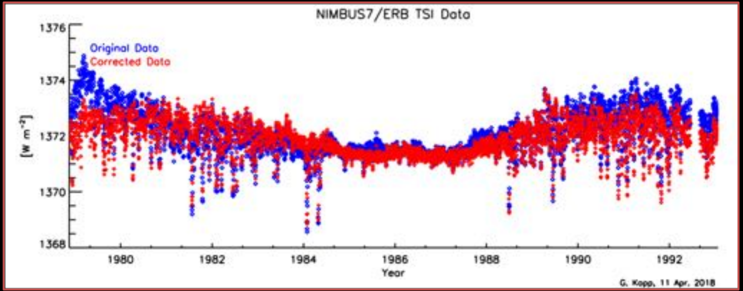
LASP / Univ. of Colorado

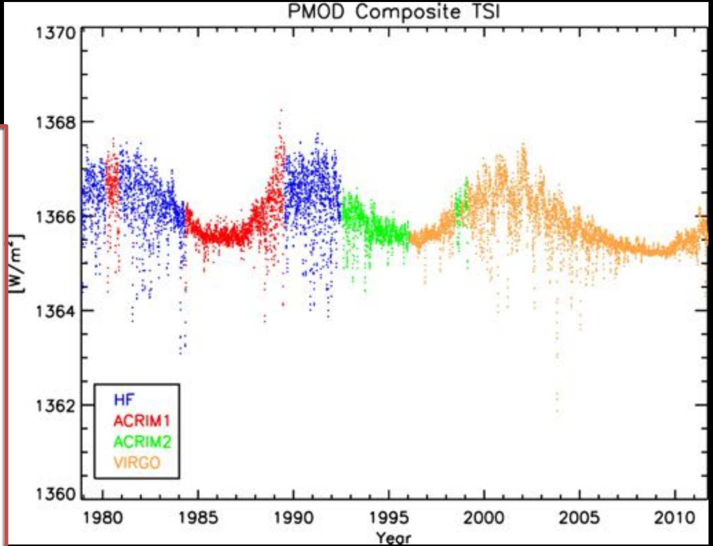
Traditional TSI Composites

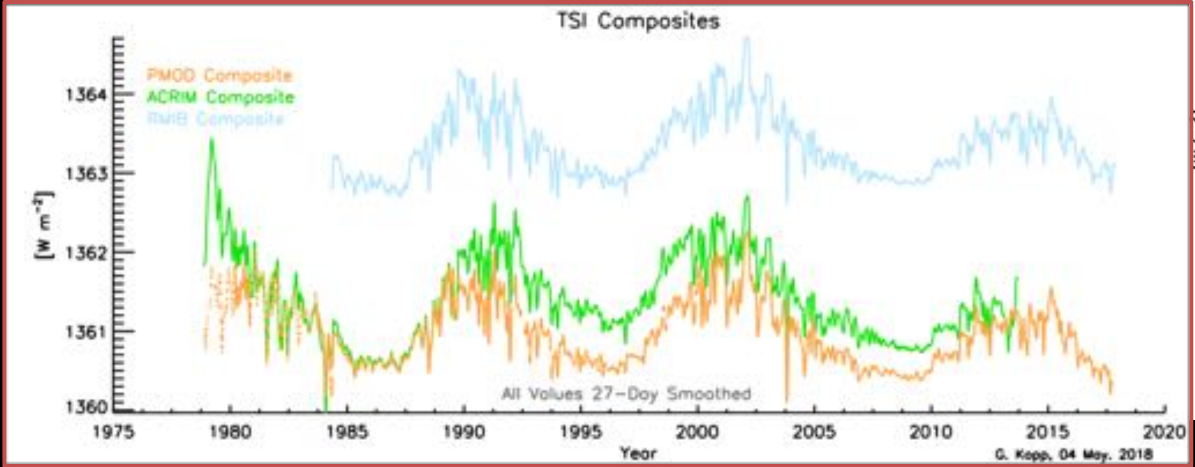


Issues with Traditional Composites

- Created by individuals (PIs)
- Binary (and biased) selection of instrument data used
  - Discontinuities at boundaries
- Controversial corrections applied to data records
- Normalizations incorrect
- Lack uncertainties

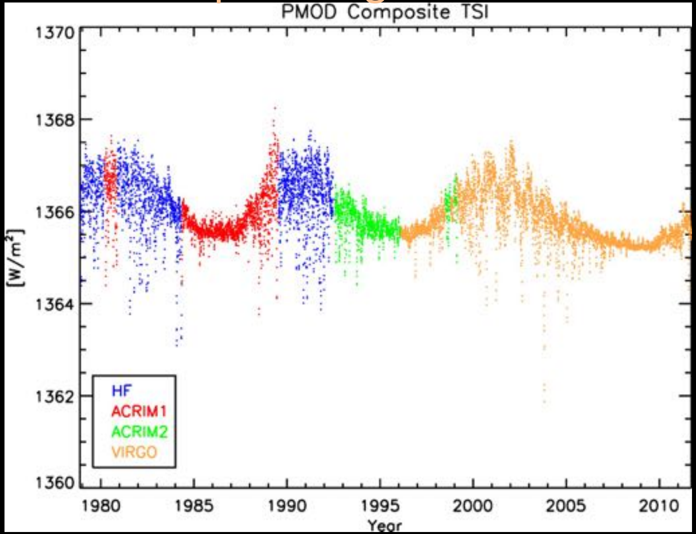




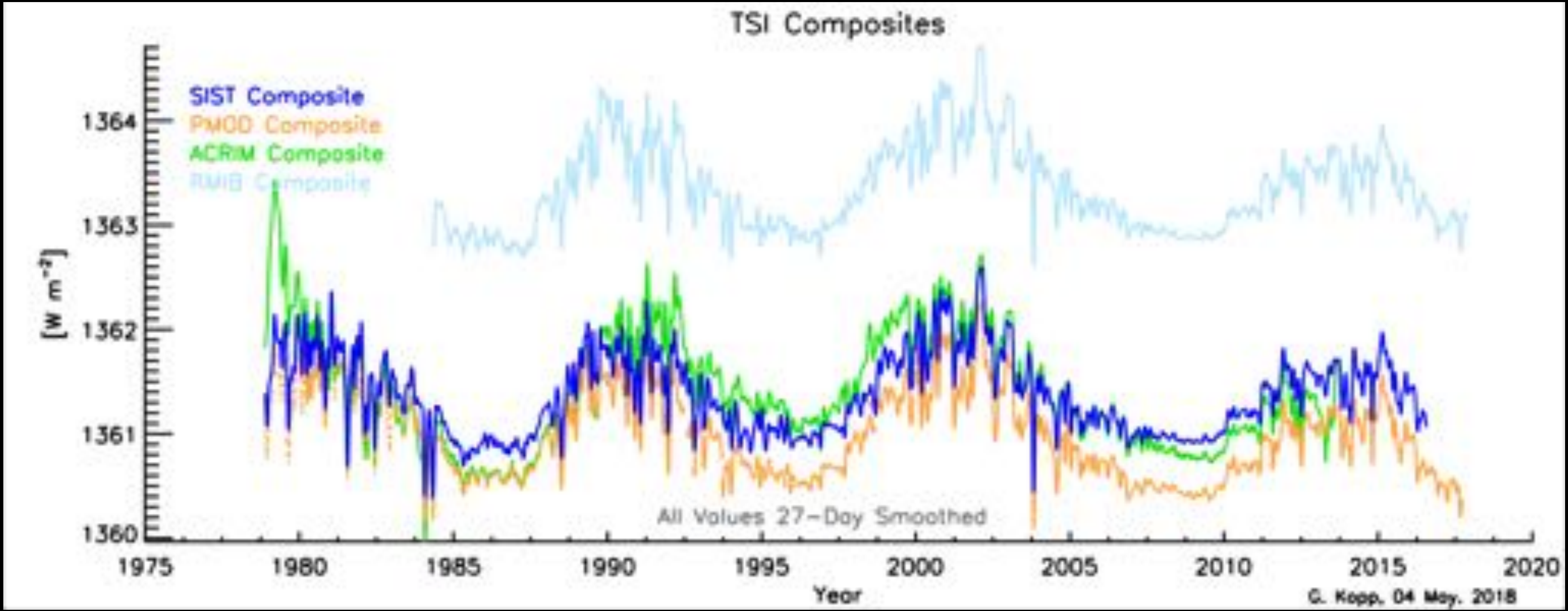


Improvements in “Community-Consensus” Composite

- Recent improvements to *absolute accuracy* in the newer TSI measurements are incorporated
  - SORCE, PREMOS, TCTE, and TSIS help transfer improved ground-based calibrations to space
- Weight data from *all available instruments*
- Use *unbiased statistically-driven approach* rather than favored instrument
- Include *time-dependent uncertainties* to indicate temporal regions where contributing data may be suspect
- Smooth transitions and gaps scale-wise



Latest "Community Consensus" TSI Composite



Includes efforts of former ISSI team and current SIST team

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

SIST Effort

1. Demonstrate, implement, and improve the computational methodology to create a new community-consensus TSI composite including time-dependent uncertainties with (partial) continued involvement from ISSI team
2. Distribute the composite to public 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

Specific Results from SIST Effort

- A *single TSI composite* having daily values over space-borne measurement era *with consensus from experts* of the TSI instruments and data
  – 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
  – Current composites do not include uncertainties (let alone time-dependent ones)
- Consolidated estimates of time-dependent uncertainties in the current and historical individual TSI instrument records
  – Proposed approach provides a relatively unbiased assessment of all data records
- Establish 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 describing the composite and the inputs

TSI-Composite Methodology Has Been Published

- TSI-community based for openness
- Uses all available instrument data
- Scale-wise weightings smoothly fill gaps
- Uses an unbiased statistical approach
- Normalized to most accurate instruments
- Has time-dependent uncertainties

AGU PUBLICATIONS

Geophysical Research Letters

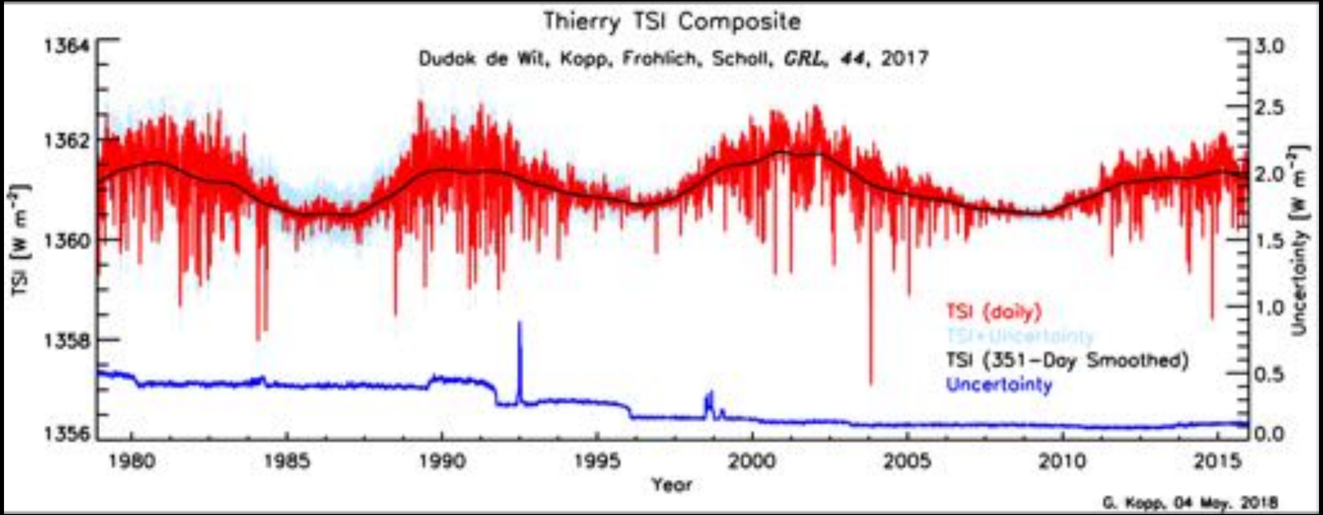
RESEARCH LETTER
10.1002/2016GL071866

Key Points:
- We present a new approach for merging different solar irradiance time series into a single composite
- We provide a new and fully traceable composite of the total solar irradiance
- We quantify uncertainties in the total solar irradiance composite and demonstrate a $1/f$ scaling in them

Methodology to create a new total solar irradiance record: Making a composite out of multiple data records

Thierry Dudok de Wit[1], Greg Kopp[2,3], Claus Fröhlich[4], and Micha Schöll[1,5]

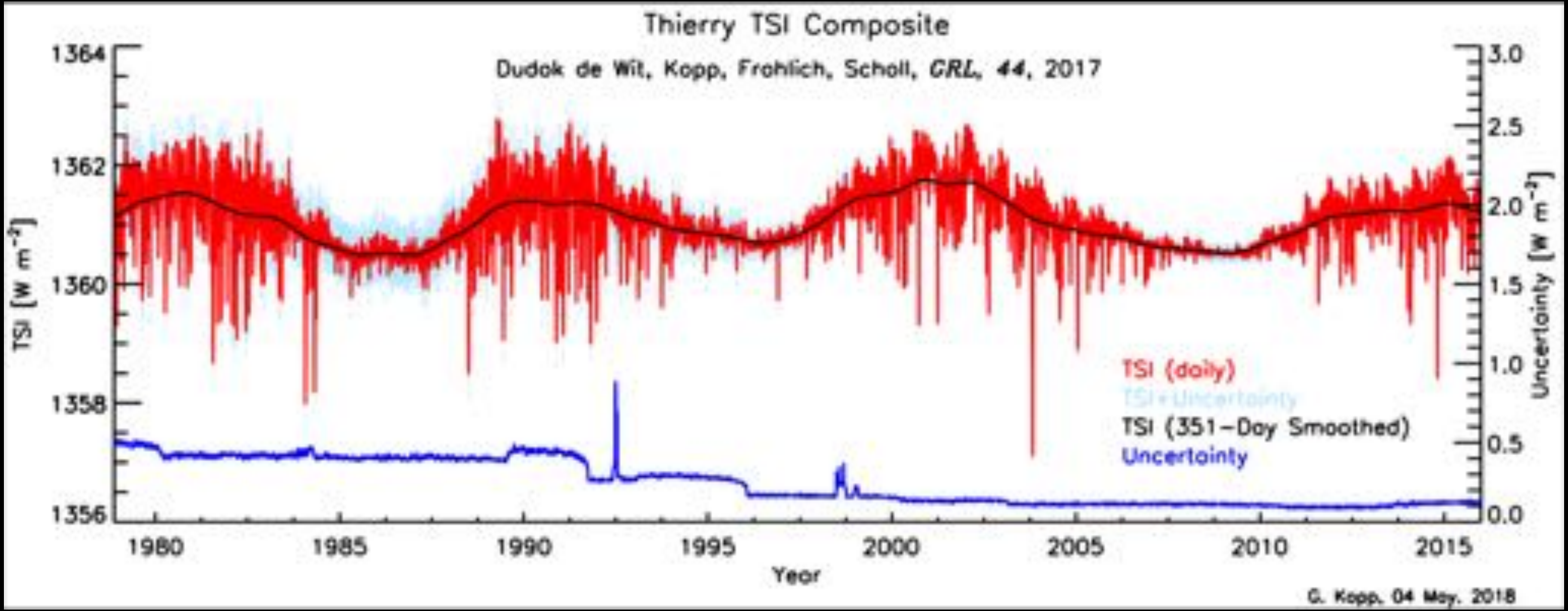
[1]LPC2E, CNRS and University of Orléans, Orléans, France, [2]Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, Boulder, Colorado, USA, [3]Max-Planck-Institut für Sonnensystemforschung, Göttingen, Germany, [4]Dählenwaldstrasse 30, Davos Wolfgang, Switzerland, [5]Physikalisch Meteorologisches Observatorium Davos and World Radiation Center, Davos Dorf, Switzerland



TSI-Composite Methodology Demonstrated

- TSI composite improved with reduced biases and better instrument-transition overlaps
  - Methodology demonstrated, but final composite needs refining
    - Agree on amount of "early increase" correction (if any) to apply
    - Estimate initial uncertainties
    - Update regularly

TSI instrument and composite data are available at:
http://spot.colorado.edu/~koppg/TSI

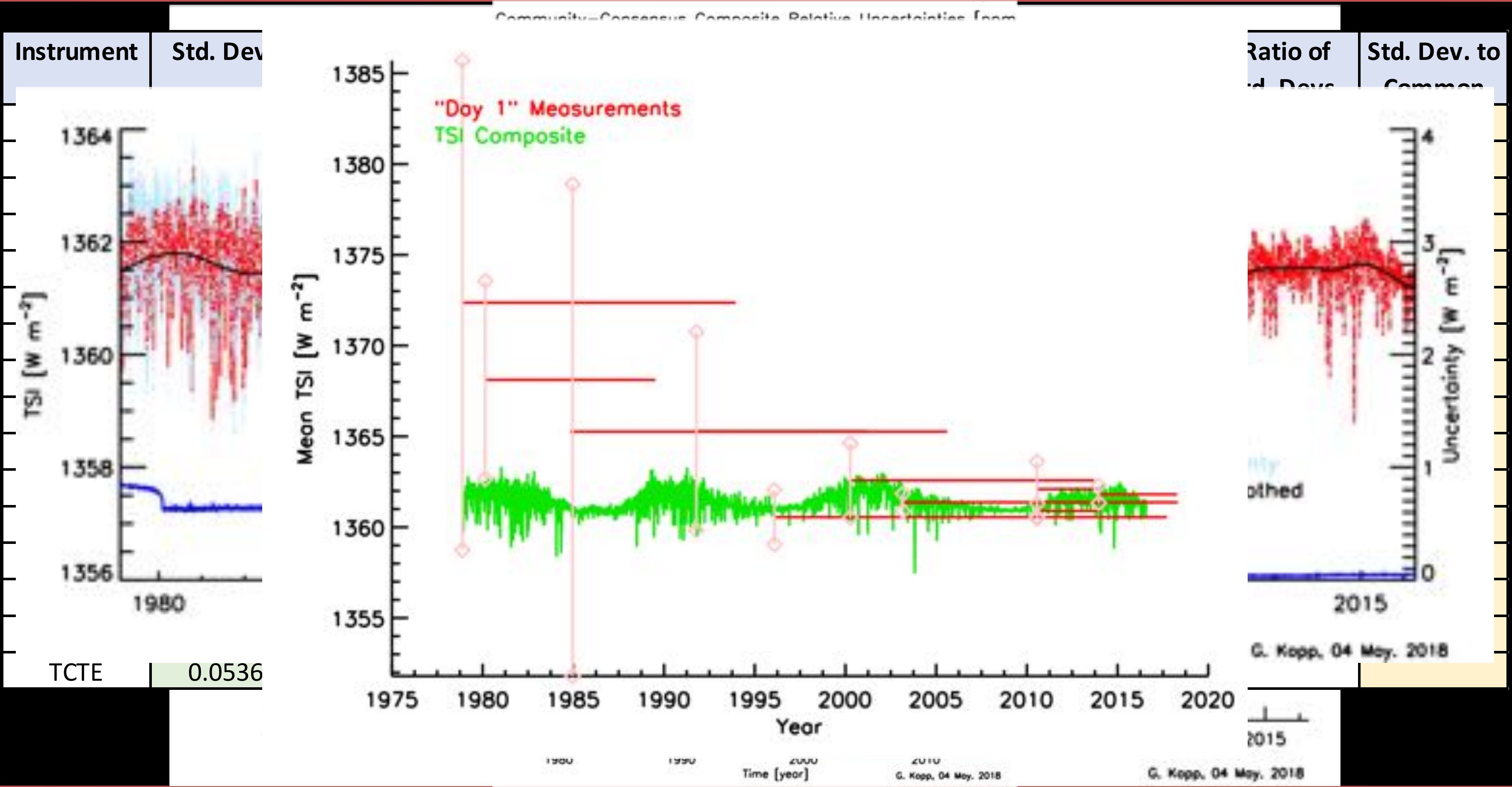


New TSI-Composite Methodology

- Estimate noise for each instrument based on high-frequency daily values
  - Predictive-model noise-estimating method agrees well with independent results from Kopp, *SWSC*, 2014
- Apply wavelet transform for scale-wise analysis
- Compute weighted average of all instrument data scale-wise based on frequency-dependent noise model
  - Extrapolate uncertainties scale-wise based on $1/f$ noise model
  - Surrounding values smooth gaps and discontinuities scale-wise
- Invert net wavelet transform
- Estimate uncertainties
  - Monte Carlo using $1/f$ noise model

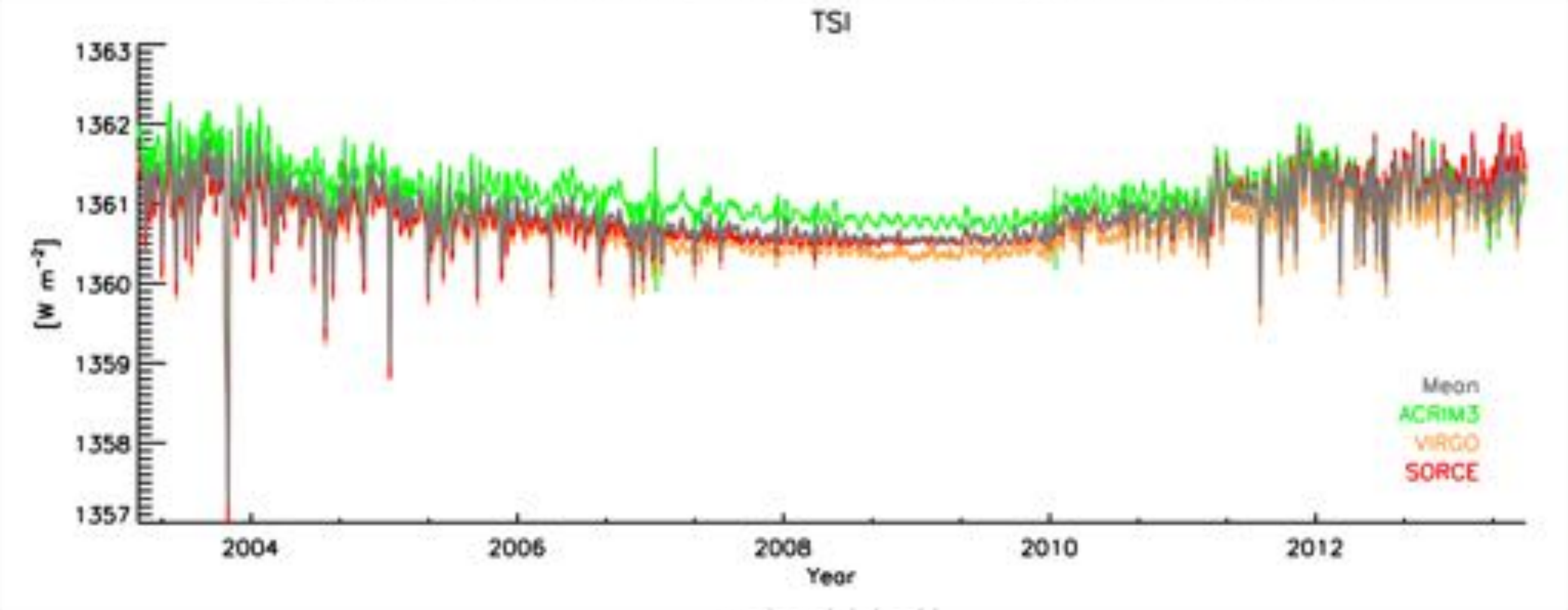
Methodology – Graphical

Instrument	Std. Dev	Ratio of d. Devs	Std. Dev. to Common
TCTE	0.0536		



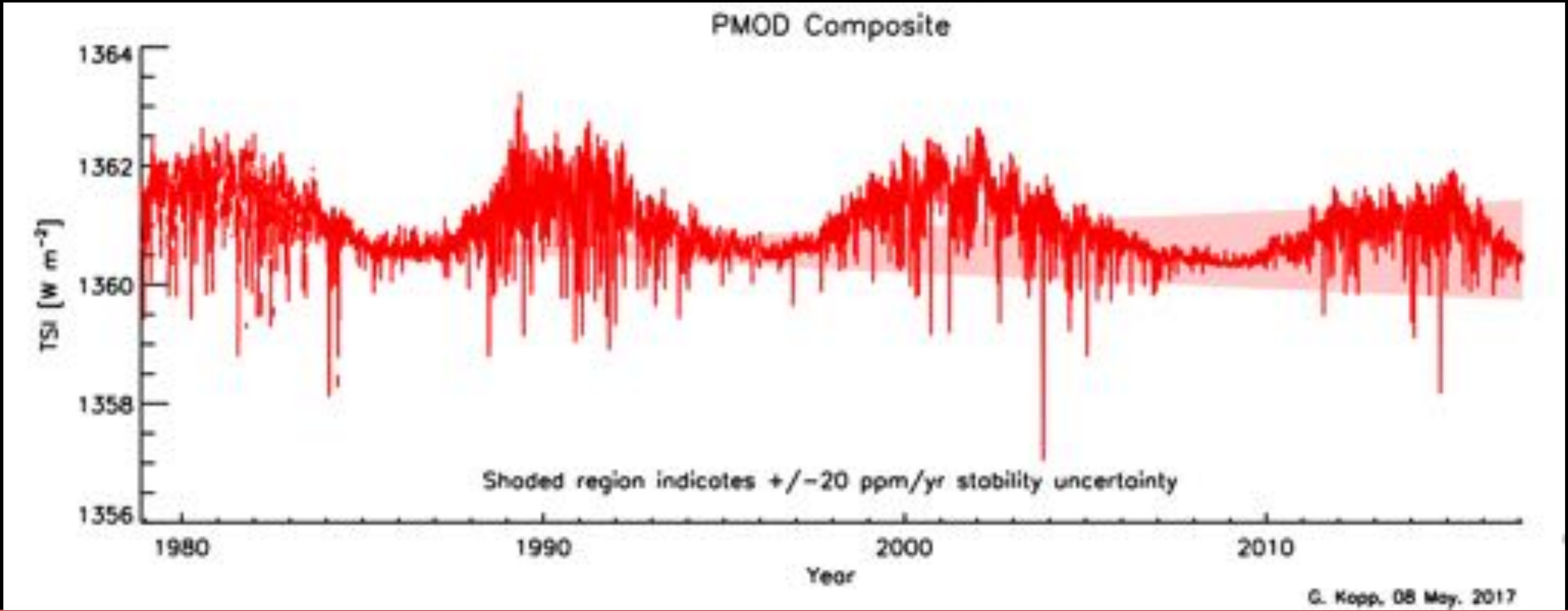
Measurement Differences Show 1/f Power Scaling

- Dispersion is not indicative of linear trends or of white noise
- Use as noise model of each instrument for scale-dependent weightings based on high-frequency predictive-model correlations

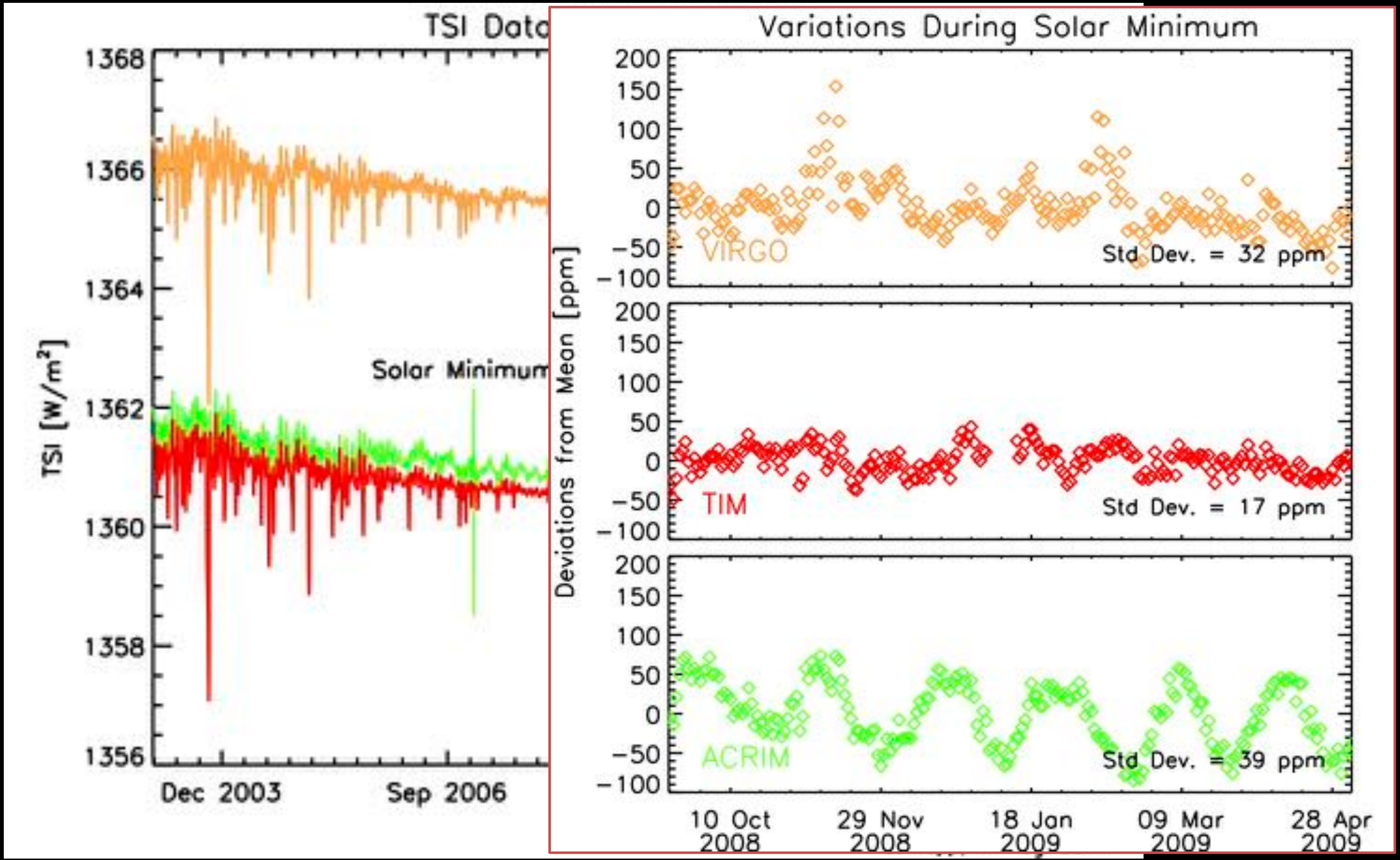


Wedge Trends in Differences Are Misleading

- Linear trends in instrument differences are not what is observed
- Linearly-increasing uncertainties overestimate actual uncertainties in time (eventually)



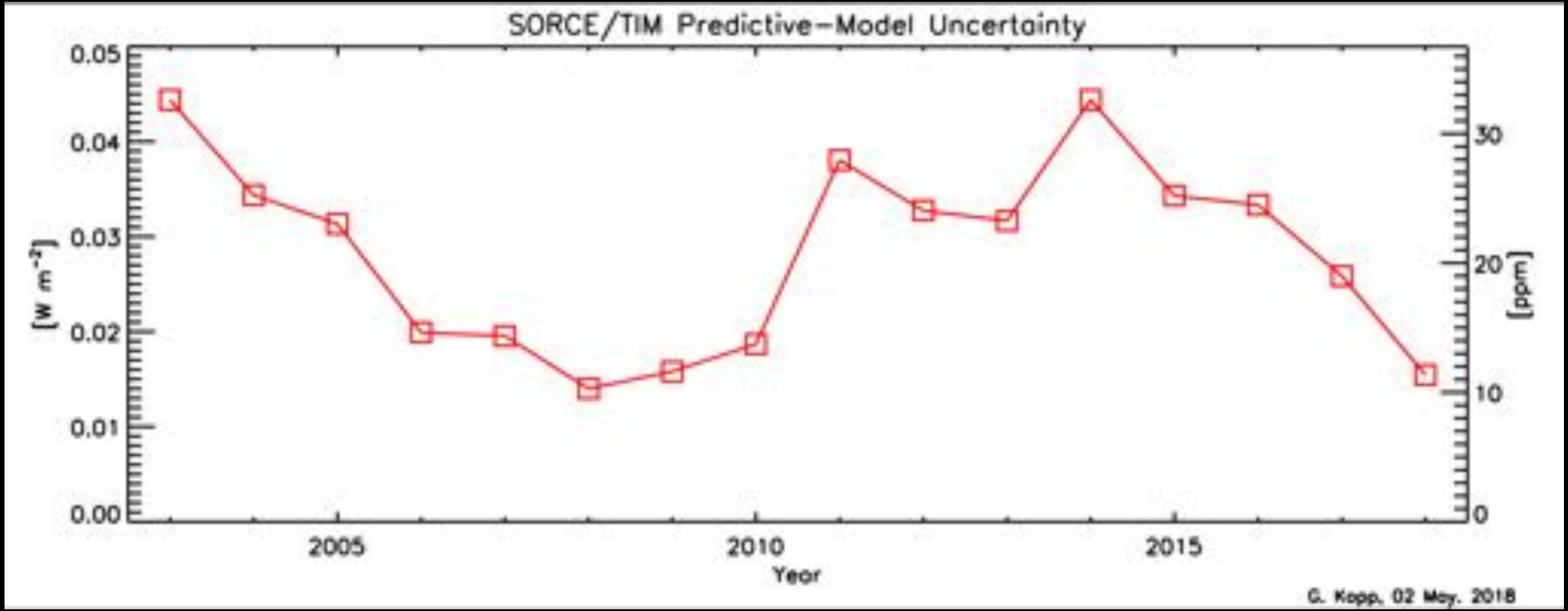
Comparisons During Solar Minimum Indicate Instrument Noise



Predictive Model Used to Estimate High-Frequency Uncertainties

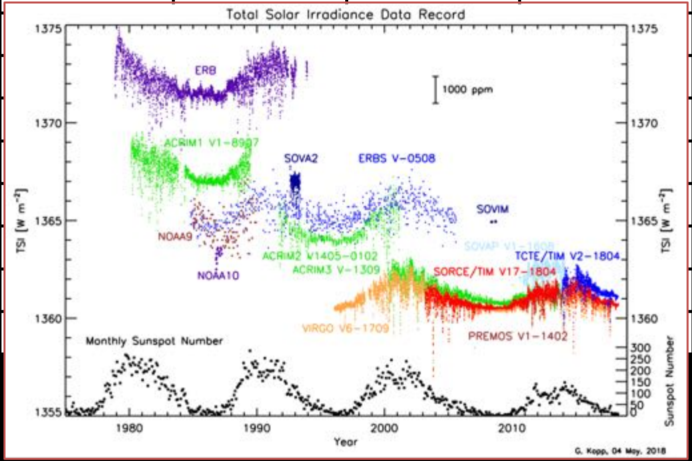
- Based on predictive model using daily values
  - Is time dependent because of solar variability

$$\hat{I}(t) = \sum_i a_i I(t_i \neq t)$$

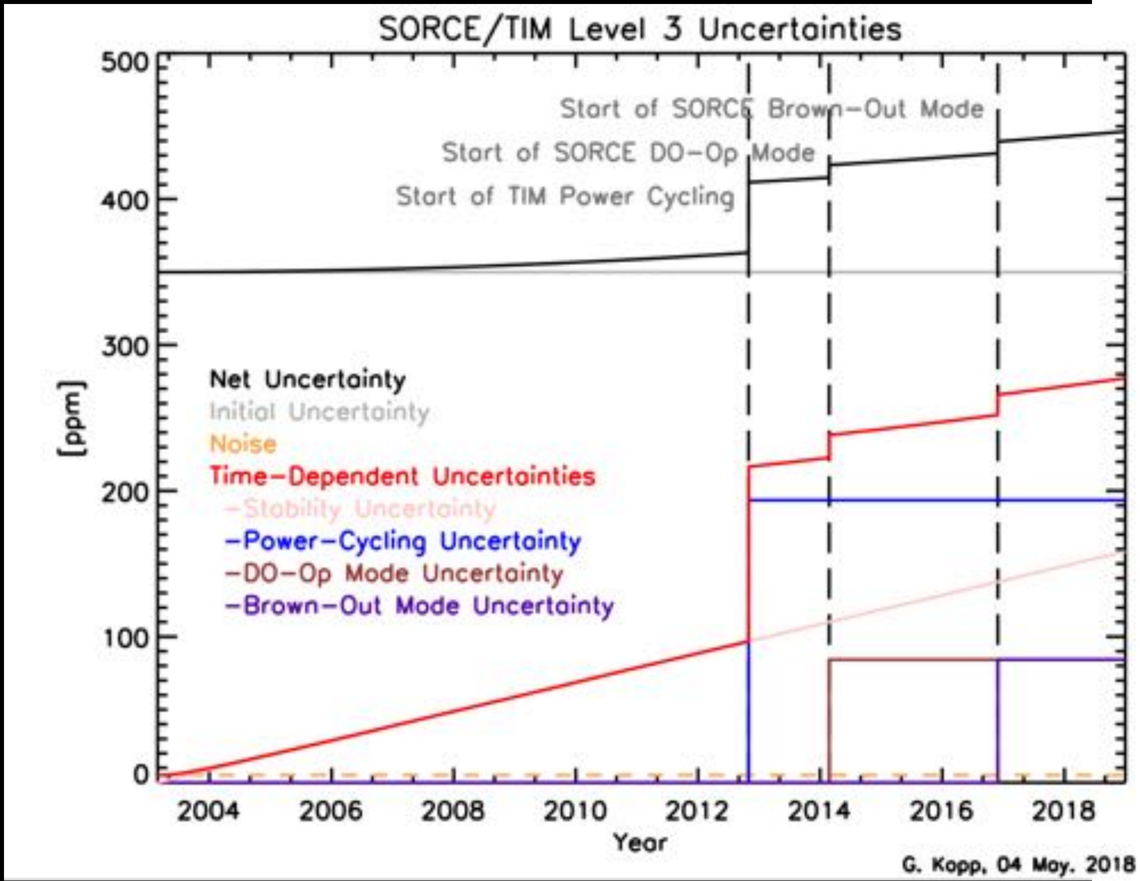


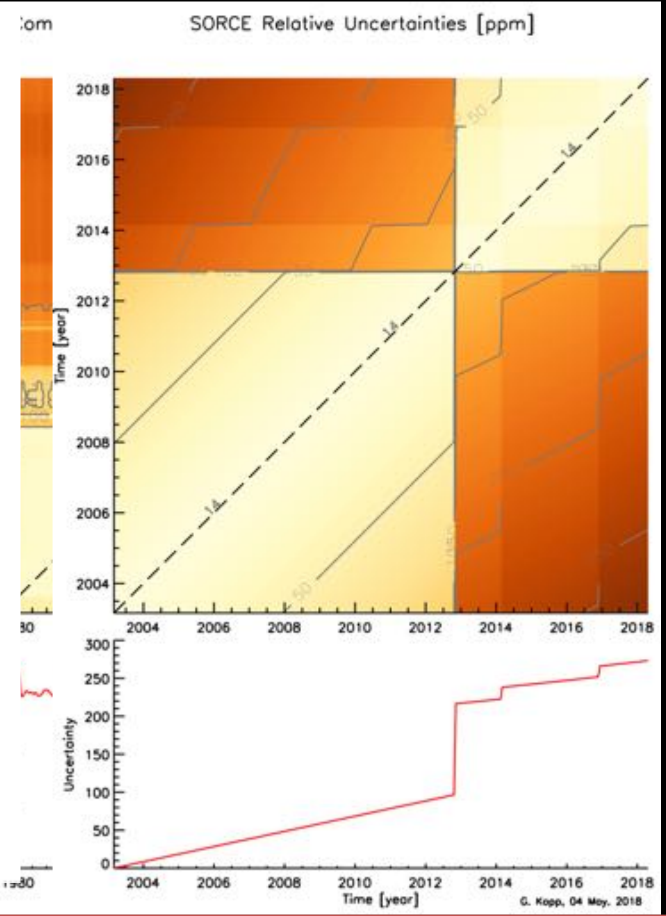
Predictive Model Used to Estimate High-Frequency Uncertainties

Instrument	Std. Dev.	R	Direct Reference	Std. Dev.	R	Overlap - Begin Date	Overlap - End Date	Ratio of Std. Devs.	Std. Dev. to Common
ACRIM1	0.1139	0.9705	NIMBUS7	0.1078	0.9727	16-Feb-1980	14-Jul-1989	*1.0561*	*0.4214*
NIMBUS7	0.1391	0.9849	ACRIM2	0.1439	0.9816	5-Oct-1991	12-Jan-1993	*0.9666*	*0.3991*
ACRIM2	0.3491	0.8560	VIRGO	0.0348	0.9975	28-Jan-1996	1-Mar-2001	*10.0277*	*0.4128*
ACRIM3	0.0326	0.9983	VIRGO	0.0424	0.9967	5-Apr-2000	17-Sep-2013	*0.7694*	*0.0317*
SORCE	0.0290	0.9977	VIRGO	0.0410	0.9946	25-Feb-2003	20-Sep-2017	*0.7058*	*0.0291*
PREMOS	0.0326	0.9953	VIRGO	0.0474	0.9901	27-Jul-2010	11-Feb-2014	*0.6885*	*0.0283*
TCTE	0.0591	0.9902	VIRGO	0.0416	0.9951	16-Dec-2013	20-Sep-2017	*1.4201*	*0.0585*
NIMBUS7	0.1099					16-Nov-1978	24-Jan-1993		
ACRIM1	0.2286					16-Feb-1980	14-Jul-1989		
ACRIM2	0.2618					5-Oct-1991	1-Mar-2001		
VIRGO	0.0412					28-Jan-1996	20-Sep-2017	common	*0.0412*
ACRIM3	0.0324					5-Apr-2000	17-Sep-2013		
SORCE	0.0286					25-Feb-2003	2-Apr-2018		
PREMOS	0.0326					27-Jul-2010	10-Feb-2014		
TCTE	0.0536					13-Dec-2013	2-Apr-2018		

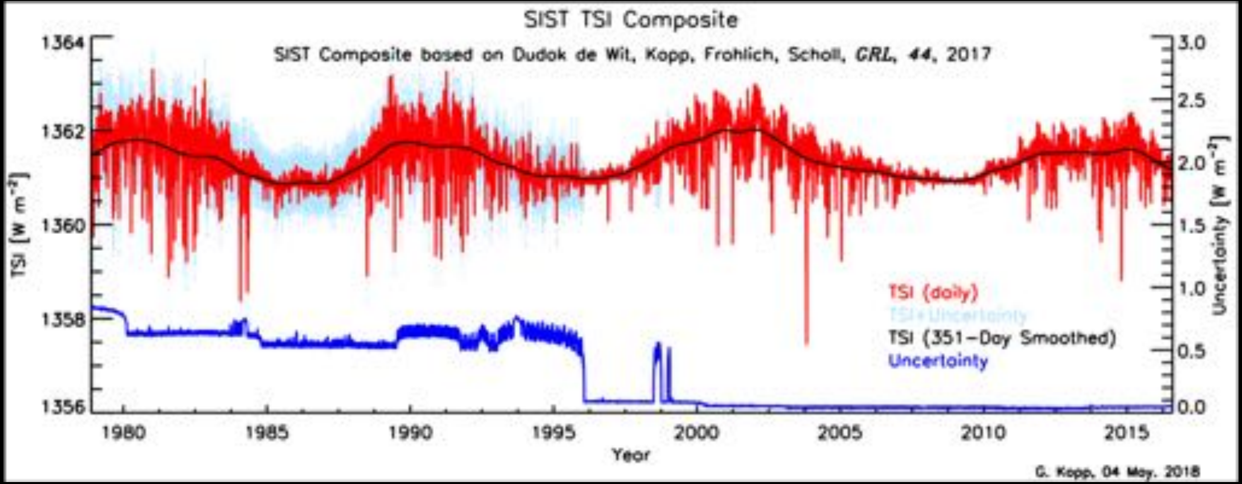


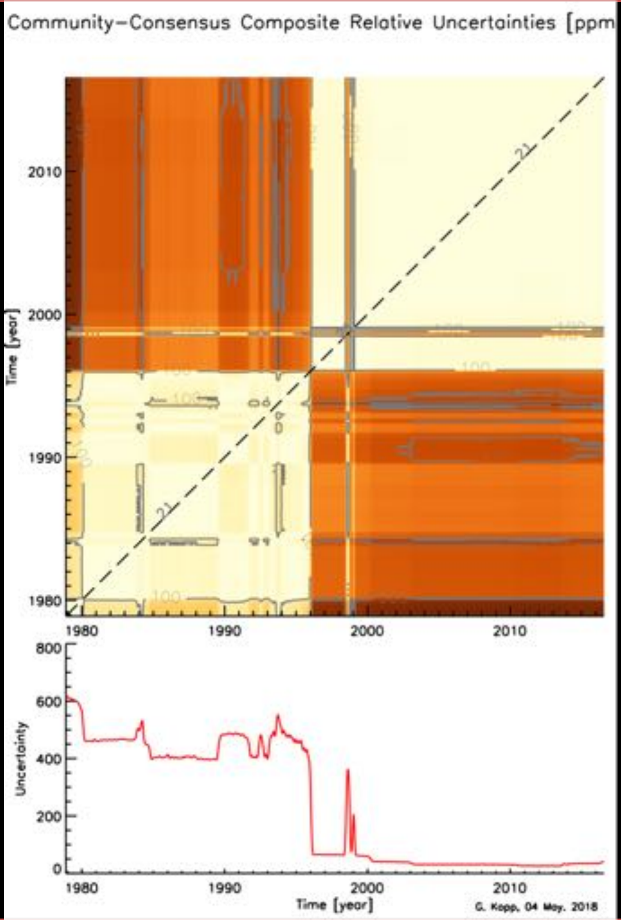
Relative Uncertainties Between Times Need to Be Expressed in 2D



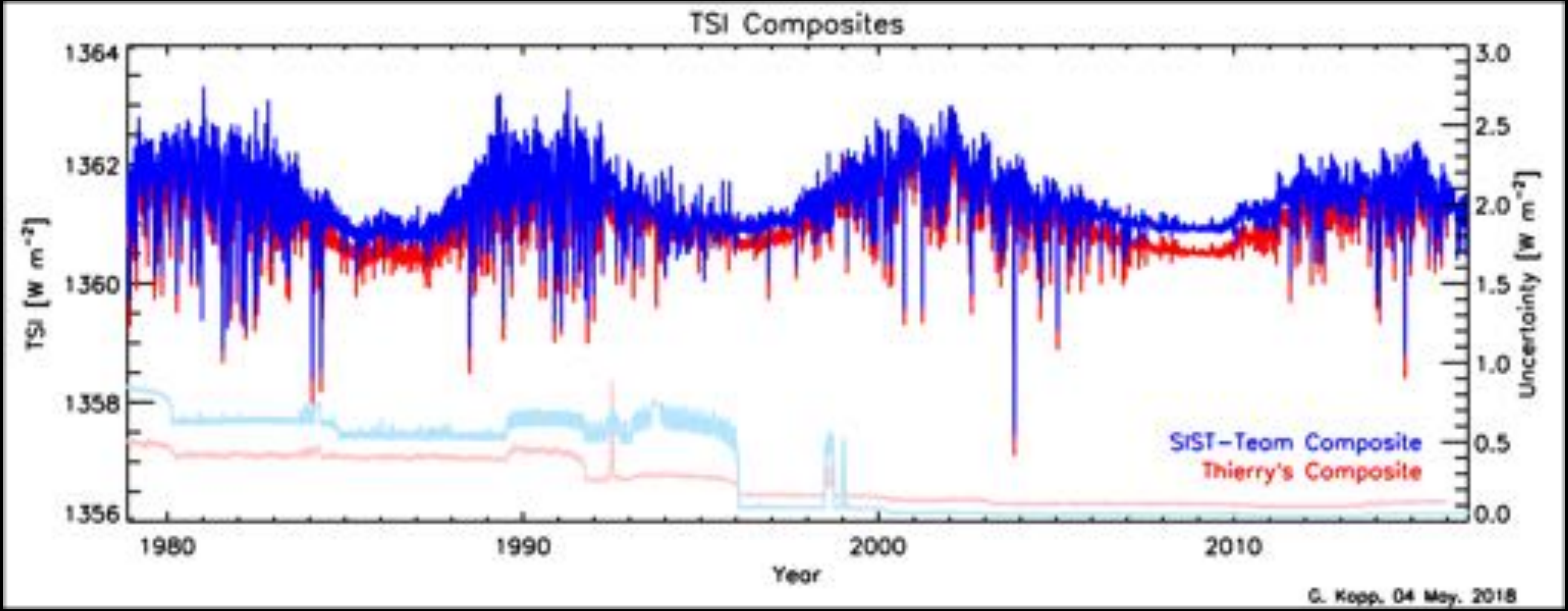


Composite Plot and Uncertainties in 2D





LASP Has Methodology in Place for Continued Updates



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

(needs updating for latest data)

Instrument	TSI Value	Stated Uncertainty	Stated Uncertainty	Begin Date	End Date	
	[SI W/m2]	[W/m2]	[ppm]			
ACRIM3	1360.78	1.36	1000.0	20-Sep-08	5-May-09	
PREMOS	1360.55	0.50	365.2	20-Sep-08	5-May-09	est. via comparisons
TIM	1360.56	0.48	350.0	20-Sep-08	5-May-09	
VIRGO	1359.19	2.60	1911.0	20-Sep-08	5-May-09	
Wgt Ave	**1360.54**	**0.36**	**266.8**	20-Sep-08	5-May-09	

Uncertainties are 1-σ

References for Team Stated Uncertainties

ACRIM3: uncertainty provided by Dick via e-mail, 14 May 2013; V.2013-11
DIARAD: included with VIRGO per decision at 1st ISSI Team Meeting and per '2014-05 VIRGO Characterization.pdf'
PREMOS: André Fehlmann thesis "Metrology of Solar Irradiance," Universität Zürich, 2011; V.2013-05
TIM: Kopp & Lean, "A New, Lower Value of Total Solar Irradiance," GRL, 38, L01706, doi:10.1029/2010GL045777, 2011; V.16
VIRGO: based on all four channels using V.7 corrected for scatter (see '2014-05 VIRGO Characterization.pdf')

Issues with Originally-Planned Approach for Absolute Value

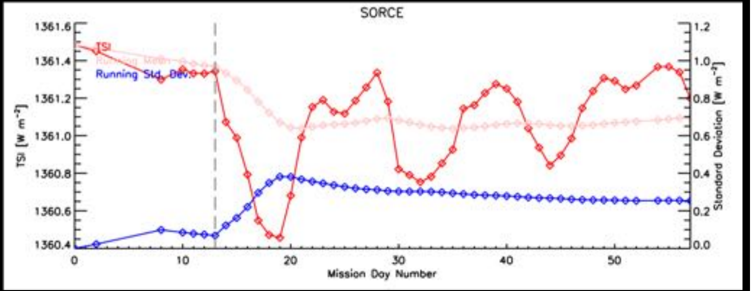
- "Latest" measurements vary with time
  - ACRIM3, PREMOS, SORCE/TIM, and VIRGO will not always be the most current measurements
    - They already aren't
  - Need to accommodate newer instruments as available
- 2008 solar-minimum temporal region of overlap isn't measured by newer instruments
- Does not use all available instruments

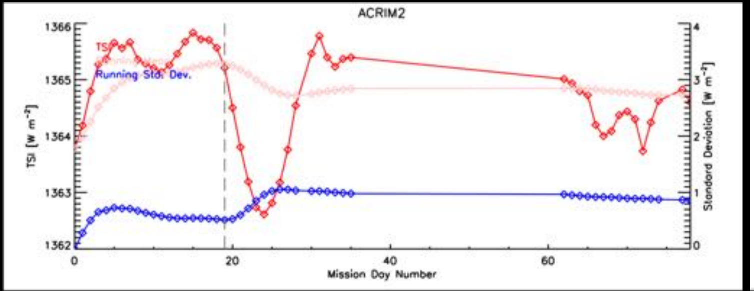
Agreed to use "Day 1" mean with weightings by estimated instrument uncertainties

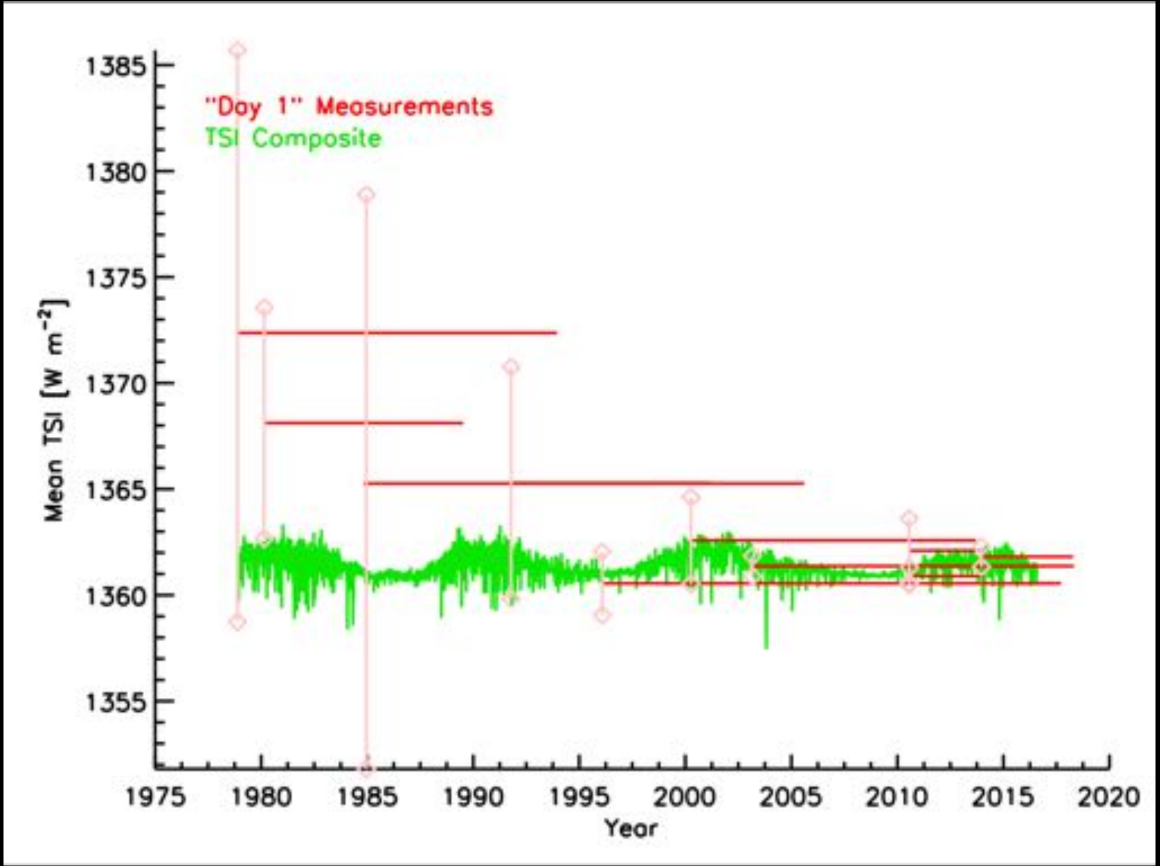
Normalize composite to resulting weighted mean

Adjust to Absolute Value Based on "Day 1" Measurements

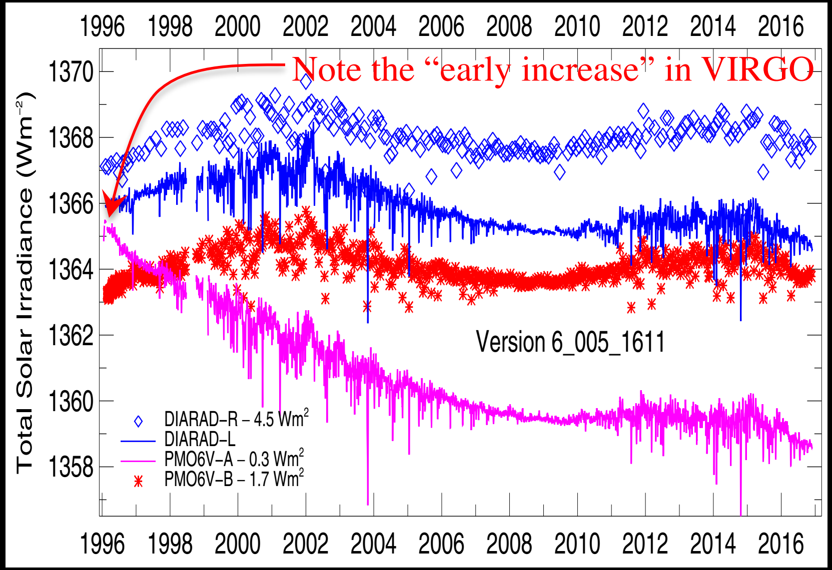
- Use data from all instruments
  - Weighted average of "Day 1" values
  - Average first few measurements







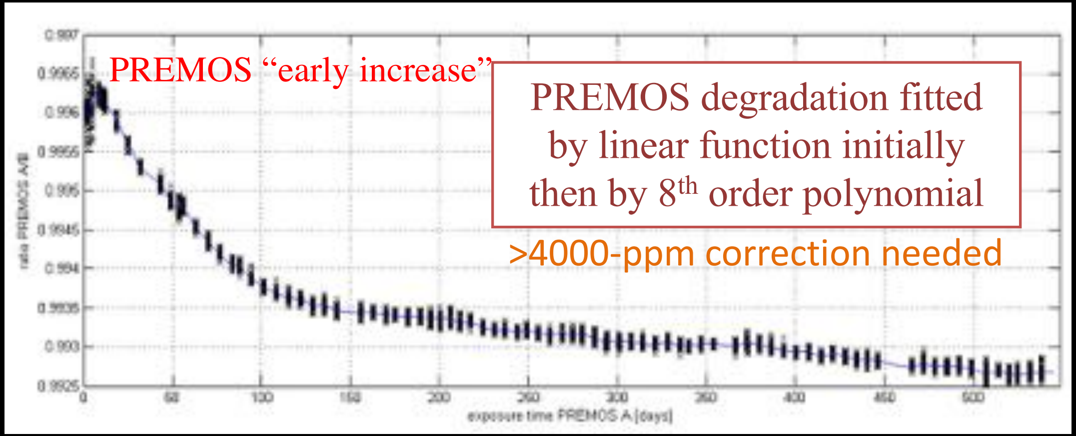
VIRGO and PREMOS Had Large "Early Increases"



VIRGO Level 1 Data (all 4 channels)

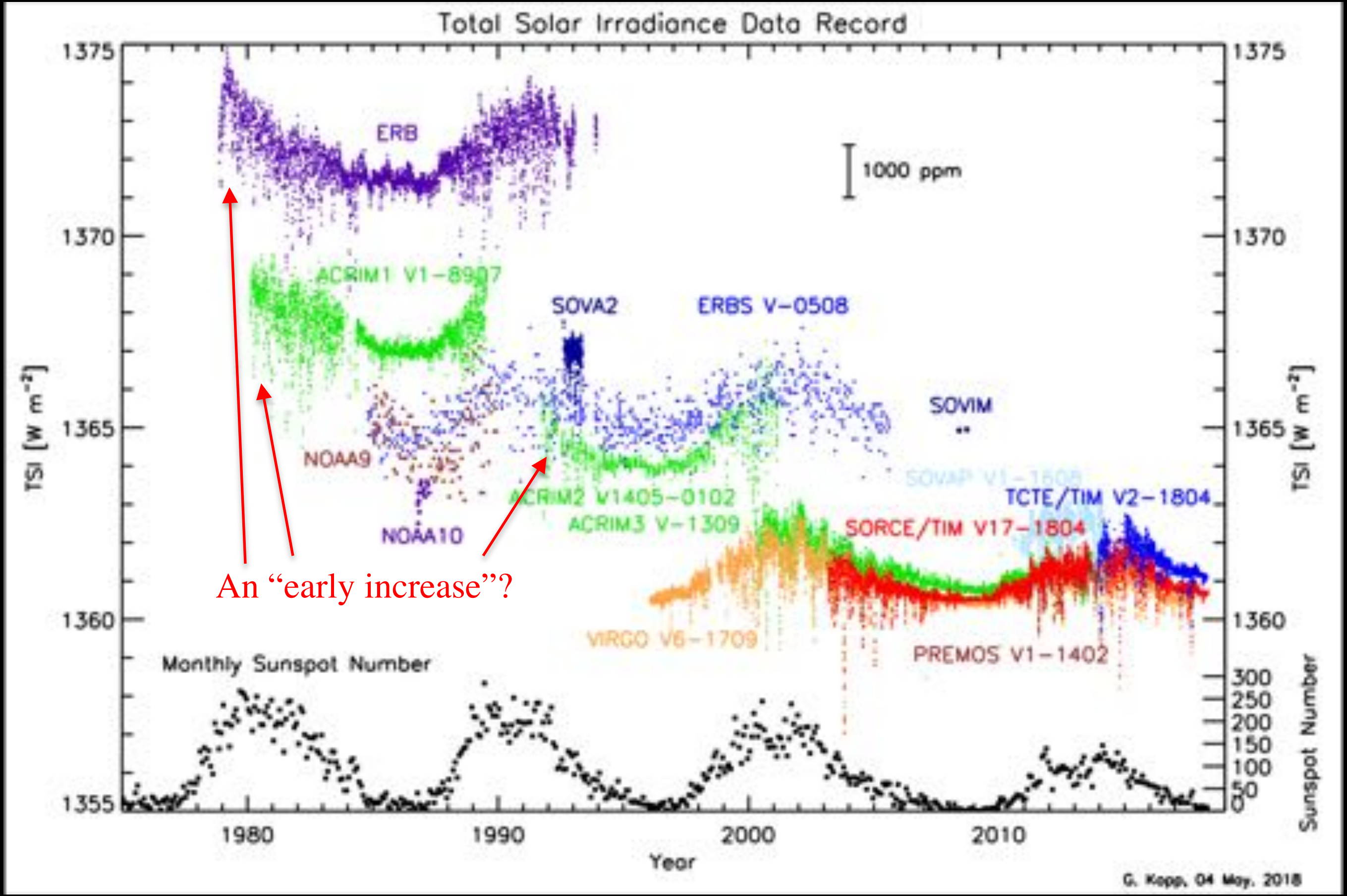
>4000-ppm correction needed

- Both the VIRGO and the PREMOS had ~600 ppm increase at very beginning of mission

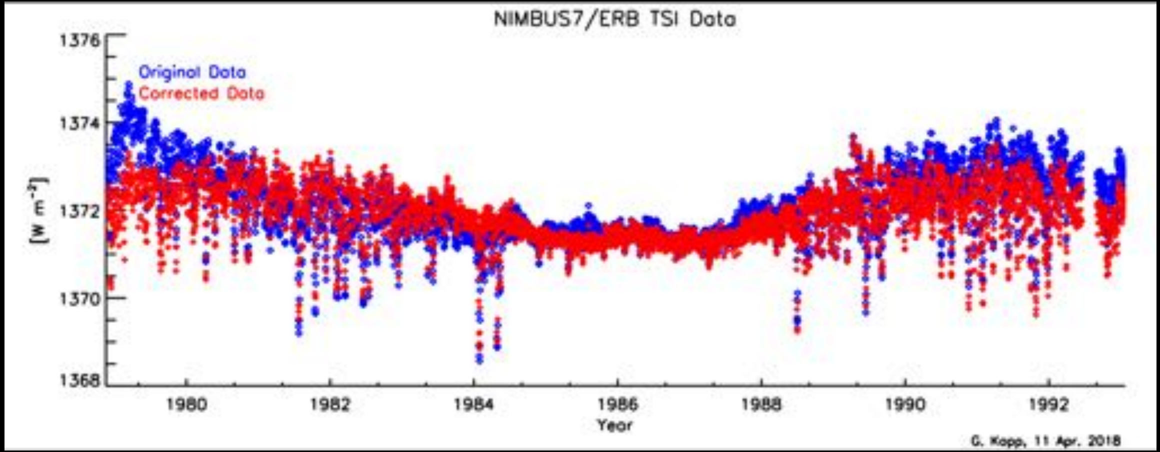


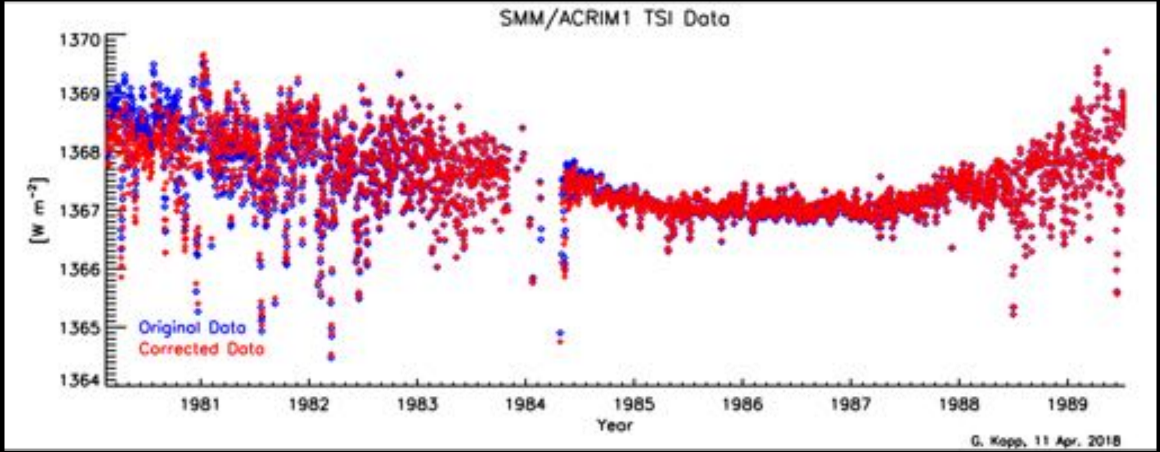
>4000-ppm correction needed

Current TSI-Measurement Record



Decided to Use "Early Increase" Corrections





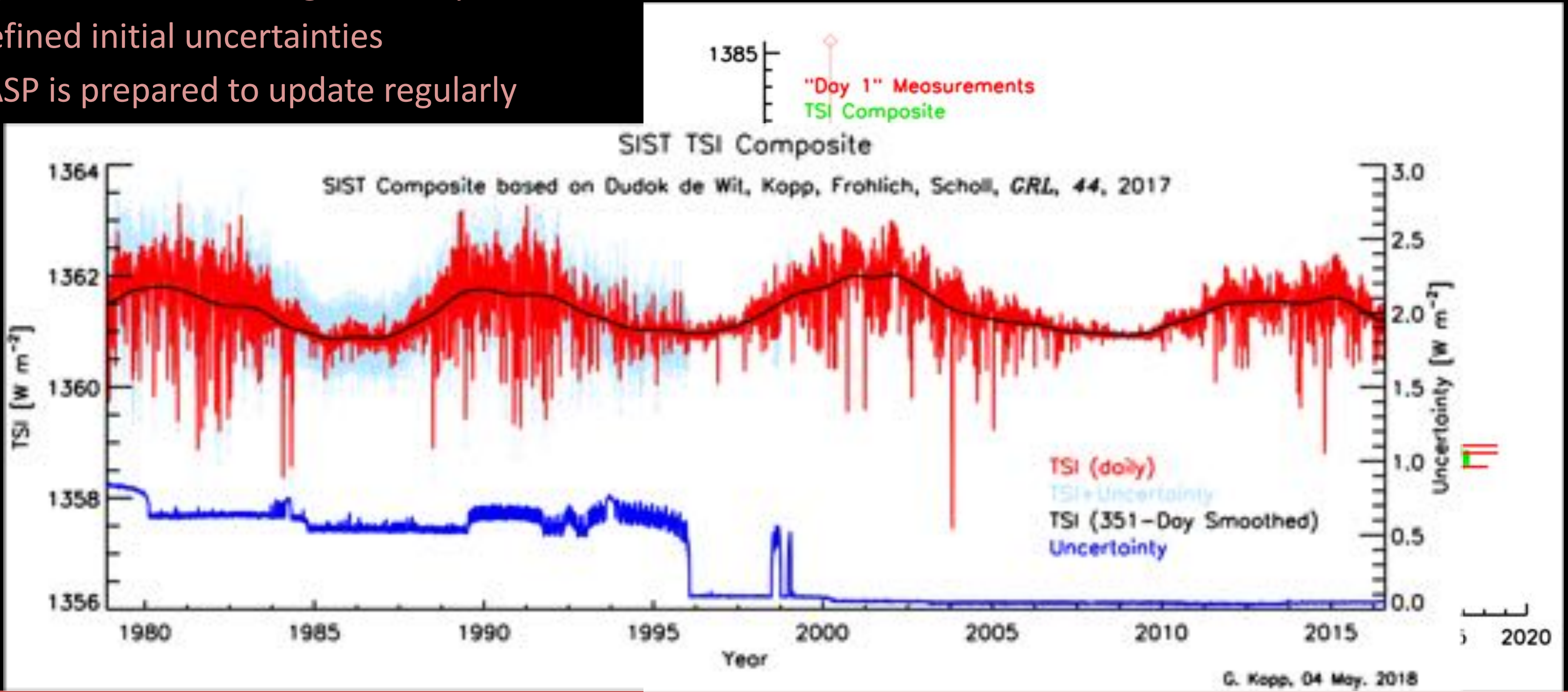
data courtesy of Claus Fröhlich

Data for Composite Must be Publicly Available

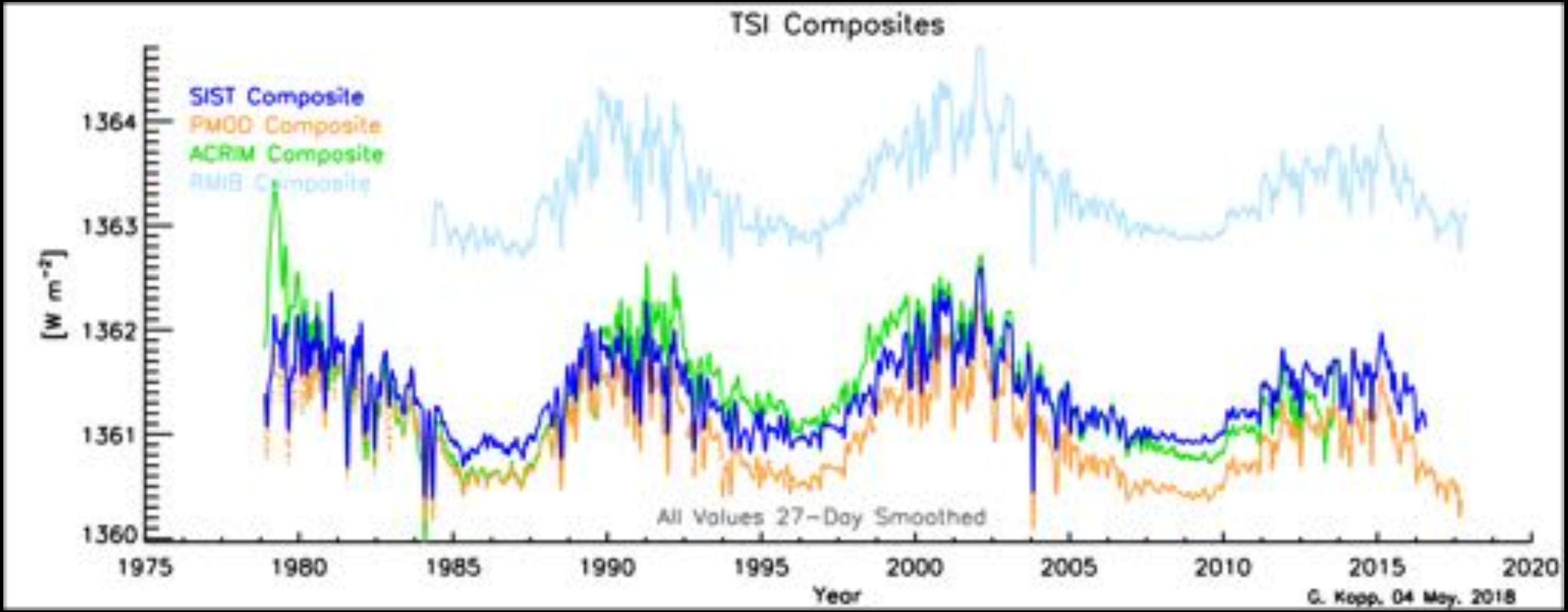
- Transparency to community is important for acceptance

"Community Consensus" TSI Composite

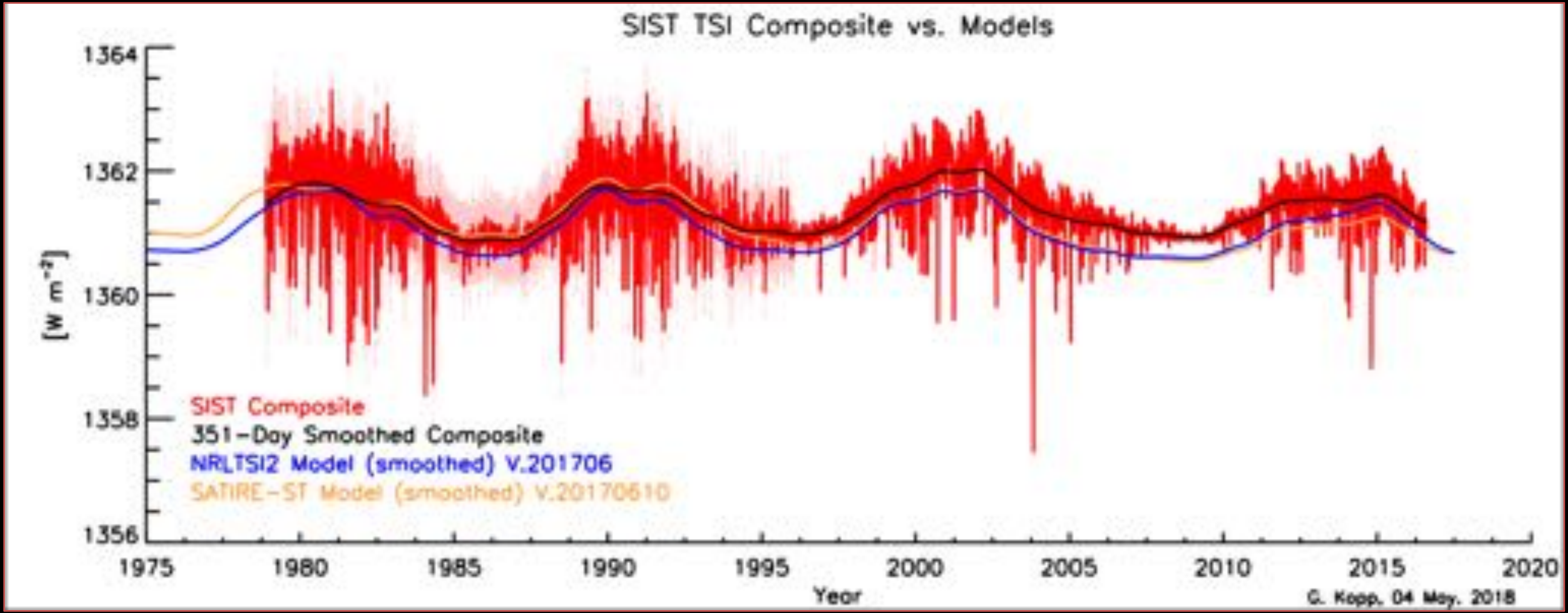
- "Community consensus" composite refinements
  - TSI teams recently agreed on using data corrected for early increases
  - Agreed to scale to weighted "Day 1" absolute value of all instruments
  - Refined initial uncertainties
  - LASP is prepared to update regularly



Comparisons of Composites



Comparisons of Models and Community-Consensus Composite



Future Efforts

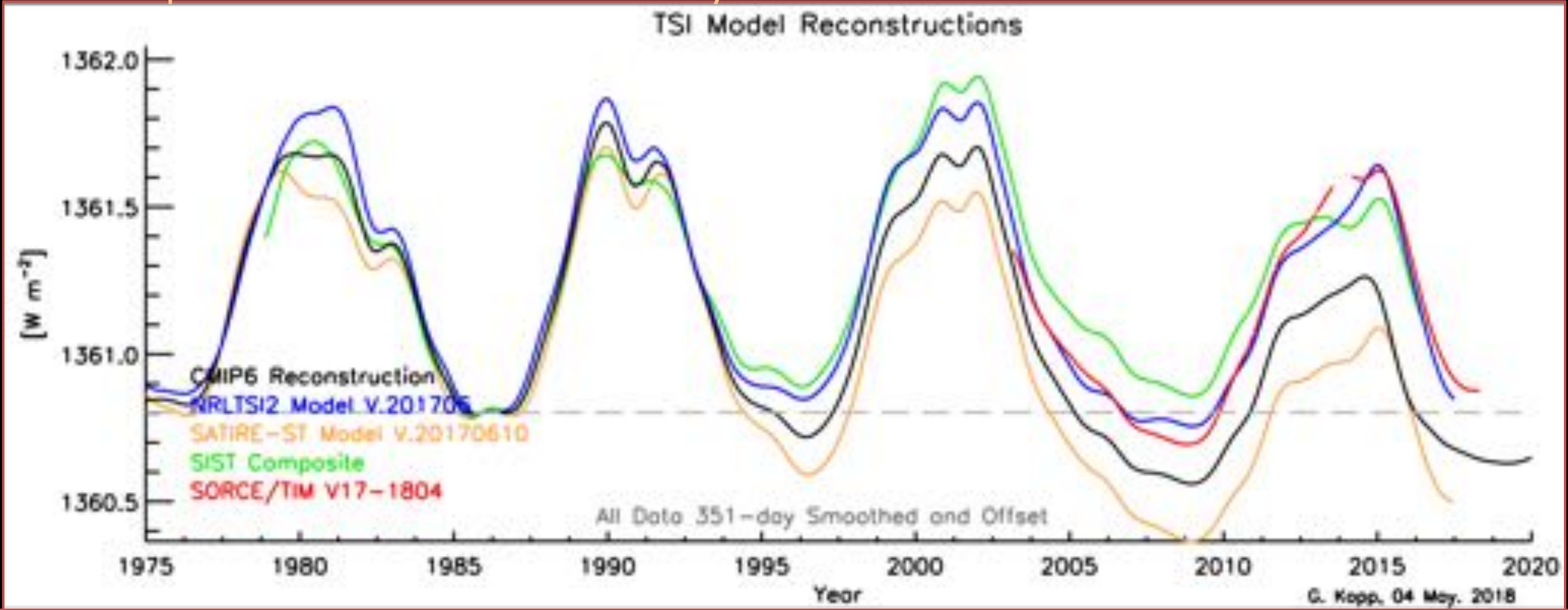
- Improvements to composite itself
  - Modify initial weightings based on known instrument artifacts
  - Refine uncertainties for early instruments relative to later ones
  - Consider appropriateness of applying 1/*f* spectral variation to all instruments
  - Improve method of adding/losing instruments
  - ”Sanity check”
- Provide regular updates as new data or instruments become available
- Publish and serve resulting composite to research community

Future Improvements / Ideas

- Predictive Model: Instead of applying from only the preceding points, apply to surrounding points
- Noise Determination: Use SVD of high-frequency components to determine common modes between two or more instruments. These are presumably solar in origin. The remainder is instrument noise.
- Data gaps: Look for common-mode between instruments from SVD. Time-extend using another instrument's wavelets for times when desired instrument lacks data.
- Consider ERBS: Is 1/*f* noise model appropriate for this instrument?

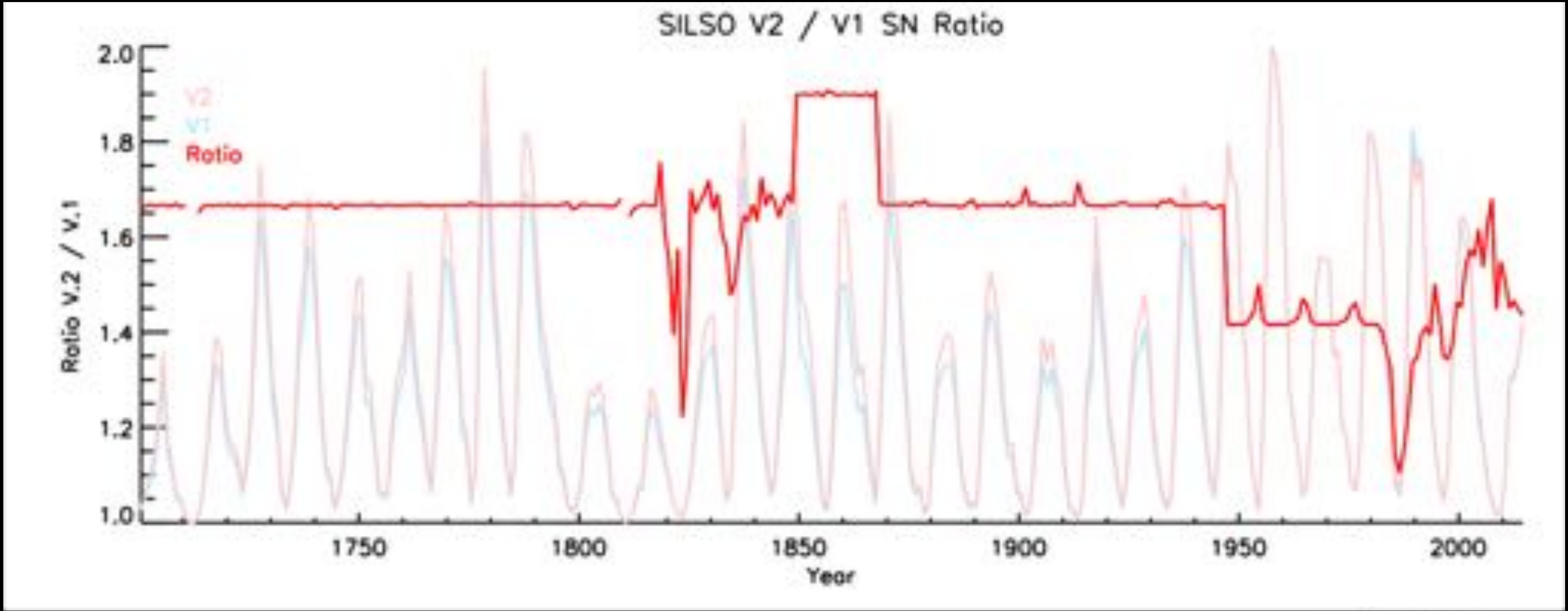
And Then What Else Is Needed?

- Models to extend to historical times are getting more sophisticated
  - But downward trend of SATIRE relative to measurements and NRLTSI in recent decades is concerning
  - CMIP6 clarity on model versions used
- The sunspot-number reconstruction may make this all irrelevant...



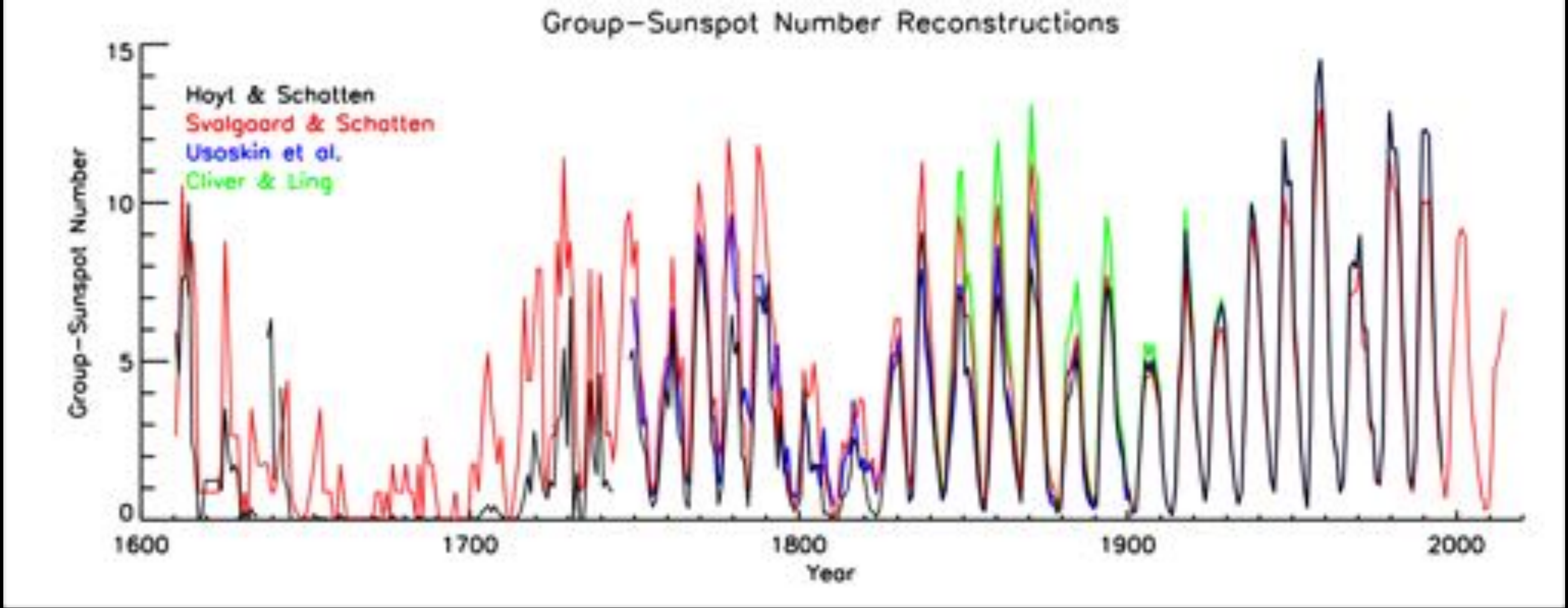
New Sunspot-Number Reconstruction(s)

- Community reanalysis of sunspot-number records lead to new series
  - Clette & Lefèvre, "The New Sunspot Number: Assembling All Corrections," *Solar Physics*, **291**, 2016



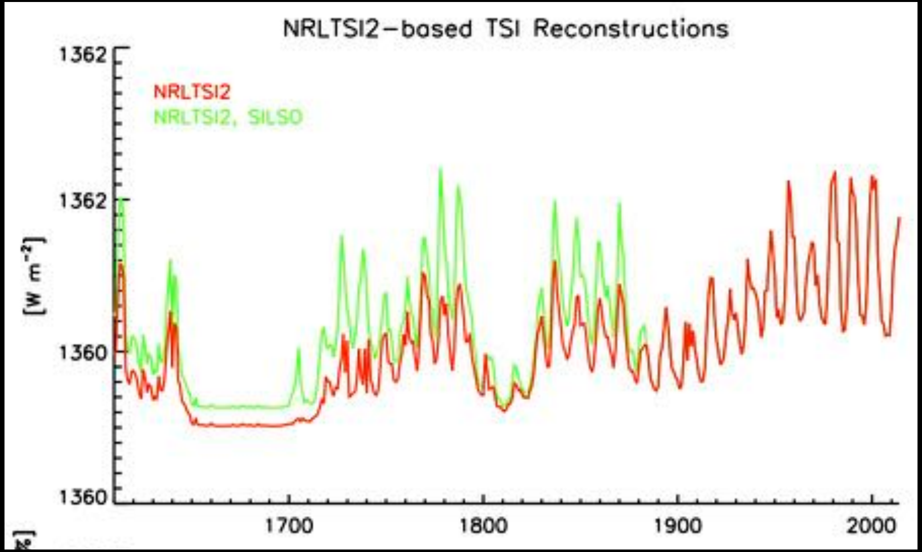
New Sunspot-Group-Number Reconstruction(s)

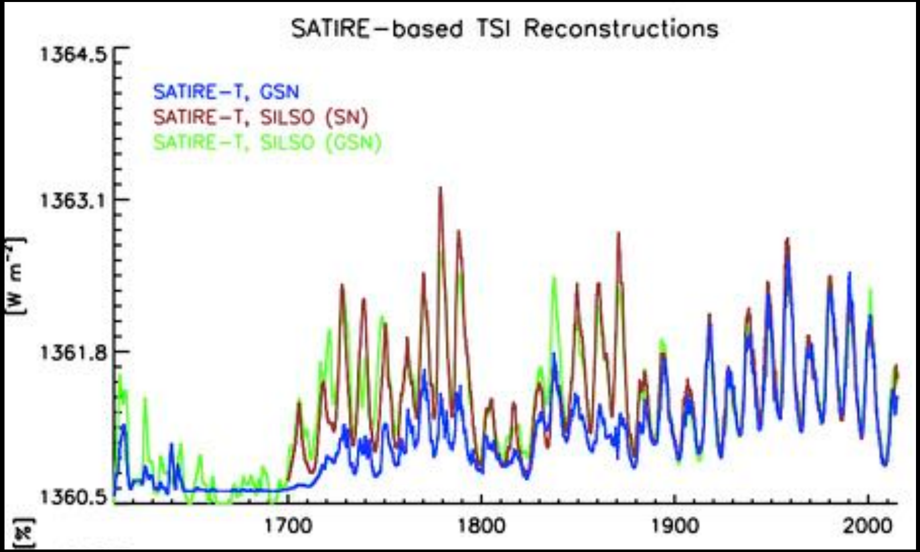
- Community reanalysis of sunspot-number records leads to new series
  - Svalgaard & Schatten, "Reconstruction of the Sunspot Group Number: The Backbone Method," *Solar Physics*, **291**, 2016



Sensitivity of TSI Models to Sunspot Record(s)

Kopp, G., Krivova, N., Lean, J., and Wu, C.J., "The Impact of the Revised Sunspot Record on Solar Irradiance Reconstructions," *Solar Physics*, 2016, doi: 10.1007/s11207-016-0853-x





“TSI Reconstructions Based on Updated TSI Composite and Sunspot Records”

- ***Update the 400-year sunspot record*** used in TSI models for historical reconstructions
- ***Re-compute flux-transport results*** to improve historical solar-variability estimates
- ***Improve the TSI-measurement composite***, providing a reference for TSI models

Team Member	Expertise
Odele Coddington	NRLTSI modeler; historical solar-irradiance extensions
Thierry Dudok de Wit	TSI-composite methodology creator; ISSI sunspot-team member
Greg Kopp	TSI instrument scientist; TSI-composite team leader; ISSI sunspot-team member
Natalie Krivova	SATIRE modeler; historical solar-irradiance extensions
Judith Lean	NRLTSI modeler; historical solar-irradiance extensions
Lisa Upton	Flux-transport and dynamo modeler
Chi-Ju Wu	SATIRE modeler; historical solar-irradiance extensions