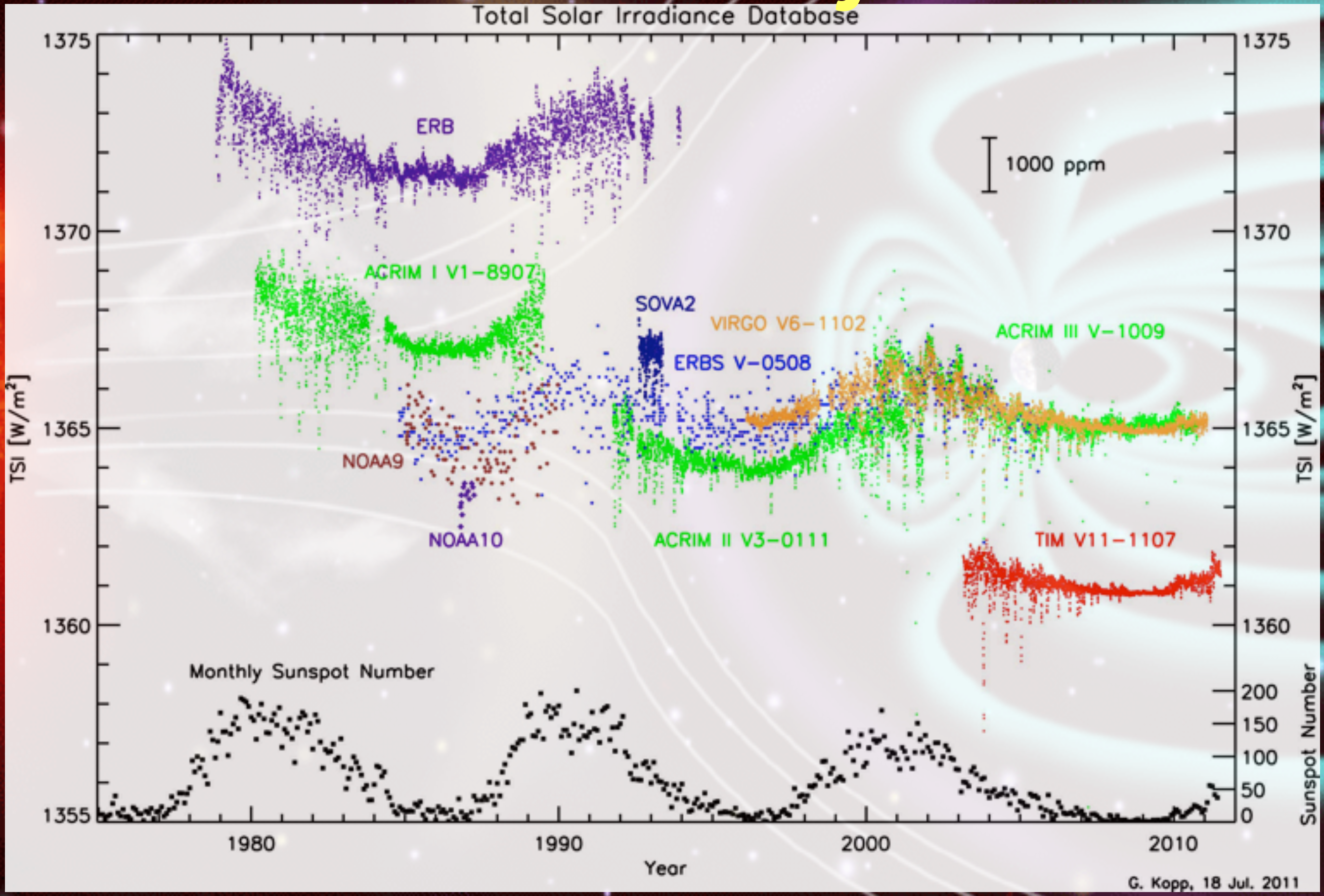
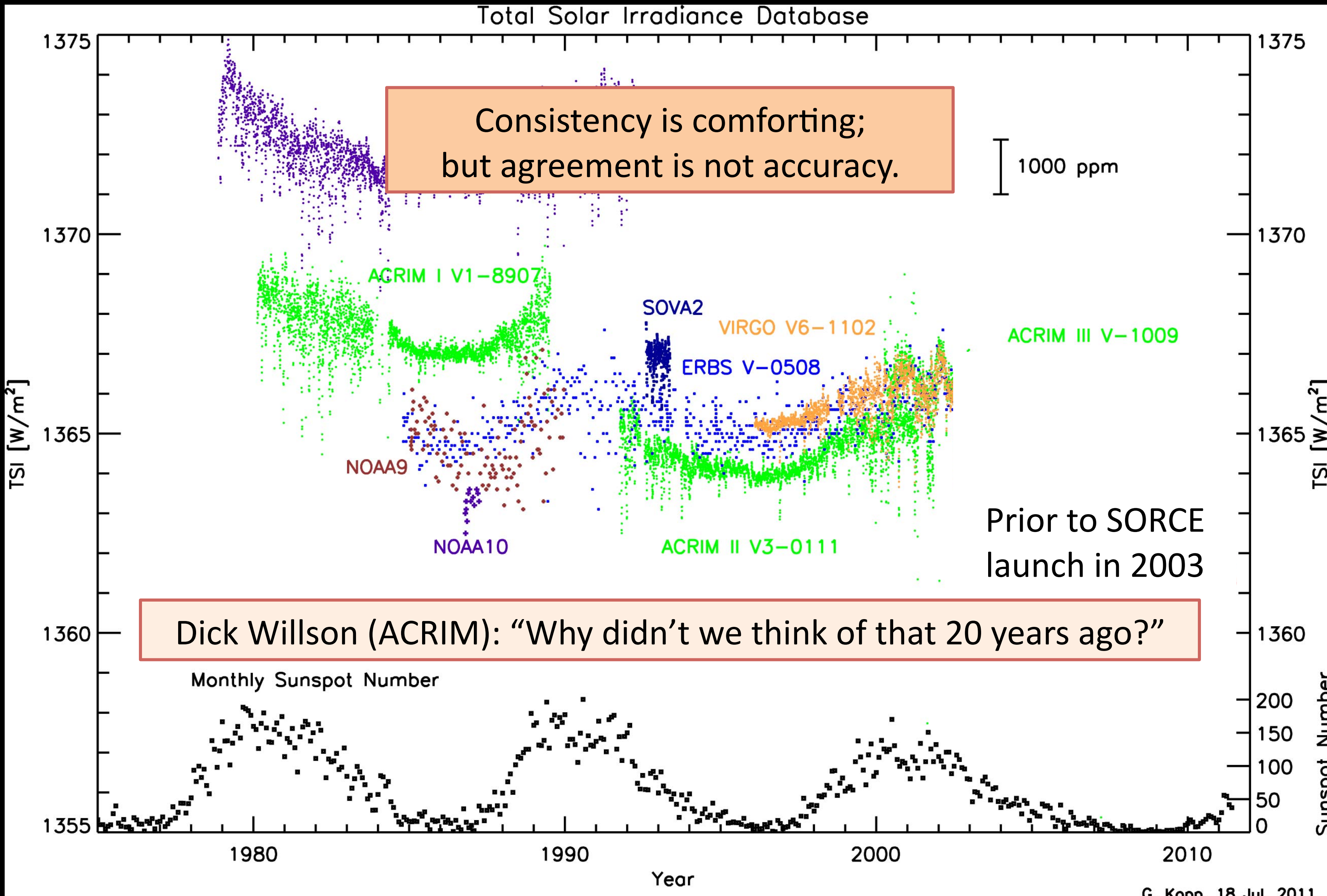
"Why Didn't You Calibrate That?" Lessons Learned from TSI



Greg Kopp

LASP / Univ. of Colorado

The Total Solar Irradiance Data Record

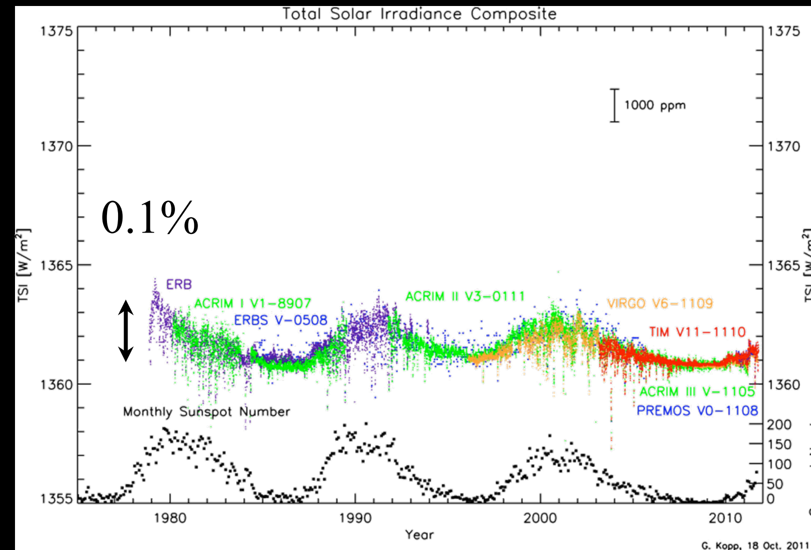


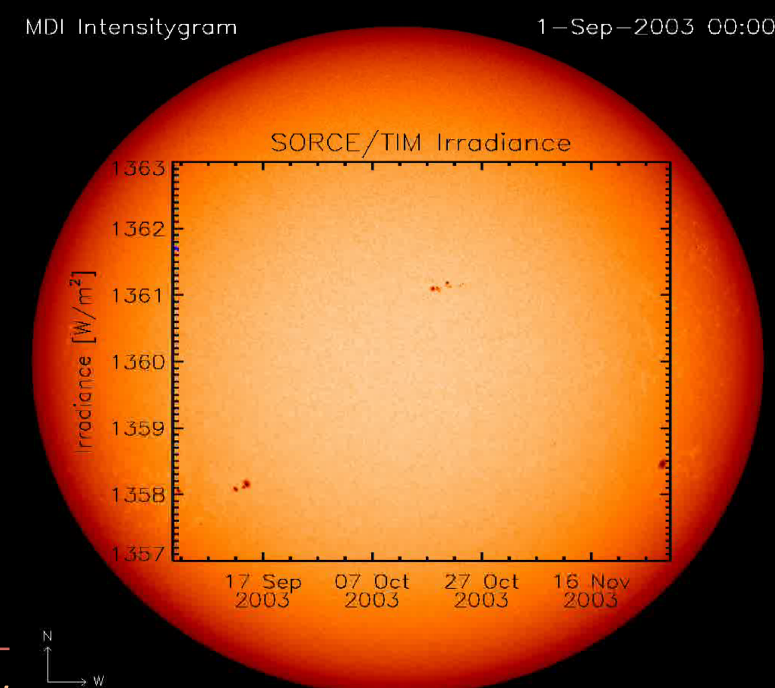
Define Requirements

- For a climate data record of TSI, need accurate measurements over long (climate scale) time periods
  - How accurate? How long?
    - Must detect small changes above natural fluctuations
    - Need estimates of expected variability
  - Drives modeling capability
  - Drives measurement stability and duration
- Patience...
  - ...Or a historical record...

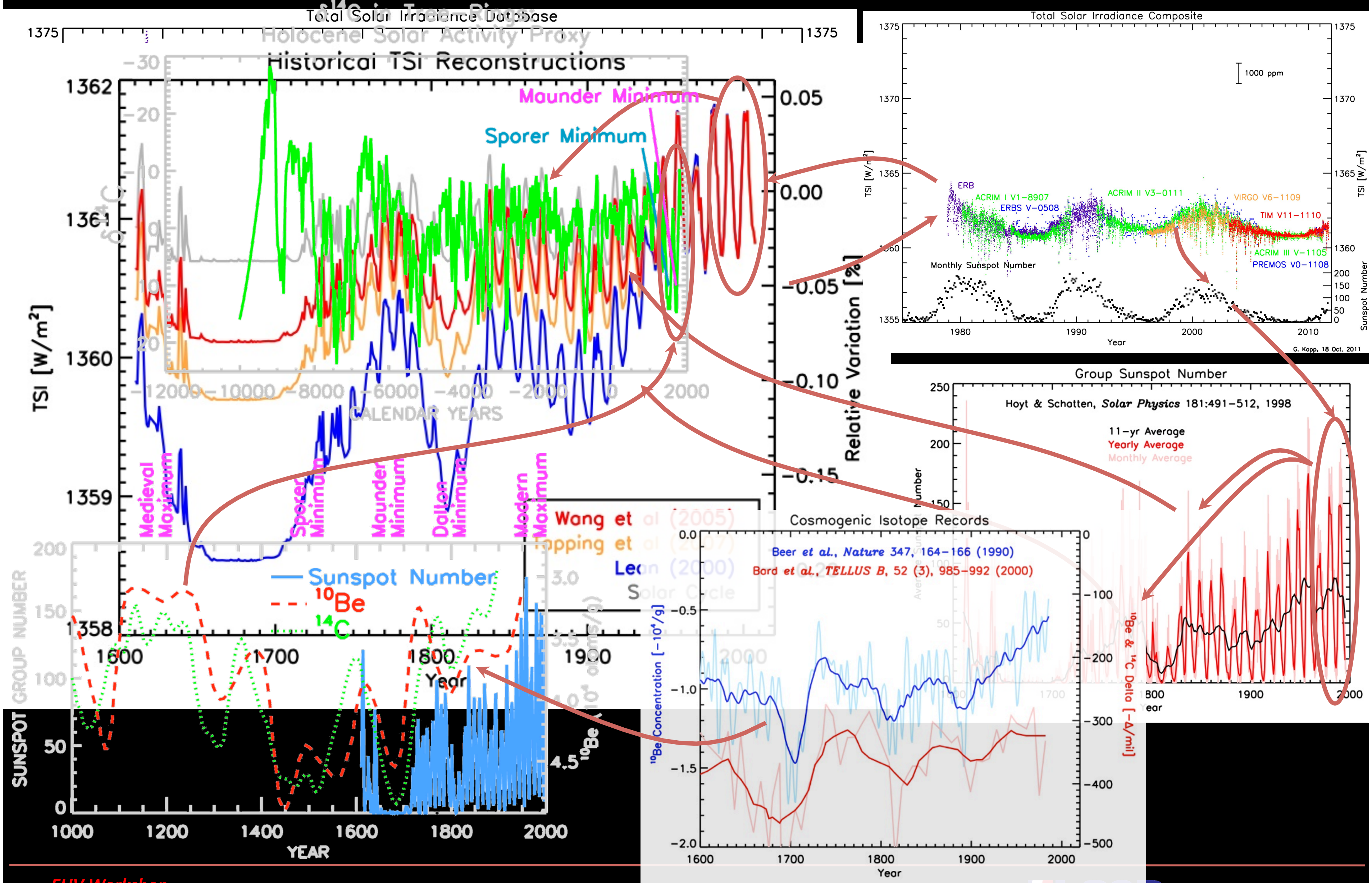
What Are the Time Scales of TSI Variability?

- 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)

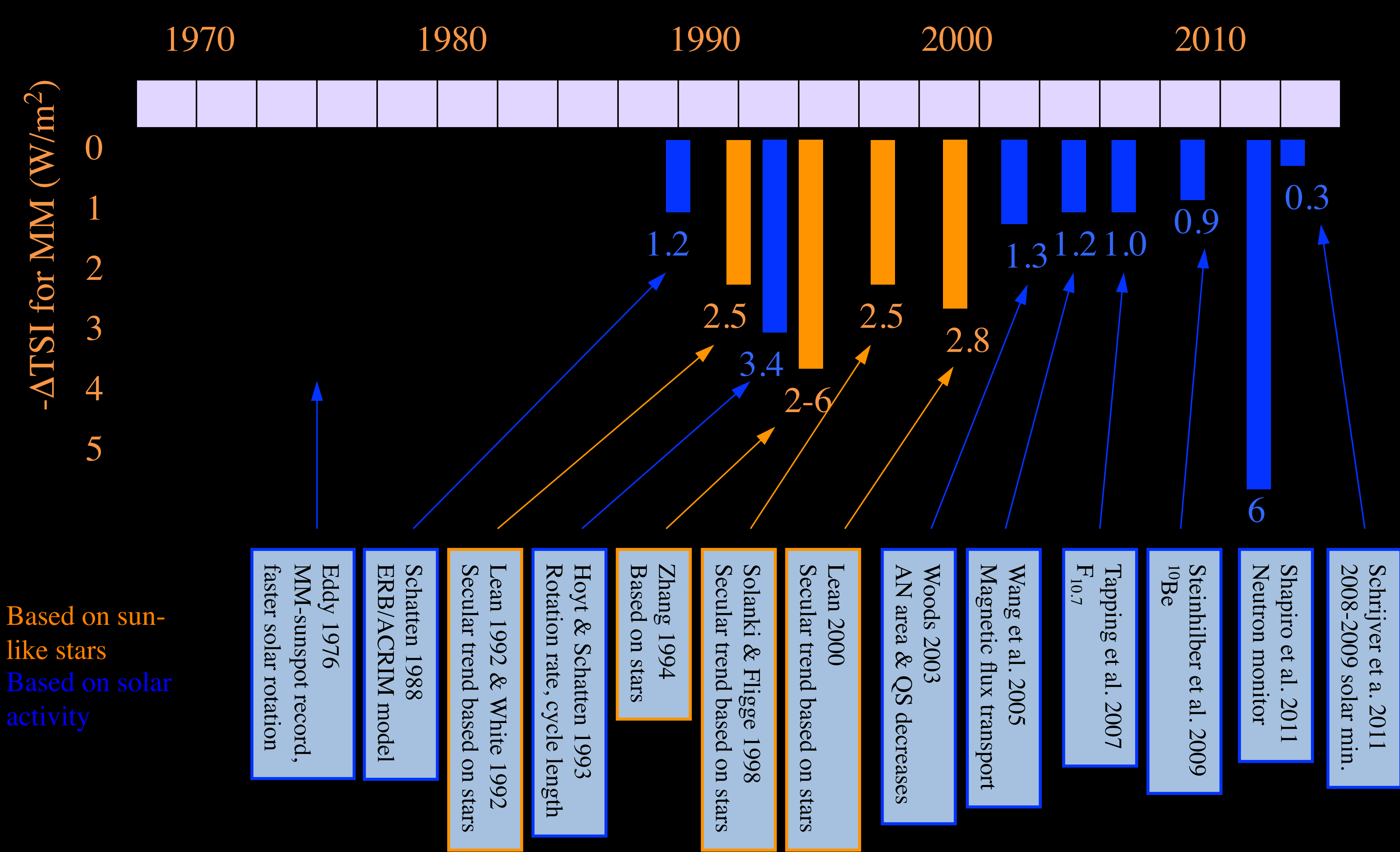




What Is Estimated Solar Variability?

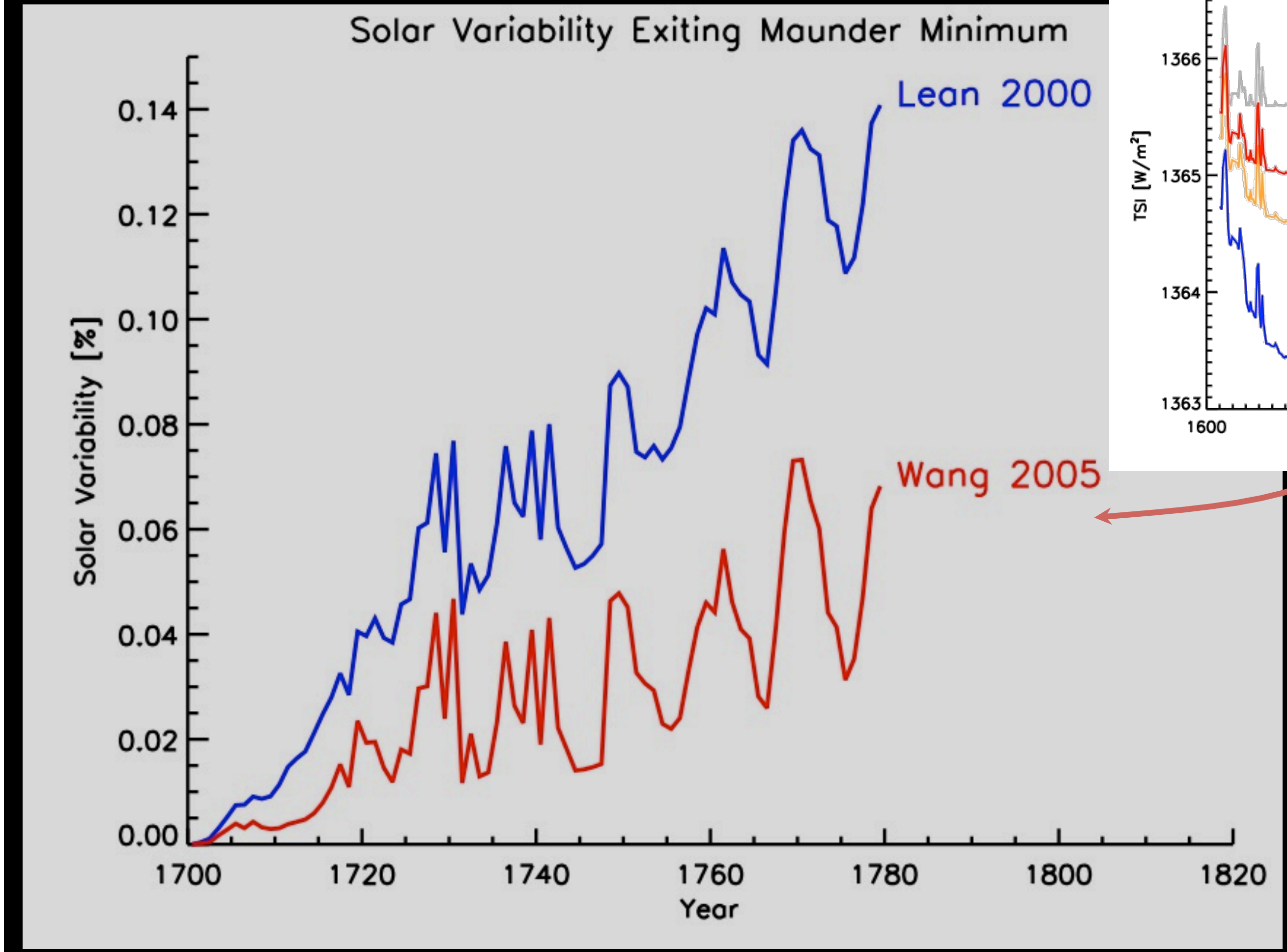


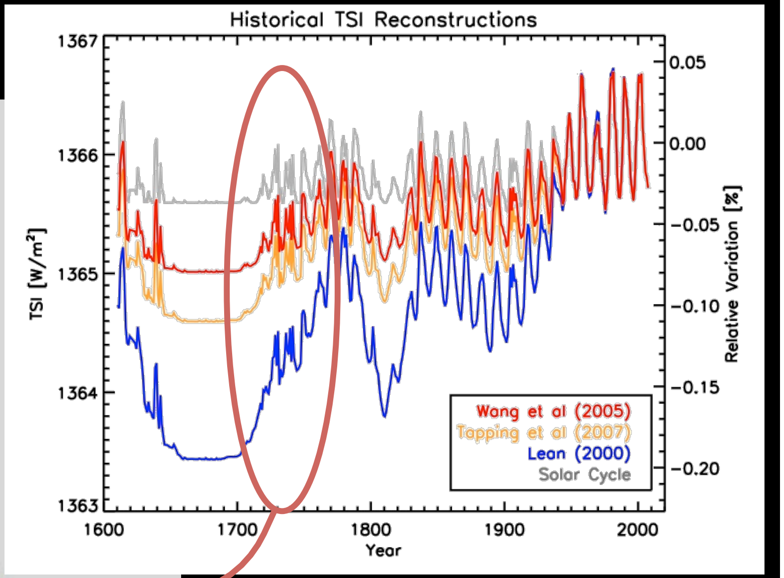
Maunder Minimum TSI Estimates



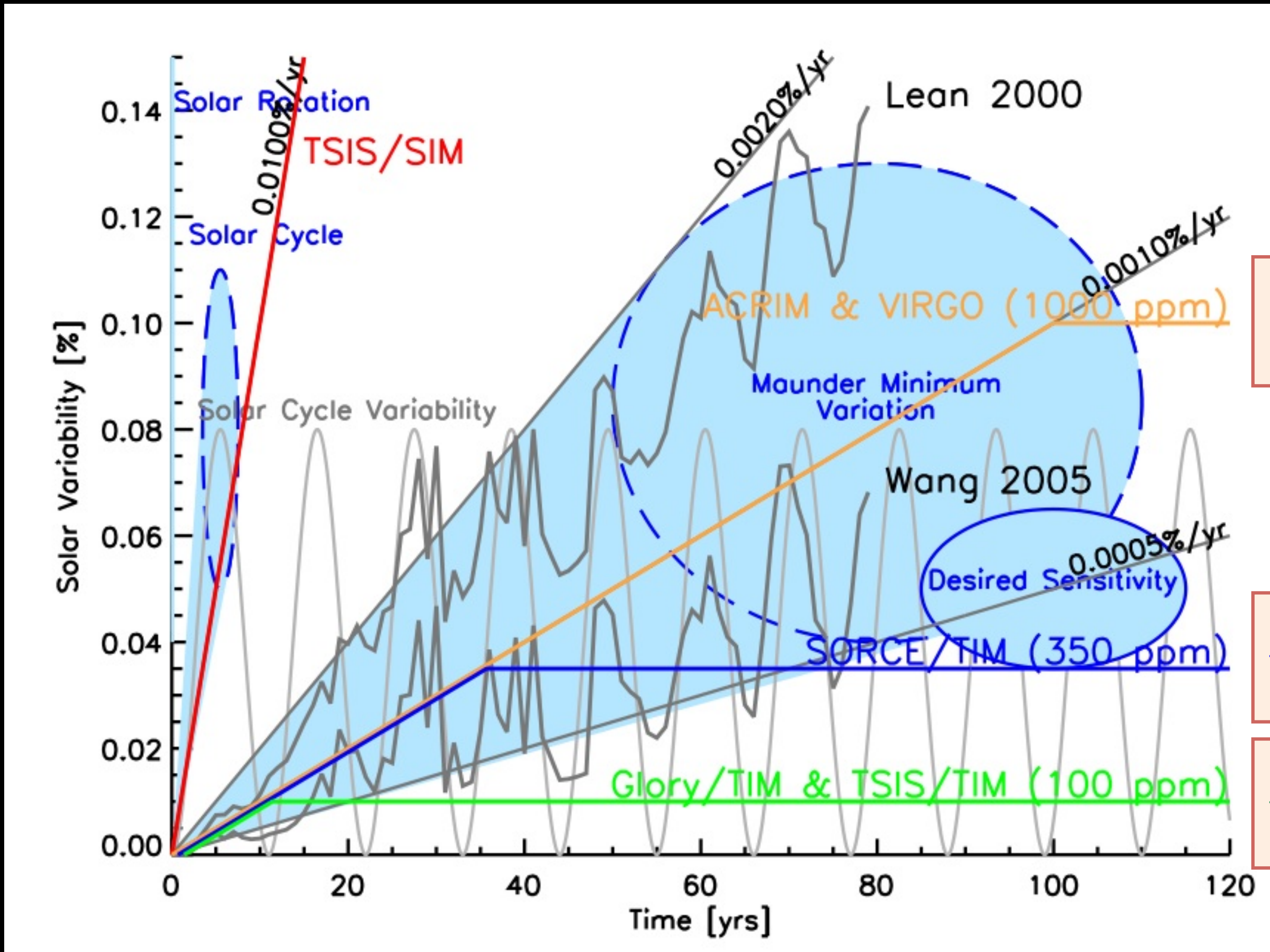
courtesy of T. Woods

Solar Variability Drives Measurement Requirements





Solar Variability Drives Measurement Requirements



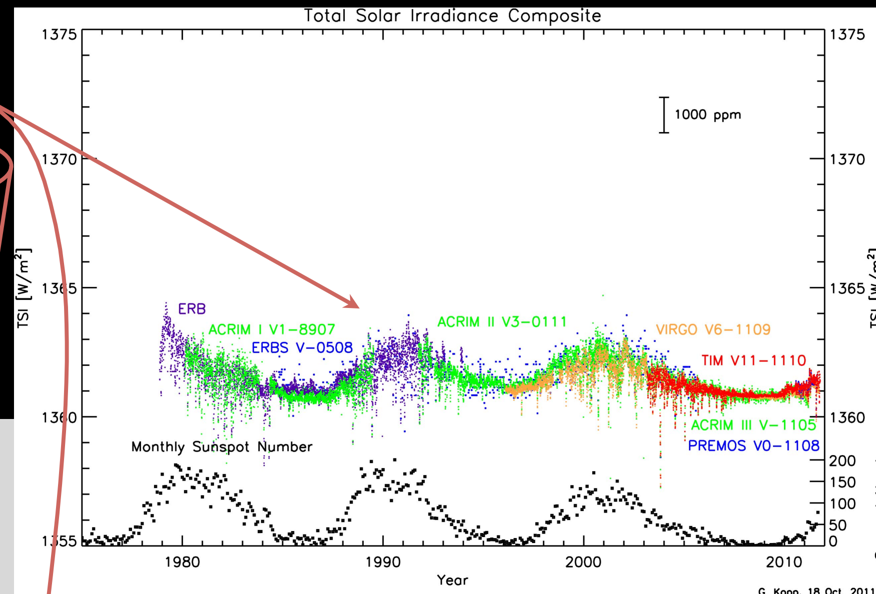
100-yrs needed for MM detection

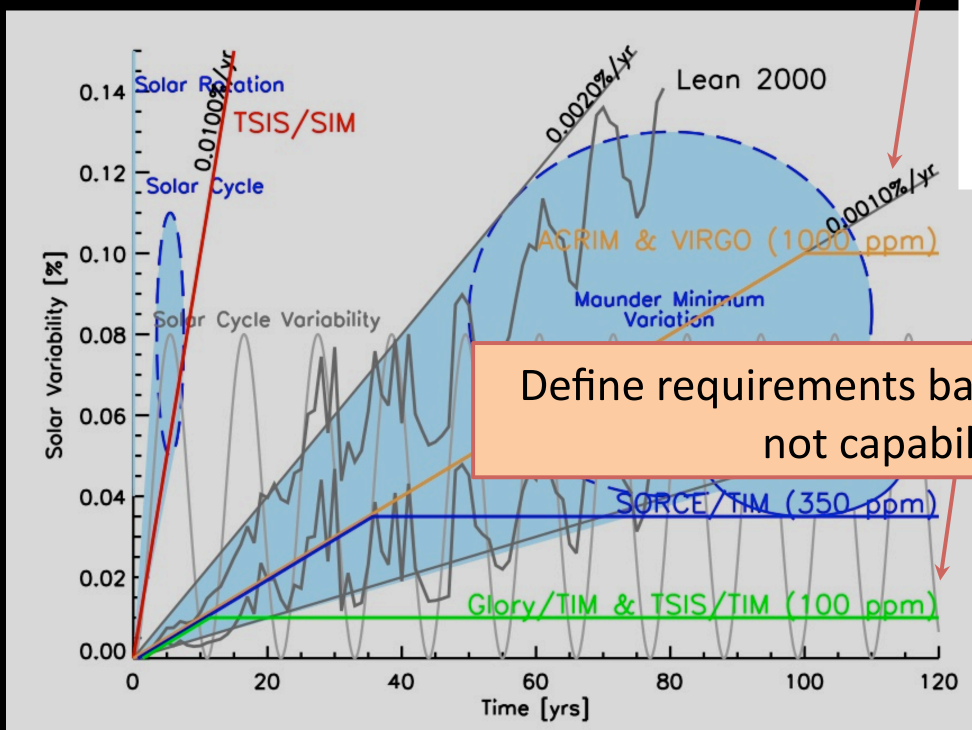
35-yrs needed for MM detection

10-yrs needed for MM detection

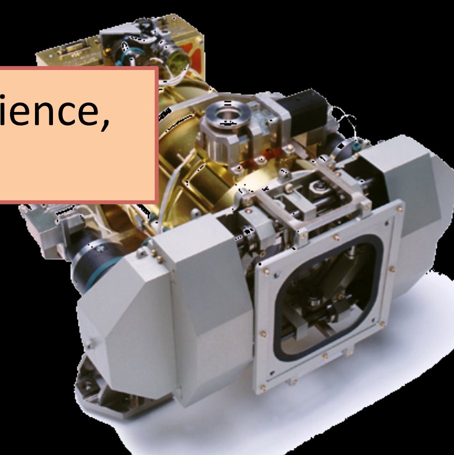
TSI Requirements To Address Climate Needs

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

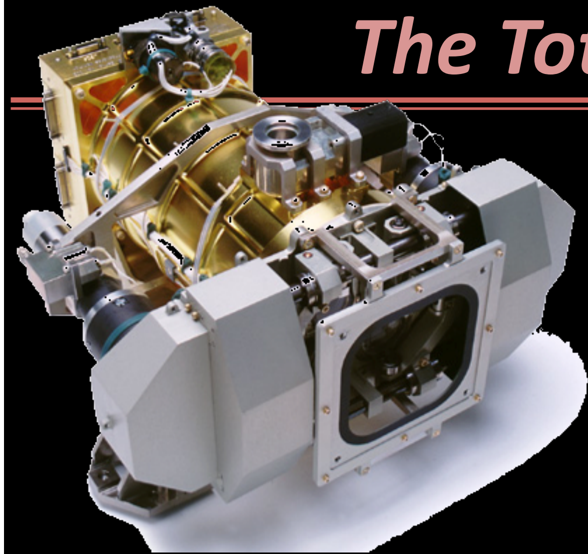




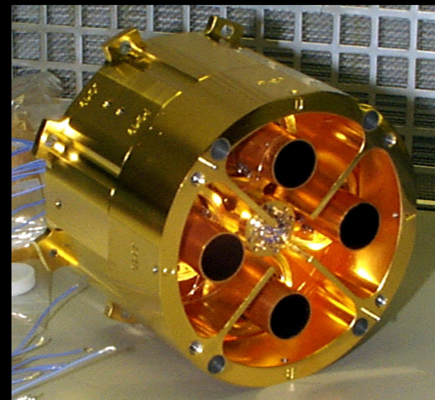
Define requirements based on science, not capability

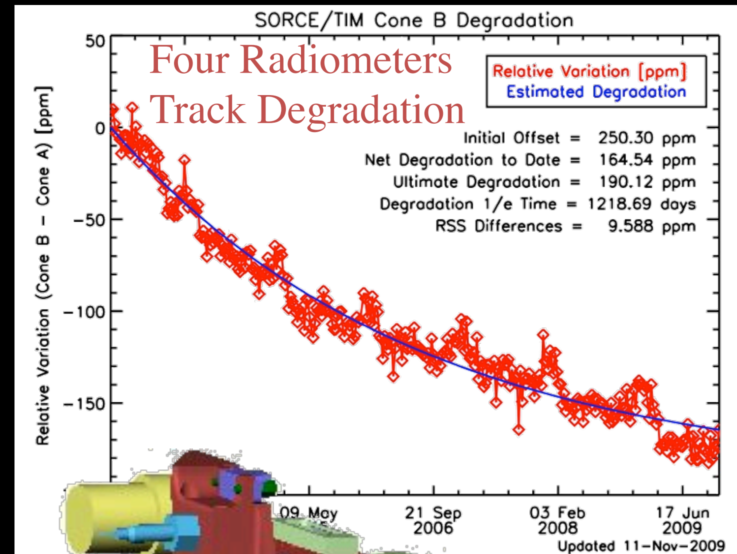


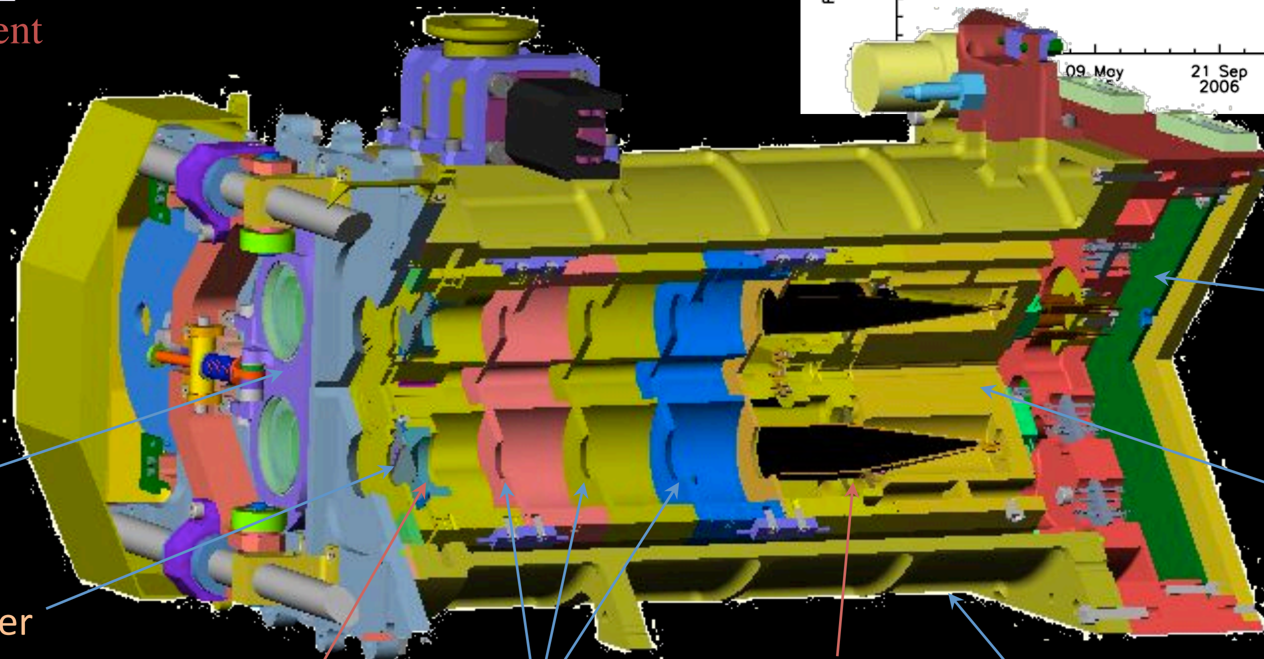
The Total Irradiance Monitor (TIM)



TIM Instrument





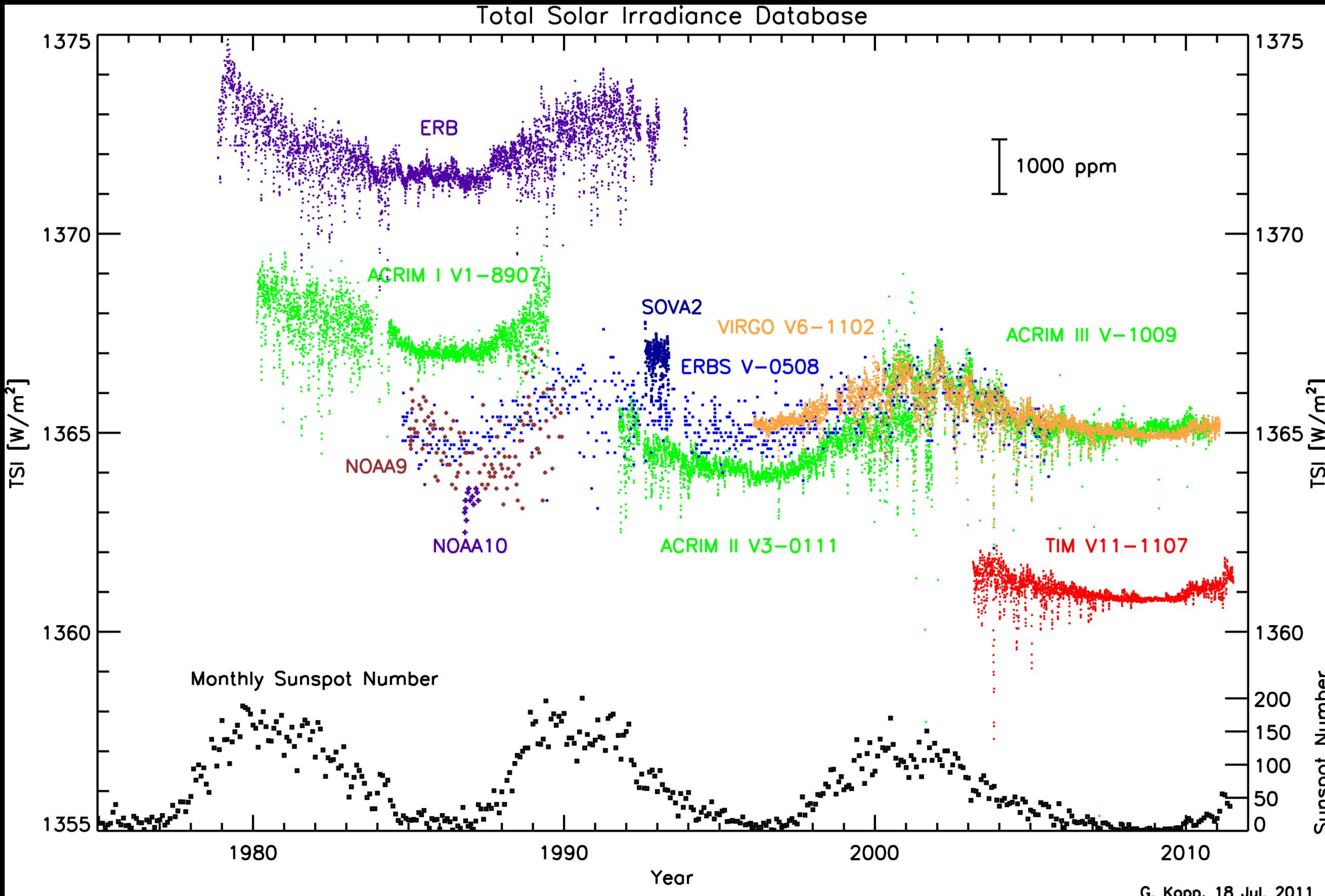


TIM Innovations Enable Accuracies & Stabilities

- The Total Irradiance Monitor, first launched on NASA's SORCE mission in 2003, introduced several measurement innovations
  - nt
  -
  -
  - C ly
  - ion
  -
  - ed

Get new blood: Heritage and experience don't guarantee expertise

Community: So What Causes the Instrument Offsets?



2005 TSI Accuracy Workshop

- Organizer: Jim Butler, NASA/GSFC
- Location: NIST Gaithersburg, MD
- Dates: 18-20 July 2005
- Attendees
  - Representatives of several TSI instruments
    - ACRIM I, II, and III
    - ERBS/ERBE
    - SORCE/TIM
    - VIRGO/PMO
    - VIRGO/DIARAD & SOLCON
  - NIST, NASA
- Approach
  - Day 1: Accuracy ("the Day 1 Problem")
  - Day 2: Stability
  - Day 3: Improved or current calibration facilities
- Dick Willson: "We haven't had a meeting like this in 20 years!"

Group Therapy Plan

- Get everyone together at neutral place (organized by NIST, NASA)
  - Discuss instrument and calibration details *ad nauseam*
  - Make uncertainty budgets consistent for comparisons
  - Discuss dirty laundry with neutral participants ("judges") in audience
  - Include diverse group (Eric Shirley, theory, diffraction)
  - Create test plans

Dick Willson (ACRIM III): "A requirement of future missions should be a comparison at the TRF."

Steven Lorentz (NIST, L1): "We quit worrying about absolute accuracy after the 100 ppm."

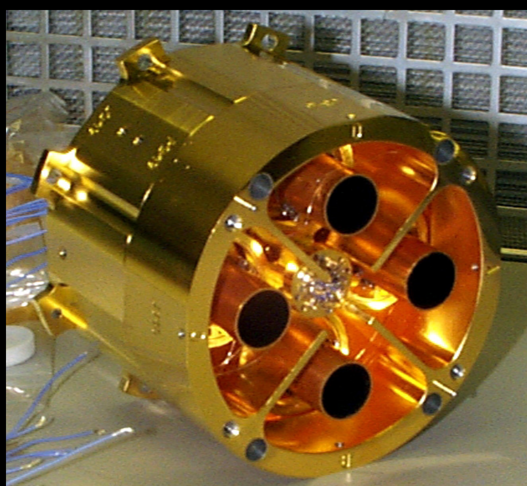
Bob Lee (ERBE): "We haven't changed anything since 1986."

Agenda

Monday, July 18

Satellite Instrument TSI Measurement Uncertainty Session: Session Lead-G. Kopp

8:30 am-8:45 am Welcome and Meeting Charge	J. Butler
8:45 am- 8:50 am Session 1 Goals	G. Kopp
8:50 am-10:00 am ACRIM I, II & III	R. Willson
10:00-10:15 am ACRIM	R. Helizon
10:35 am-12:00 pm TIM on SORCE	G. Kopp
1:00 pm-2:25 pm PMO6V on VIRGO/SoHO	C. Frohlich
2:25 pm- 3:50 pm The DIARAD type instruments, principles and error estimates	D. Crommelynck & S. Dewitte
4:10 pm-5:35 pm ERBE on ERBS	R. Lee
5:35 pm-5:55 pm Disscussion and Session wrap-up	G. Kopp



Multiple Radiometers Should Indicate Consistency With Stated Uncertainties

- Review Instrument Designs
  - Are there systematic differences that could cause TSI offsets?
- Review Calibrations & Uncertainties
  - How accurately is each instrument calibrated?
  - What were goals and actuals?
- Intra-instrument Consistency
  - Do intra-instrument cavity comparisons agree with stated uncertainties?

Summary of Instruments

Instrument	Comments on Instruments
ERB (NIMBUS 7)	1 cavity; the best TSI measurement made when it started!
ACRIM I	3-cavity; darks are modeled (corroborated w/ measurement); passive thermal; TRW aperture calibration questionable; on-board V & I monitors; specular black paint; front-to-back cavities; internal precision apertures
ACRIM II	3-cavity; darks are modeled (corroborated w/ measurement); passive thermal; JPL Metrology Lab aperture calibration; questionable calibrations; extended cone tips; on-board V & I monitors; specular black paint; front-to-back cavities; internal precision apertures
ACRIM III	3-cavity; darks are modeled (corroborated w/ measurement); passive thermal; JPL aperture calibration (OMIS II); on-board V & I monitors; specular black paint; front-to-back cavities; internal precision apertures
ERBE	1 cavity; bi-weekly 3-min TSI measurements; dark measurements; large thermal variations during operations; lacks several correction factors (servo not settled before shutter transition); 13-bit resolution; specular black paint; front-to-back cavities; internal precision aperture
VIRGO-PMO	2-cavity; darks are modeled; good passive thermal stability at L1; low-frequency ‘shutter’; on-board V & I monitors; front-to-back cavities; internal precision apertures
VIRGO-DIARAD	2-cavity; darks are modeled; good passive thermal stability at L1; poor inter-cavity agreement on SOHO; on-board V & I monitors; diffuse black paint; side-by-side cavities; internal precision apertures
TIM	4-cavity; frequent dark measurements; active thermal control; aperture and shutter at front; pulse width modulation ESR heating; V & R are references; pulse width non-linearities corrected from ground TIMs; diffuse black NiP; side-by-side cavities

Summary of Instruments

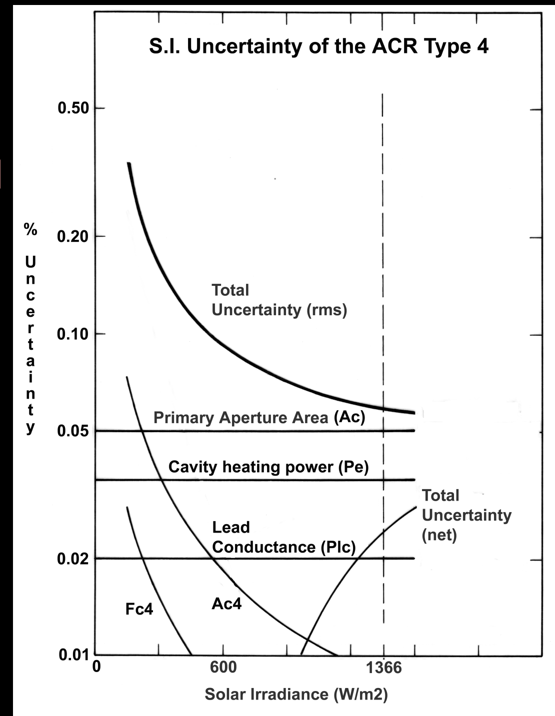
Instrument	Cav #	Cavity Layout	Precision Aperture Position	V Mon	I/R Mon	Black	Black Type	Active Therm Control	Dark Meas. Freq.	Comments
ERB	1	?	internal	?	?	paint	specular	no	every meas.	
ACRIM I	3	cones, front to back	internal	yes	yes	paint	specular	no	low	
ACRIM II	3	cones, front to back	internal	yes	yes	paint	specular	no	low	
ACRIM III	3	cones, front to back	internal	yes	yes	paint	specular	no	low	
ERBE	1	cones, front to back	internal	yes	yes	paint	specular	no	every meas.	one 3-min meas every 2 wks
VIRGO-PMO	2	inverted cones, front to back	internal	yes	yes	paint	specular	passive at L1	none	low-freq. shutter
VIRGO-DIARAD	2	cylinders, side by side	internal	yes	yes	paint	diffuse	passive at L1	none	
TIM	4	cones, side by side	front of instrum.	no	no	NiP	diffuse	yes	every orbit	pulse-width modulation

Reviewed Uncertainties (in Different Languages)

SORCE/TIM

Correction	Value [ppm]	SORCE	Worst Case
Distance to Sun, Earth & S/C	33,537	0.1	0.1
Doppler Velocity	57	0.7	0.7
Shutter Waveform	100	1.0	1.0
Aperture	1,000,000	55	652
Cone Reflectance	250	54	108
Equivalence Ratio, ZH/ZR	7, AC	23	46
Servo Gain	16,129	0.0	0.0
Standard Volt + DAC	1,000,000	7.0	100
Pulse Width Linearity	1,000,000	186	300
Standard Ohm + Leads	1,000,000	17	25
Dark Signal	2,693	10	25
Scattered Light & IR	100	25	50
Measurement Repeatability (Noise)		1.5	2.0
Total RSS		**205**	**737**
Cone Agreement Accuracy		266	266

ACRIM



VIRGO/PMO

Uncertainty of the PMO6V WRR/SI traceability @ 1400W/m2

Component	Value	u	c	(u*c)^2
Area	N/A			
Pclosed	45 mW	0.0000045	5.00E+04	0.050625
Popen	17 mW	0.0000017	5.00E+04	0.007225
CNE	1	5.00E-04	1.40E+03	0.49
CR	N/A	7.00E-05	1.40E+03	
CSt	N/A	1.00E-04	1.40E+03	
CLH	N/A	3.00E-05	1.40E+03	
CApH	N/A	5.00E-04	1.40E+03	
Cdiff	N/A	1.00E-04	1.40E+03	
WRR-Factor	1	6.00E-04	1.40E+03	0.7056
WRR/SI	1	9.00E-04	1.40E+03	1.5876
				2.84105
		Uncertainty abs		1.6855 W/m2
		Uncertainty rel		1685.5 ppm
		95% Uncertainty		3371.1 ppm

VIRGO/DIARAD L

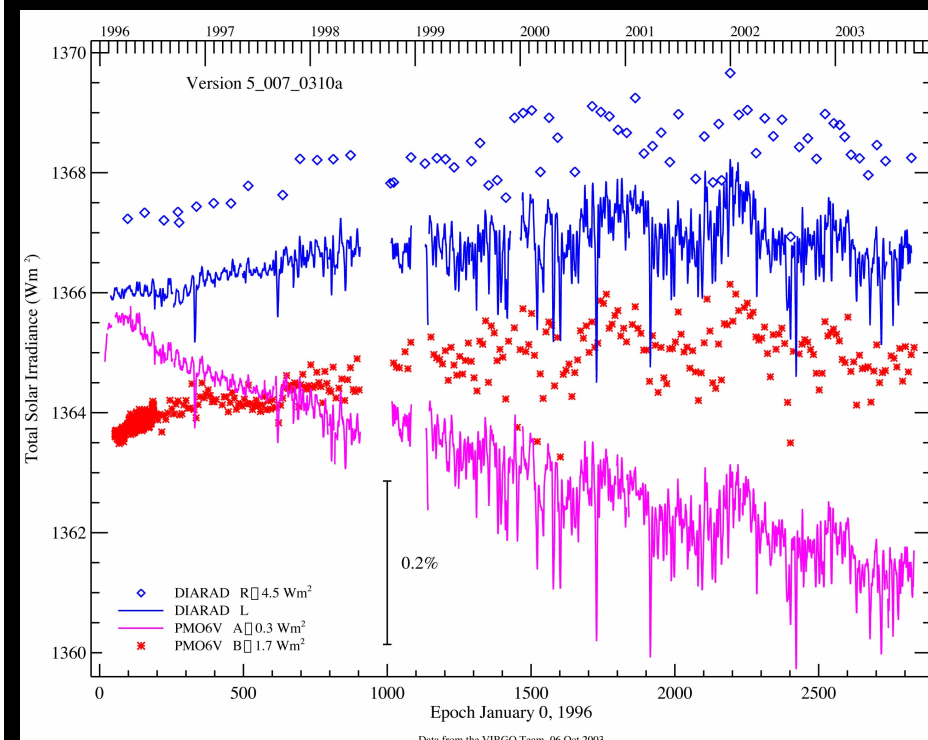
	Relative	W/m2
Area	0.000425	0.58
Thermal efficiency	0.000130	0.18
Eectrical. Power	0.000150	0.20
Cavity absorption	0.000030	0.04
Total	**0.000735**	**1.00**
RSS	0.000470	0.64

Check Internal Instrument Consistency

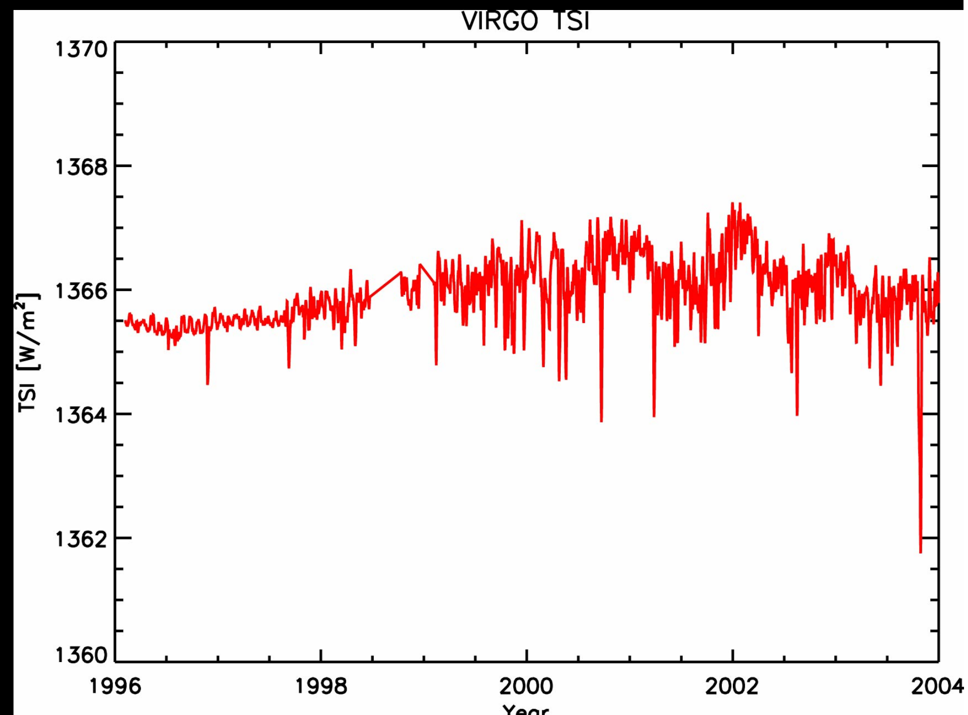
- Level 1 VIRGO data demonstrate level of variations of individual channels

Consistency is comforting;
but agreement is not accuracy.

Level 1 Data (all 4 channels)



Level 2 Data (VIRGO)



Summary of Stated Instrument Accuracies

Instrument	TSI Value [W/m^2]	Stated Uncertainty [ppm]	Cavity Variations σ [ppm]	Comments
ERB (NIMBUS 7)	1371.9	5000	-	
ACRIM I	1367.5	1000	511	
ACRIM II	1364.2	1000	2046	apertures? cone tips?
ACRIM III	1366.1	1000	1036	
ERBE	1365.2	833	-	lacks several corrections
VIRGO	1365.7	1000	2271	DIARAD 5.7 W/m^2 difference
VIRGO-PMO	1365.7	1204	299	
VIRGO-DIARAD	1366.4	470	2858	5.7 W/m^2 cavity difference
DIARAD-like	1366.4	600	1612	SOVA, SOLCON, DIARAD
SORCE/TIM	1361.0	350	301	

- Uncertainties are 1-σ

Translate to a Common Language

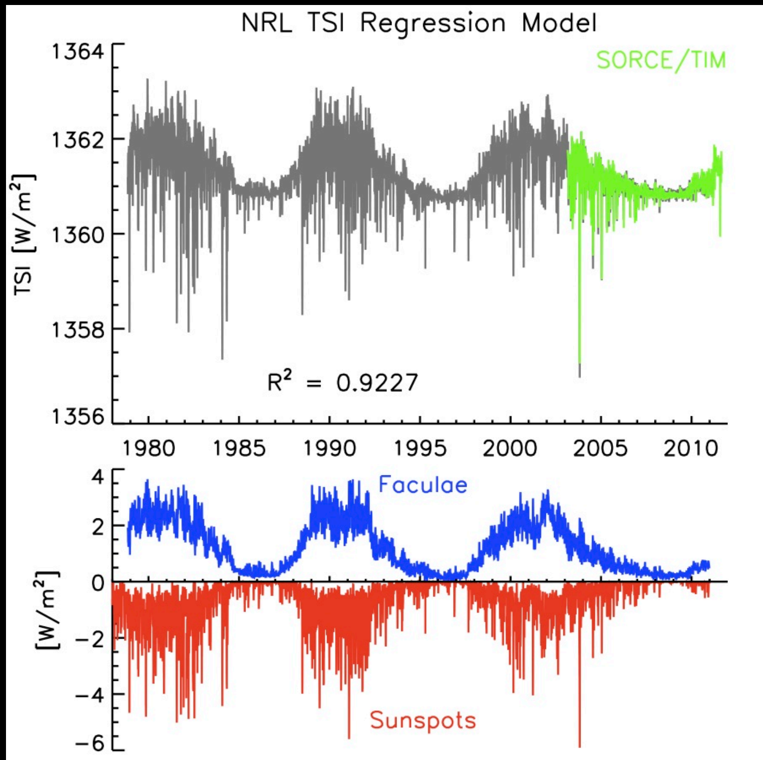
Instrument	SORCE TIM	
Correction	Value [ppm]	σ [ppm]
Aperture	1,000,000	30
Diffraction	452	47
Cone Reflectance	170	54
Non-Equivalence, ZH/ZR - 1	7, AC	23
Standard Volt + DAC	1,000,000	186
Standard Ohm + Leads	1,000,000	17
Servo Gain	16,129	0.0
Dark Signal	2,693	10.0
Scattered Light & IR	100	25
Shutter Waveform	100	1.0
Distance to Sun, Earth & S/C	33,537	0.1
Doppler Velocity	57	0.7
Pointing		10.0
Measurement Repeatability		1.5
Total RSS		205.5
Cone Agreement Accuracy		301

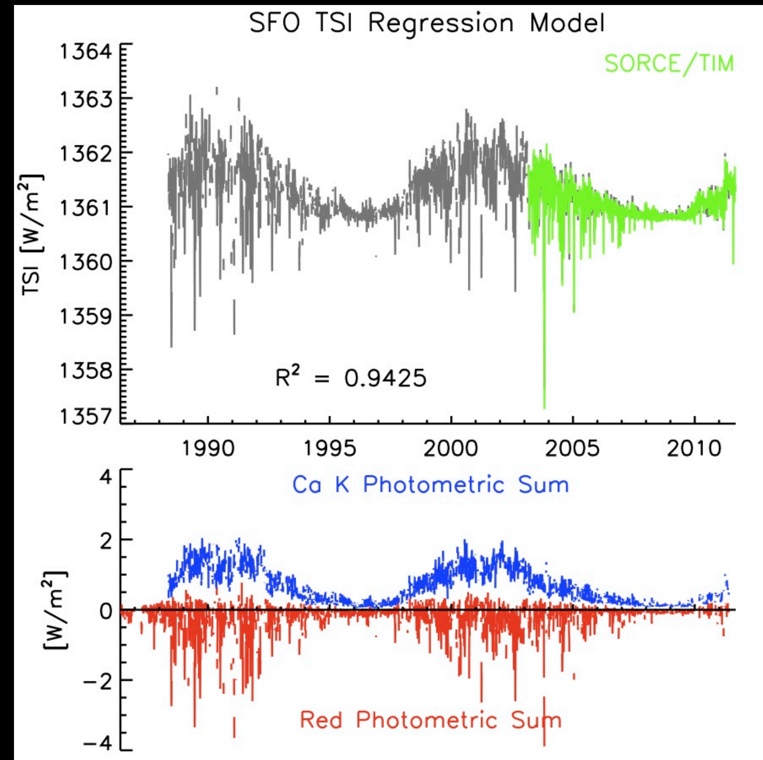
Instrument	ACRIM III	
Correction	Value [ppm]	σ [ppm]
Aperture	1,000,000	280
Diffraction	1,200	120
Cone Reflectance	500	200
Non-Equivalence, ZH/ZR - 1		
Standard Volt + DAC	1,000,000	101
Standard Ohm + Leads	1,000,000	
Servo Gain		
Dark Signal		
Scattered Light & IR		
Shutter Waveform		
Distance to Sun, Earth & S/C	33,537	0.1
Doppler Velocity	57	0.7
Pointing		
Measurement Repeatability		
Total RSS		378.1
Cone Agreement Accuracy		1,036

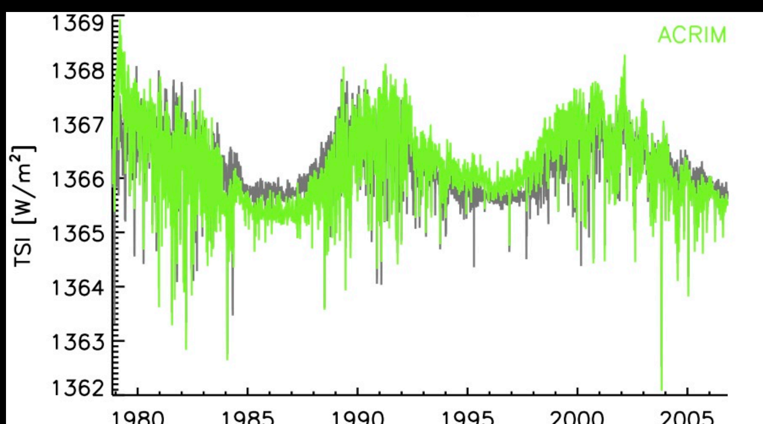
Instrument	PMO	
Correction	Value [ppm]	σ [ppm]
Aperture	1,000,000	501
Diffraction		100
Cone Reflectance	330	70
Non-Equivalence, ZH/ZR - 1	2,900	500
Standard Volt + DAC	1,000,000	
Standard Ohm + Leads	1,000,000	30
Servo Gain		
Dark Signal		
Scattered Light & IR	320	100
Shutter Waveform		
Distance to Sun, Earth & S/C	33,537	0.1
Doppler Velocity	57	0.7
Pointing		
Measurement Repeatability		223.6
Total RSS		759.7
Cone Agreement Accuracy		299

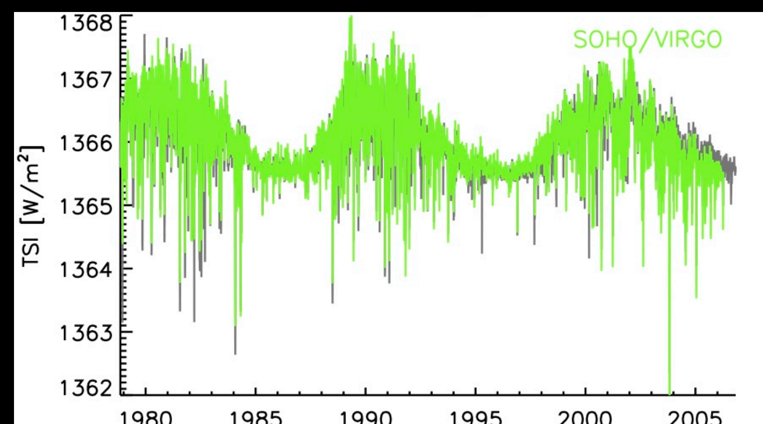
Instrument	DIARAD	
Correction	Value [ppm]	σ [ppm]
Aperture	1,000,000	400
Diffraction		
Cone Reflectance	250	250
Non-Equivalence, ZH/ZR - 1	0	200
Standard Volt + DAC	1,000,000	150
Standard Ohm + Leads	1,000,000	
Servo Gain	329	
Dark Signal		
Scattered Light & IR		
Shutter Waveform		
Distance to Sun, Earth & S/C	33,537	0.1
Doppler Velocity	57	0.7
Pointing		
Measurement Repeatability		
Total RSS		533.9
Cone Agreement Accuracy		2,858

What Do Models Show?









CERES and TIM Are Improving Radiative Balance Understanding

TIM: 340.3 W/m^2

Imbalance: 4.2±2.2 W/m^2 (1-σ uncertainties)

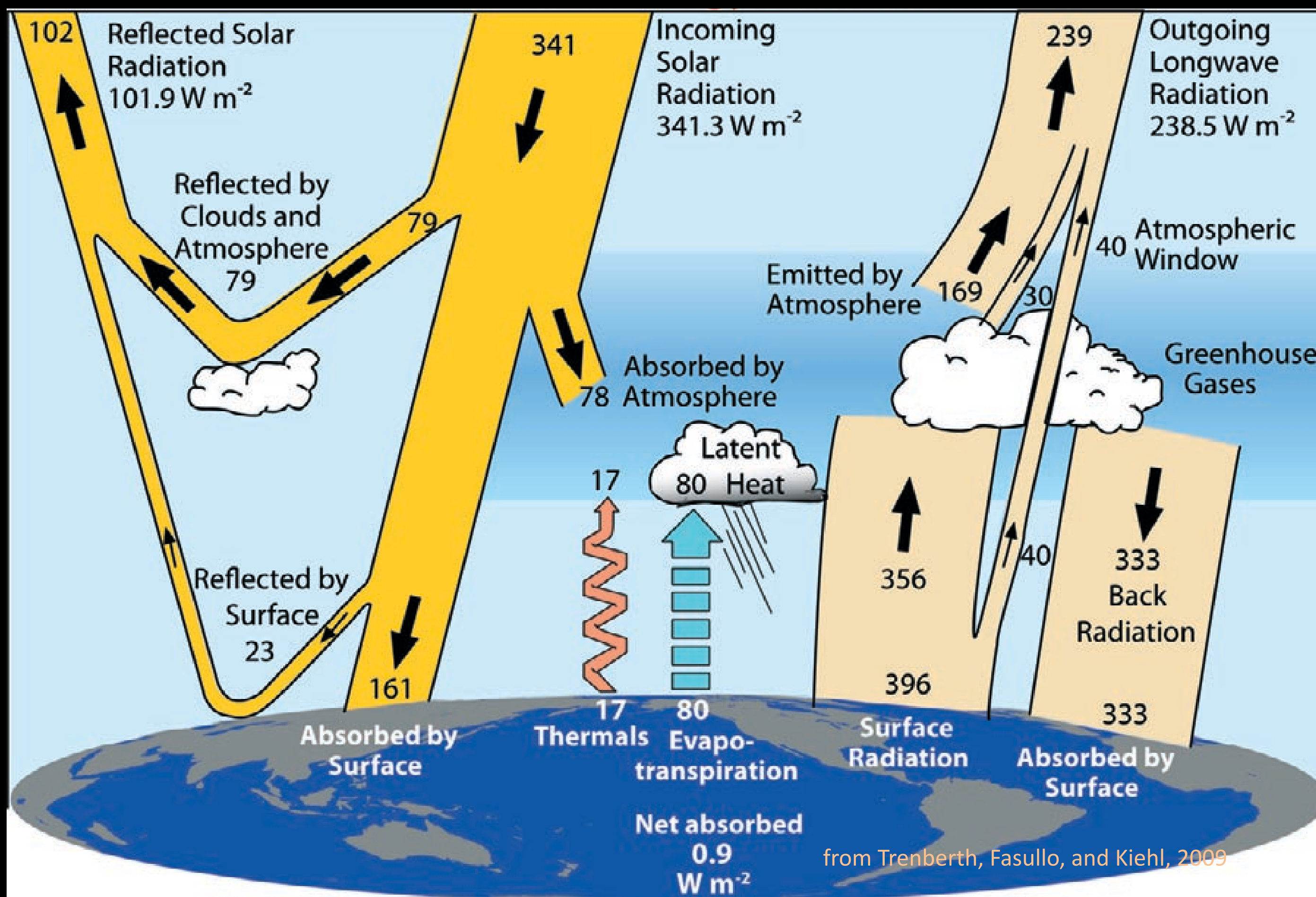
Expand beyond your instruments

Oceans: 0.85 W/m^2
Earth Sph: 0.16 W/m^2
Terminator: 0.3 W/m^2

CERES SW: 97.7 W/m^2

CERES LW: 237.1 W/m^2

values from Loeb *et al.*, 2008



from Trenberth, Fasullo, and Kiehl, 2009

Possible Causes of Differences in Absolute Values

- **Underestimated Uncertainties**: Is this simply the state of the art in these radiometric measurements, with all uncertainties being underestimated?
- **Apertures**: Measurements from different facilities have greater variations than stated aperture measurement uncertainties.
  - Does not account for 0.3% TSI difference
  - Does not explain inter-cavity variations within single instrument
- **1 AU**: 149.59787066 x 10^6 km (SORCE value)
- **Darks**: Uncertainties in dark corrections are large.
  - These are large corrections, depend on FOV, and vary with temperature.
  - Darks are not measured regularly on several instruments.
- **TIM Linearity**: Non-linearities were only measured on ground units. The TIM uses pulse width modulation while other radiometers are DC.
  - Very unlikely to have 0.3% difference
- **Scatter Prior to Limiting Aperture**: Instruments with oversized (non-limiting) aperture near front of instrument allow much more sunlight into instrument. (The TIM precision aperture and shutter are at the front of the instrument, so this is a difference.)
  - Scatter will increase the signal through the limiting aperture.
- **Diffraction**: This is a 0.12% effect in ACRIM and is not made
- **Aperture Heating:** Uncertainties in heating due to different aperture materials, conduction, mounting, emissivities

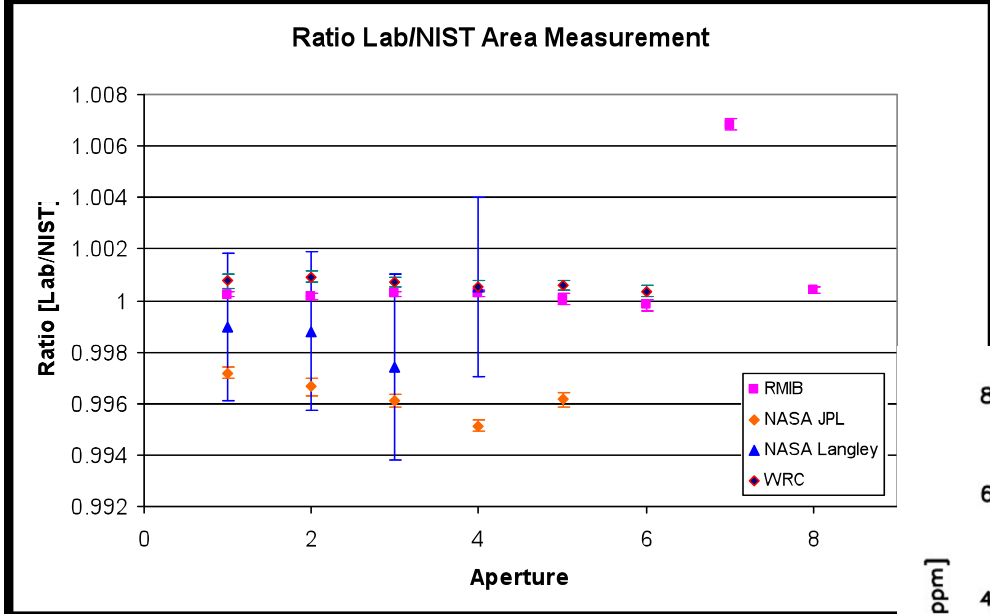
Experimentalists are optimistic

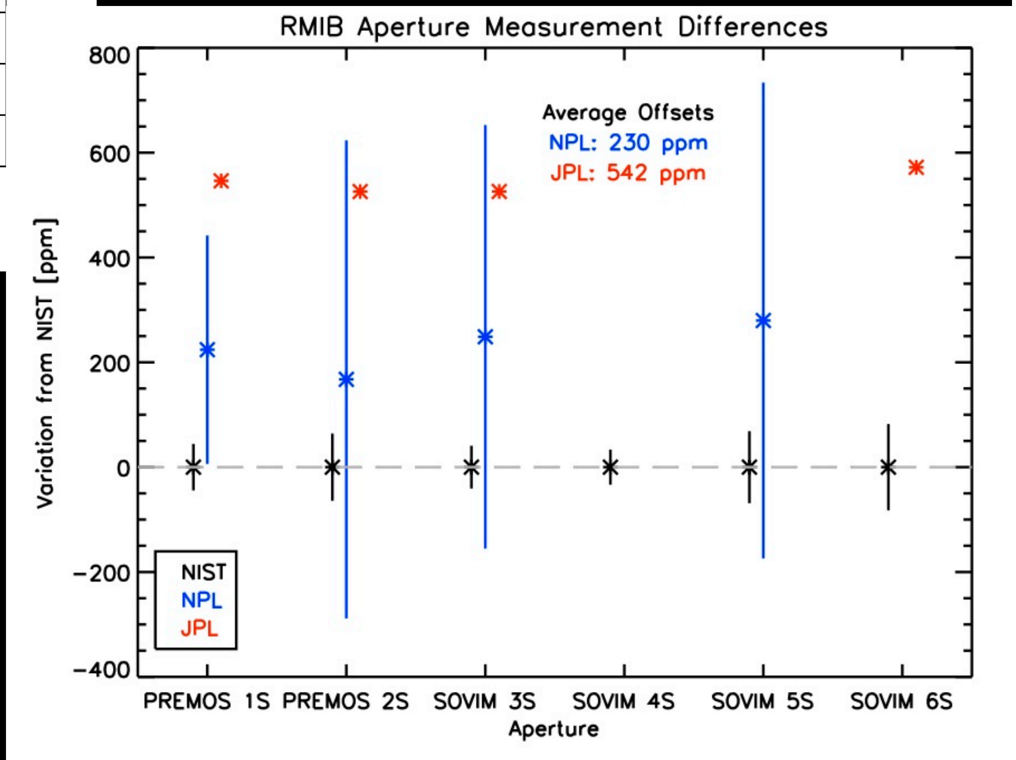
Things To Do

- Uncertainties are higher than stated and difference isn't unexpected.
  - The best comparisons are currently being done in space, and ground-based comparisons are not needed as differences are simply due to large uncertainties.
- Complete aperture comparison measurements
  - Get ACRIM apertures included in NIST aperture comparison
- Power comparison
  - NPL power trap comparison
  - NIST power cryo comparison
  - 0.05% accuracy
- Consider a PMOD World Radiation Reference or a JPL Table Mountain Observatory inter-comparison
  - These are not absolute measurements, merely relative comparisons
- NASA's Glory program is creating a cryo radiometer facility to compare TSI instruments on an <u>absolute</u> scale

NIST Aperture ~~Comparison~~ Saga

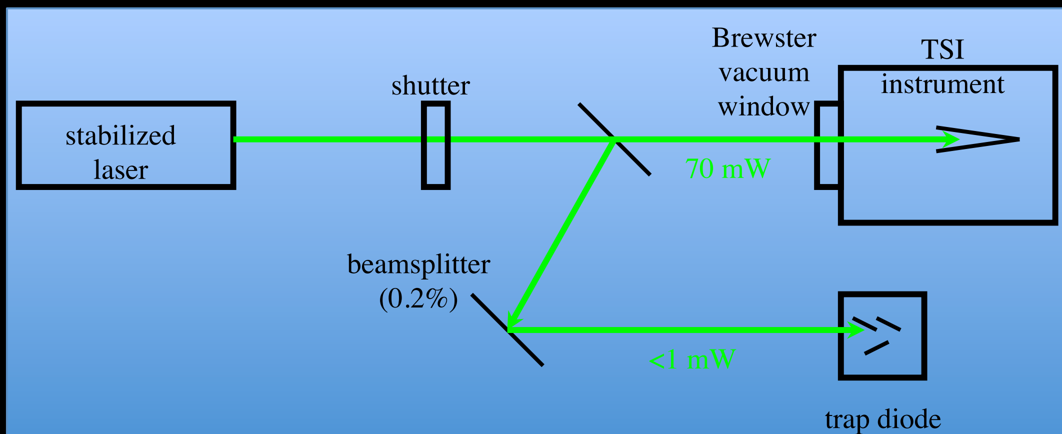
The dog ate my homework

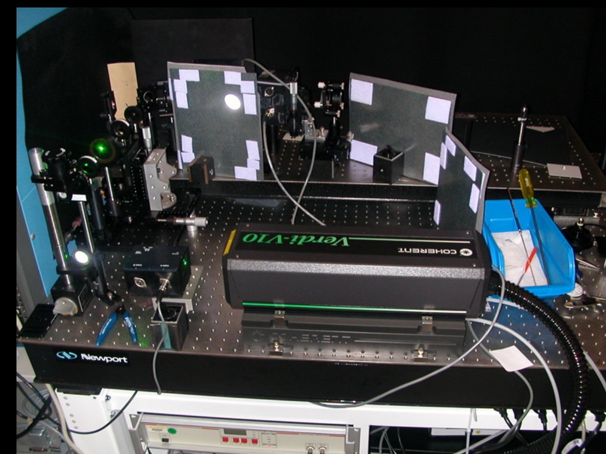


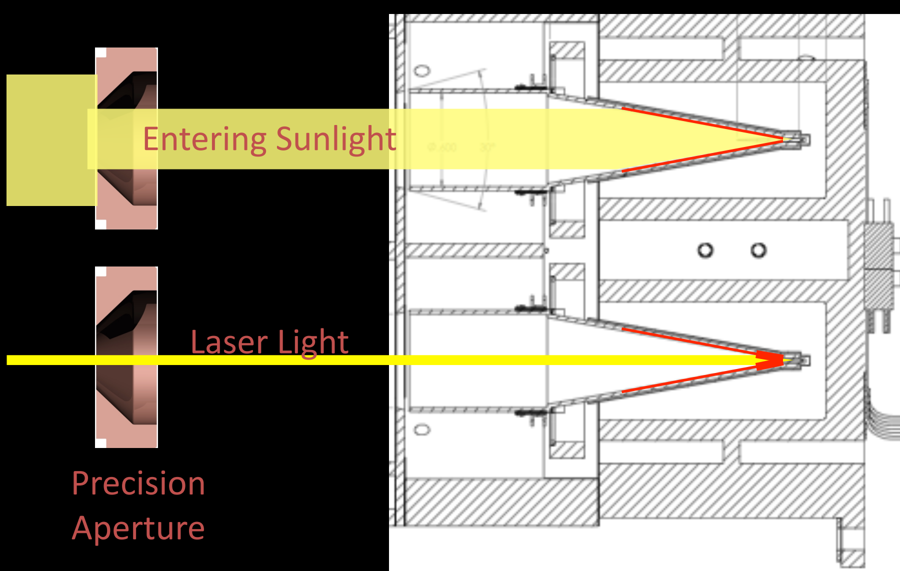


TIM Optical Power Comparisons at NIST

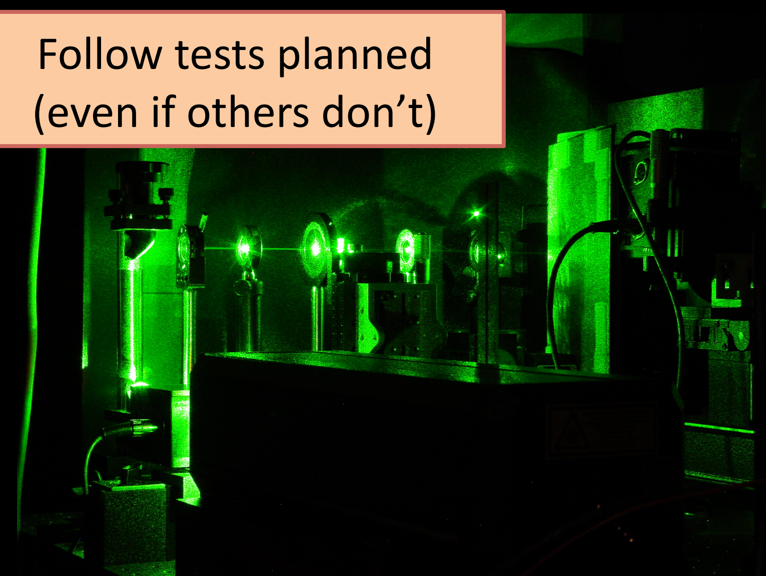
- NIST and LASP completed optical power comparisons between a trap diode transfer standard and a ground-based TIM







Follow tests planned (even if others don't)

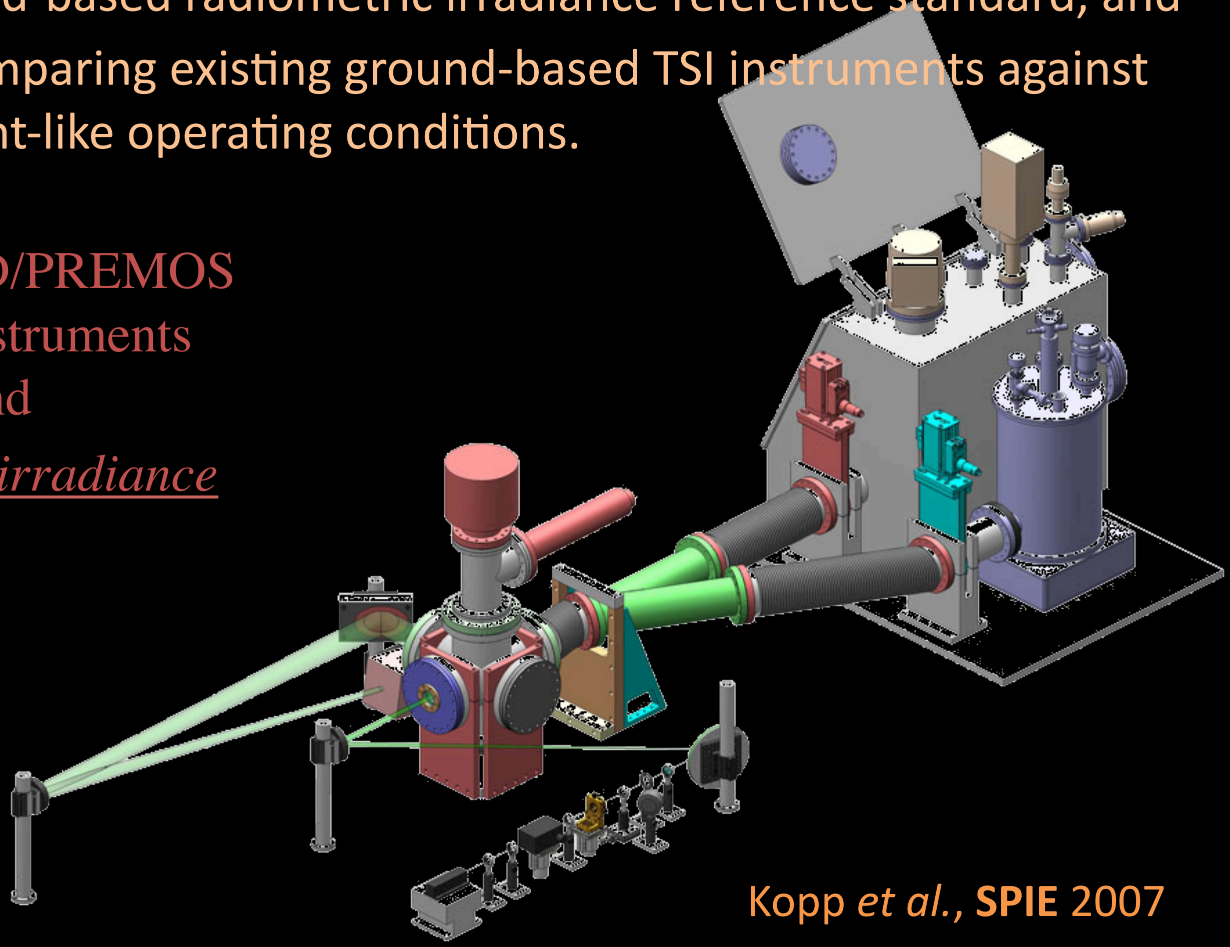


TSI Radiometer Facility (TRF) Measures Irradiance

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

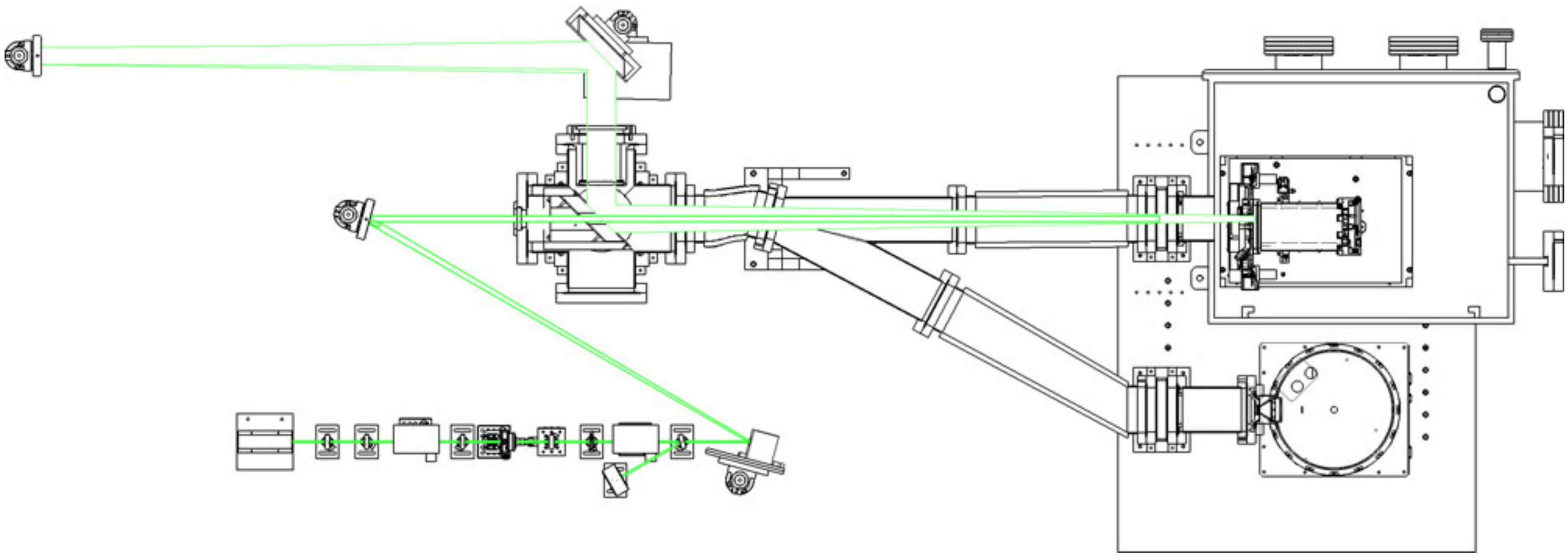


Kopp *et al.*, **SPIE** 2007

Build Needed Facilities

- The facility is designed to allow a TSI instrument or the cryogenic radiometer to sample exactly the same beam
  - Beam is not displaced, instruments are placed at the same location in a stationary beam

Top-view of optical path: TSI instrument in beam



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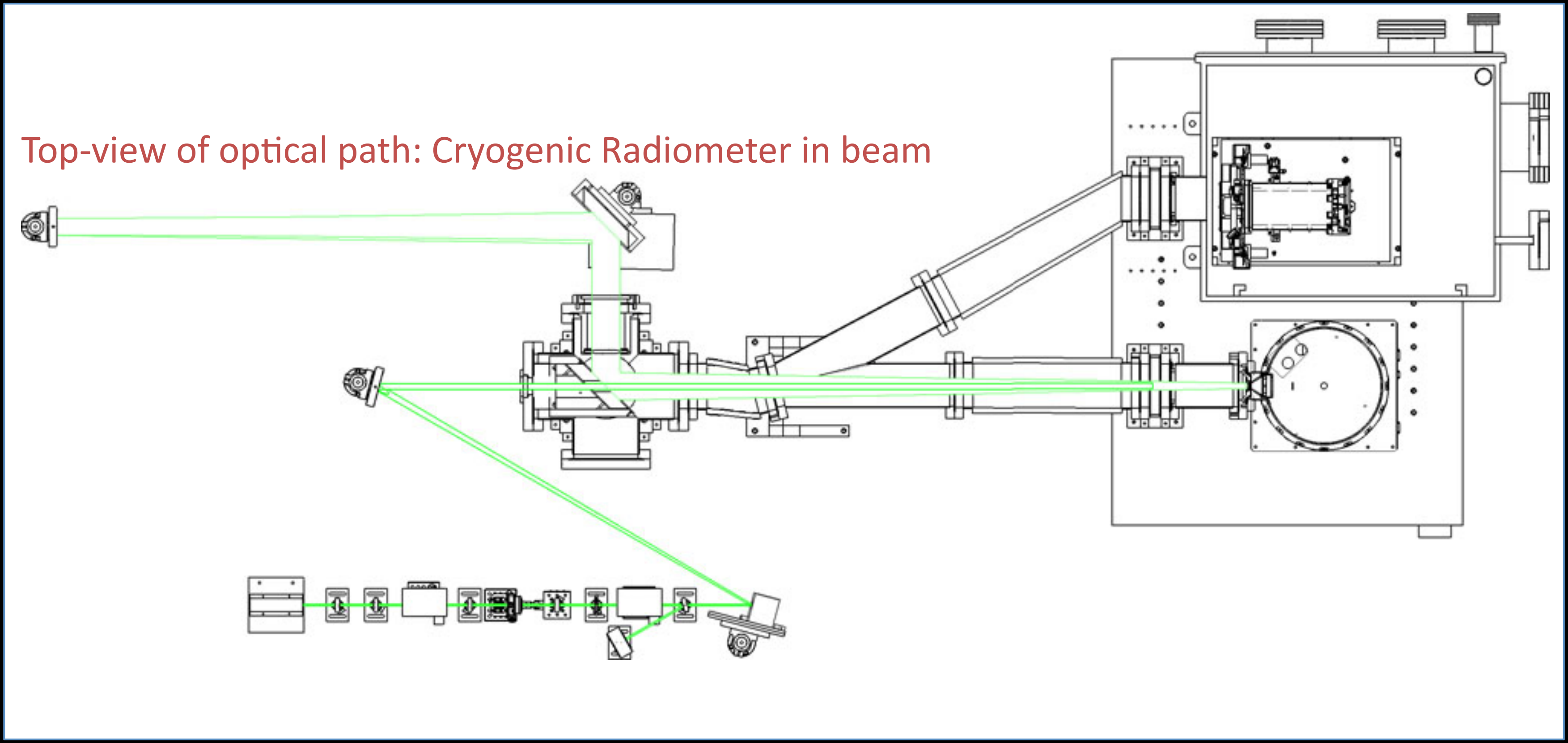


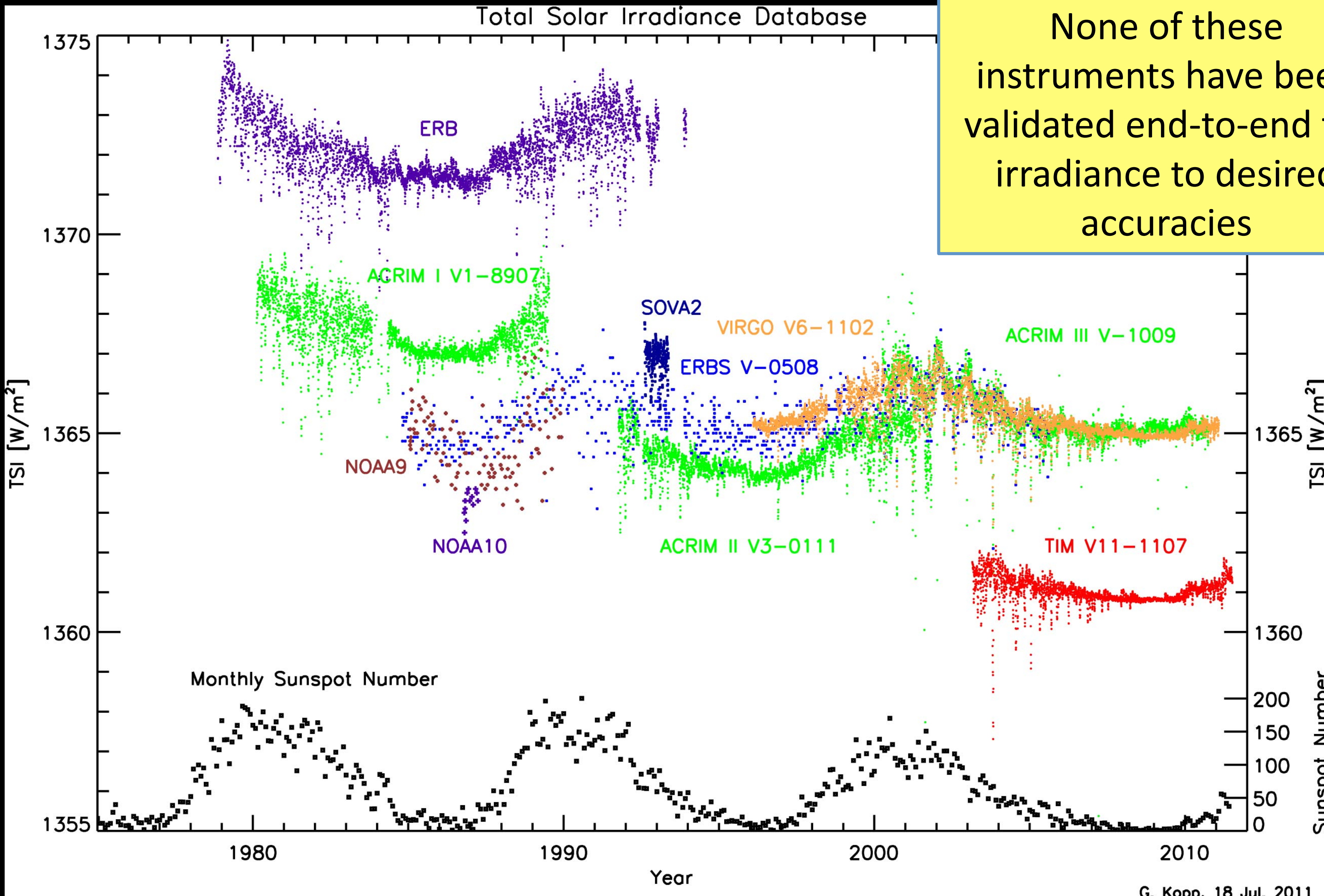
Follow-Up Workshop – 2010

- Discuss improvements in instrument calibrations, particularly newly possible end-to-end validations and diagnostics being done on TSI Radiometer Facility, since the 2005 TSI Accuracy Workshop
- Plan future calibration methods of improving TSI record

What has been done to validate instrument accuracy in the five years since the 2005 TSI Accuracy Workshop?

Get instrument people together alone.
Lock the door.

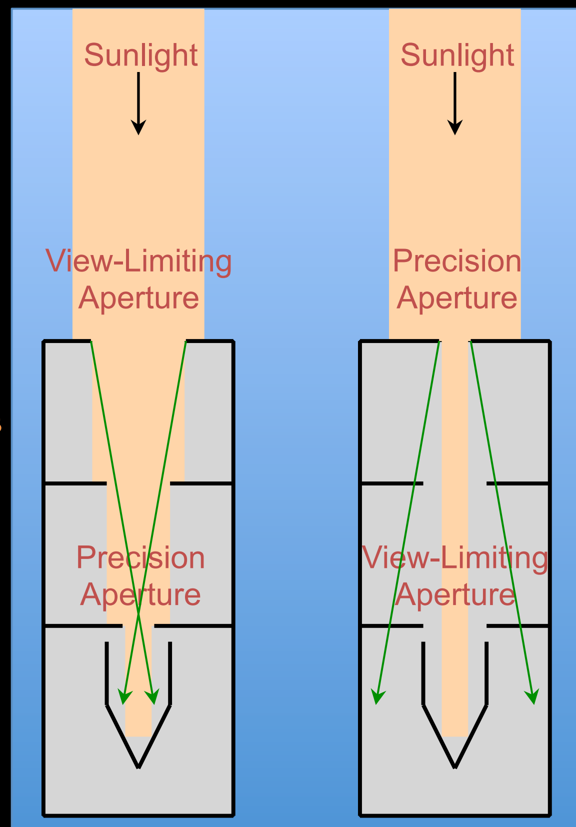
So What Causes the Instrument Offsets?



None of these instruments have been validated end-to-end for irradiance to desired accuracies

Diffraction & Scatter Erroneously Increase 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

"It's not enough to show that you're right – you have to show why others are wrong."
George Lawrence's advisor

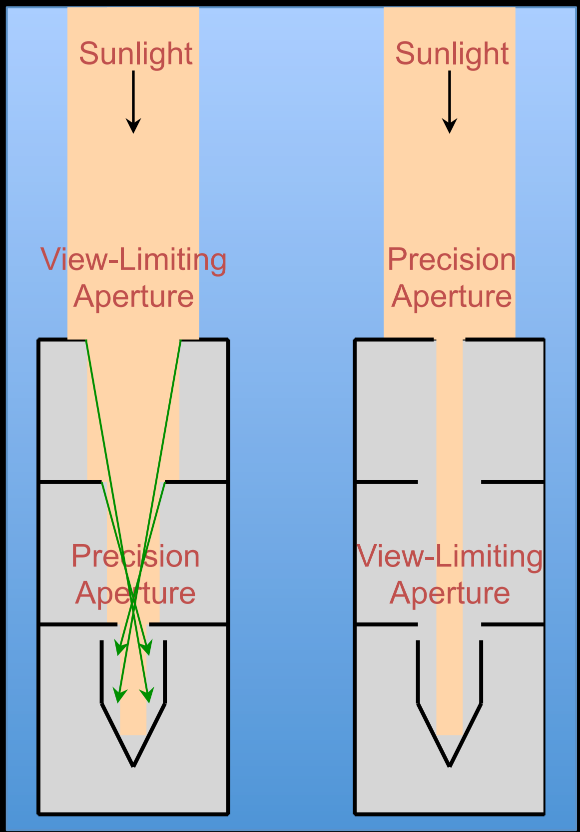
NIST calculates this to be a 0.16% effect in the ACRIM instruments

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



TIM geometry

Additional light allowed into instrument can scatter into cavity

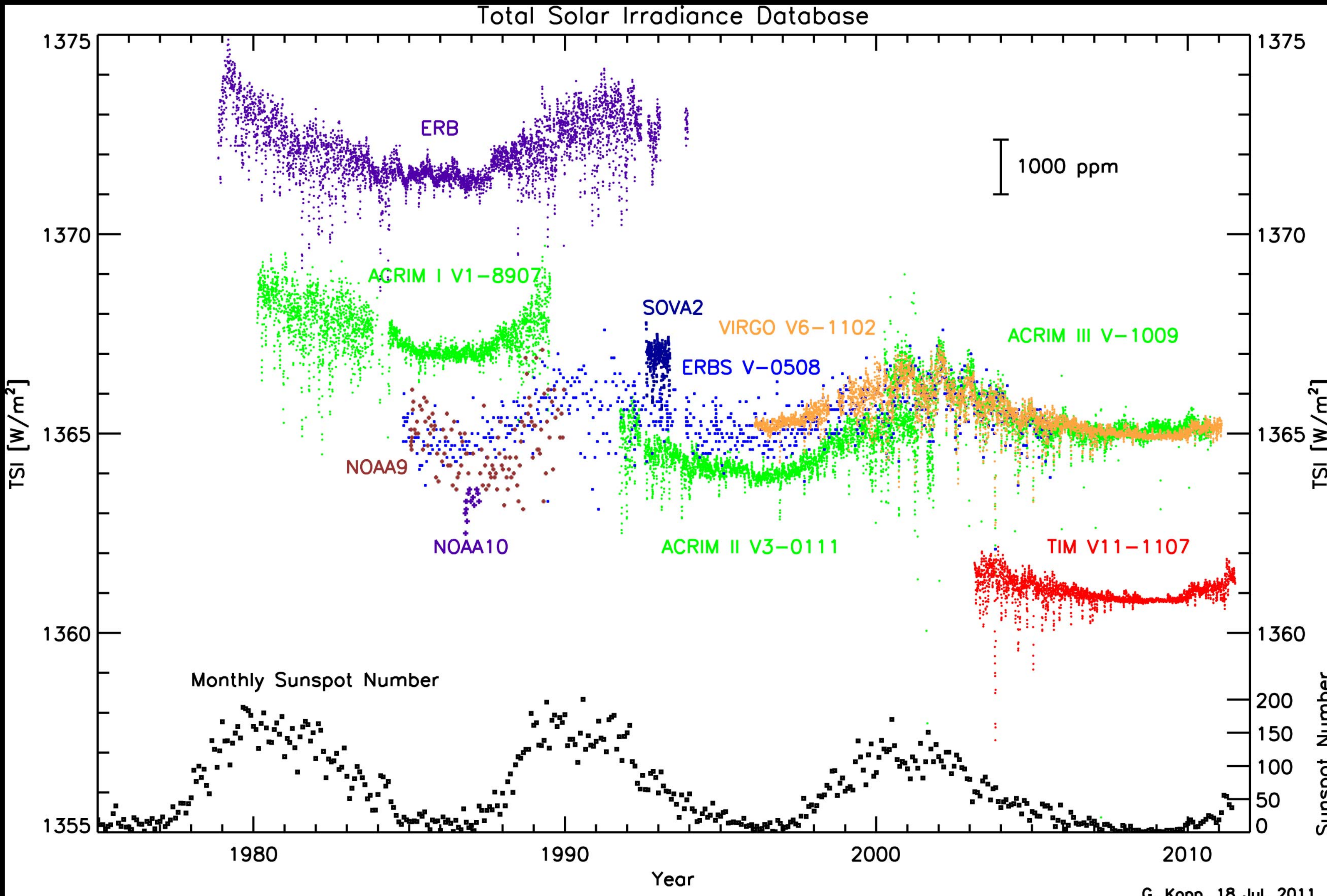
Majority of light is blocked before entering instrument

Measured increases due to uncorrected scatter/diffraction are surprisingly large

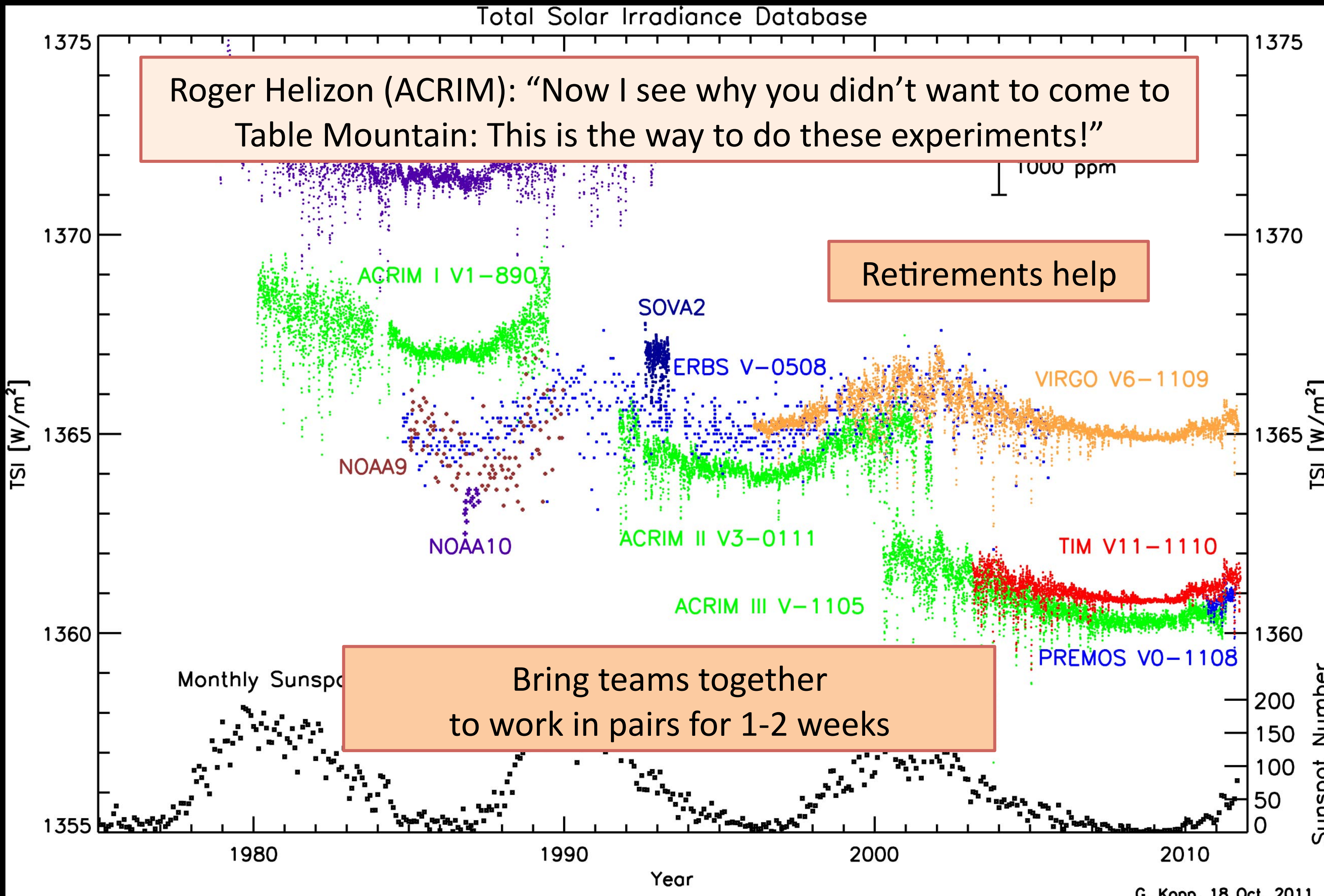
Instrument	Increase
PREMOS-1	0.10%
PREMOS-3	0.04%
VIRGO	0.15%
ACRIM-3	0.51%

Social aspects are even more impressive!

TRF Corrections Now Applied by ACRIM Team ...



... And PREMOS Data Are Recently Available

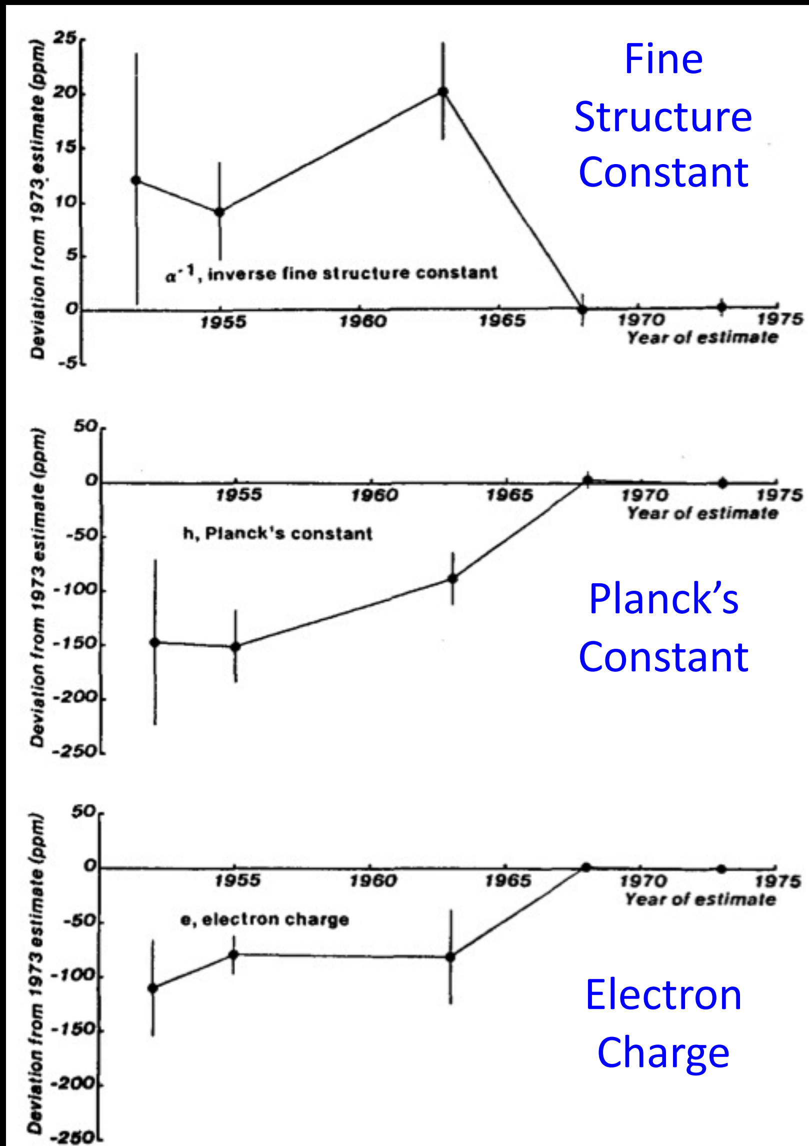


Roger Helizon (ACRIM): “Now I see why you didn’t want to come to Table Mountain: This is the way to do these experiments!”

Retirements help

Bring teams together
to work in pairs for 1-2 weeks

"Evolution" of Physical 'Constants'



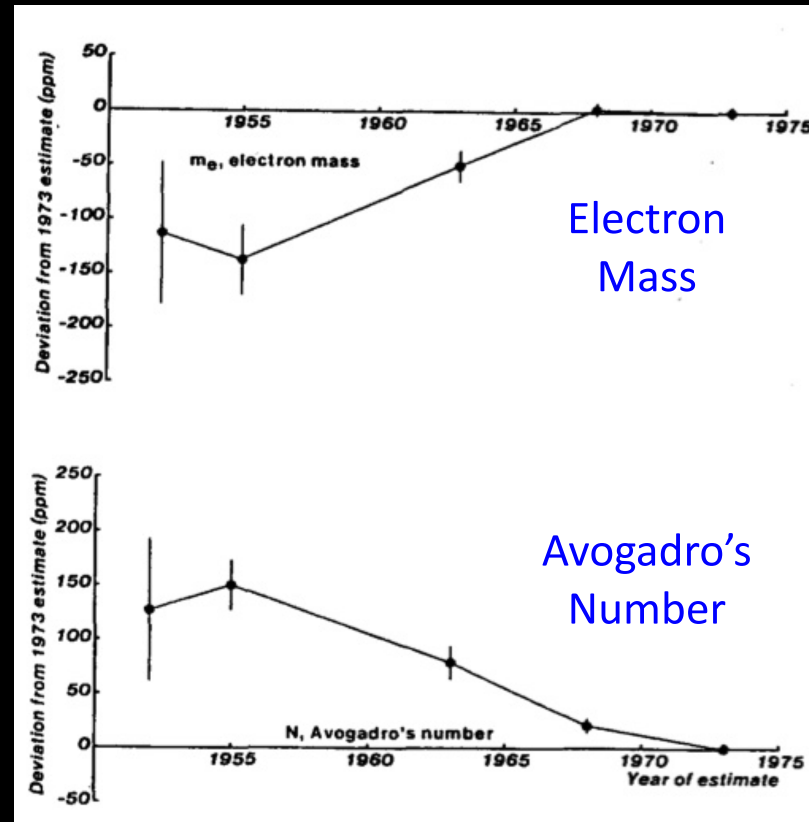


Fig. 3. Recommended values for fundamental constants; 1952–1973.

Experimentalists are optimistic

courtesy of Bob Cahalan, GSFC

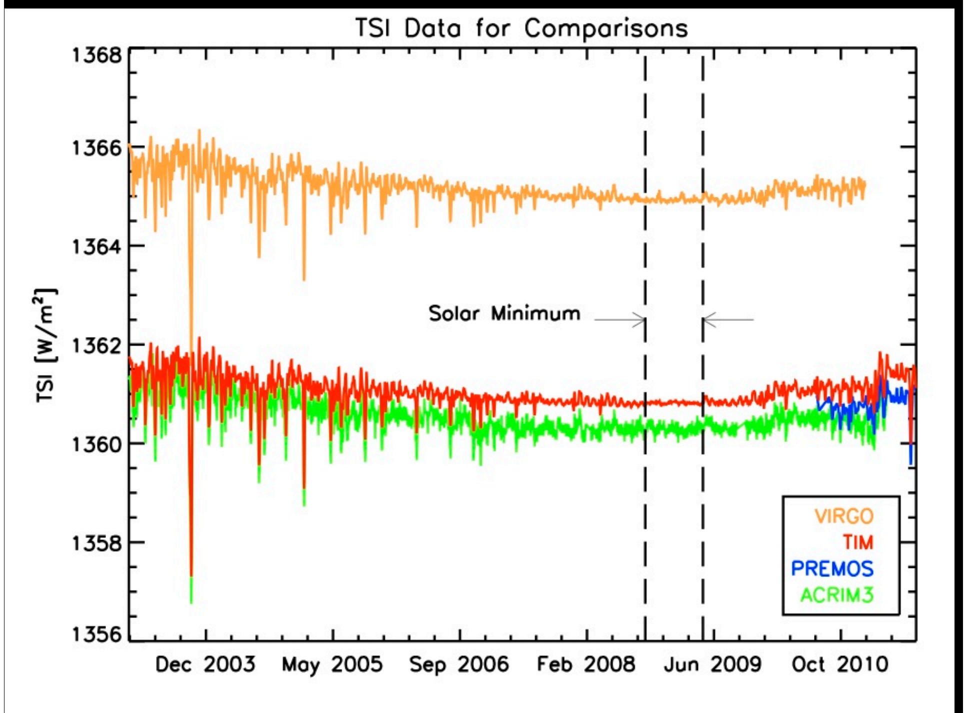
"A New Value for the Solar Constant Is Determined"

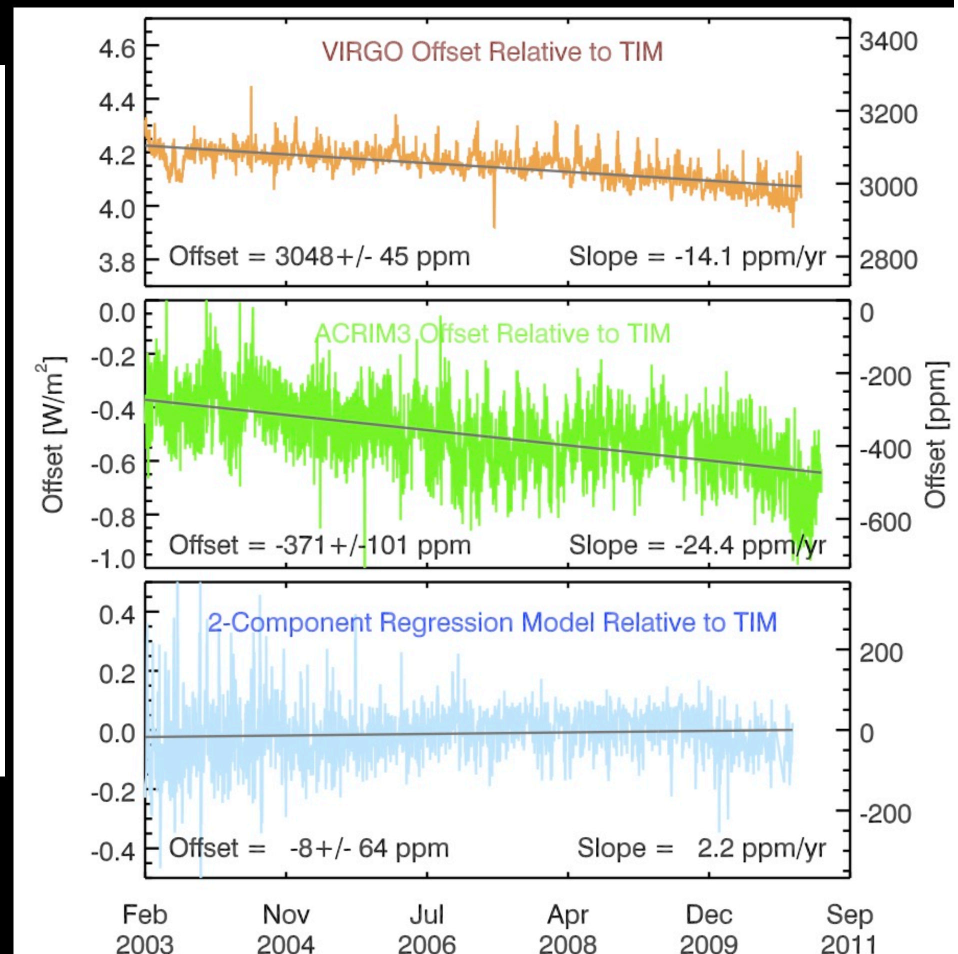
Measurement	Value [W/m²]
Ground extrapolations (Johnson, 1954)	1369
B-57 jet (2 flights, July-Aug. 1966)	1358
B-57 jet (4 flights, March 1967)	1360
CV-990 jet (Oct. 1967)	1362
X-15 rocket (Oct. 1967)	1361

from "New Value for the Solar Constant of Radiation," by A.J. Drummond, J.R. Hickey, W.J. Scholes, and E.G. Laue, *Nature*, **218**, #5138, April 1968.

Desired Stabilities Not Yet Achieved

- There remain significant differences between existing instruments

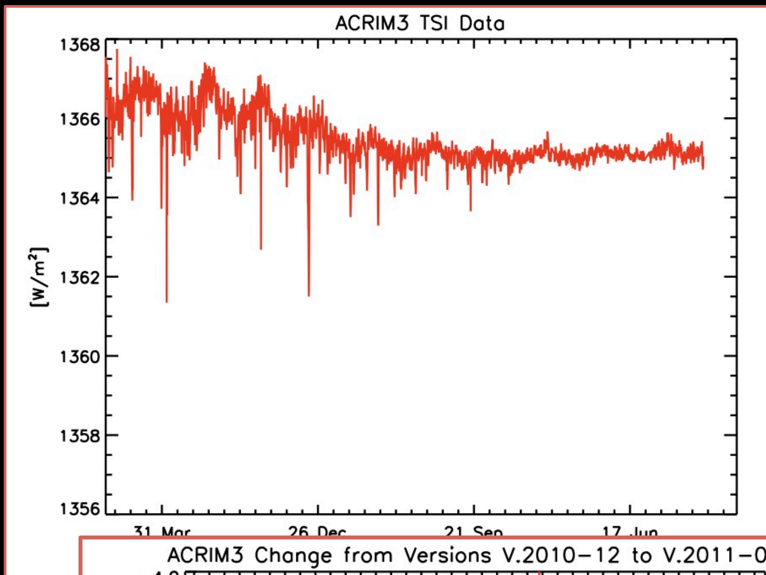


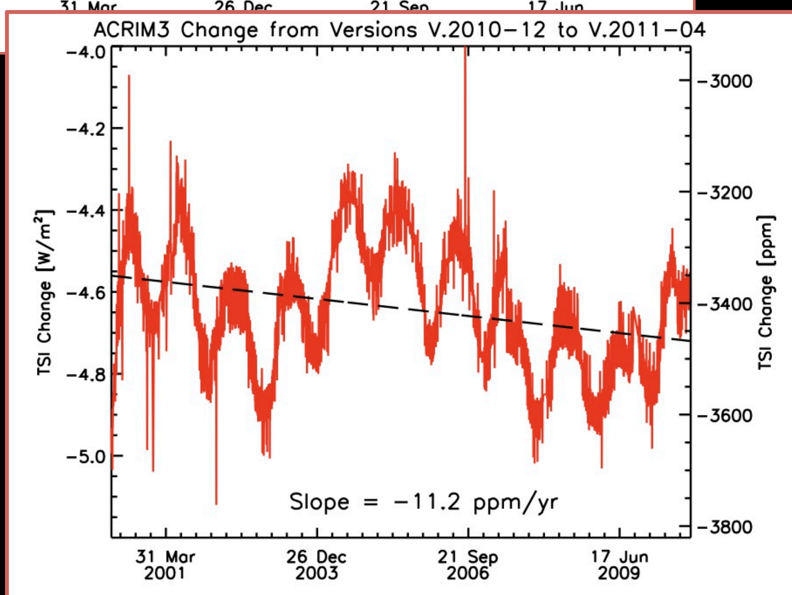


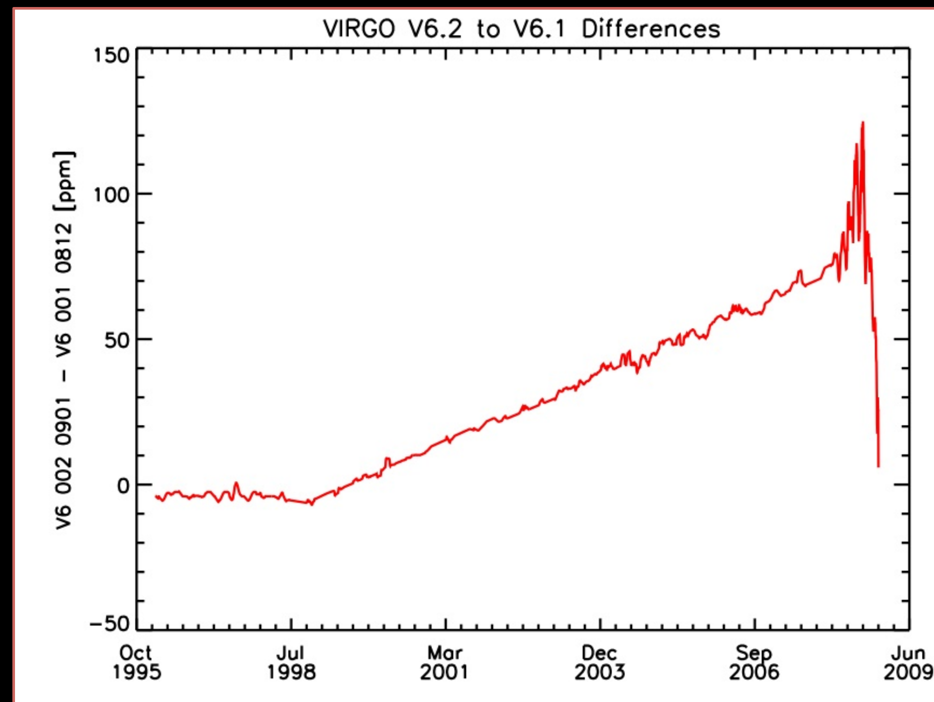
NRL, SATIRE, SFO models

Desired Stabilities Not Yet Achieved

- There are significant differences between instrument data versions

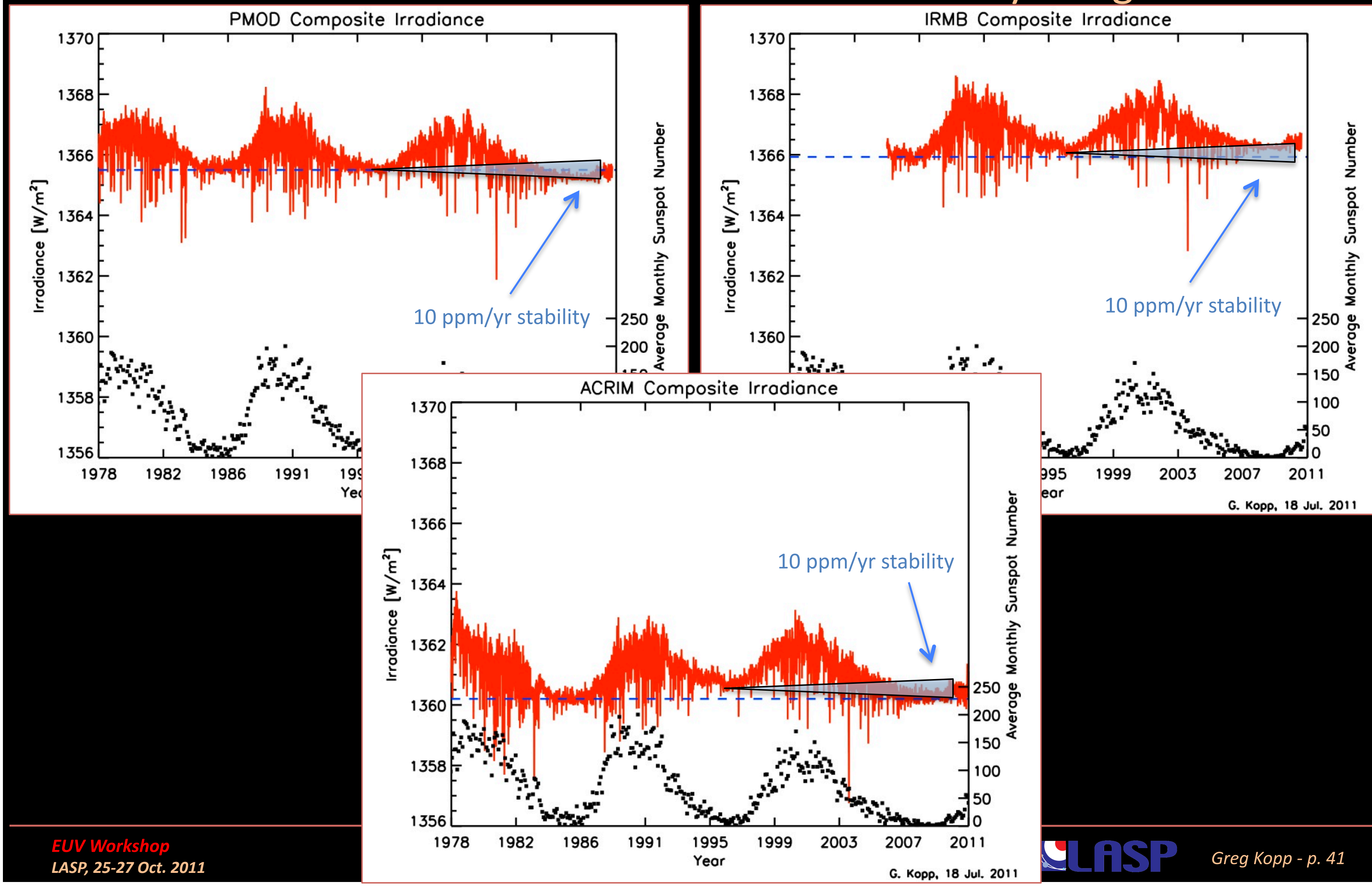




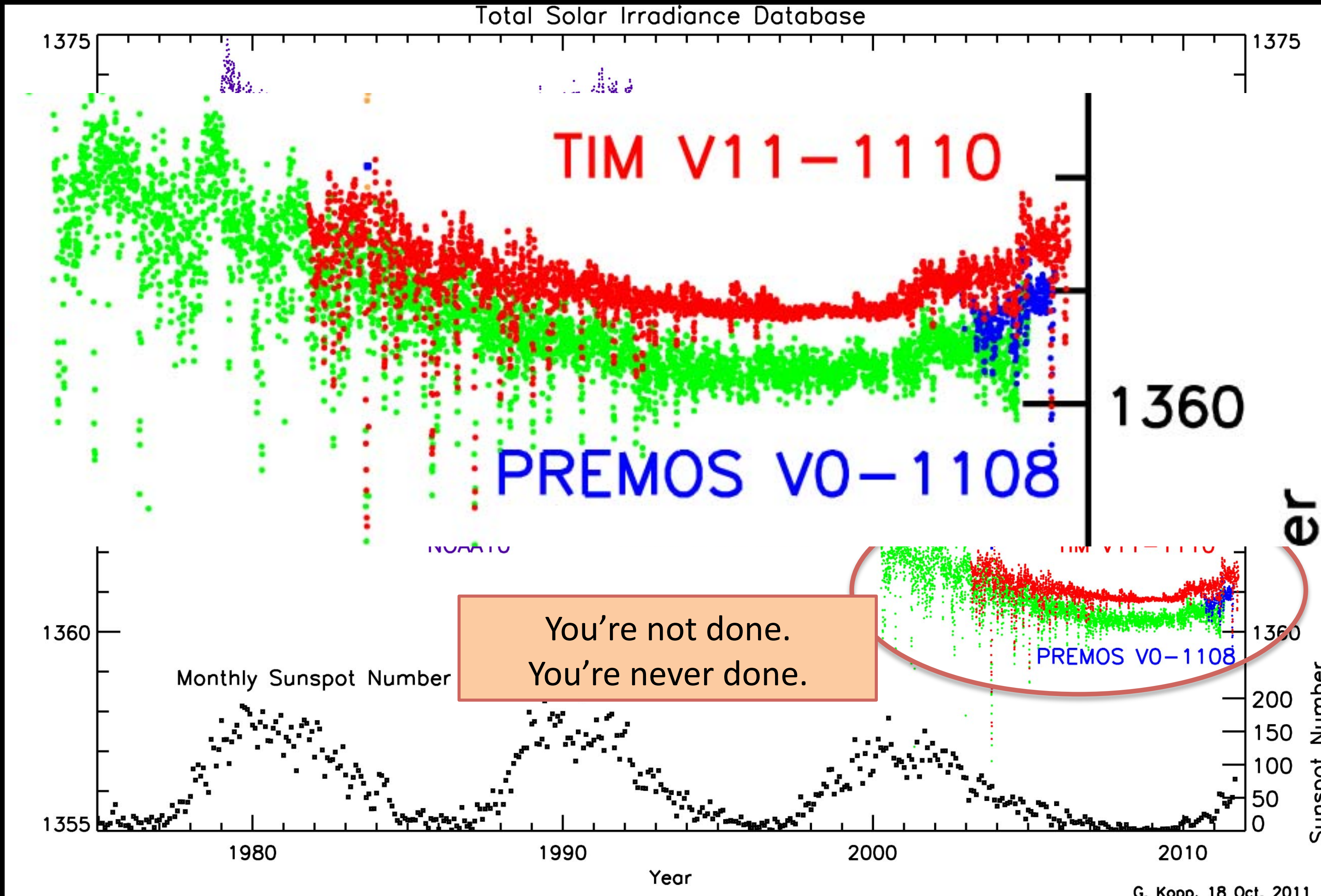


How Good Are Resulting Composites?

- Trend detection between solar minima is currently marginal



Are We There Yet?



You're not done.
You're never done.

Fundamental Solar Irradiance Science Questions

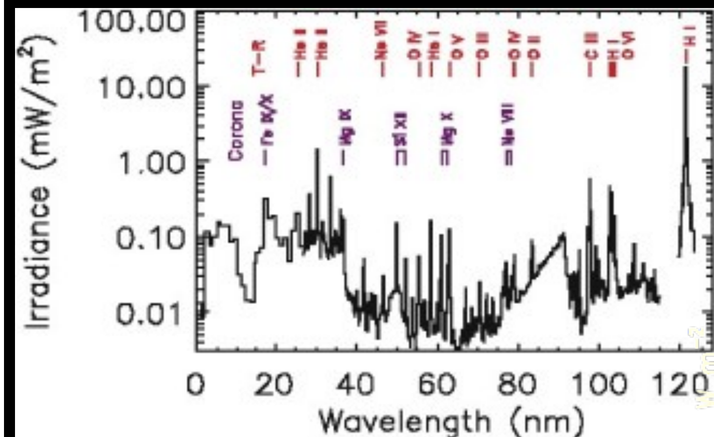
- What is the value of the TSI on an absolute scale?
  - Relevant for radiation balance
- How variable is the Sun over decades/centuries?
  - Relevant for climate change and historical perspective
- What solar activities cause irradiance fluctuations?
  - Relevant for understanding solar physics and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

Keep perspective

Lessons

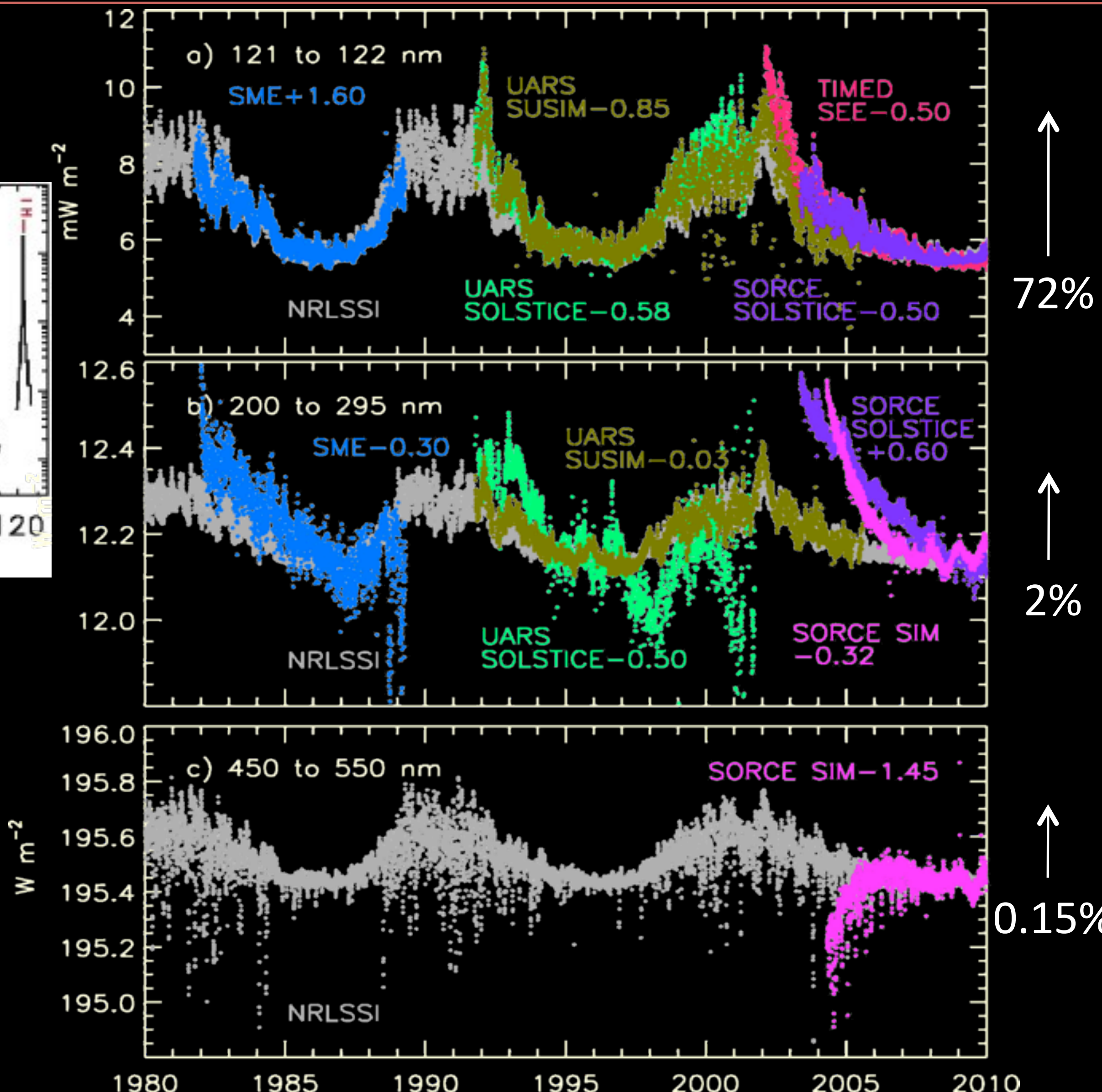
- "Consistency is comforting; but agreement is not accuracy."
- Define requirements based on science, not capability
- Get new blood: Heritage and experience don't guarantee expertise
- Get everyone together at neutral place (organized by NIST, NASA)
  - Discuss instrument and calibration details *ad nauseam* and create test plans
  - Make uncertainty budgets consistent for comparisons
  - Discuss dirty laundry with neutral participants ("judges") in audience
  - Include diverse group (Eric Shirley, theory, diffraction)
- Expand beyond your instruments
- Follow tests planned (even if others don't)
- "It's not enough to show that you're right – you have to show why others are wrong."
- Build new facilities after getting inputs
- Start with broad external community (NASA, NIST, ESA, ...) driving to get things going
- Then get instrument people together alone. Lock the door.
  - Discuss instrument and calibration details (*ad nauseam*)^2
- Bring teams together to work in pairs for 1-2 weeks
- Retirements help
  - Always be open to new ideas (don't let stagnation be you!)
- Be open, honest, and respectful in front of and behind people
- "You're not done. You're never done."
- Keep perspective

Now I'm Eager to Listen and Learn – Good Luck!



Solar EUV Irradiance Inter-Calibration and Validation Workshop

– Boulder, CO 25-27 Oct. 2011



courtesy of Judith Lean, NRL