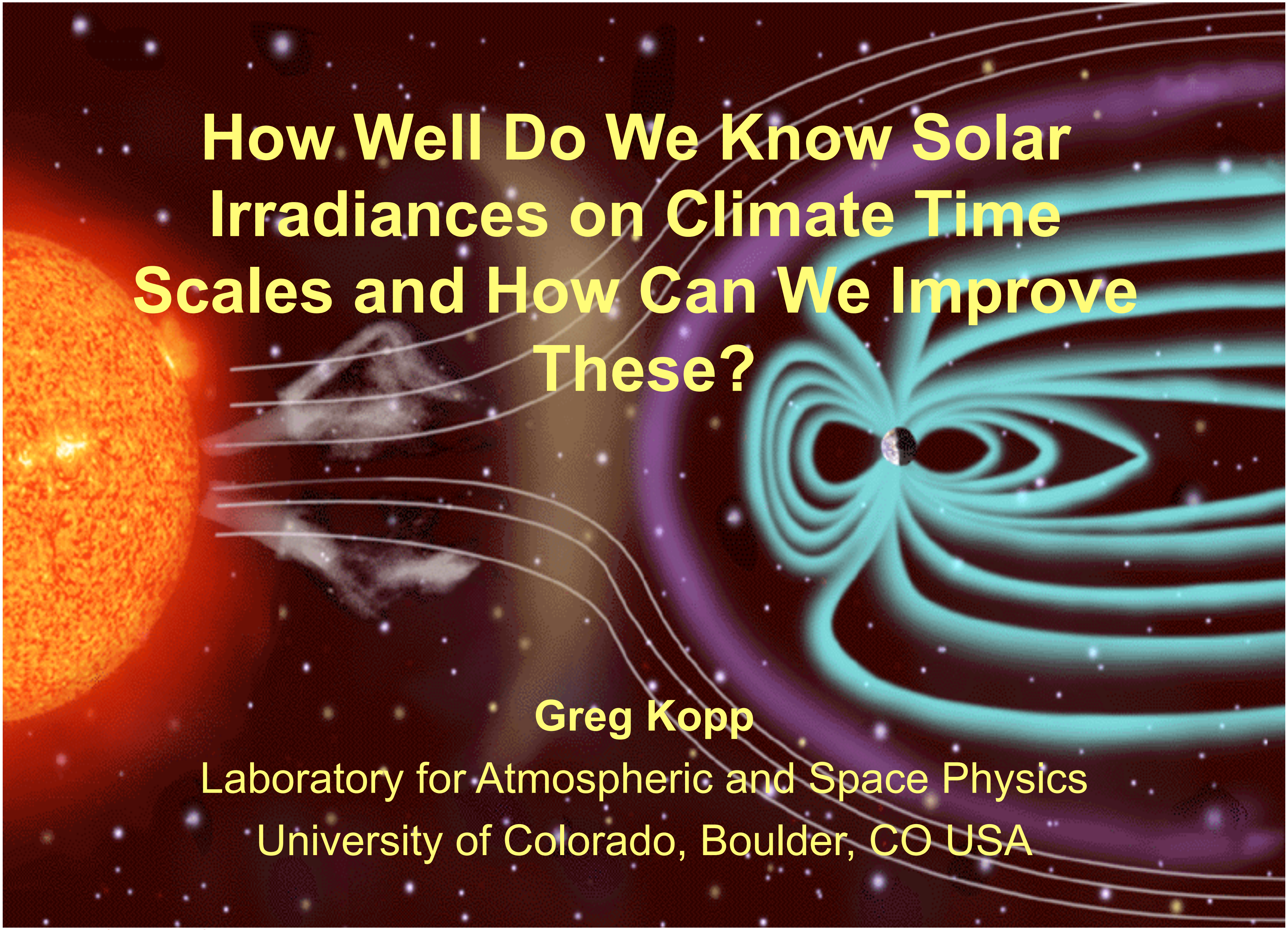
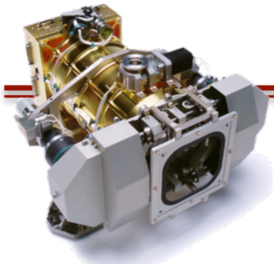


How Well Do We Know Solar Irradiances on Climate Time Scales and How Can We Improve These?

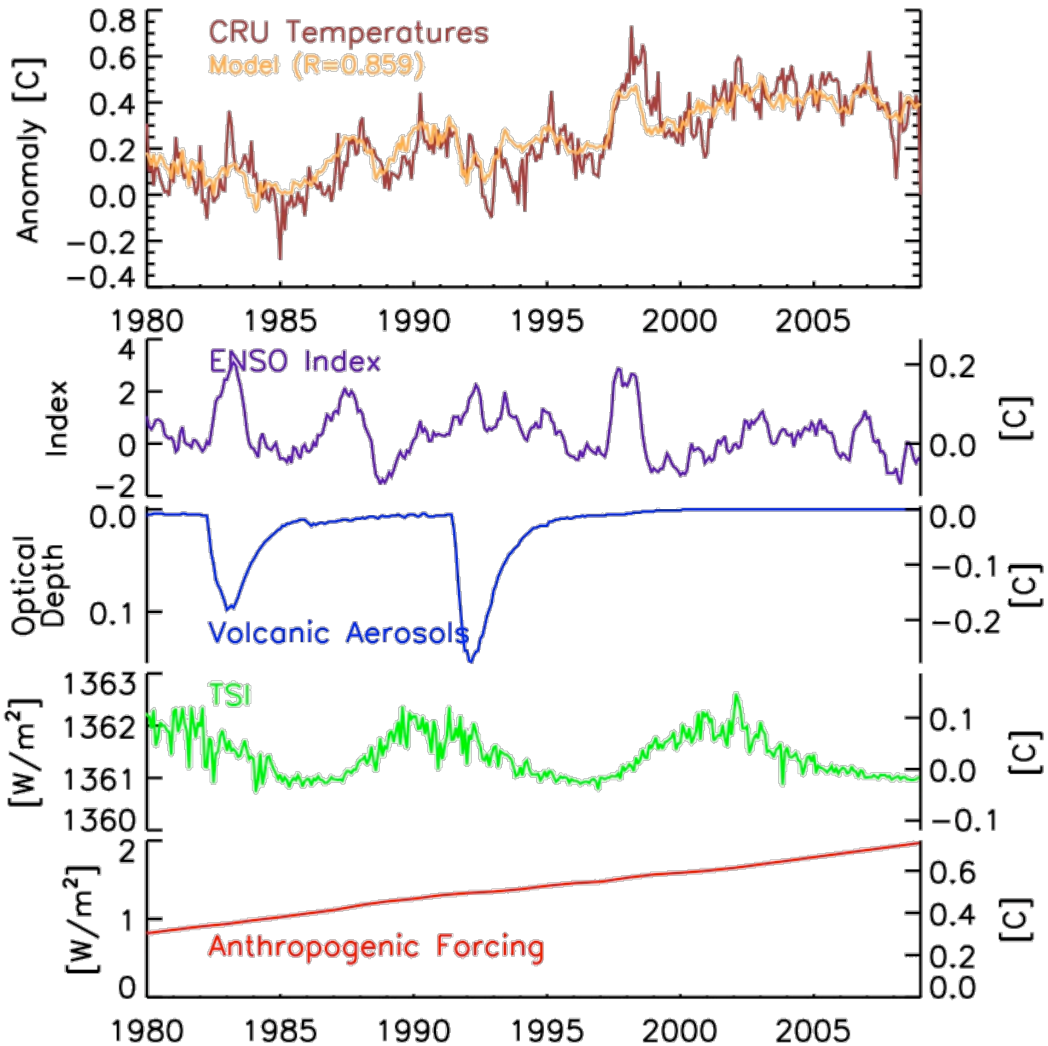
Greg Kopp

Laboratory for Atmospheric and Space Physics

University of Colorado, Boulder, CO USA



Global Surface Temperature Responds to Natural and Anthropogenic Influences



76% of observed temperature variance explained by:

1. *ENSO +*
2. *volcanic aerosols +*
3. *solar activity +*
4. *anthropogenic influences*

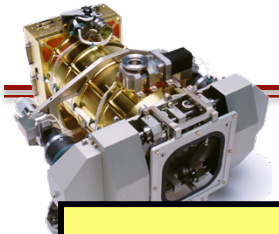
lack of warming for over a decade…

decreasing solar irradiance since 2002 + 2008 La Nina

1998 the warmest year on record…

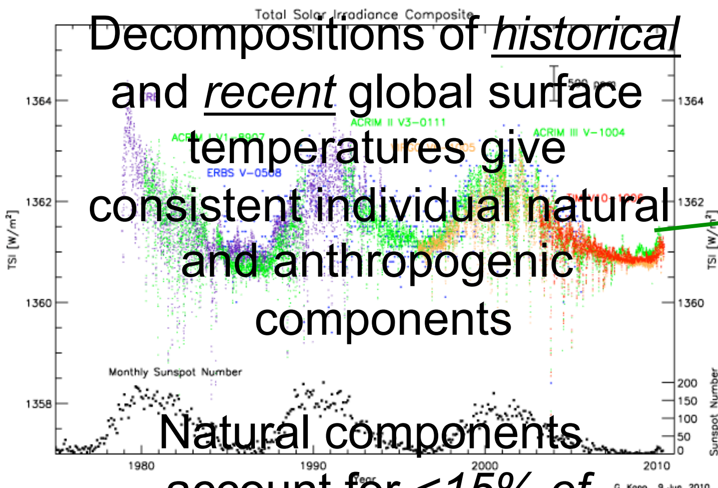
super El Nino, no volcano

courtesy of Judith Lean



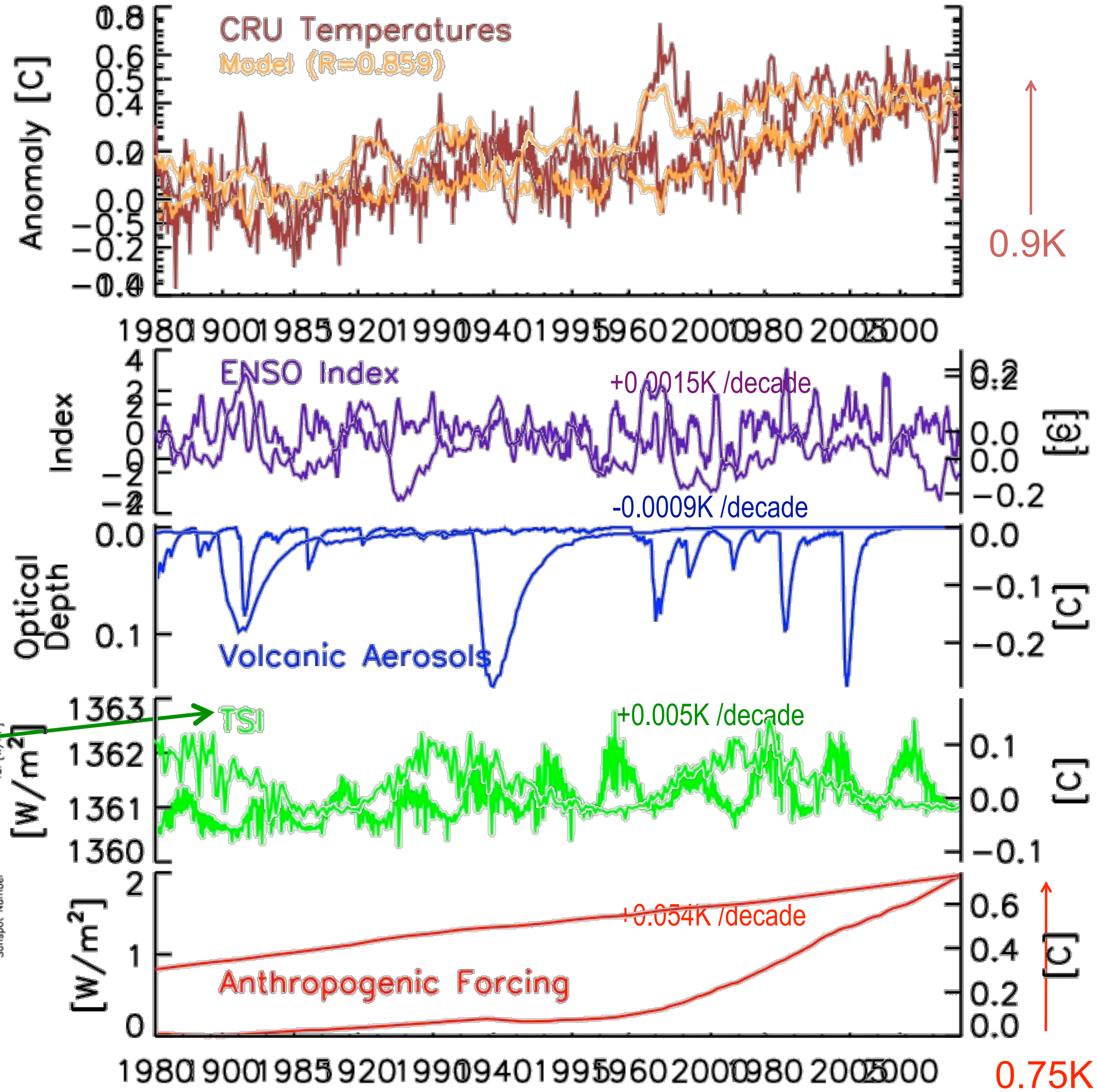
TSI Is The Dominant Driver of Earth's Climate

Solar activity proxies based on the 30-year TSI record provide inputs used in climate models.

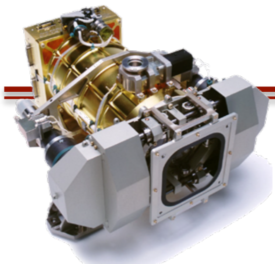


Decompositions of *historical* and *recent* global surface temperatures give consistent individual natural and anthropogenic components

Natural components account for *<15% of warming* since 1890

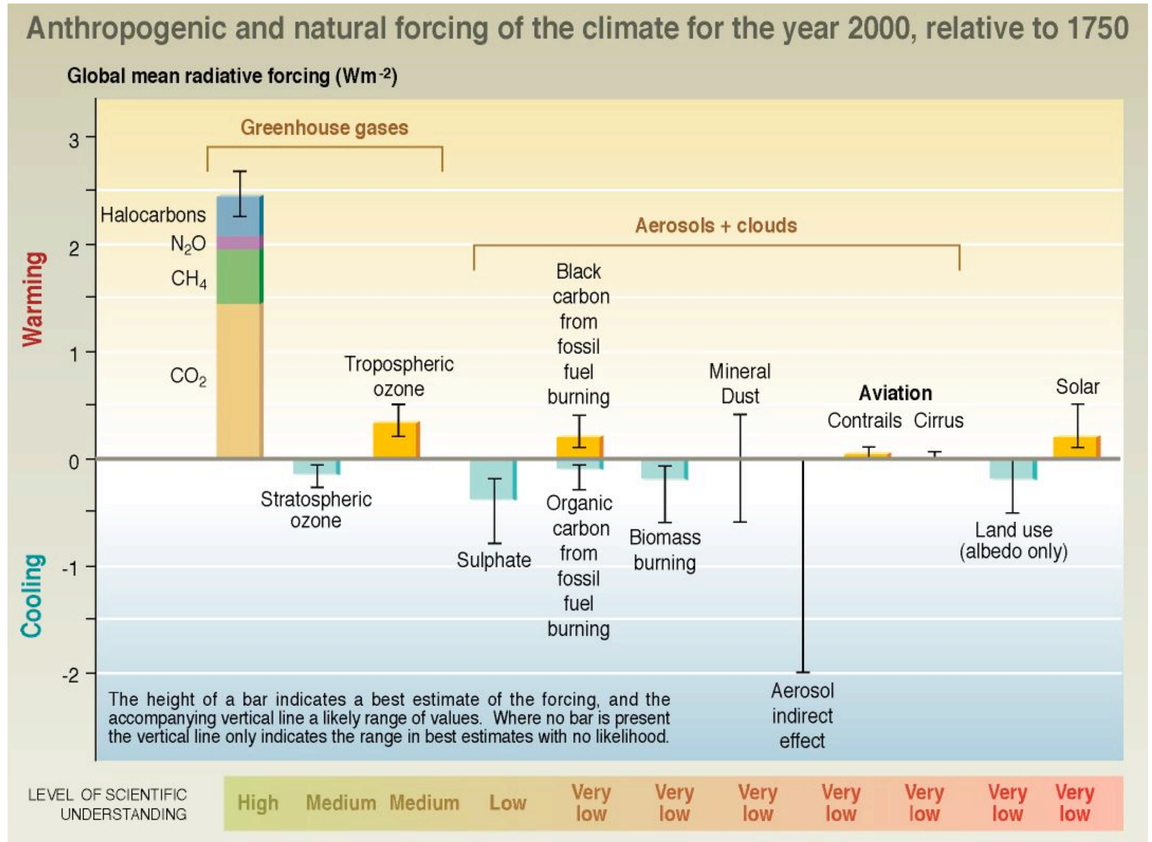


courtesy of Judith Lean

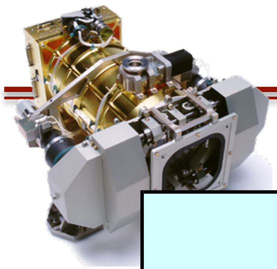


Primary Climate Forcing Agents

- Anthropogenic effects
- Solar irradiances
- Volcanoes
- ENSO



Uncertainties in these primary drivers of climate generally exceed the *net effects* of more minor drivers



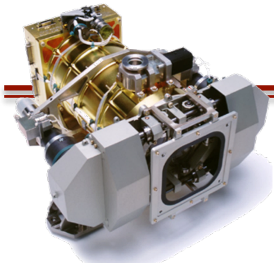
Where Does the Earth Get Its Energy?

Heat Source	Heat Flux* [W/m^2]	Relative Input
Solar Irradiance	**340.25**	**1.000**
Heat Flux from Earth's Interior	0.0612	1.8E-04
Radioactive Decay	0.0480	1.4E-04
Geothermal	0.0132	3.9E-05
Infrared Radiation from the Full Moon	0.0102	3.0E-05
Sun's Radiation Reflected from Moon	0.0034	1.0E-05
Energy Generated by Solar Tidal Forces in the Atmosphere	0.0034	1.0E-05
Combustion of Coal, Oil, and Gas in US (1965)	0.0024	7.0E-06
Energy Dissipated in Lightning Discharges	0.0002	6.0E-07
Dissipation of Magnetic Storm Energy	6.8E-05	2.0E-07
Radiation from Bright Aurora	4.8E-05	1.4E-07
Energy of Cosmic Radiation	3.1E-05	9.0E-08
Dissipation of Mechanical Energy of Micrometeorites	2.0E-05	6.0E-08
Total Radiation from Stars	1.4E-05	4.0E-08
Energy Generated by Lunar Tidal Forces in the Atmosphere	1.0E-05	3.0E-08
Radiation from Zodiacal Light	3.4E-06	1.0E-08
Total of All Non-Solar Energy Sources	*0.0810*	*2.4E-04*

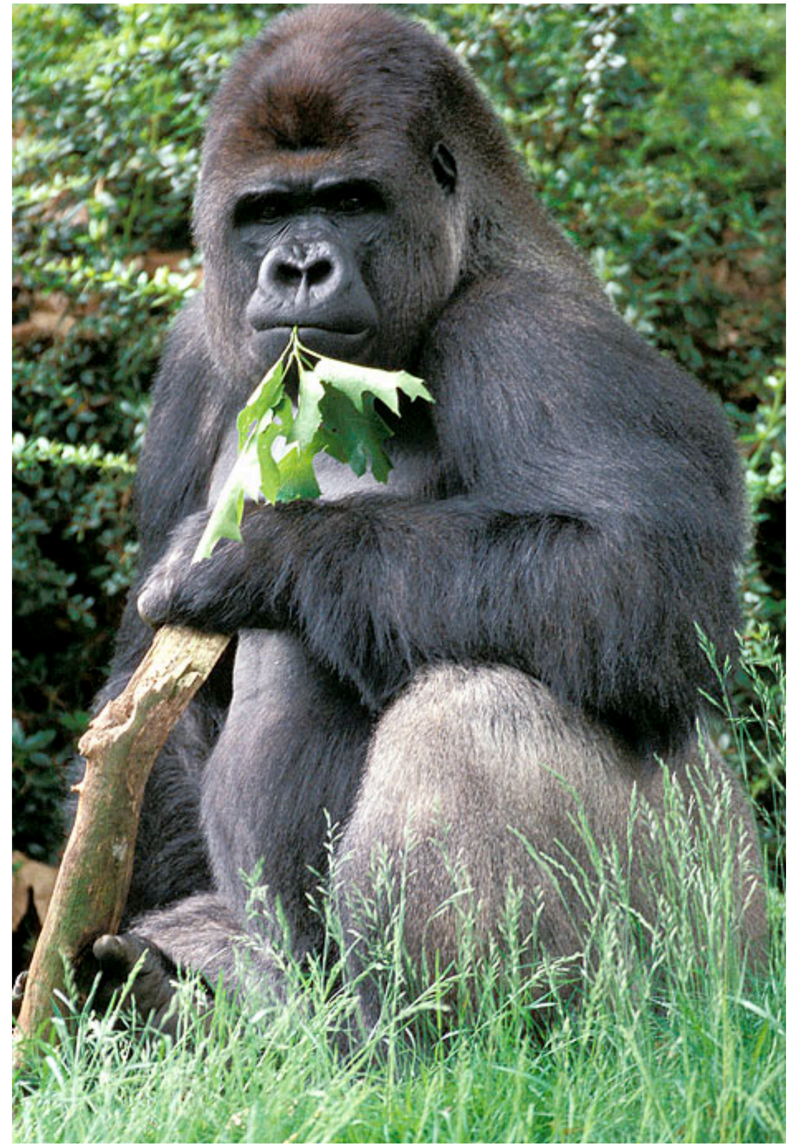
* global average

*Greenhouse gases are not an energy **source**.*

Physical Climatology, W.D. Sellers, Univ. of Chicago Press, 1965
Table 2 on p. 12 is from unpublished notes from
H.H. Lettau, Dept. of Meteorology, Univ. of Wisconsin.



The Sun Is THE Dominant Driver of Earth's Climate



Fortunately, this 800 lb gorilla is very placid

Heat Source	Heat Flux* [W/m²]	Relative Input
Solar Irradiance	340.25	1.000
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Total of All Non-Solar Energy Sources	*0.0810*	*2.4E-04*

* global average

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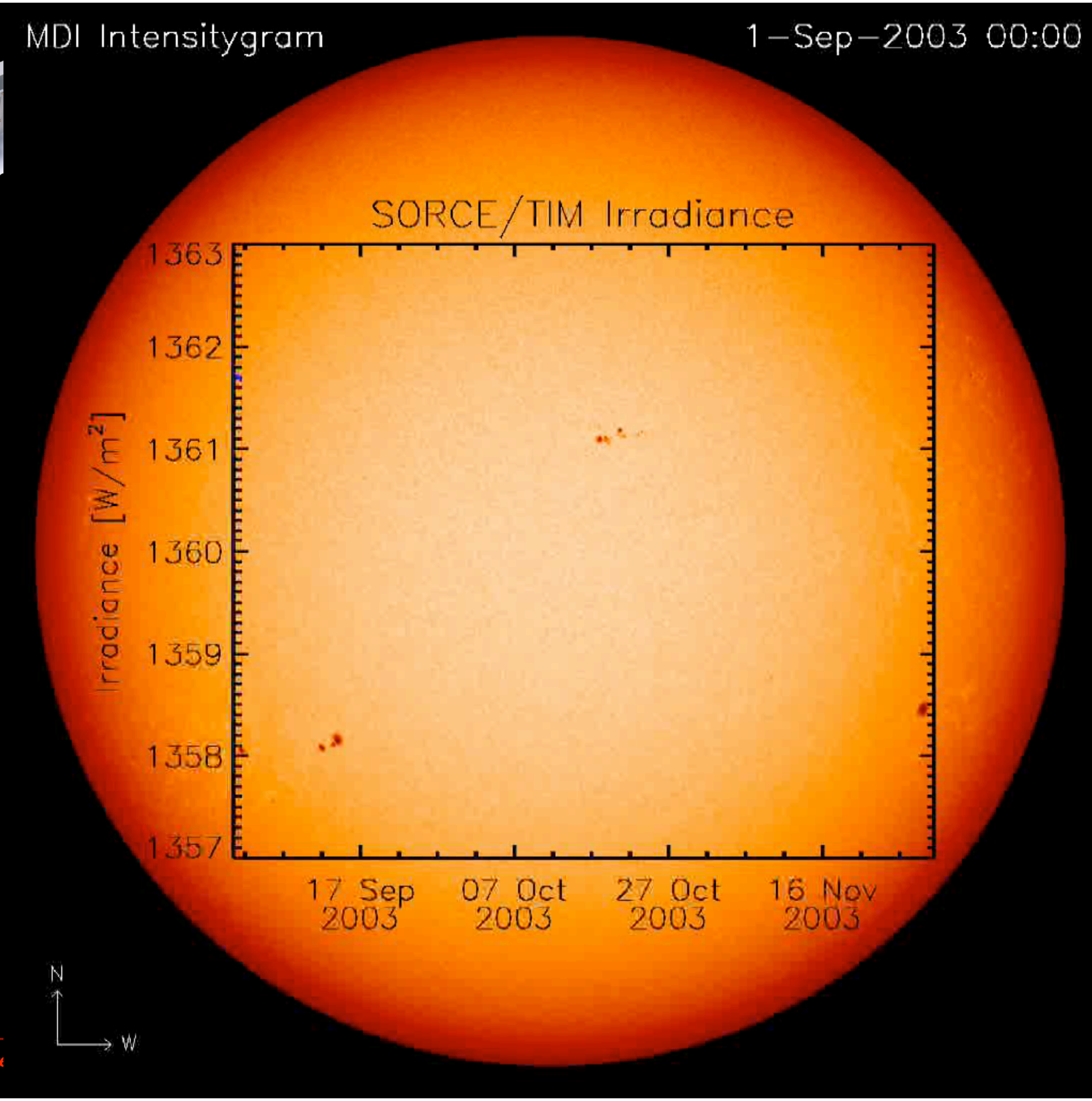
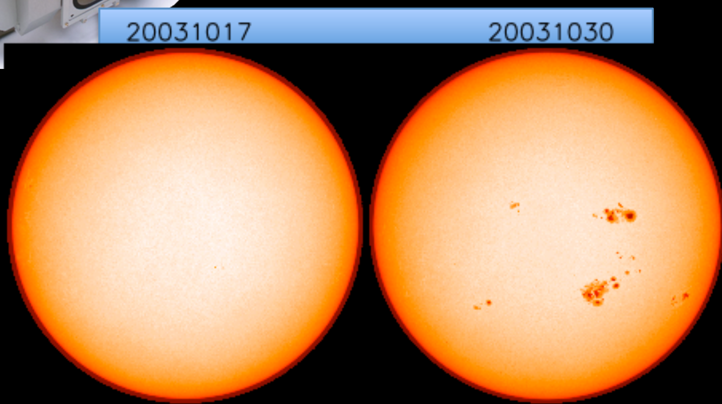
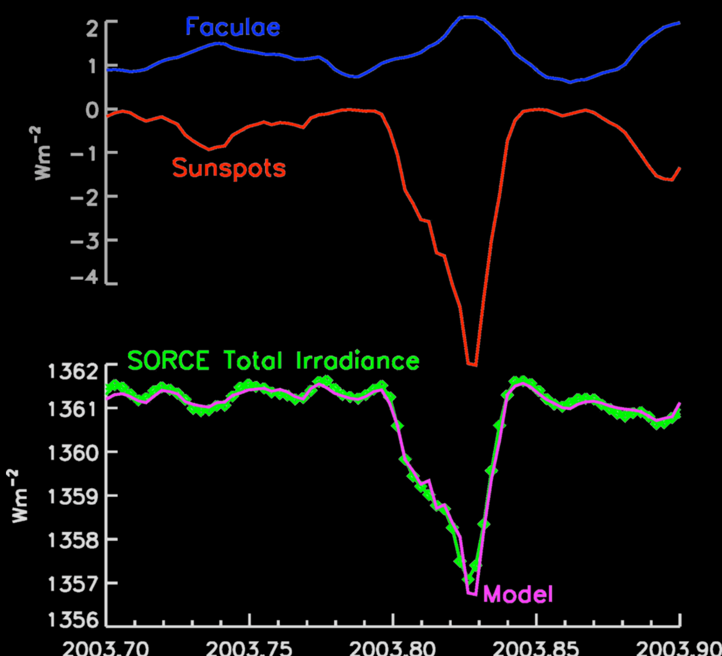
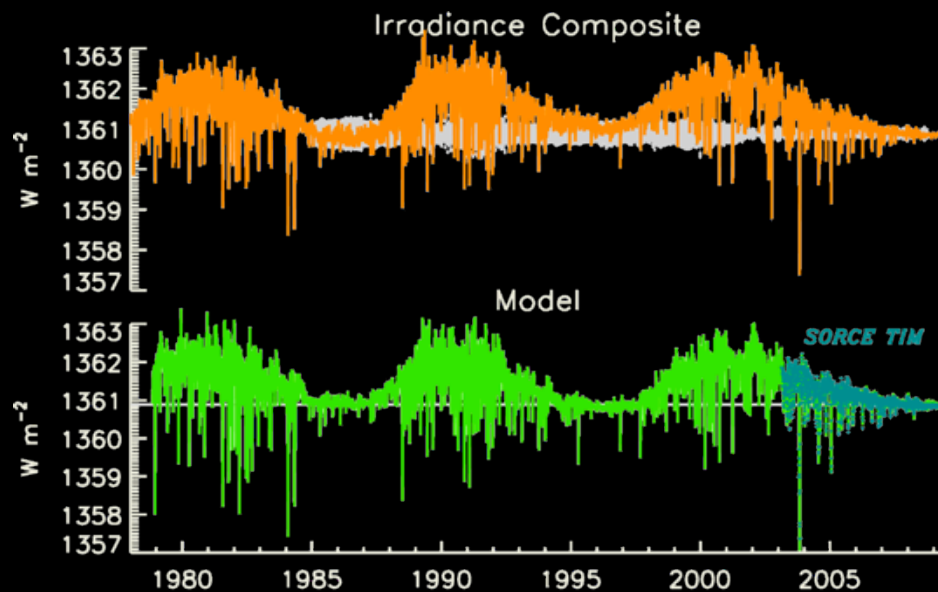


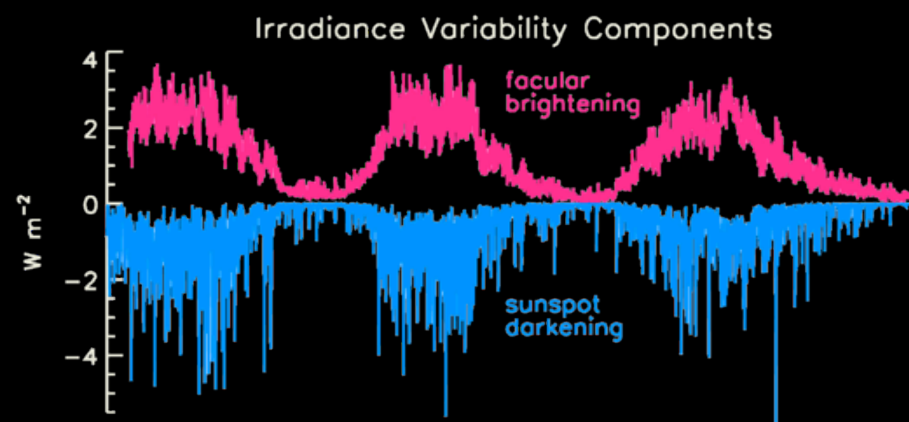
MDI Intensitygram
1–Sep–2003 00:00
SORCE/TIM Irradiance
Irradiance [W/m²]
1363
1362
1361
1360
1359
1358
1357
17 Sep 2003
07 Oct 2003
27 Oct 2003
16 Nov 2003
N
W

Why Does Total Solar Irradiance Vary?

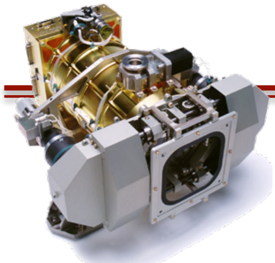








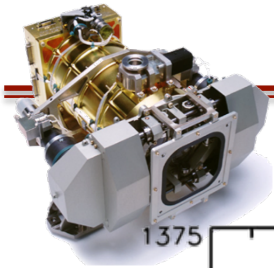
plots courtesy of Judith Lean



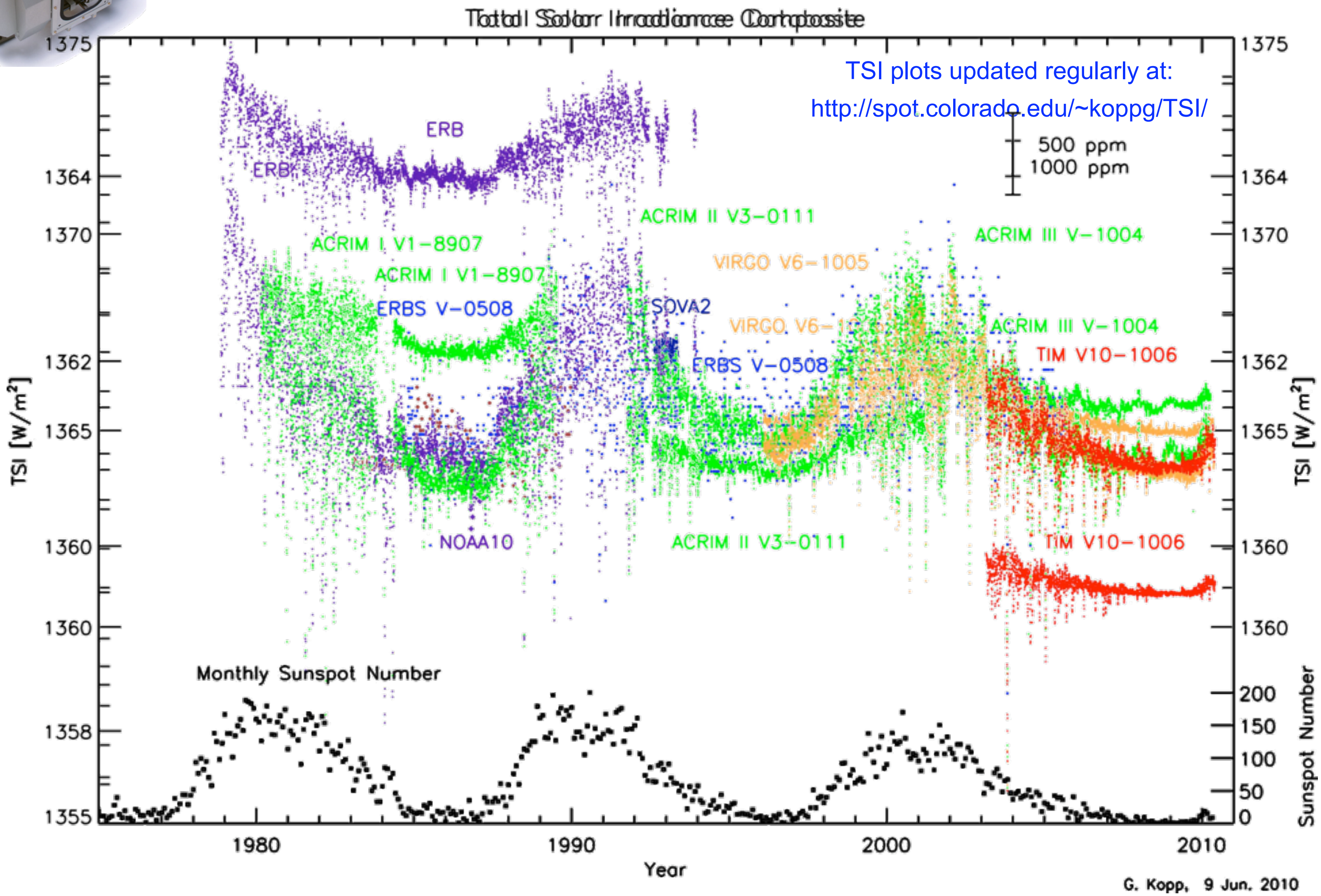
*But We Need Climate Data Records**

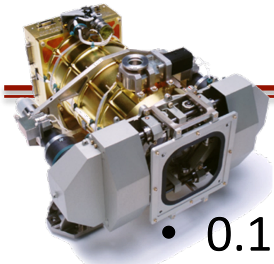
- What do we need to know...
  - For climate (multi-decadal)?
  - For solar cycle (to understand solar causes and atmospheric response)?
  - For short-term (space weather)?
- What do we know?
  - What are measurement accuracies, stabilities, and durations?
  - Do we understand the solar proxies and the Earth climate influences?
- What will improve the climate records?
  - Improved calibrations and understanding instrument artifacts
  - Inclusion of uncertainties in data records and composites
  - Consensus on composite records

* Climate considerations are not specific to TSI or to solar studies

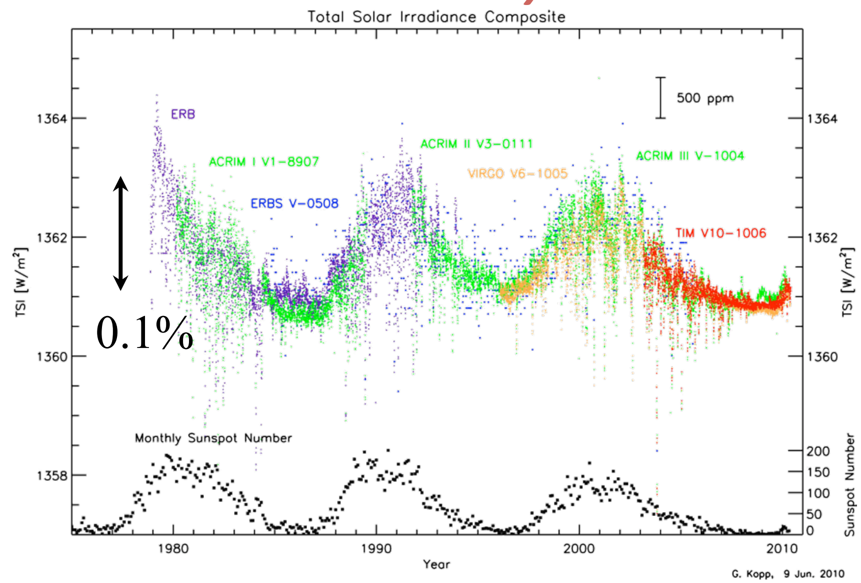


The TSI Climate Data Record



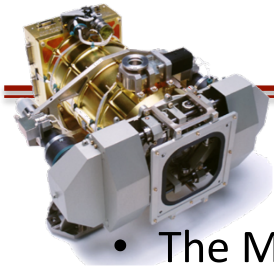


What Is the Natural TSI Variability?



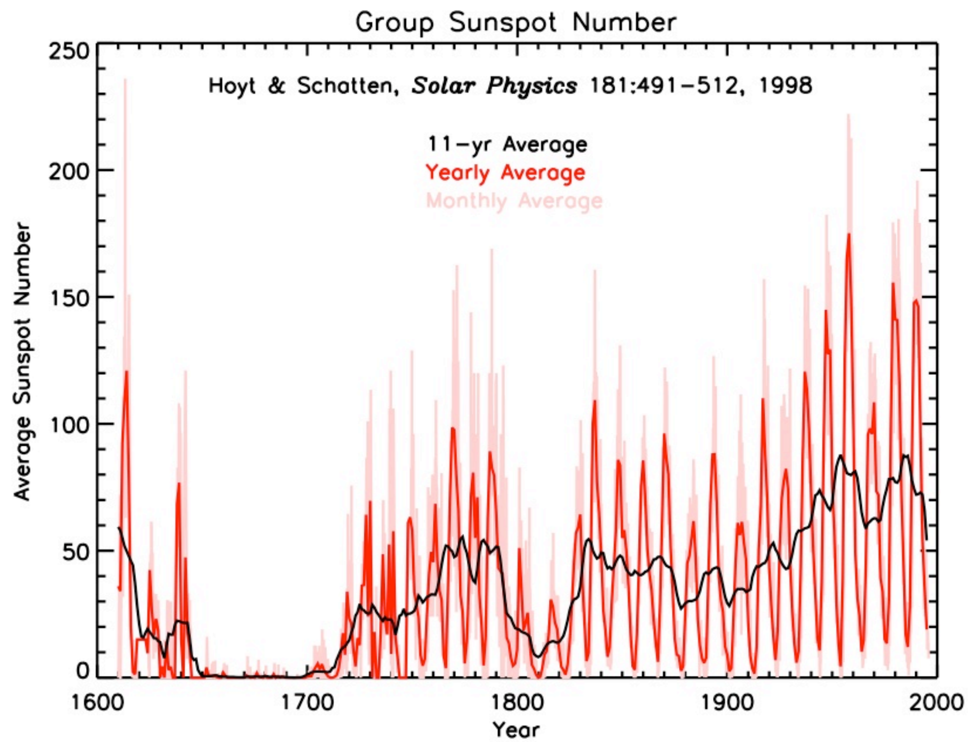
- 0.1-0.3% over a few days
  - Short duration causes negligible climate effect
- 0.1% over 11-year solar cycle
  - Small but detectable effect on climate
- 0.05-0.3% over centuries (unknown)
  - Direct effect on climate (Maunder Minimum and Europe's Little Ice Age)

- An unequivocal link between climate change and TSI has been established over the past three decades.
  - Magnitude of natural climate forcing needs to be known for setting present and future climate policy regulating anthropogenic forcings.
  - Future long-term solar fluctuations, similar to historical variations, are not known from current measurements or TSI proxies.

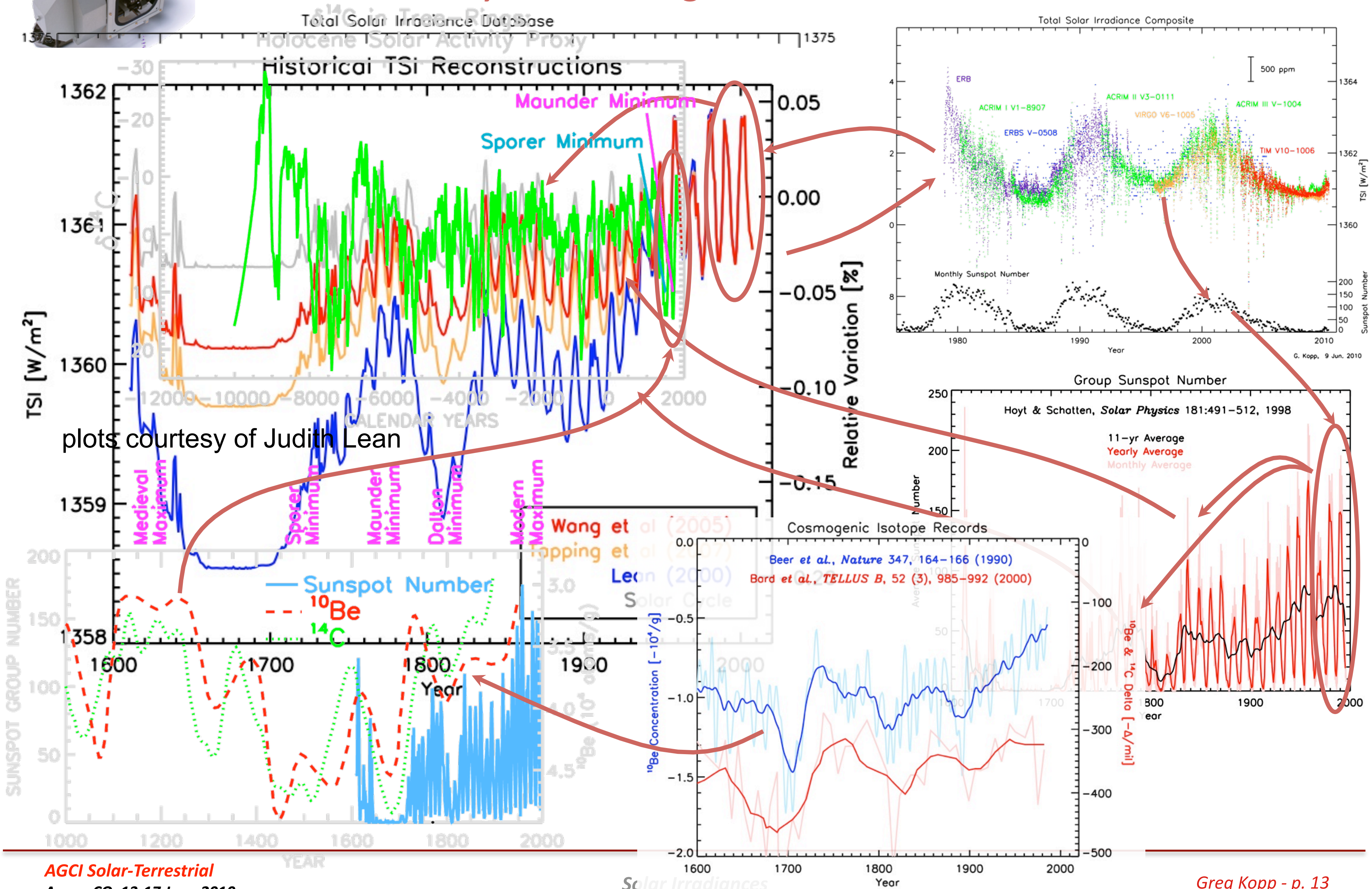


Long-Term Solar Variability Trends

- The Maunder Minimum in the late 1600's is a significant long-term change
  - Solar output decreased 0.05-0.3% for 70 years
  - Earth temperatures were ~0.2-0.4 C colder than the early 1900s (Little Ice Age)
- *Want to resolve <0.1% change in TSI over ~100 years*
  - This solar variability rate comparable to current 0.001%/year instrument stability
  - Improved absolute accuracy helps this detection over long time scales

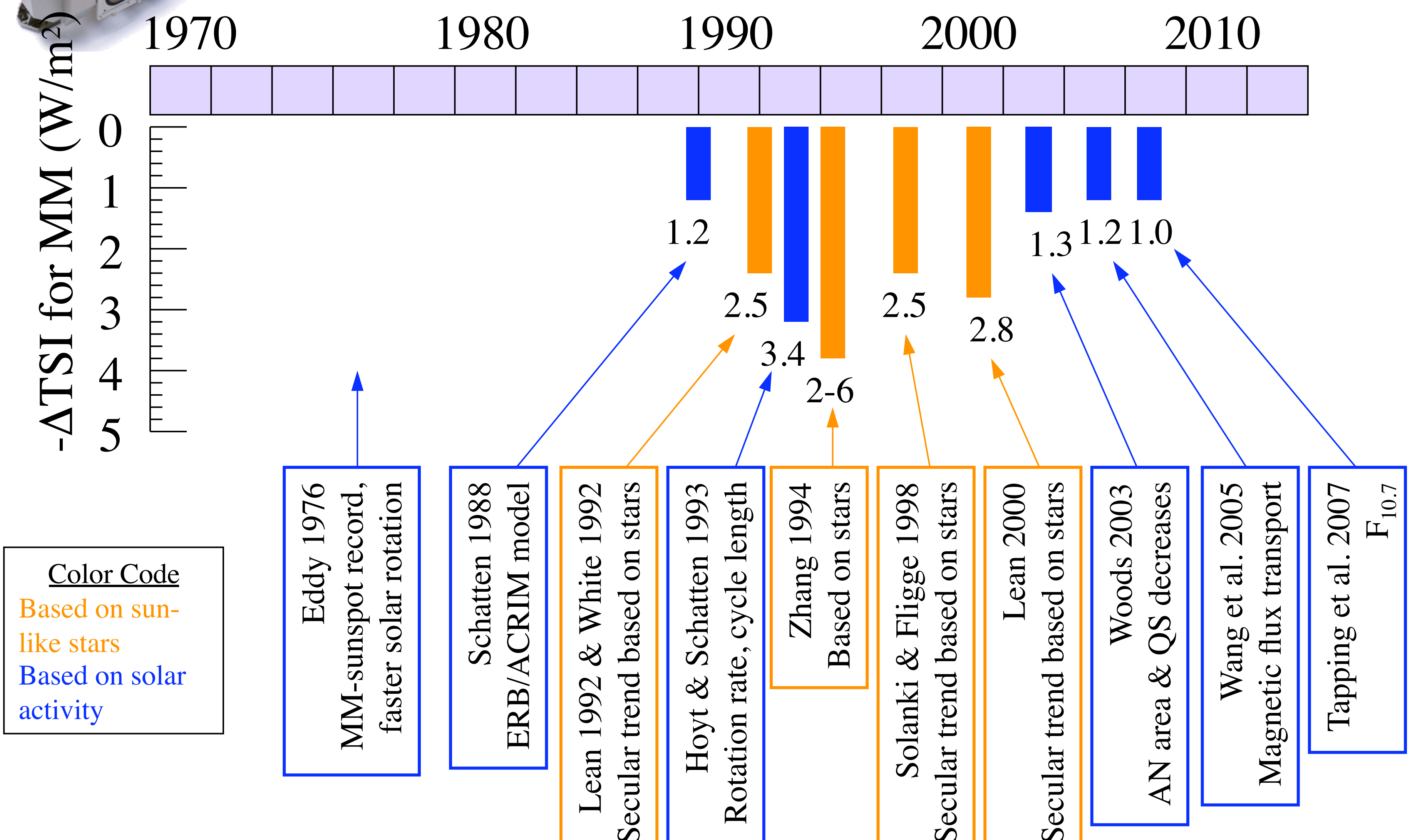


Solar Variability – Creating Historical TSI Reconstructions

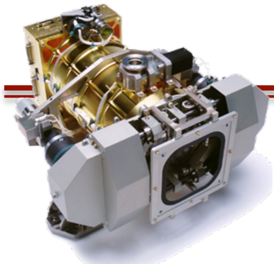


SORCE
SOlar Radiation & Climate Experiment

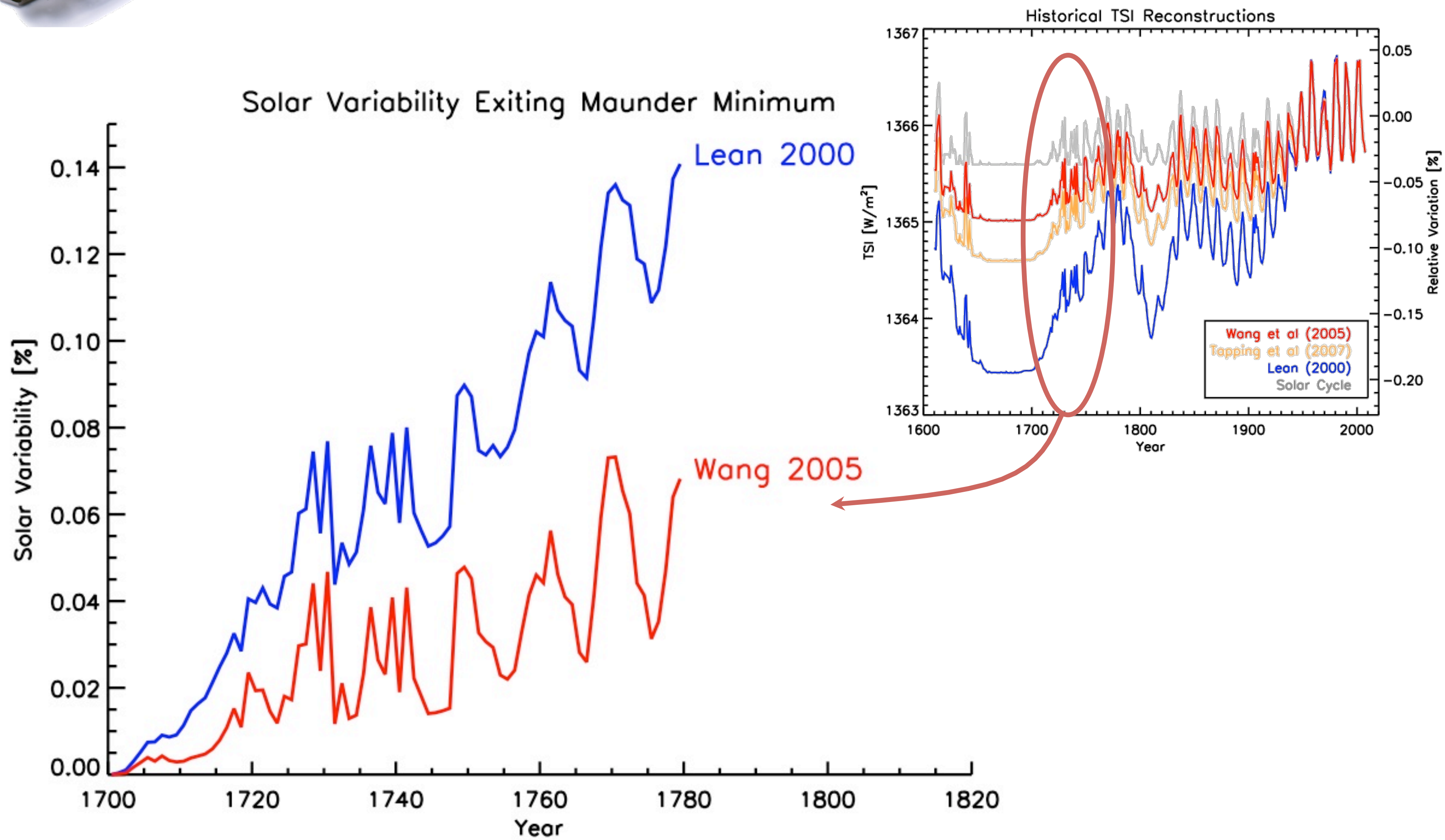
Maunder Minimum TSI Estimates

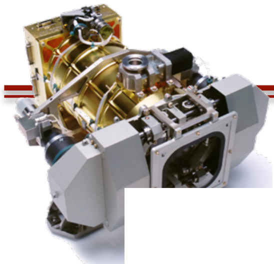


courtesy of T. Woods

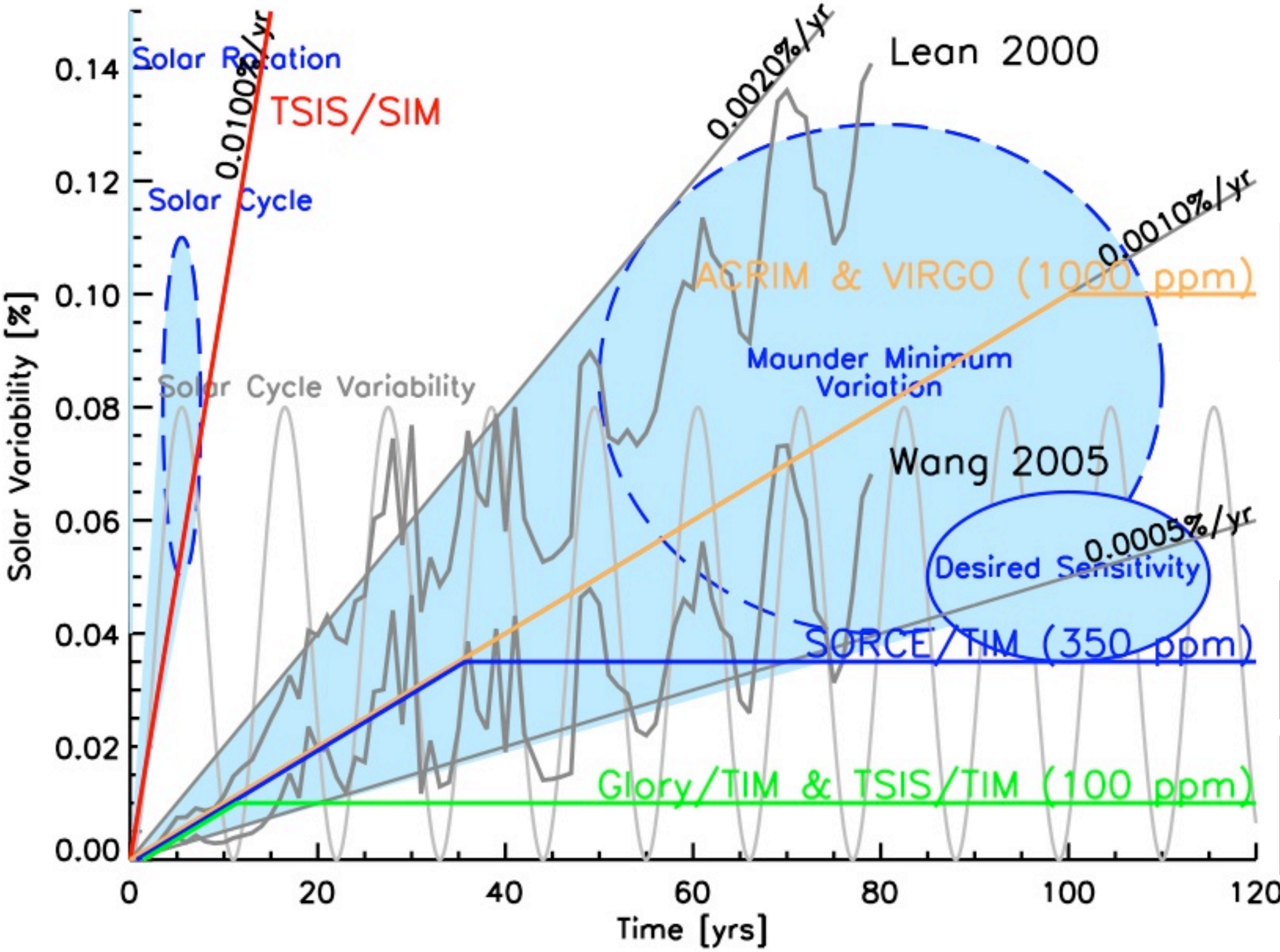


Solar Variability – Historical Solar Variability





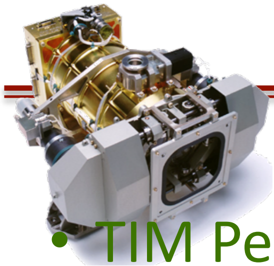
Solar Variability and Measurement Requirements



100-yrs needed for MM detection

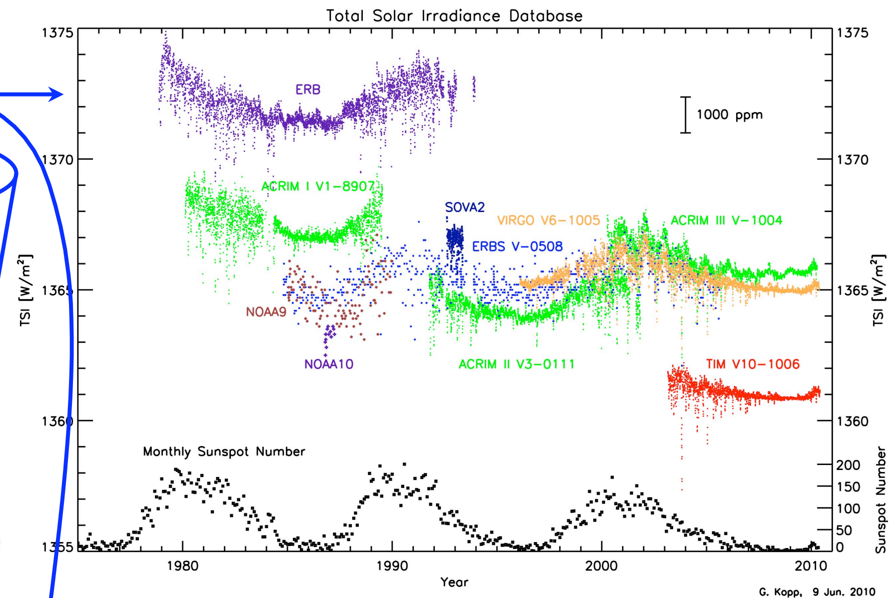
35-yrs needed for MM detection

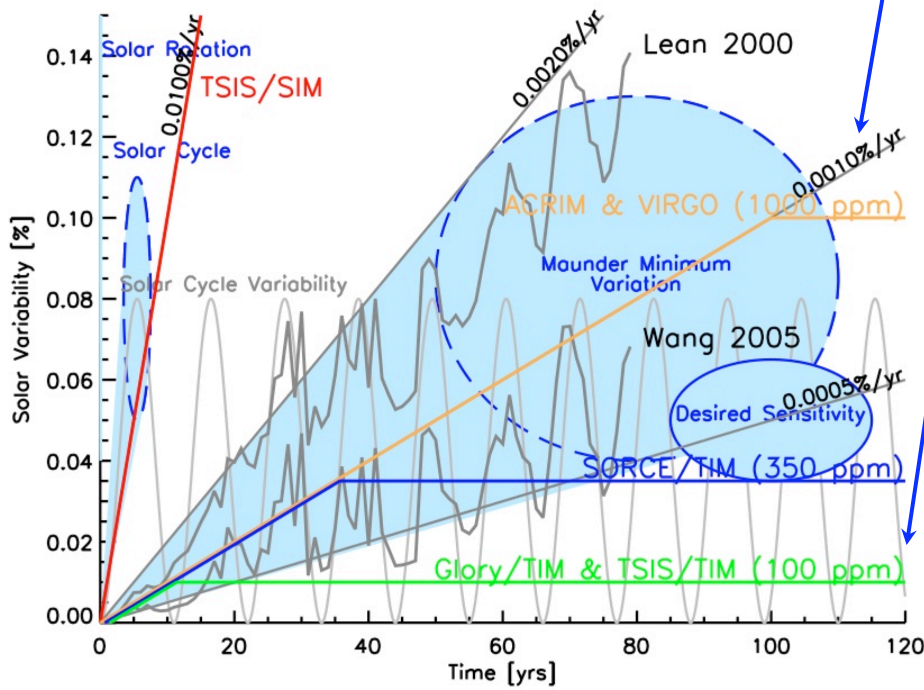
10-yrs needed for MM detection

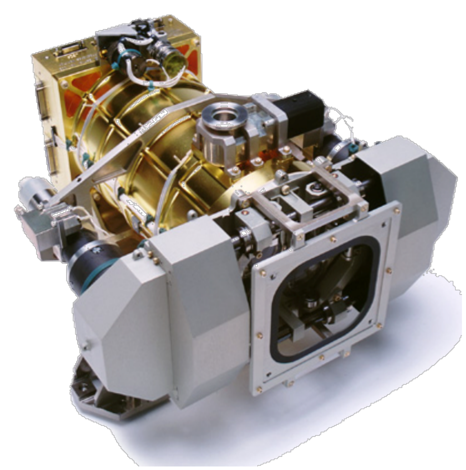


TIM Requirements Address Climate Needs

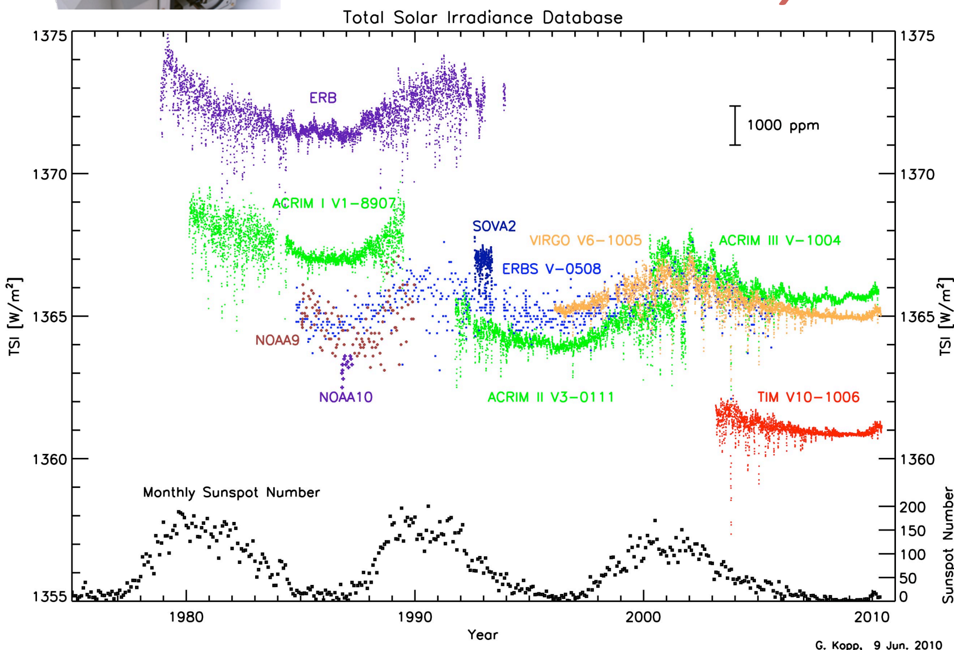
- TIM Performance Requirements
  - Accuracy 0.01% (1 σ)
  - Stability 0.001%/yr (1 σ)
  - Noise 0.001% (1 σ)

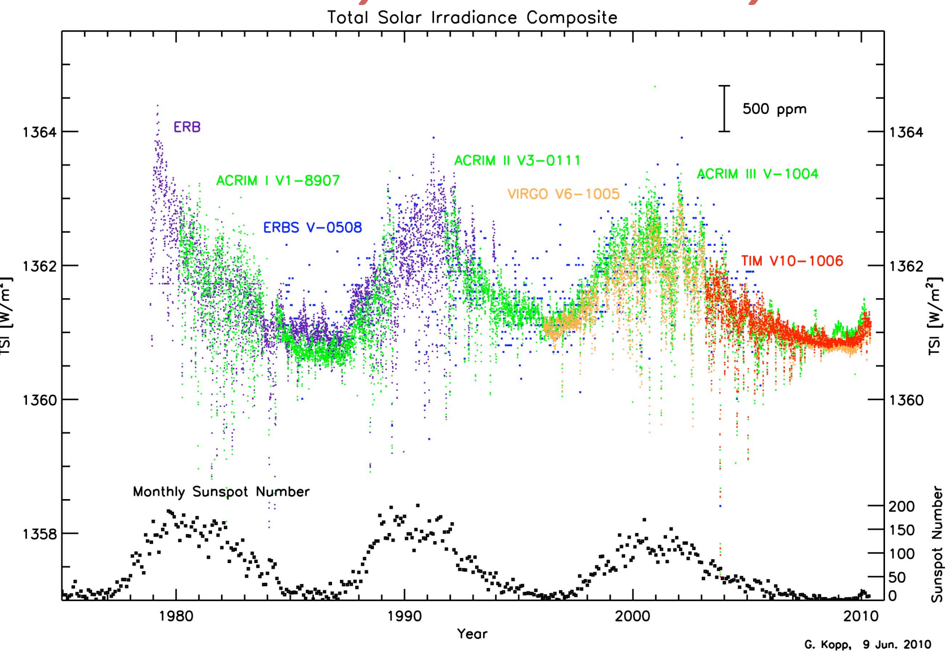


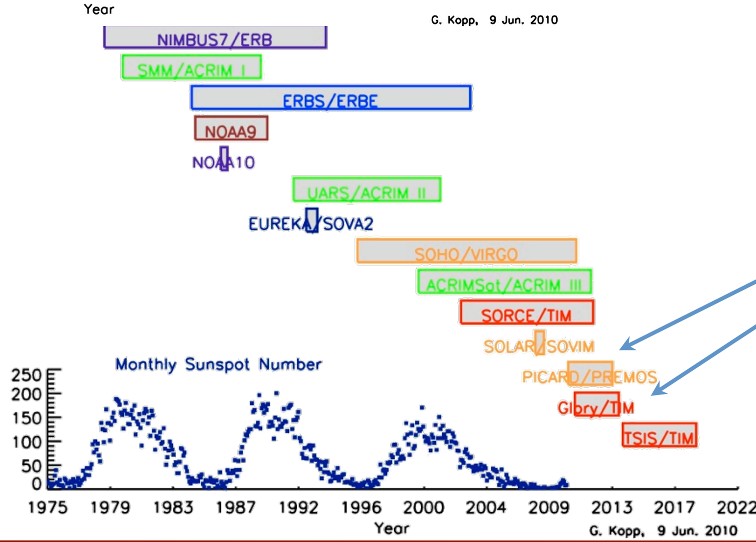




Record Currently Relies on Stability & Continuity

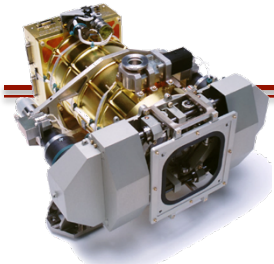






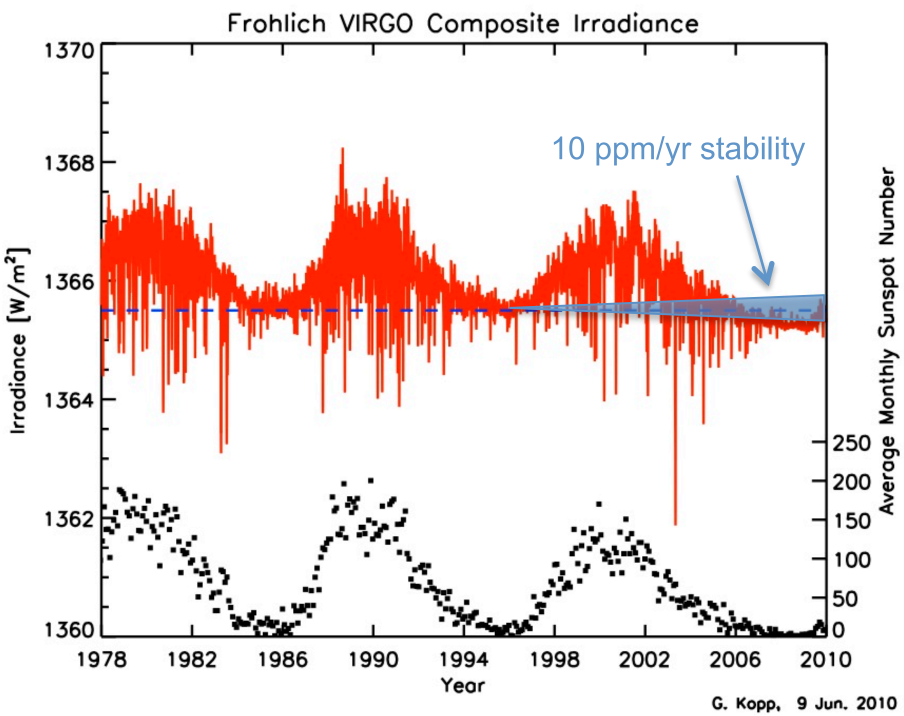
Glory/TIM and PICARD/ PREMOS extend TSI record after SORCE, SoHO, & ACRIMSat

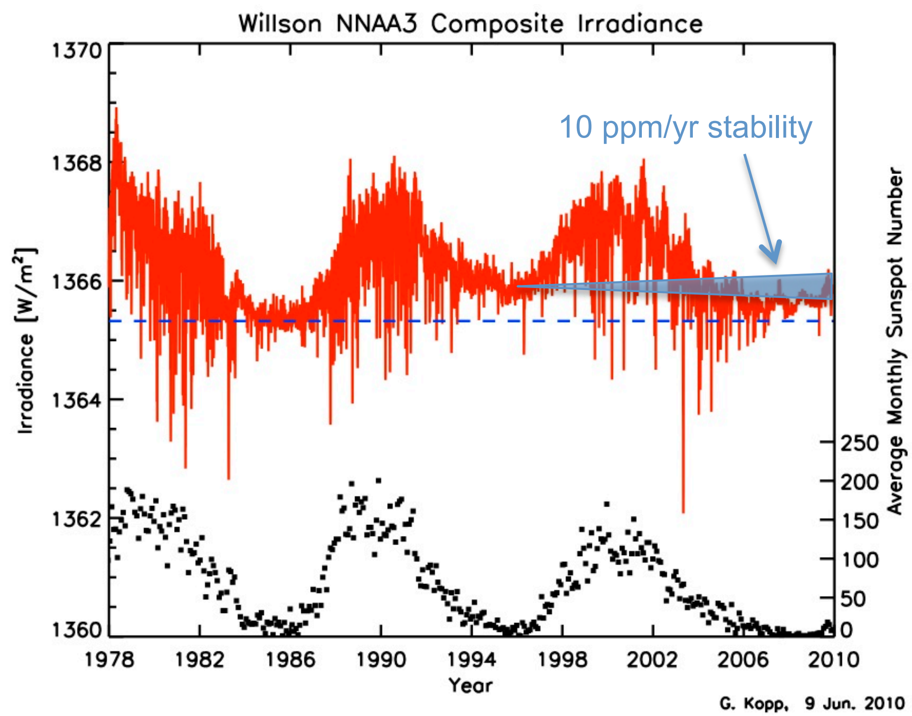
TSI plots updated regularly at:
http://spot.colorado.edu/~koppg/TSI/

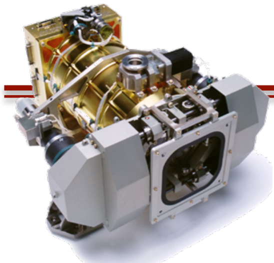


How Good Are Resulting Composites?

- Trend detection between solar minima is currently marginal

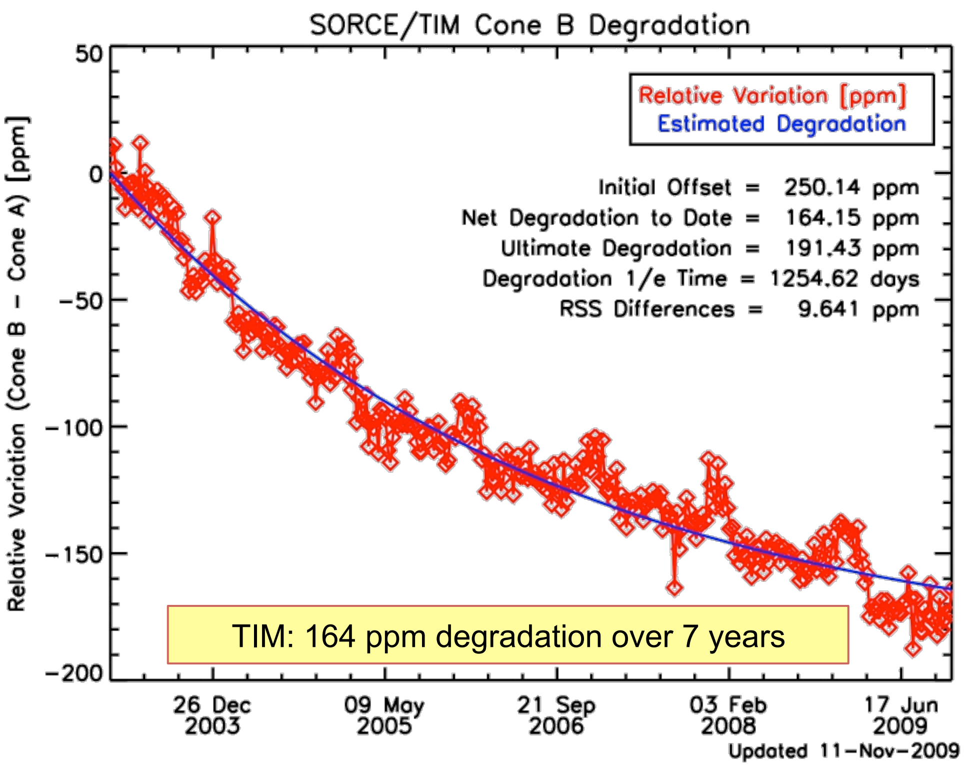


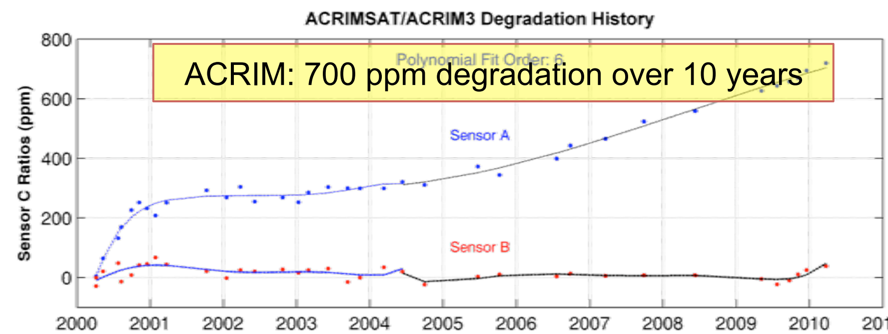


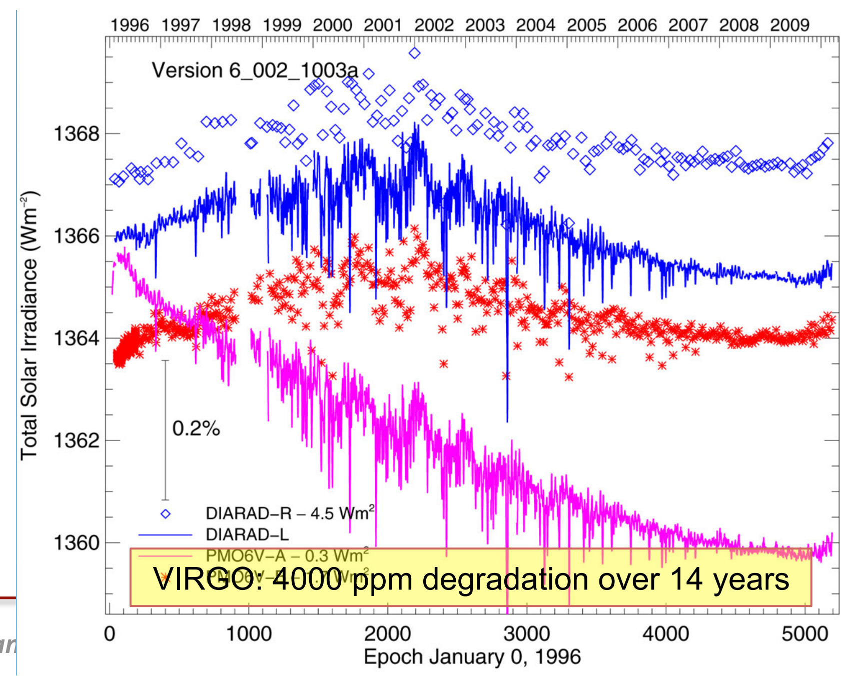


Newer Instruments' Stabilities Are Improving

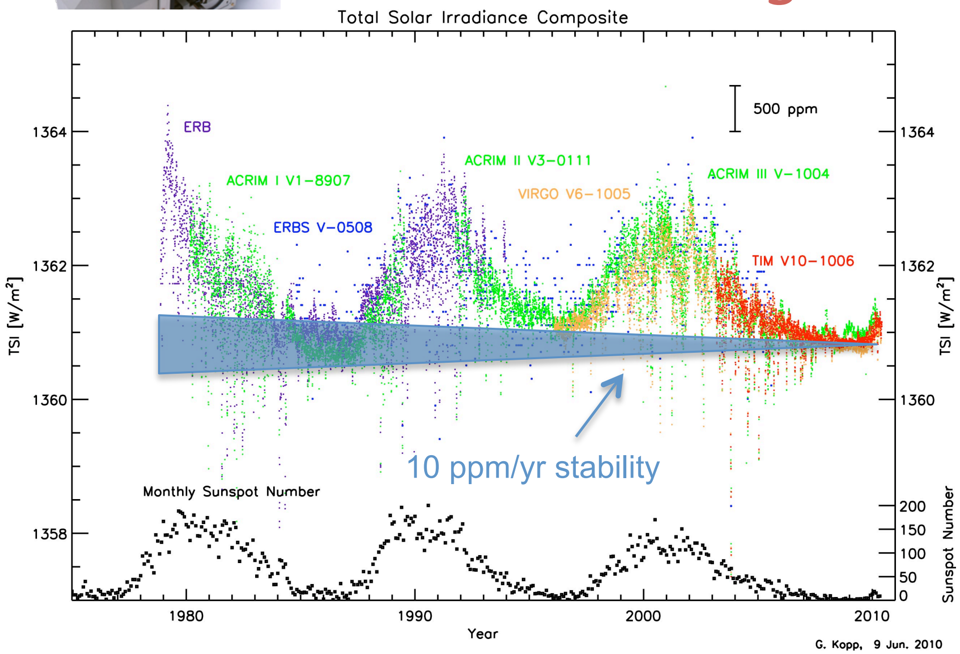
- The SORCE TIM has lower degradation than other instruments
  - All instruments correct for measured degradation

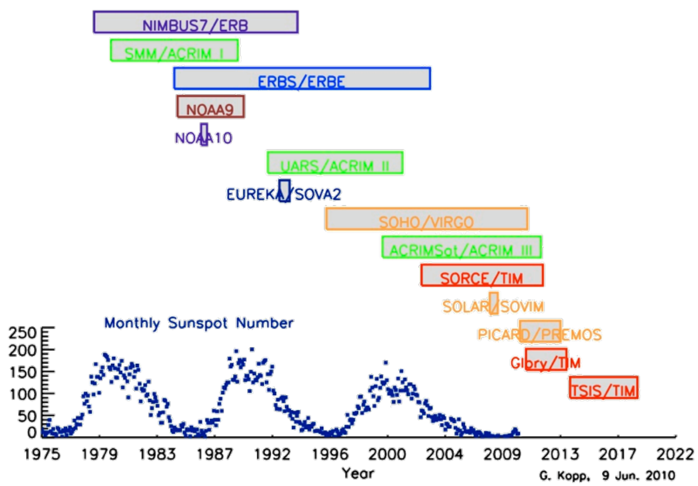




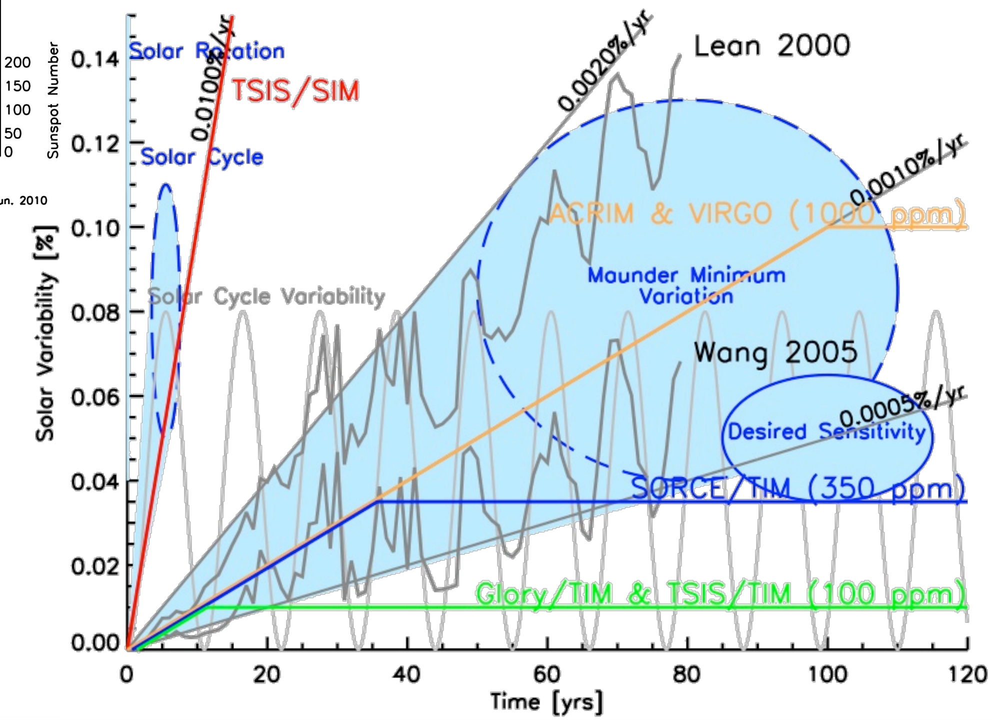


How Long Do We Need Continuity?

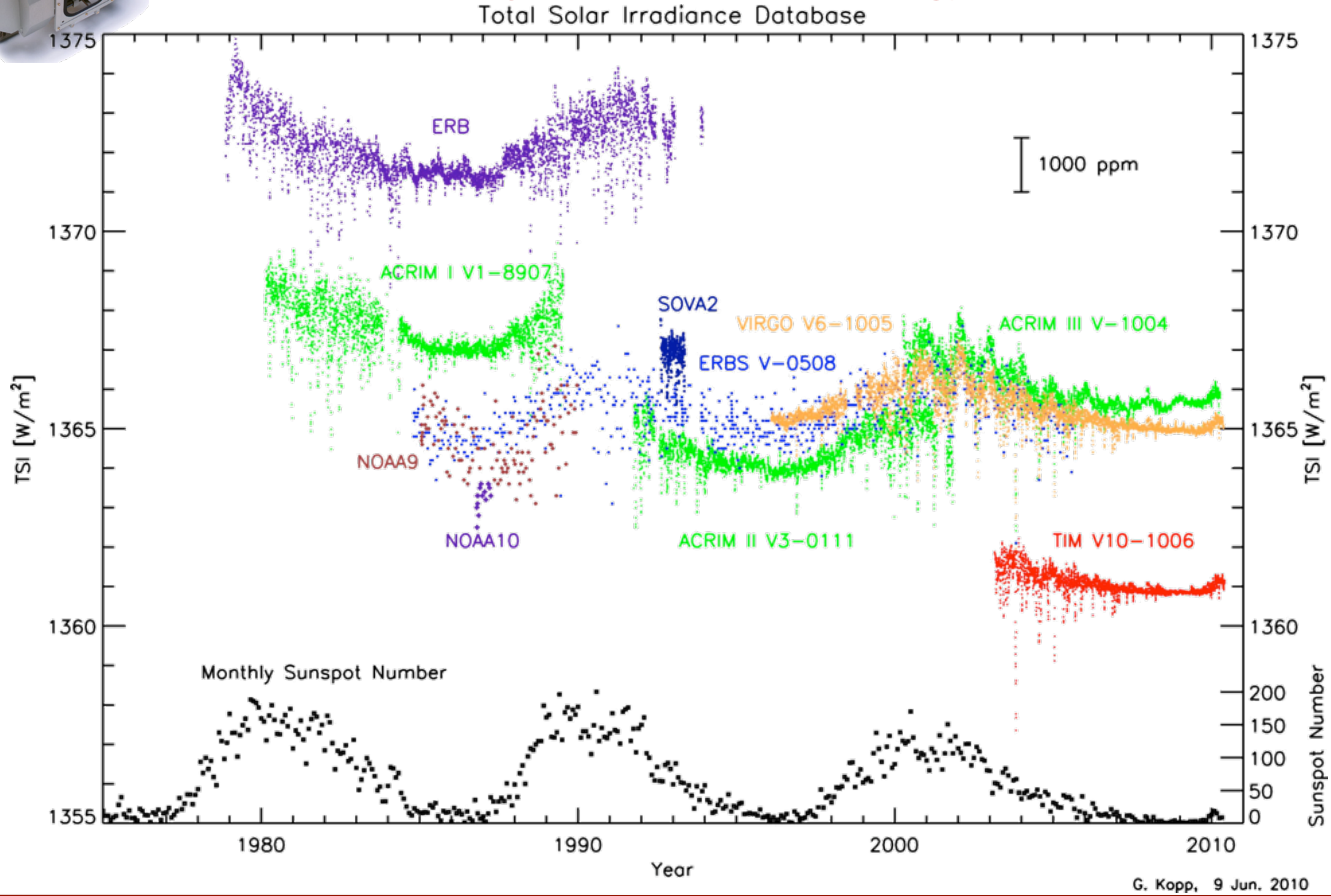




- Until instrument stability is insufficient to detect expected trends
  - Then rely on absolute accuracy

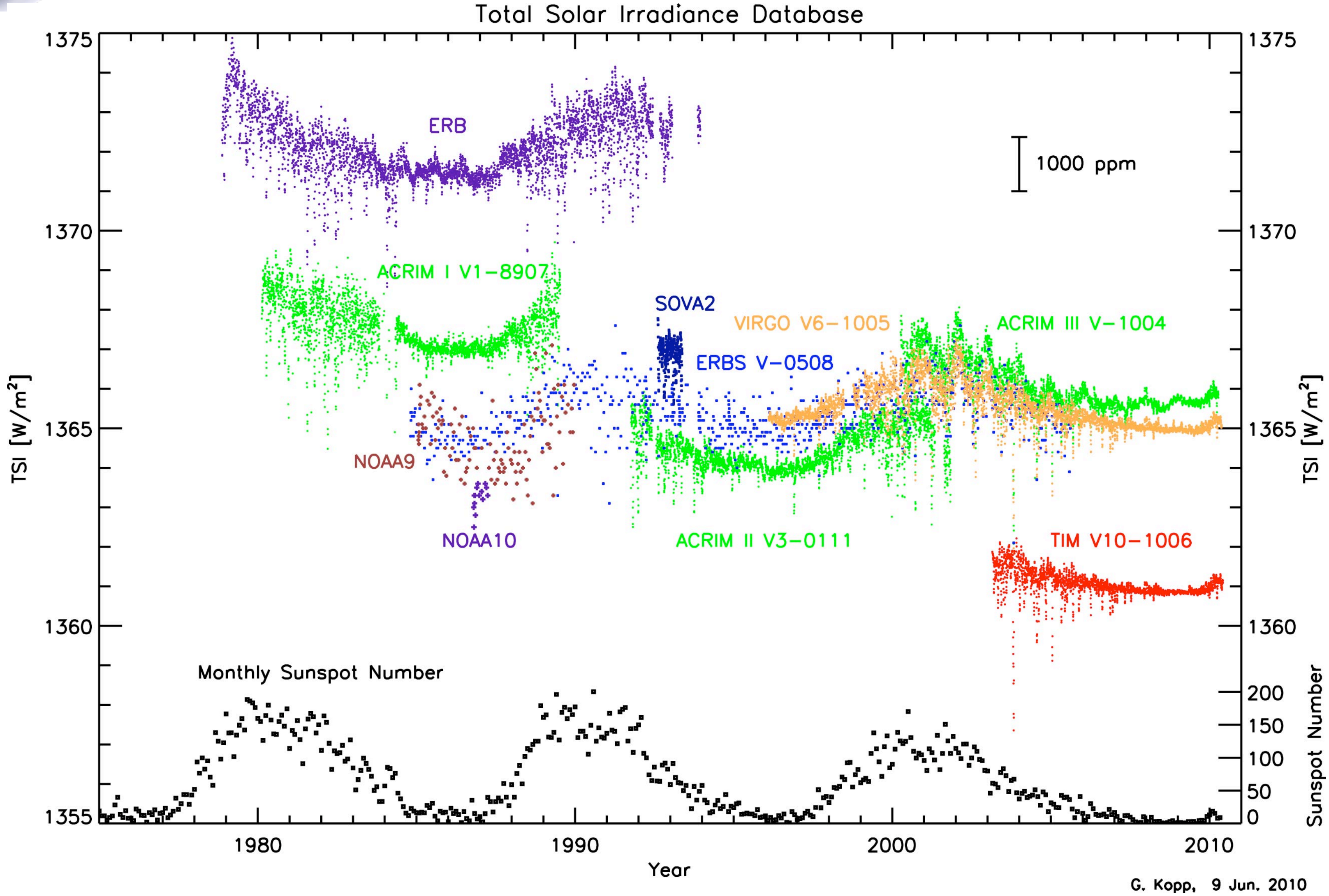


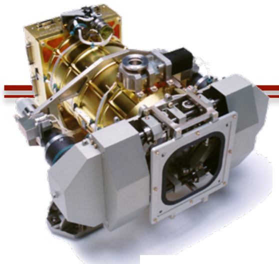
So Why the Instrument Offsets?



Offsets Cannot Be Resolved By SIM

(Answer to Jerry Meehl's Question)





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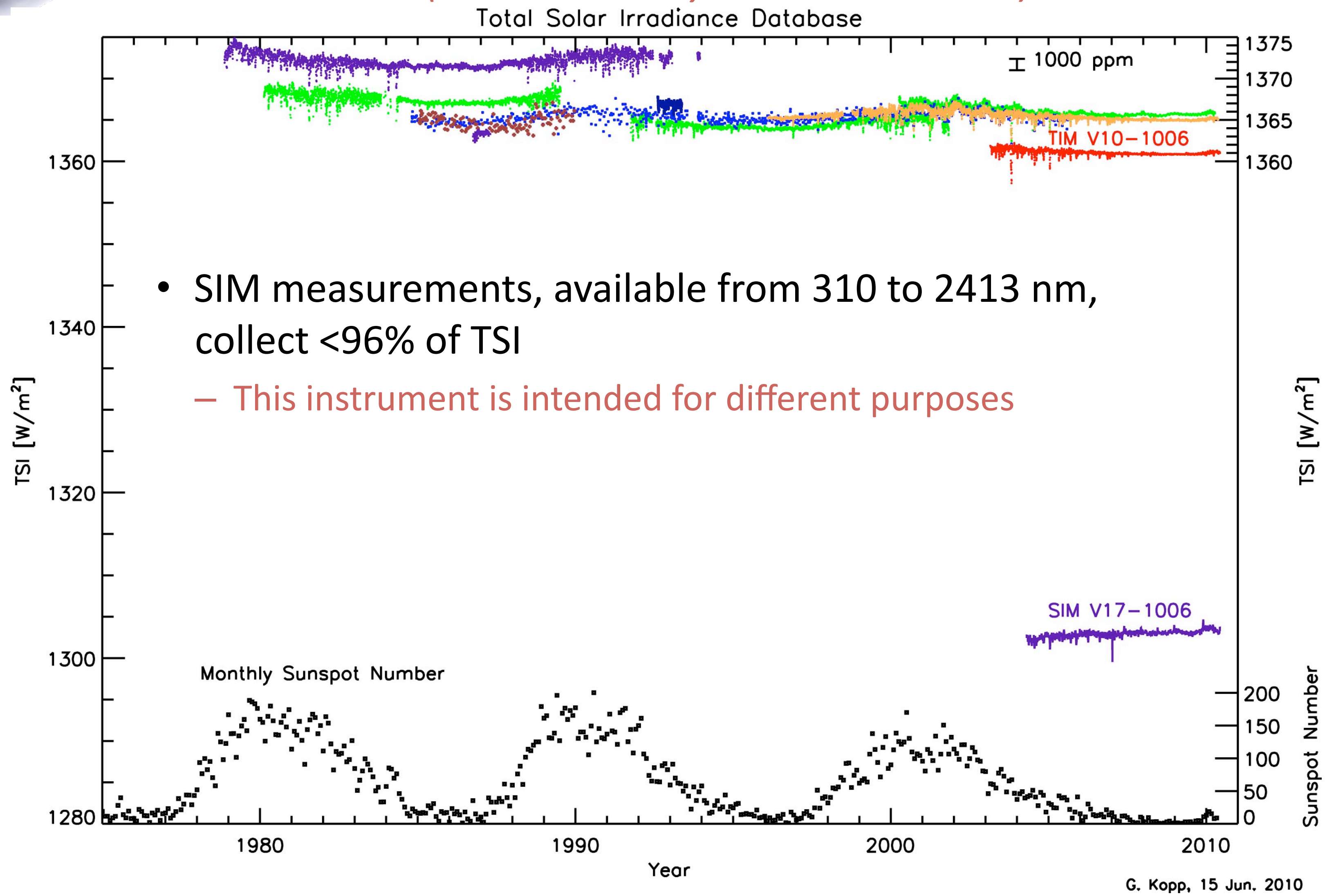
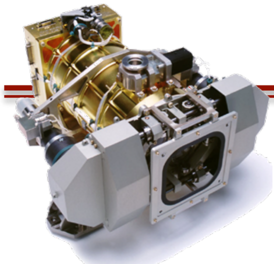


- SIM measurements, available from 310 to 2413 nm, collect <96% of TSI
  - This instrument is intended for different purposes



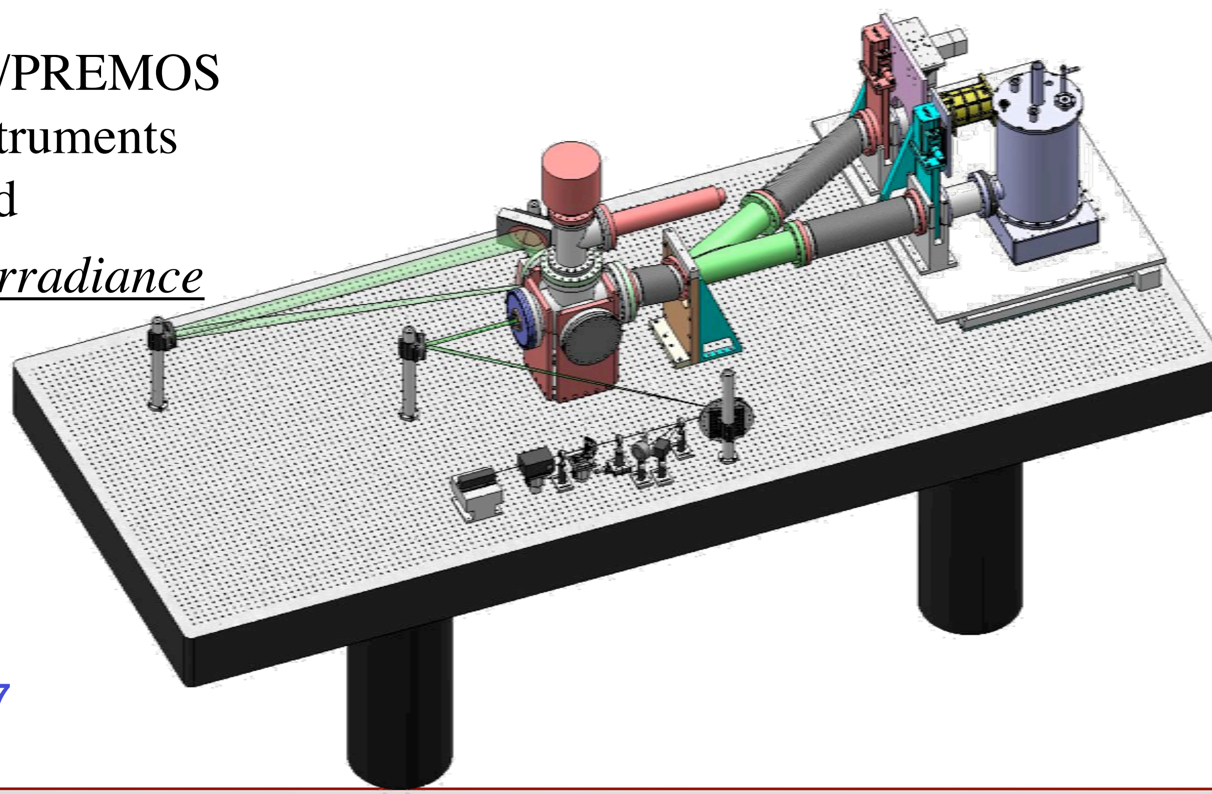
TSI Radiometer Facility (TRF) Measures Irradiance

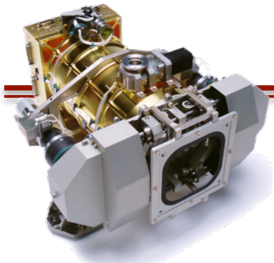
The TRF

1. Improves the calibration accuracy of future TSI instruments,
2. Establishes a new ground-based radiometric irradiance reference standard, and
3. Provides a means of comparing existing ground-based TSI instruments against this standard under flight-like operating conditions.

- Glory/TIM and PICARD/PREMOS are the first flight TSI instruments to be validated end-to-end
- First facility to measure *irradiance*
  - at solar power levels
  - in vacuum
  - at desired accuracies

Kopp *et al.*, **SPIE** 2007

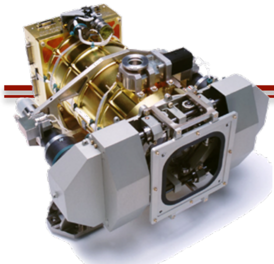




Glory/TIM and SORCE/TIM TRF Validation Results

- Glory TIM was validated end-to-end for *irradiance* against NIST-calibrated TRF cryogenic radiometer in Jan. 2009 & April 2010
  - The first end-to-end irradiance validation of a flight TSI instrument
  - Provides traceability to NIST to given uncertainties

Channel	Offset [ppm]	σ [ppm]
Glory A	-161	202
Glory B	-50	198
Glory C	-145	200
Glory D	-130	201
Mean	-122	
Standard Deviation	49	
SORCE Witness C	-377	285
SORCE Witness D	-358	318

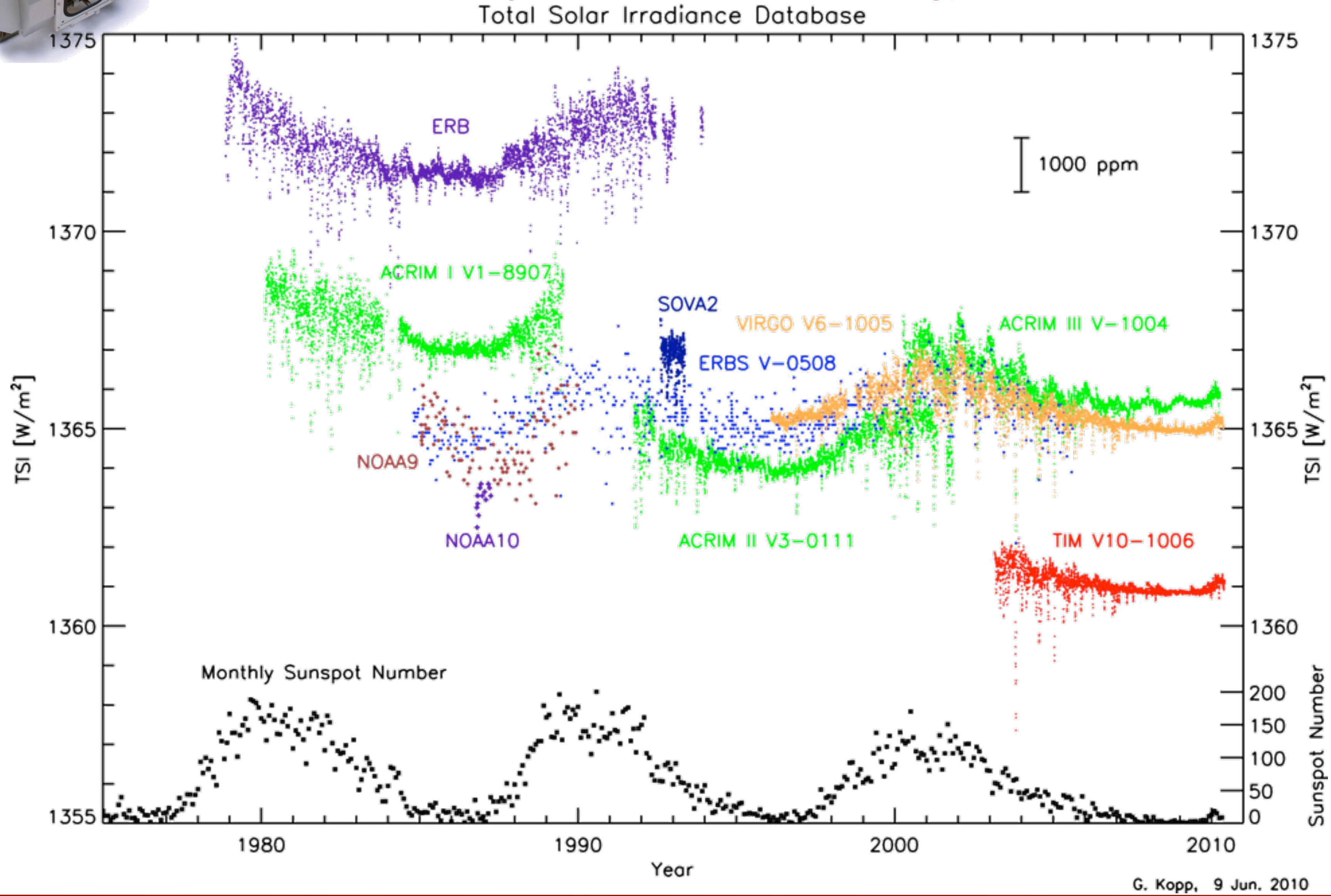


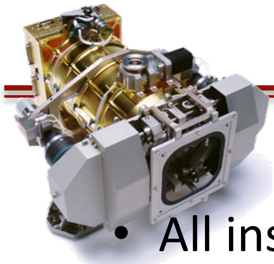
TRF Measurements Validating TSI Instruments

- Currently performed on SORCE/TIM Witness, Glory/TIM, PICARD/PREMOS-1 and PREMOS-3, and VIRGO-2
- Planned with ACRIM and EURECA

Difference Relative to TSI Radiometer Facility [ppm]					
Instrument	**Cavity A**	**Cavity B**	**Cavity C**	**Cavity D**	**Uncertainty**
SORCE/Witness			-377	-358	318
Glory/TIM	-161	-50	-145	-130	202
PREMOS-1	-837				~380
PREMOS-3	-58*				~270
VIRGO-2	320*				~250
ACRIM III	Aug. - Sept. 2010				
EURECA	hopefully in 2011				
*after correcting for 0.63% (PREMOS-3) & 0.73% (VIRGO) optical power offsets					

So Why the Instrument Offsets?

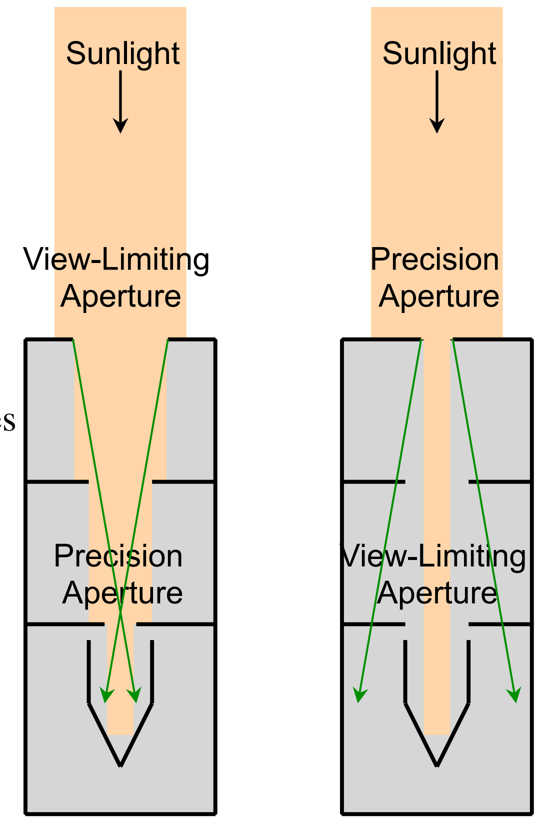




Diffraction Can Erroneously Change Signal

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

all other TSI instrument geometries



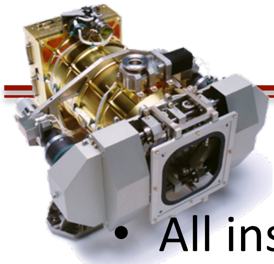
TIM geometry

Failure to correct for light diffracted <u>into</u> cavity erroneously <u>increases</u> signal

Failure to correct for light diffracted <u>out of</u> cavity erroneously <u>decreases</u> signal

NIST calculates this to be a 0.13% effect in the ACRIM instruments, and it is not corrected.

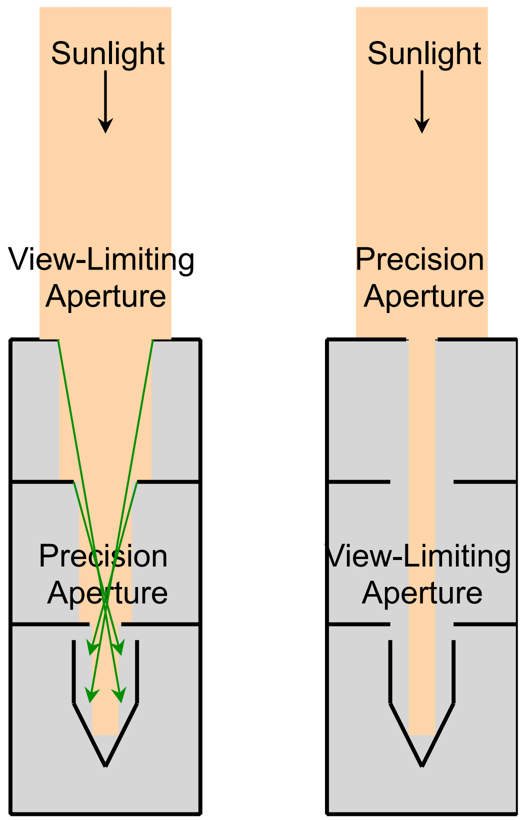
NRL repeated this calculation with similar result.



TRF Beam Control Allows for Diagnostics

- 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 of instrument



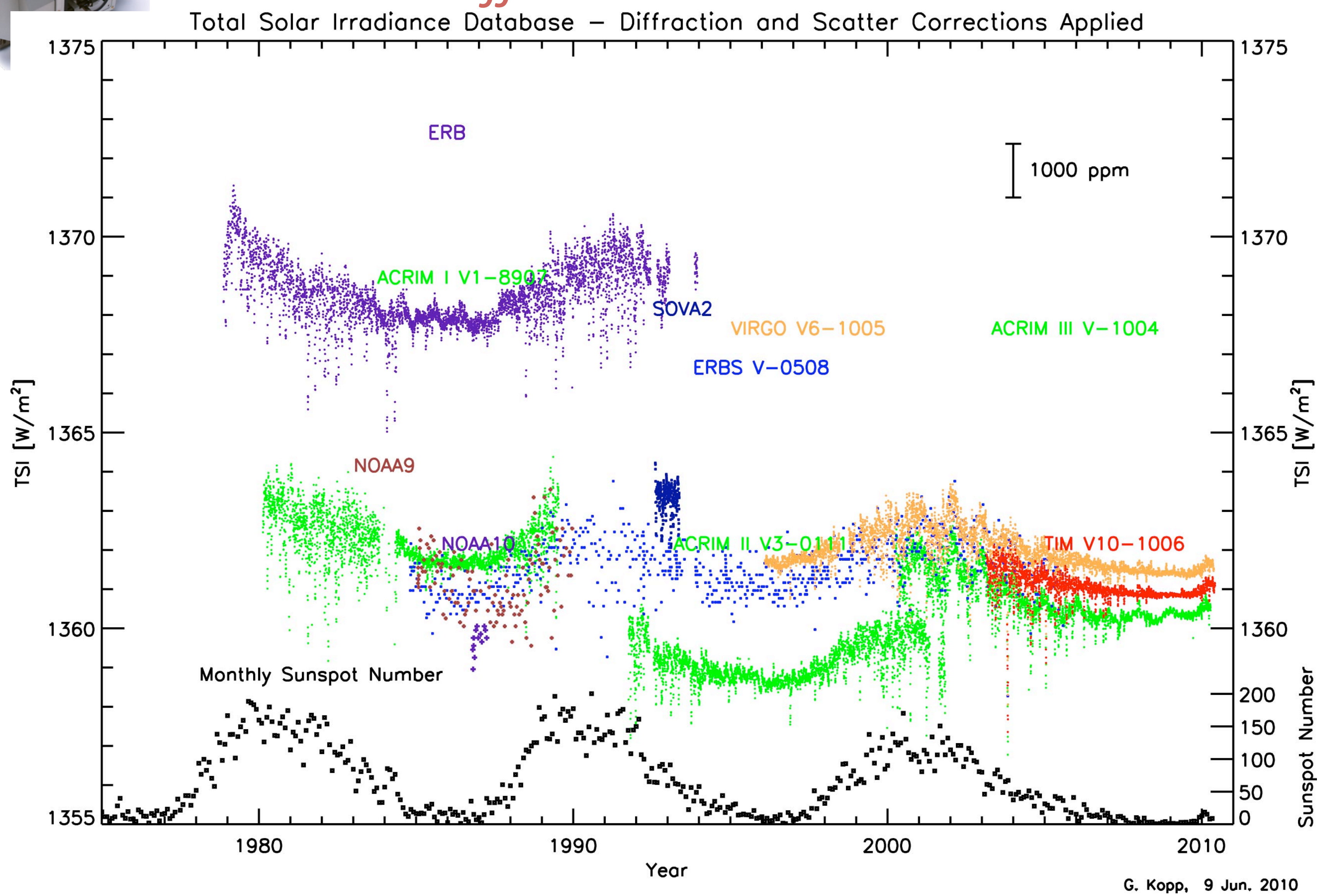
Additional light allowed into instrument can scatter into cavity

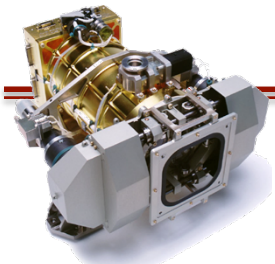
Majority of light is blocked before entering instrument

Measured increases due to uncorrected scatter/diffraction are surprisingly large

Instrument	Increase
PREMOS-1	0.20%
PREMOS-3	0.14%
VIRGO	0.26%

Correction Effects on TSI Climate Data Record





TSI Instrument Validation Plans

- Upcoming flight instruments (PICARD/PREMOS, Glory/TIM) have been validated on TRF
- Will compare to ACRIM III (2010) and EURECA (2011) ground-based flight spares
- Understand and correct for large effect of scatter & diffraction

Difference Relative to TSI Radiometer Facility [ppm]					
Instrument	**Cavity A**	**Cavity B**	**Cavity C**	**Cavity D**	**Uncertainty**
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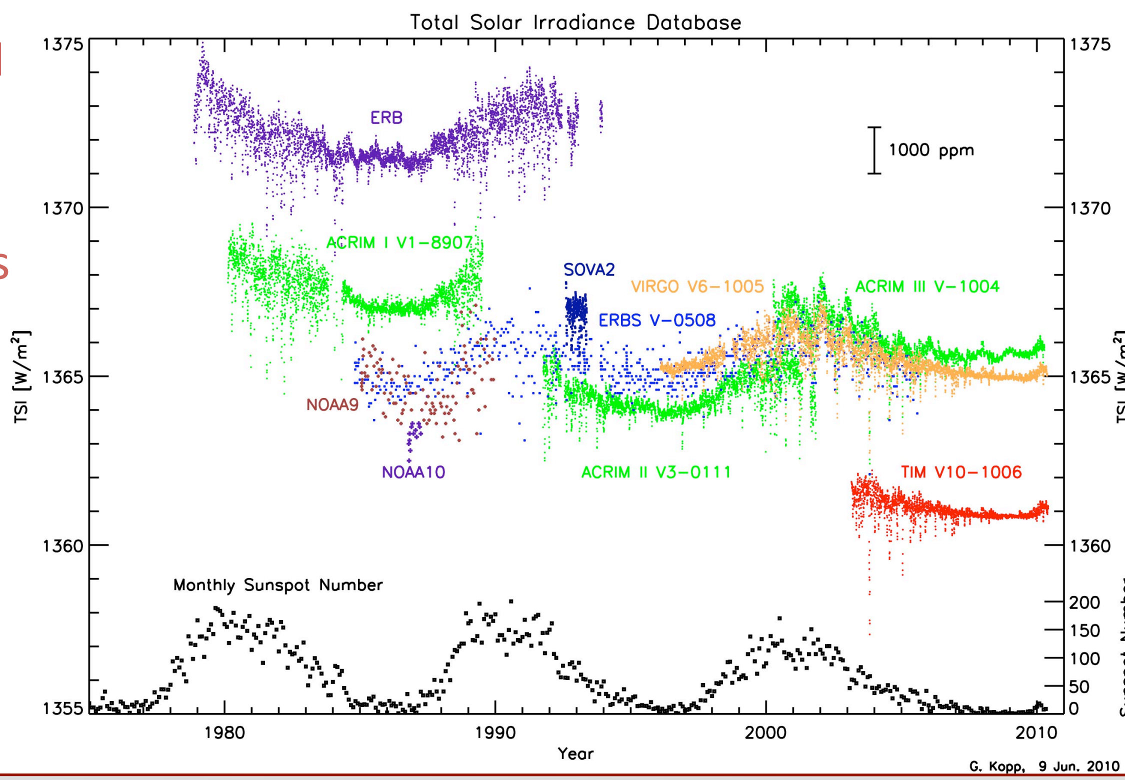
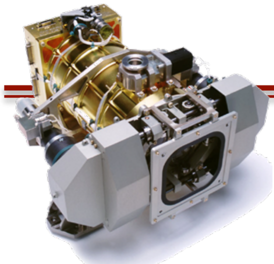
TSI Absolute Accuracies

- Needs for improved TSI absolute accuracy
  1. Mitigate against potential future data gap, which would currently lose connectivity with existing 30-year data record
  2. Understand Earth's energy balance
- TRF helps achieve such accuracies
  1. Can validate future TSI instrument accuracies
  2. Can diagnose instrument differences to understand offsets
  3. Establish ground-based reference linking current and future instruments

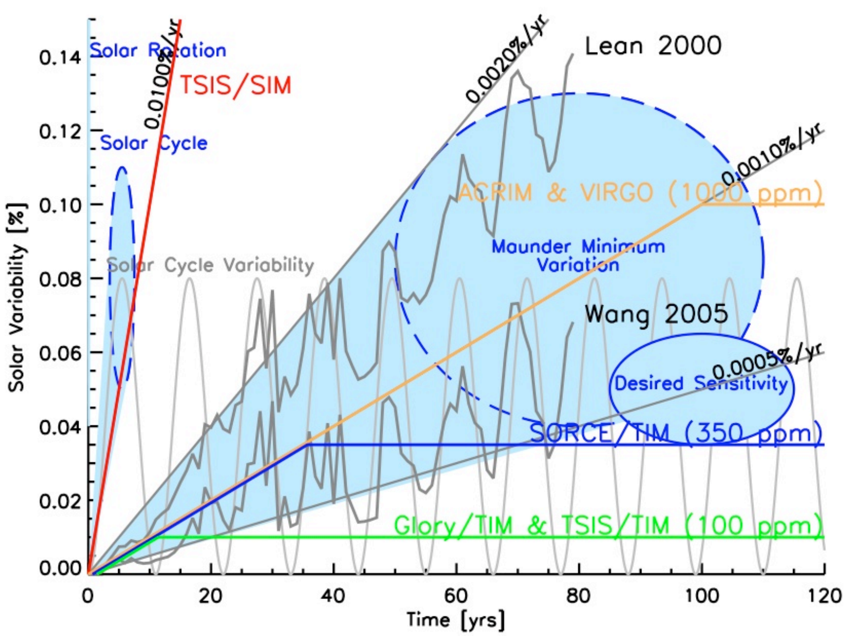


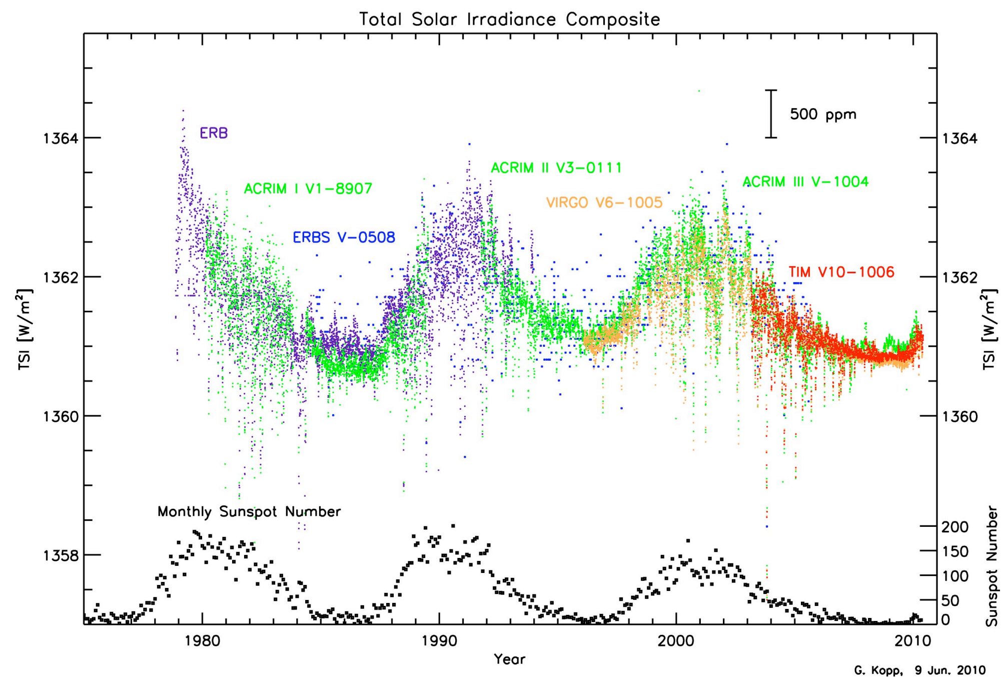


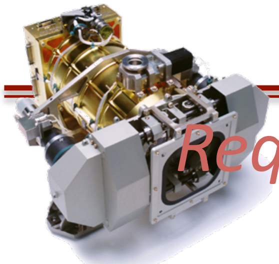
Value of TSI Measurements for Climate Science

TSI Measurements

1. Are the most stable solar irradiance measurements
   – Achieve stabilities necessary to detect climate-relevant solar variability
2. Provide >30 year solar irradiance record of entire radiative input to Earth's climate system

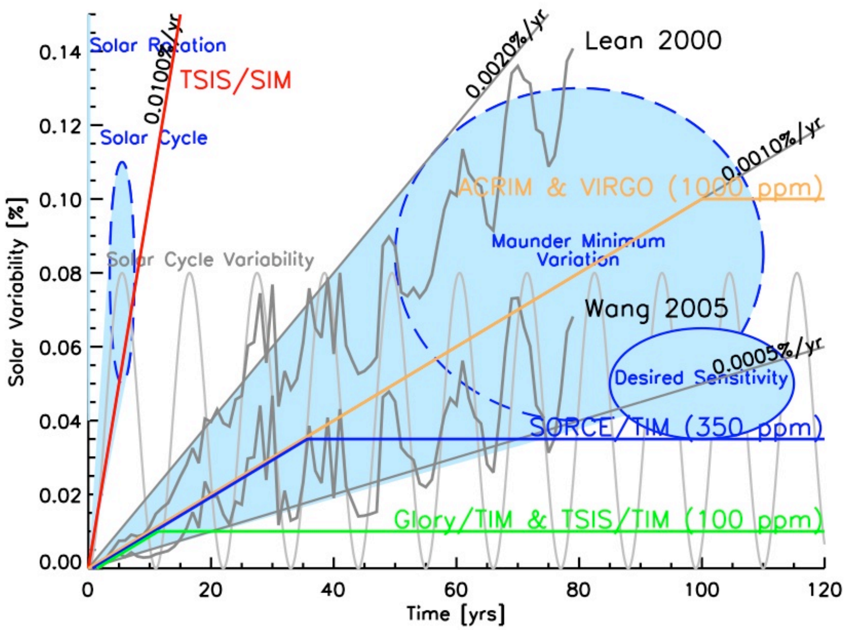


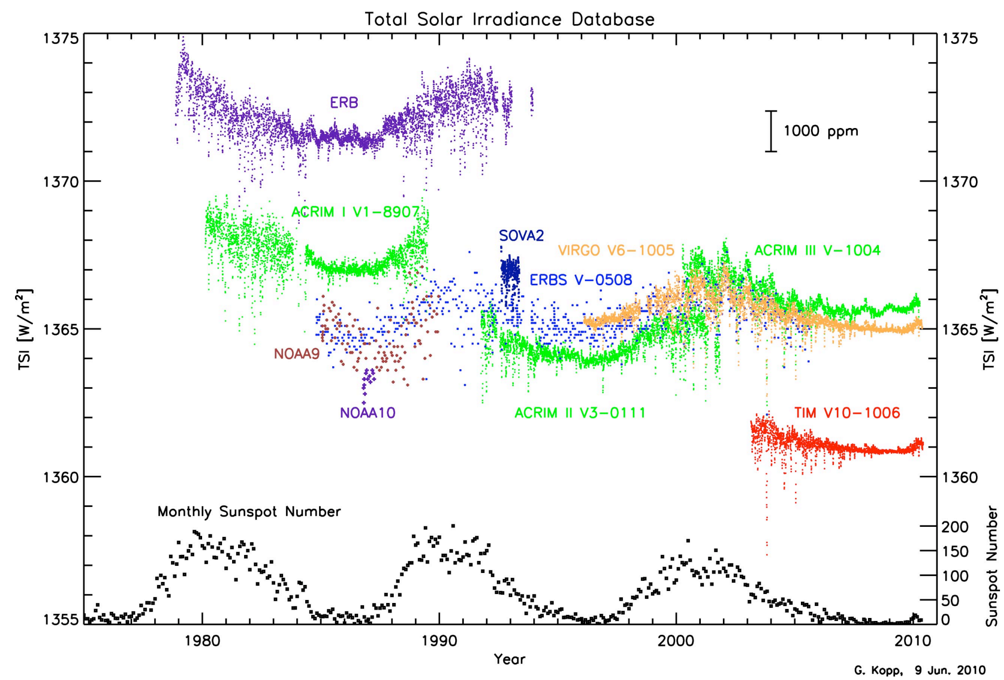


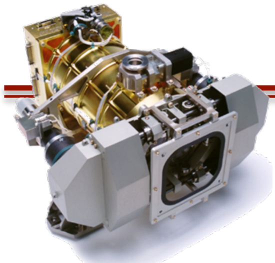


Requirements of TSI Measurements for Climate Science

1. Improve absolute accuracy to 100 ppm. In the meanwhile,
2. Continue to rely on stabilities of <10 ppm/yr (plus continuity)
3. Perform end-to-end ground irradiance validations against an SI-traceable reference (such as TRF)

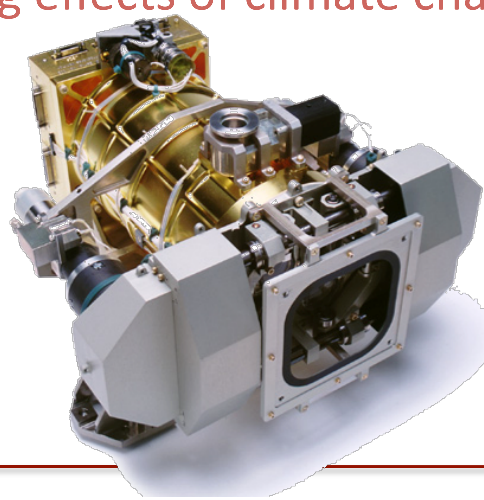


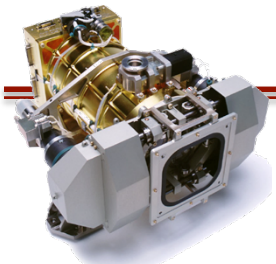




Fundamental TSI Science Questions

- What is the value of the TSI on an absolute scale?
  – Relevant for radiation balance
- How variable is the Sun over decades/centuries?
  – Relevant for climate change and historical perspective
- What solar activities cause TSI fluctuations?
  – Relevant for understanding solar physics and TSI proxies
- How sensitive is the Earth's climate to solar variability?
  – Relevant for quantifying effects of climate change





Conclusions (applicable to more than TSI)

- Need composite climate data records with associated uncertainties for four primary climate forcing agents
  - Requires community self-imposed discipline or national centralization to determine consensus and maintain records
  - Uncertainties important when applying data records in another climate subfield
- Climate measurements need absolute accuracy to reduce reliance on continuity for long-term records
  - Sufficient absolute accuracy for climate research is thrust of TIM TSI measurements and new CLARREO Earth Science Decadal Survey mission