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ACCURATE SOLAR POWER MEASUREMENTS FROM IMPROVED PYRHELIOMETERS II - 2009

by

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under contract to Sandia National Laboratories,

and ,

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Sandia National Laboratories

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

- **ABSTRACT**
- **In order to provide the low measurement uncertainties required by fields as disparate as photovoltaic efficiency and modeling for global warming, we develop simple modifications to presently available pyrheliometers. First, we thermally separate the pyrheliometer from the tracker and the front face of the pyrheliometer from the sun. These procedures alone save 1 - 2 % in the pyrheliometer's uncertainty budget and solve a long-standing puzzle in accurate solar radiometry. Second, we track the pyrheliometer's temperature which we show can be related in software to the radiometer's zero. The ability to make a zero correction for every reading saves about another 0.5% in uncertainty depending on the weather. We will also discuss numerous other techniques for improving data taking, and we make several suggestions for improving construction of the pyrheliometer itself. Overall subject matter is similar to our review in 2008 but with many new visuals and with written explanations.**

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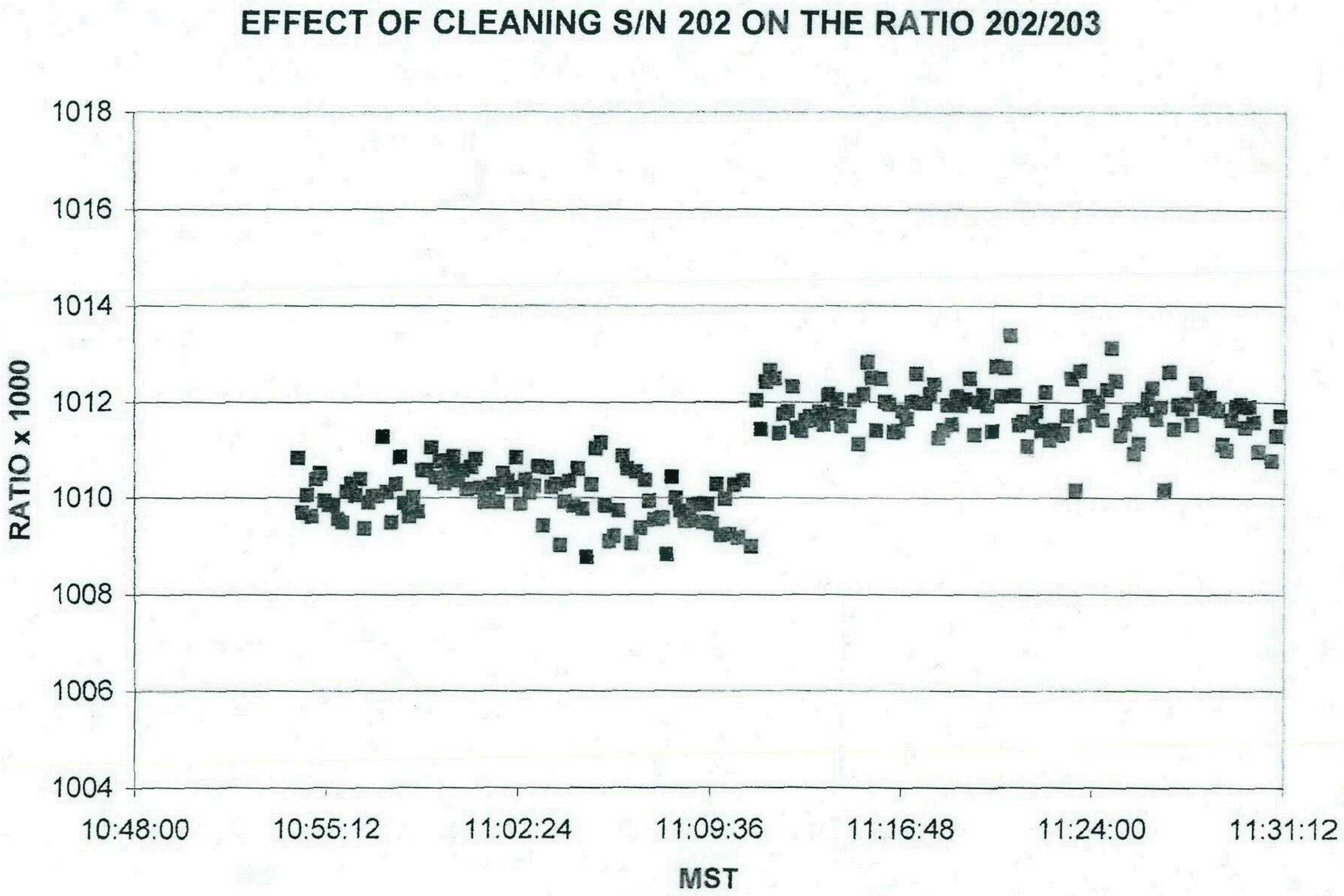
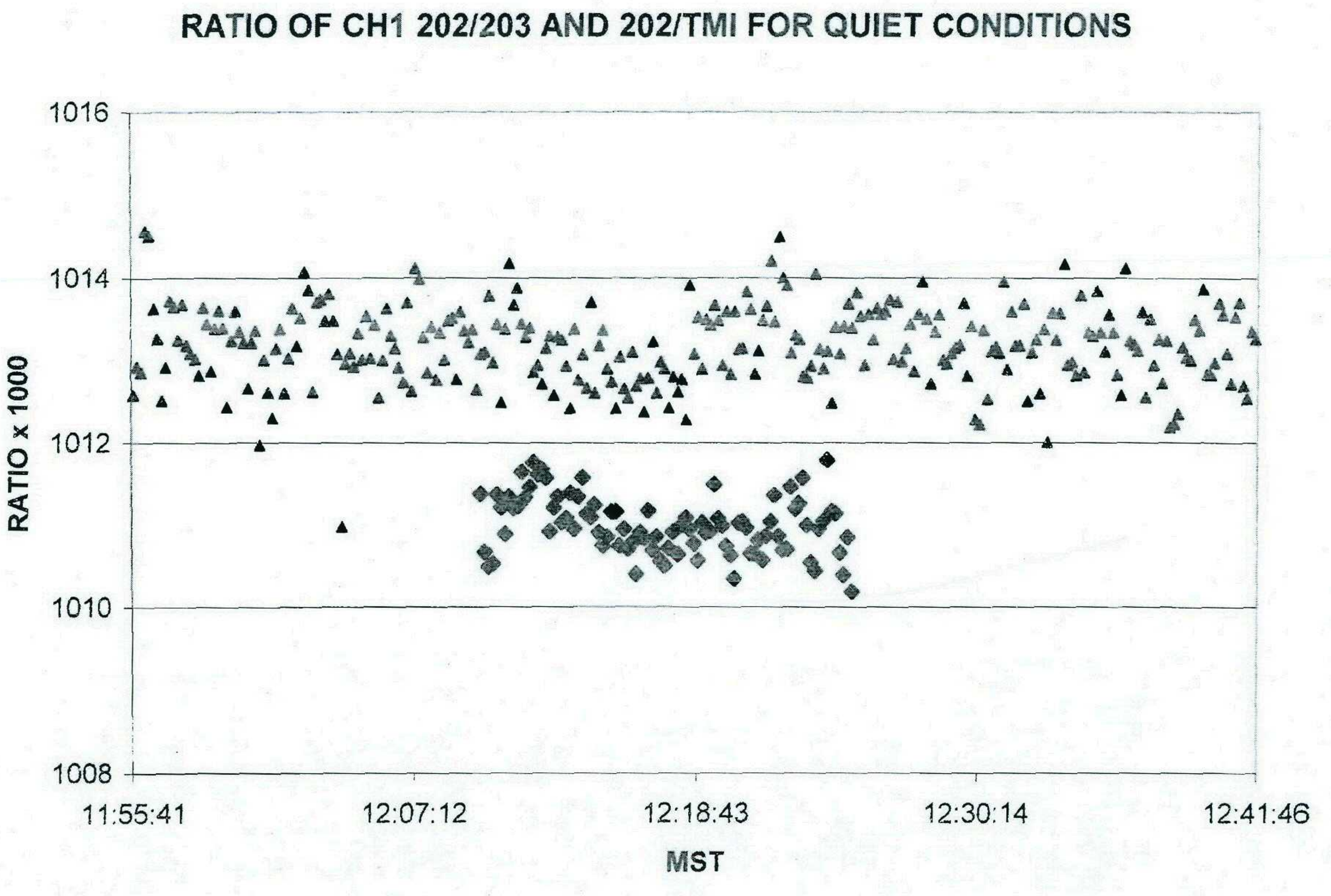

EFFECT OF CLEANING S/N 202 ON THE RATIO 202/203
1018
1016
1014
1012
1010
1008
1006
1004
RATIO x 1000
10:48:00
10:55:12
11:02:24
11:09:36
11:16:48
11:24:00
11:31:12
MST

- **FIG 1. Dirty Radiometer Windows**
-
- **Dirty windows result in the most common error in radiometer output. Figure 1 shows the 0.2 % improvement in transmission of an apparently clean CH1. [Ref. 1]**
- **[In response to questions: Cleaning should be done once a day until experience determines a better interval or intervals. Both WEB and PDT use a soft wipe and condensation from breathing on the window.]**



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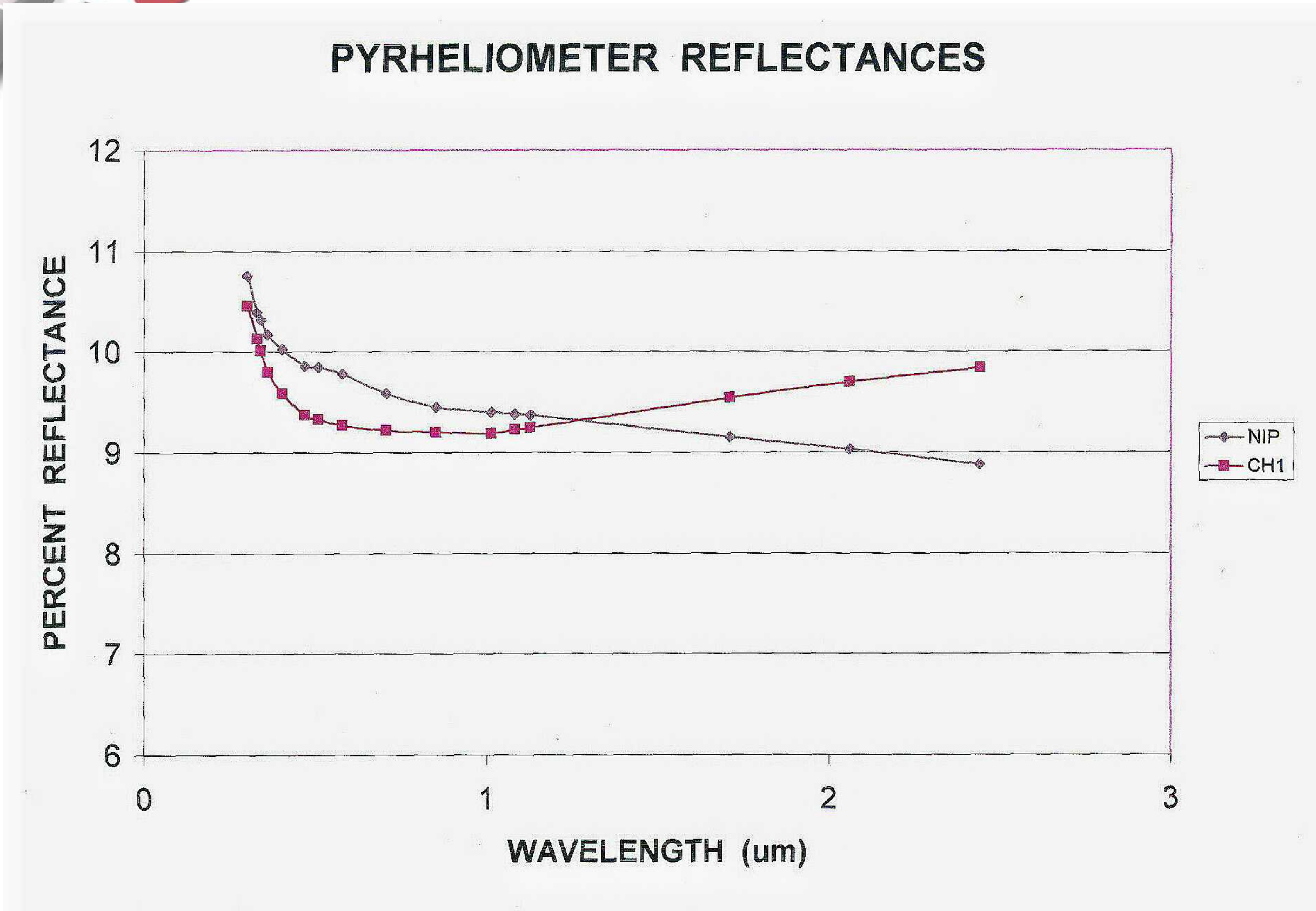
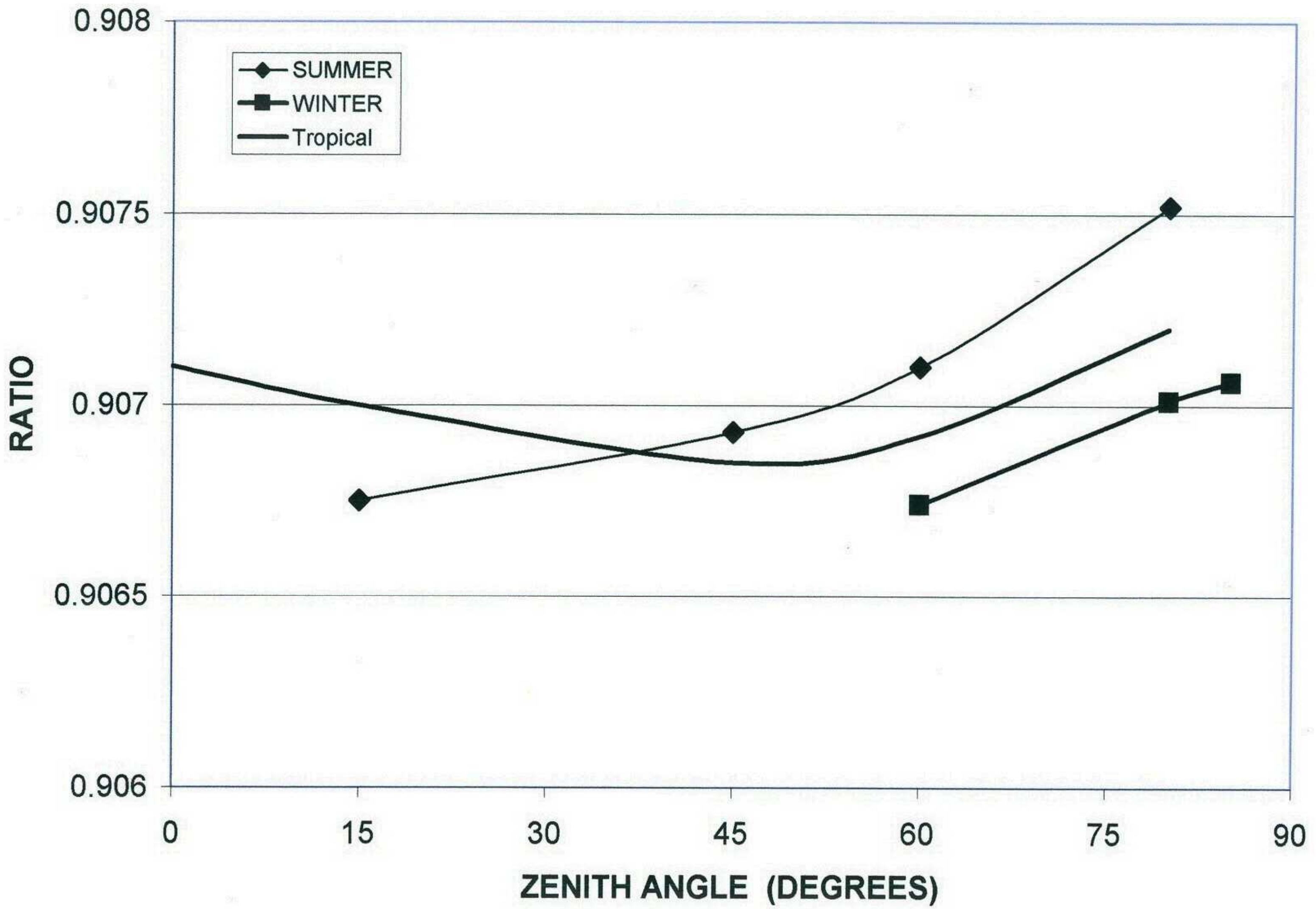
- FIG 2. Electrical Noise.
- The electrical noise in Fig.2 is that for the ratio of two CH1’s and for CH1/TMI (lower curve) [Ref. 1]. Such precision in mV signals requires proper grounding and shielding, good Cu-to-Cu contacts, multiple samples of each voltage, and minimization of interfering signals.

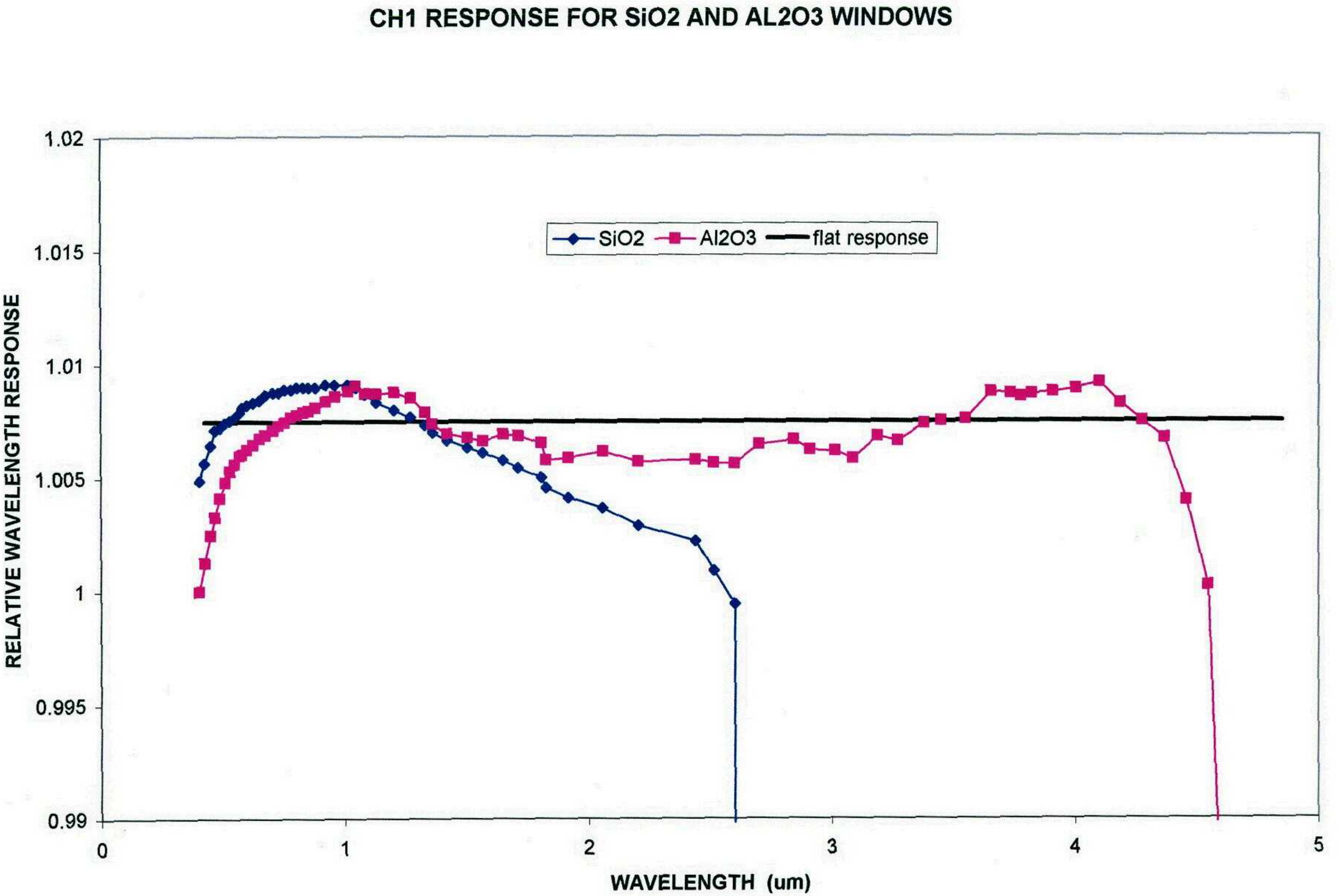

PYRHELIOMETER REFLECTANCES
PERCENT REFLECTANCE
12
11
10
9
8
7
6
0
1
2
3
WAVELENGTH (um)
NIP
CH1

- **FIG. 3. Pyrheliometer Reflectance**
- **Wavelength dependences of the reflectance of the NIP and CH1 absorbing blacks. [Ref. 2]. Included are the summed effect of reflections at the front and back surfaces of the windows in combination with the material's absorbance. The NIP uses 3M black and the CH1 uses a carbon black. [Refs.3 ,4]**

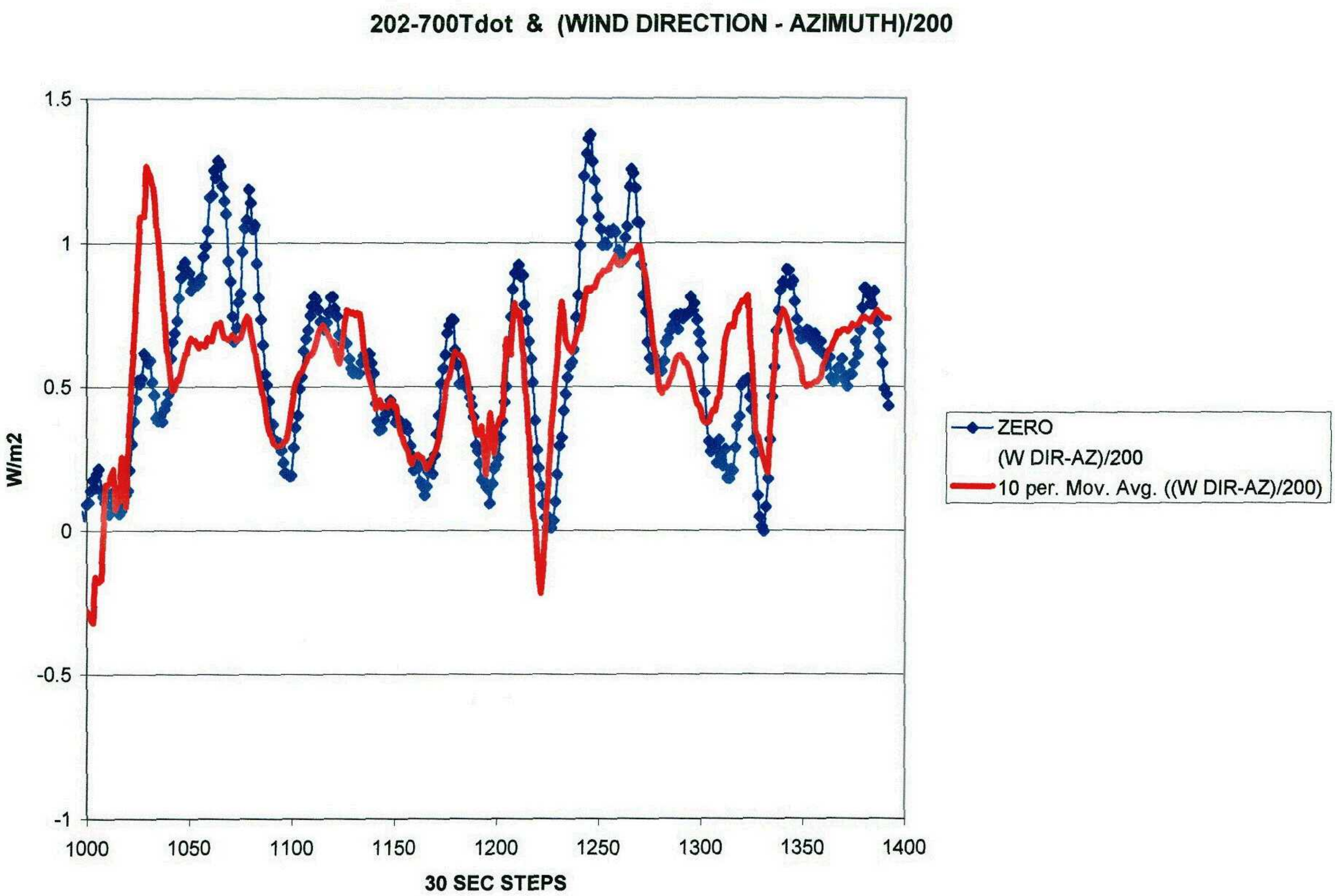
CH1 / TMI SPECTRAL SHIFT ON CLEAR DAYS IN ALBUQUERQUE



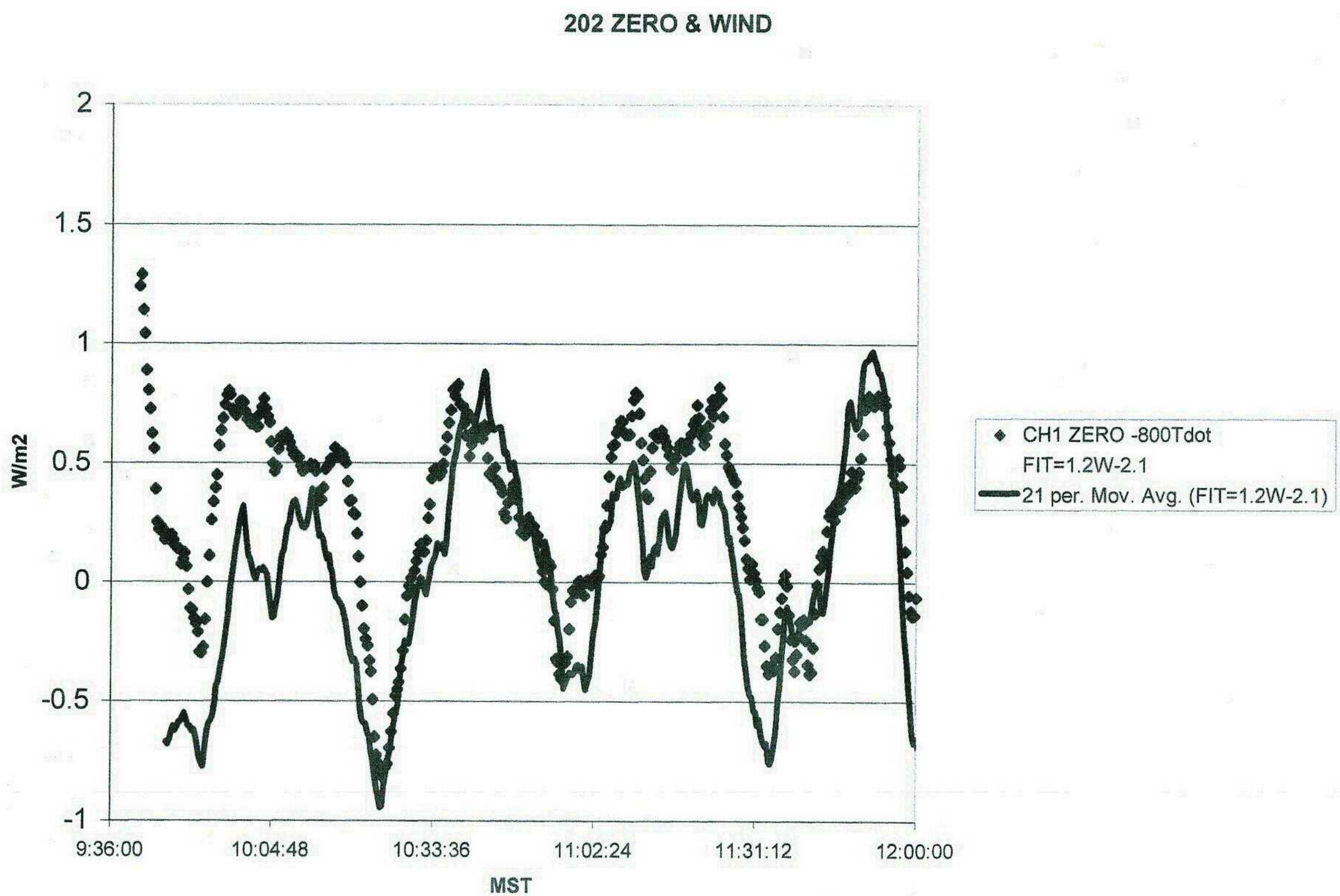
- **FIG. 4 Window Spectral Shifts: CH1 & NIP / TMI .**
- **Spectral shifts in the responsivity of a CH1 and a NIP can be calculated for various LOWTRAN model atmospheres. Shown are mid-latitude summer and winter as well as tropical atmospheres, were any such to be found around Albuquerque. Calculations for the spectral window shift of a NIP pretty much track that of a CH1.**


CH1 RESPONSE FOR SiO2 AND AL2O3 WINDOWS
SiO2
Al2O3
flat response
RELATIVE WAVELENGTH RESPONSE
1.02
1.015
1.01
1.005
1
0.995
0.99
0
1
2
3
4
5
WAVELENGTH (um)

- **FIG. 5 The CH1 Response to Windows of Al2O3 and SiO2**
- **The peak transmissions have been arbitrarily set to 1.009 for both materials. Then for Al2O3 the entire transmission band from 0.57 um to 4.36 um is lies within +/- 0.16 % of the average. Not only that, but the (small) transmission band between 3.5 um and 4.2 um can be sampled. The importance of radiation greater than > 4 um was shown by PMOD calculations [Ref 5.] to amount to 0.8% of sunlight filtering through a tropical atmosphere and 1.4% for a WIN atmosphere. These contributions could not be measured at all with the present fused quartz windows on the NIP and CH1.**


202-700Tdot & (WIND DIRECTION - AZIMUTH)/200
W/m2
1.5
1
0.5
0
-0.5
-1
1000
1050
1100
1150
1200
1250
1300
1350
1400
30 SEC STEPS
ZERO
(W DIR-AZ)/200
10 per. Mov. Avg. ((W DIR-AZ)/200)

- **FIG. 6.	Effect of the Wind on the Pyrheliometer's Zero**
-
- **The effect of the difference between wind direction and the solar azimuth (DIR – AZ) on the pyrheliometer's zero. More work, both theoretical and experimental, is required before limits can be put on the wind.**



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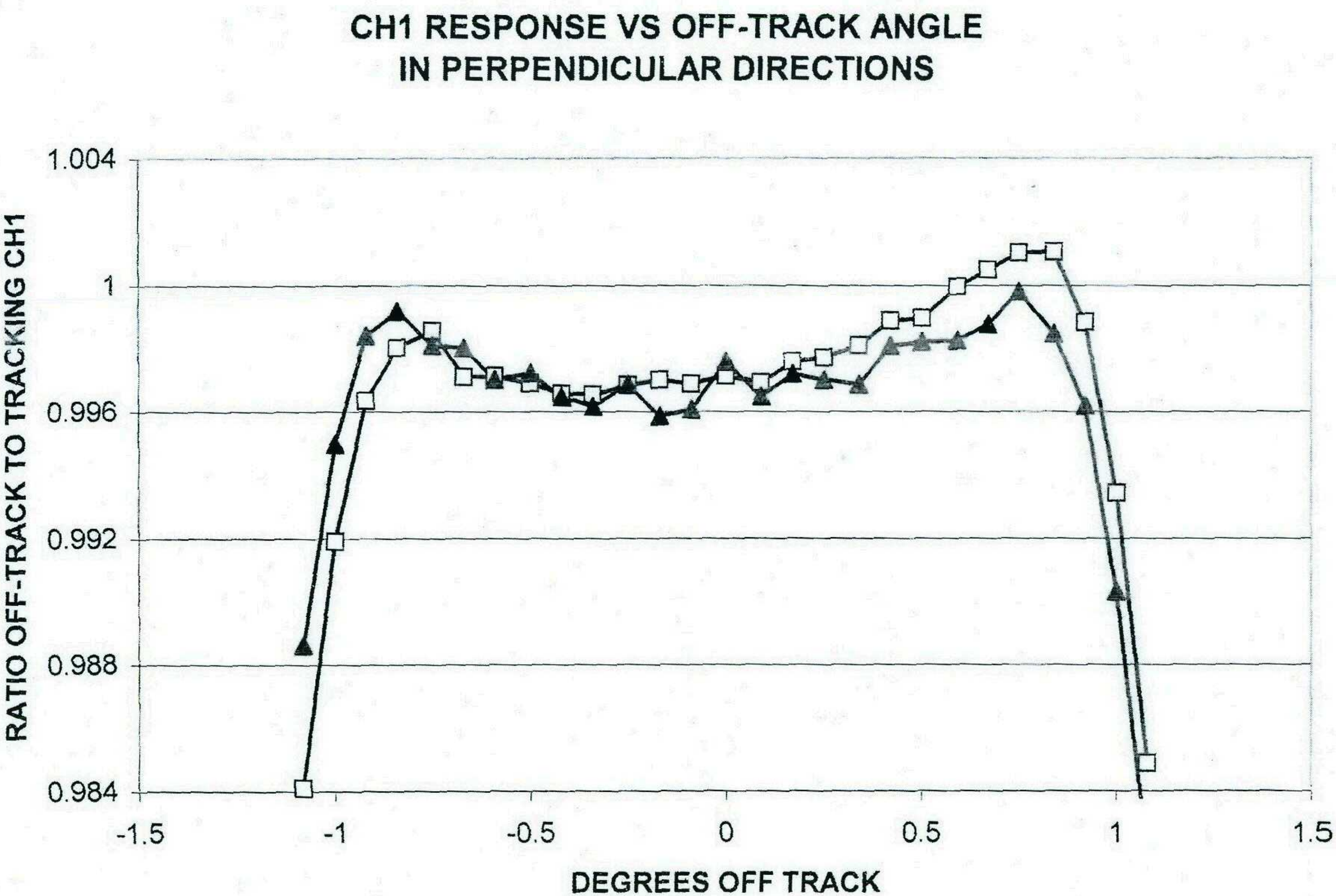
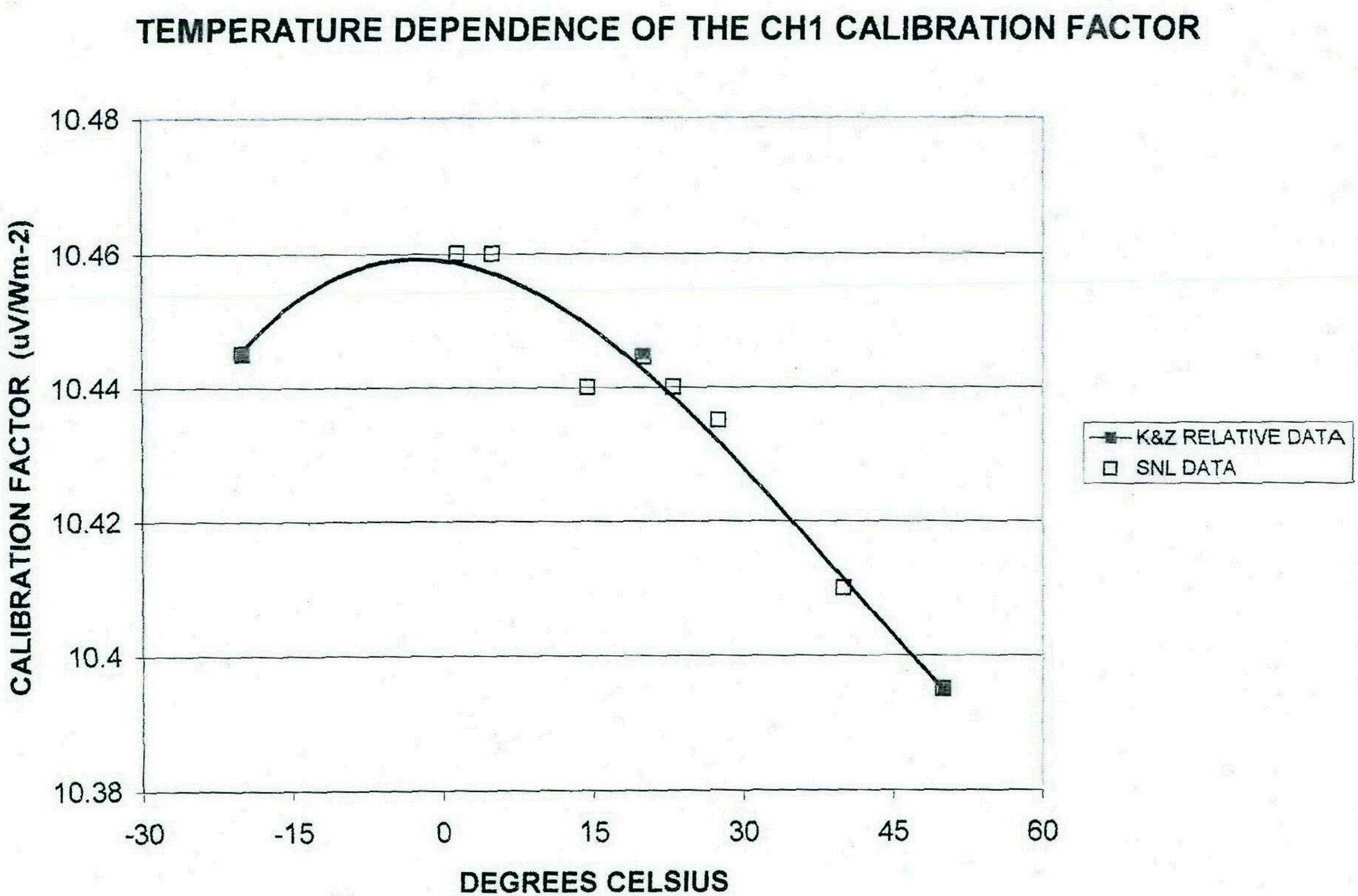
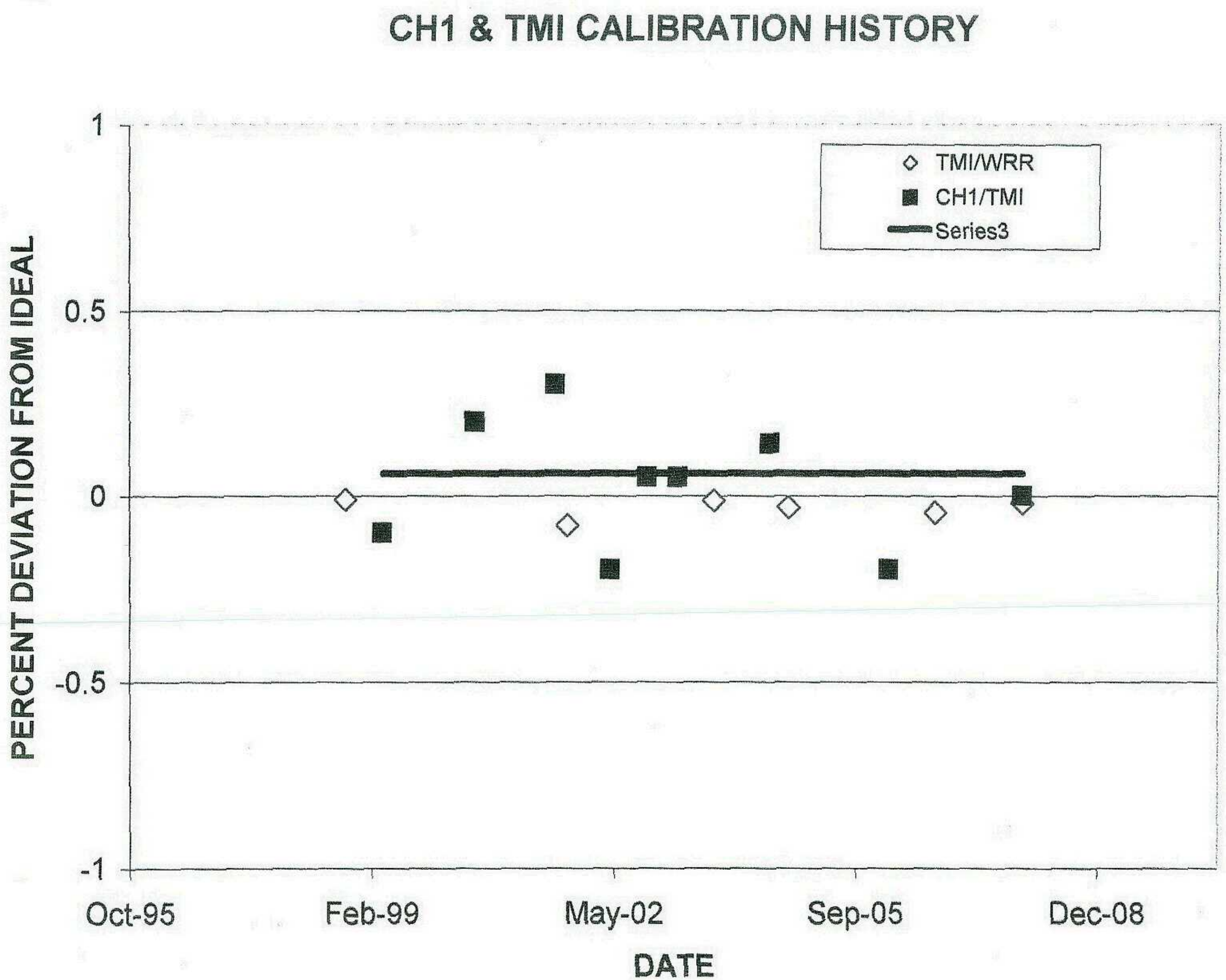
- **FIG. 7. More Wind**
- **The 800Tdot mentioned in the legend is the time derivative of the temperature. Tdot will be covered later in these slides.**


CH1 RESPONSE VS OFF-TRACK ANGLE
IN PERPENDICULAR DIRECTIONS
RATIO OFF-TRACK TO TRACKING CH1
1.004
1
0.996
0.992
0.988
0.984
-1.5
-1
-0.5
0
0.5
1
1.5
DEGREES OFF TRACK

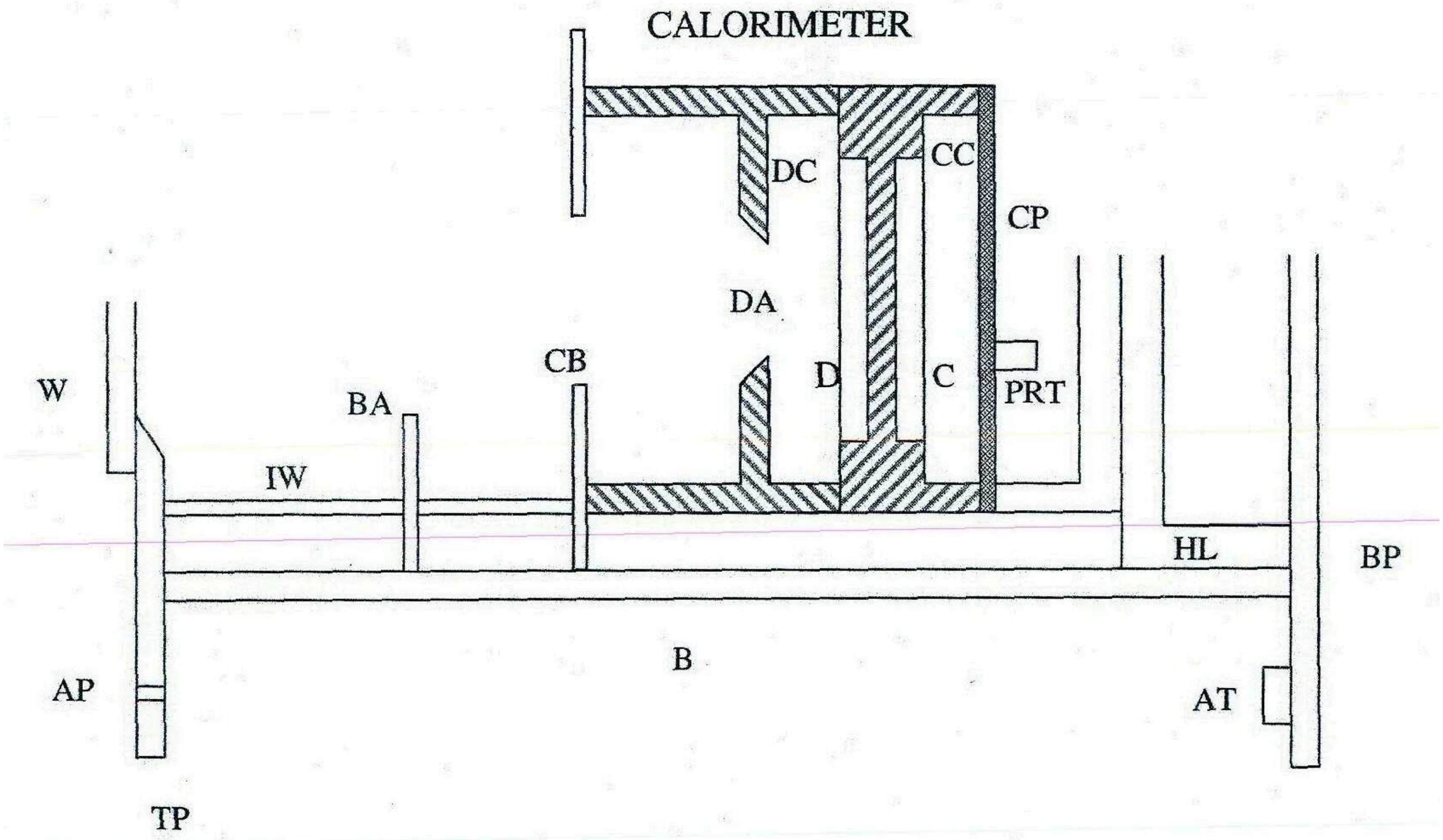
- **FIG. 8 CH1 Response to Off-Track Angle**
- **The CH1 receiver appears close to circularly symmetric but is rather radially asymmetric. The sun, with its 0.5-degree diameter, will therefore have a variability of response with an approximate range of R = 0.2%.- much too large for a cos theta dependence.**
- **Data were taken by setting the CH1 several degrees ahead of the sun, as judged by sun's position on the pinhole target, and measuring the ratio to a tracking CH1.**


TEMPERATURE DEPENDENCE OF THE CH1 CALIBRATION FACTOR
CALIBRATION FACTOR (uV/Wm-2)
10.48
10.46
10.44
10.42
10.4
10.38
-30
-15
0
15
30
45
60
DEGREES CELSIUS
K&Z RELATIVE DATA
SNL DATA

- FIG. 9. Temperature Dependence of the CH1 Calibration Factor
- The graph was generated by sliding the manufacturer’s relative measurements in the vertical direction for a best-fit range of R = 0.1%.


CH1 & TMI CALIBRATION HISTORY
TMI/WRR
CH1/TMI
Series3
PERCENT DEVIATION FROM IDEAL
1
0.5
0
-0.5
-1
Oct-95
Feb-99
May-02
Sep-05
Dec-08
DATE

- **FIG. 10   Calibration Histories of the Standards**
- **The ratio of TMI to WRR scales is made at NREL, and the ratio of CH1 to TMI is made at Sandia. An increasing calibration interval could be justified for both these instruments because of good behavior (low drift and low scatter). However, the top of the pyramid given by TMI / WRR is represented by a single instrument and it is best to review it often.**



CALORIMETER
DC
CC
CP
DA
CB
W
BA
D
C
PRT
IW
HL
BP
B
AP
AT
TP

- FIG. 11 Cut-away of a Pyrheliometer
- The CH1, as inferred from the drawing in their Instruction manual [Ref. 4.] and simplified.
- Key:
- W Window — C Compensator
- AP Alignment Pinhole — CC Compensator Cavity
- TP Top Plate — CP Compensator Plate
- IW Interior Wall — PRT Pt Resistance Thermometer
- B Barrel — HL Heat Leak
- BA Barrel Aperture — AT Alignment Target
- CB Calorimeter Baffle — BP Base Plate
- DA Detector Aperture
- DC Detector Cavity
- D Detector
- The calorimeter itself is shown by the cross hatched metal, and the most important parts of that metal are a detector (D) on which the sunlight is absorbed and the detector aperture that defines the area of absorption. Next come the Compensating Cavity (CC) and the Detector Cavity (DC) . Infrared from the CC falls on the Compensating detector which is designed to give a signal that is just opposite and equal to the Detector's infrared signal from the DC + CB + BA. The Pinhole and target are discussed with reference to Fig. 8.
- A more complete thermal analysis is made in our paper on calibration of the AHF and TMI. [Ref. 6] An approximation made in that paper turned out to be useful for calibrating the NIP & CH 1; namely,
-
$$Z(\text{corked}; mV(t)) = A + B(\langle dT/dt \rangle), \qquad (1)$$
- where <..> represents an average with respect to time t and T is the temperature measured by the PRT. The thermopile output mV(t) is that for which the input corked or blocked.
- The utility of Eq 1 lies in its ability to correct the measured irradiance data by the zero reading in real time and even using data from a another A, B, and dT/dt are first curve fit. We used trial and error and all kinds of averaging for the T in dT/dt, and we found nothing to recommend strongly. The ability of Eq. 1 to fit the data is shown by Fig. 12.

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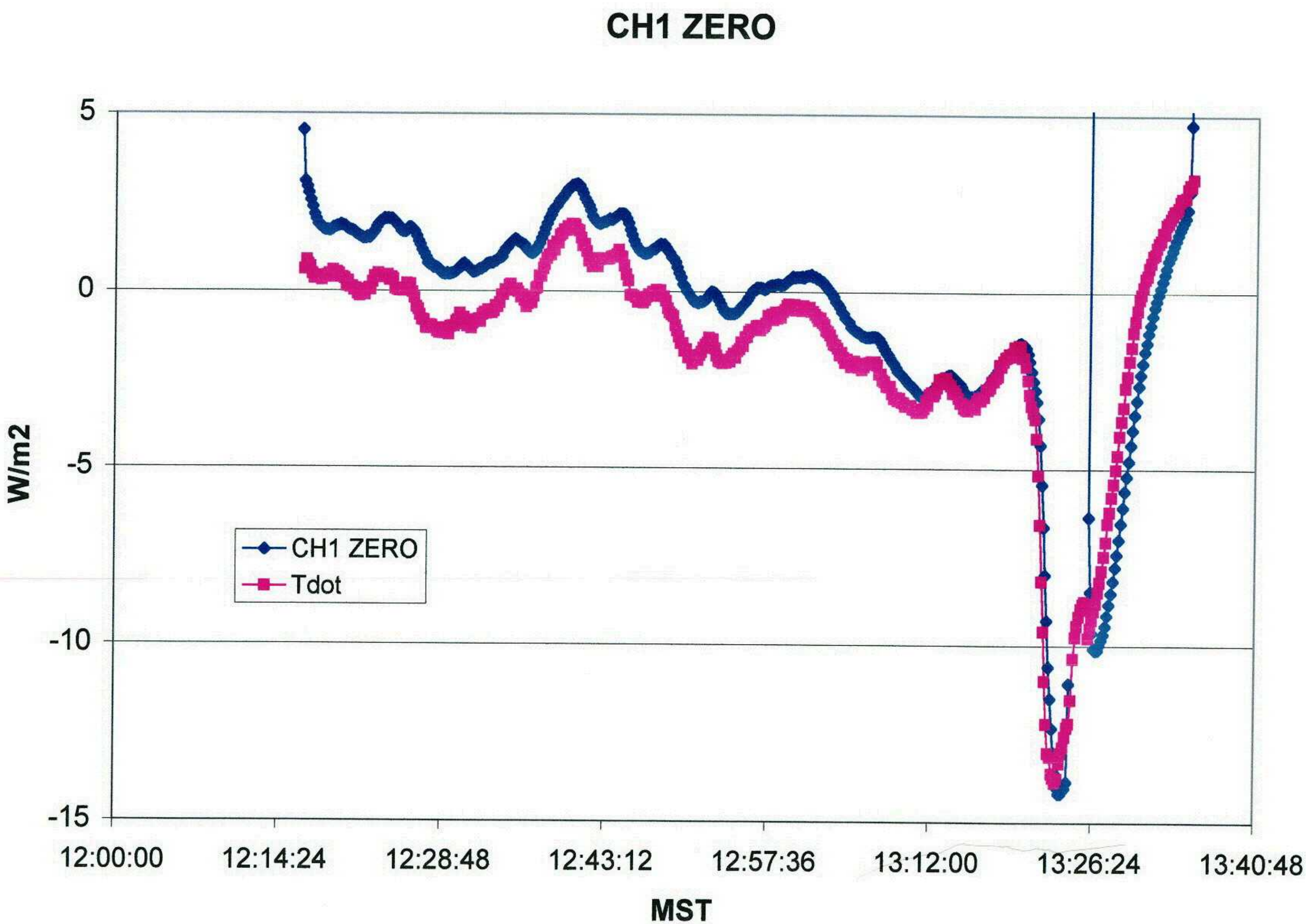
CH1 ZERO
5
0
-5
-10
-15
W/m2
CH1 ZERO
Tdot
12:00:00
12:14:24
12:28:48
12:43:12
12:57:36
13:12:00
13:26:24
13:40:48
MST

- **FIG.12. The Outdoors (and Corked) Zero during a Sudden Squall**
- **This figure shows the excellent ability of Eq. 1 to calculate the zero as measured directly and as calculated from dT/dt and aligned at the point of maximum deviation. Deviation of the zero curve from 0 W/m2 is 1.5%. Deviation of the difference between measured and calculated zeroes is only 0.15 %.**

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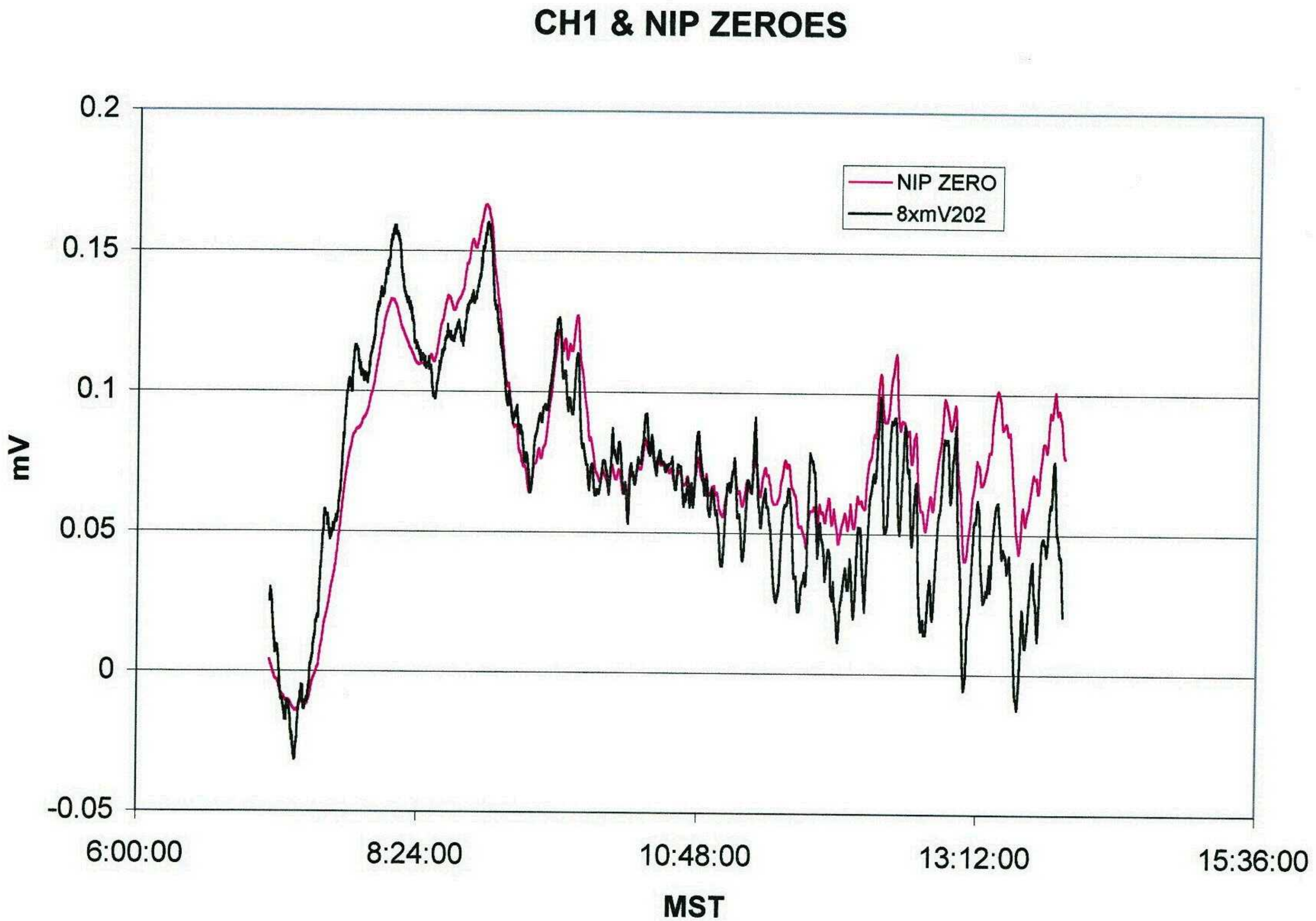
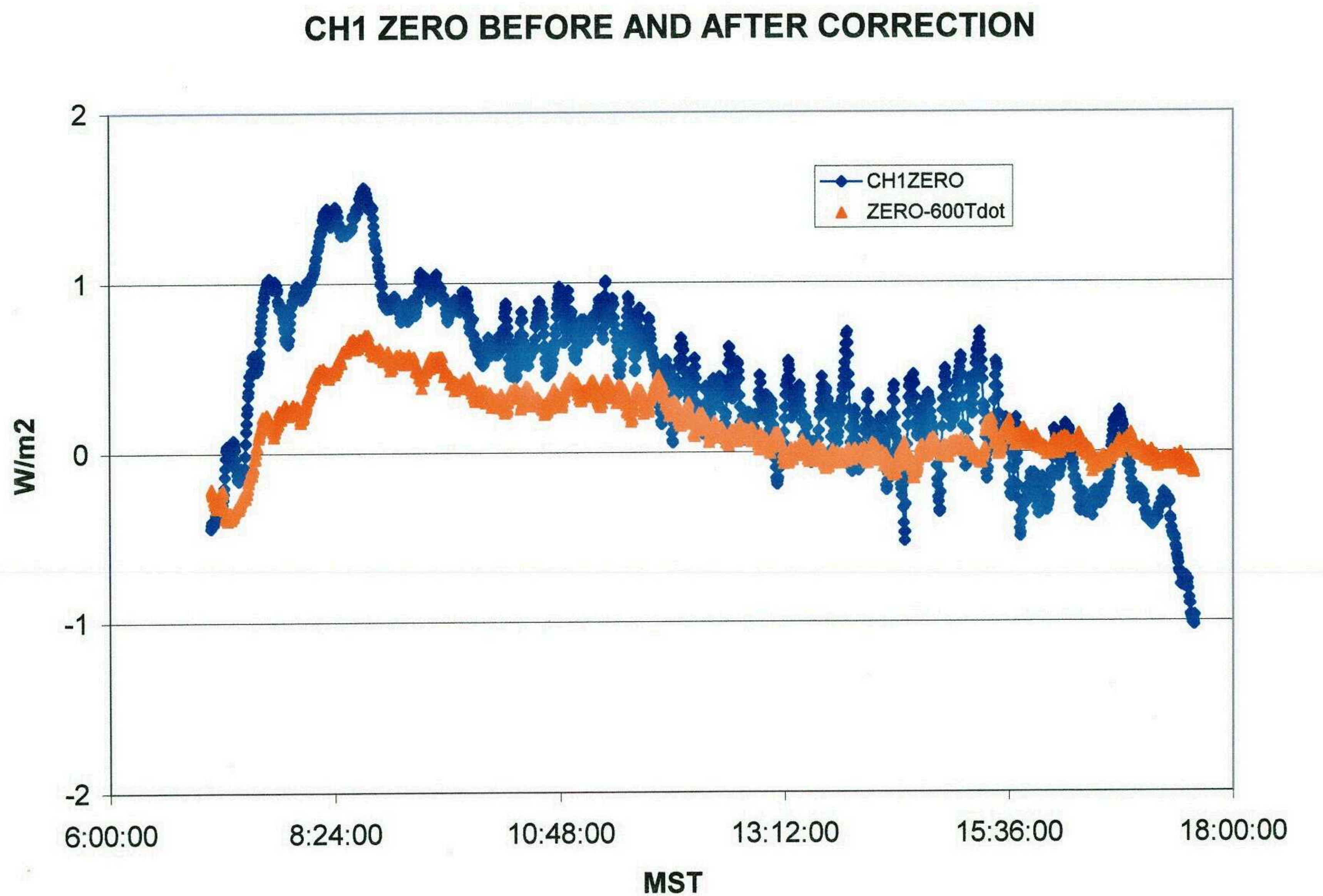
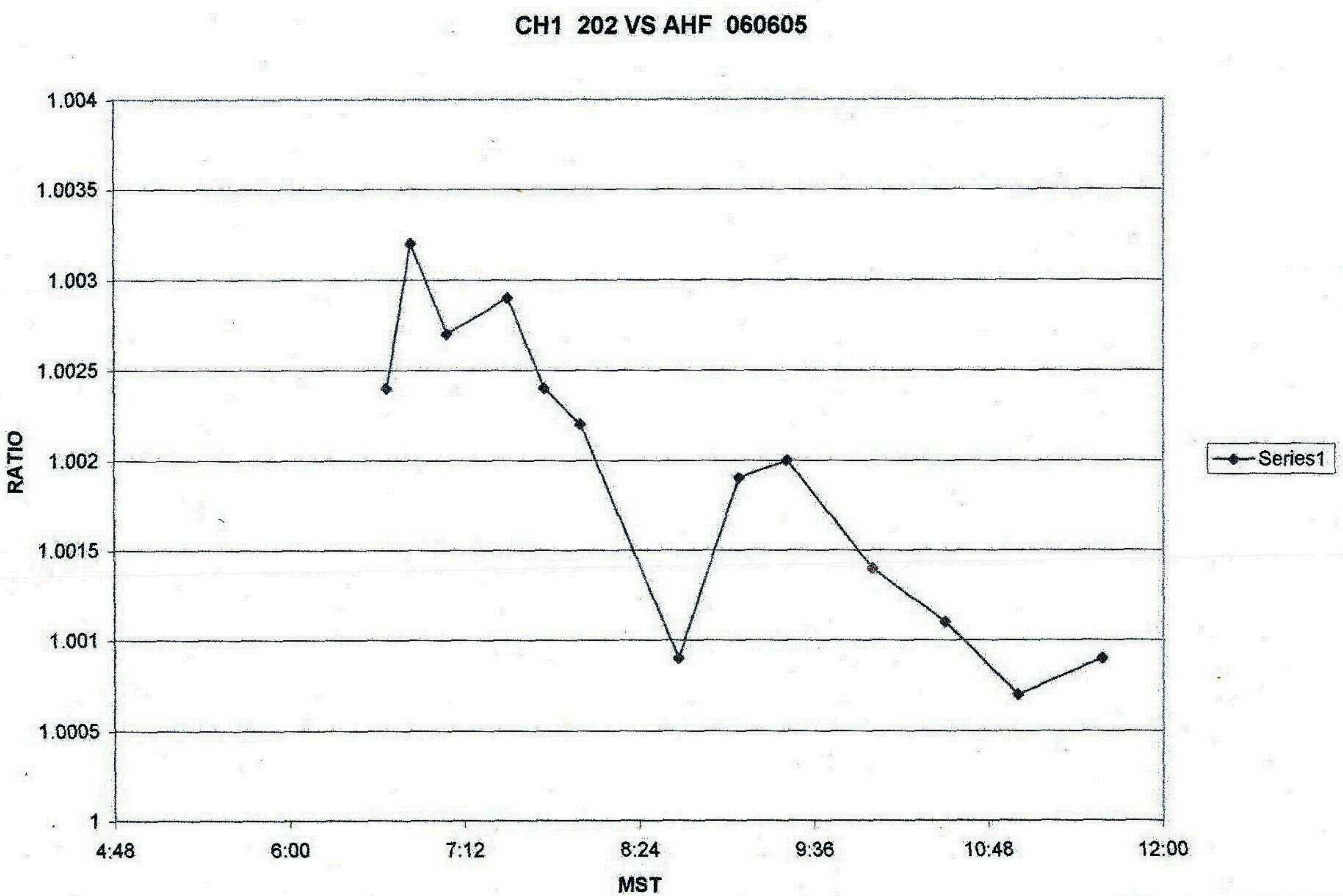

CH1 & NIP ZEROES
NIP ZERO
8xmV202
0.2
0.15
0.1
0.05
0
-0.05
mV
6:00:00
8:24:00
10:48:00
13:12:00
15:36:00
MST

- **FIG. 13 Comparison of Zeroes from NIP and CH1.**
- **Full day outdoors comparison of zeroes from a NIP and a CH 1 showing that relatively different thermal construction leads to similar thermal behavior.**


CH1 ZERO BEFORE AND AFTER CORRECTION
CH1ZERO
ZERO-600Tdot
2
1
0
-1
-2
W/m2
6:00:00
8:24:00
10:48:00
13:12:00
15:36:00
18:00:00
MST

- **Fig. 14 CH 1 Outdoor Zero Before and After Application of Eq. 1.**
- **Note the decrease of “fast” noise and the ability to set large regions of calculated zero to “zero”.**

- **Morning Calibration**
- **Probably the earliest misbehavior found for the pyrheliometer during calibrations in the mountain west was an elevated cal factor k in the morning. The effect was so frequent and so obvious that a modification of the uncertainty statement was required, to wit, "… and for times up to two hours after sunrise, an additional 2 % must be added to the uncertainty." We added uncertainties because, even though presently an unorthodox procedure, the uncertainty itself has nothing to do with a random variable. (Figures 15 and 16 show two behaviors exhibited by the same S/N CH 1: a 0.2% effect and a 1.5% effect.)**



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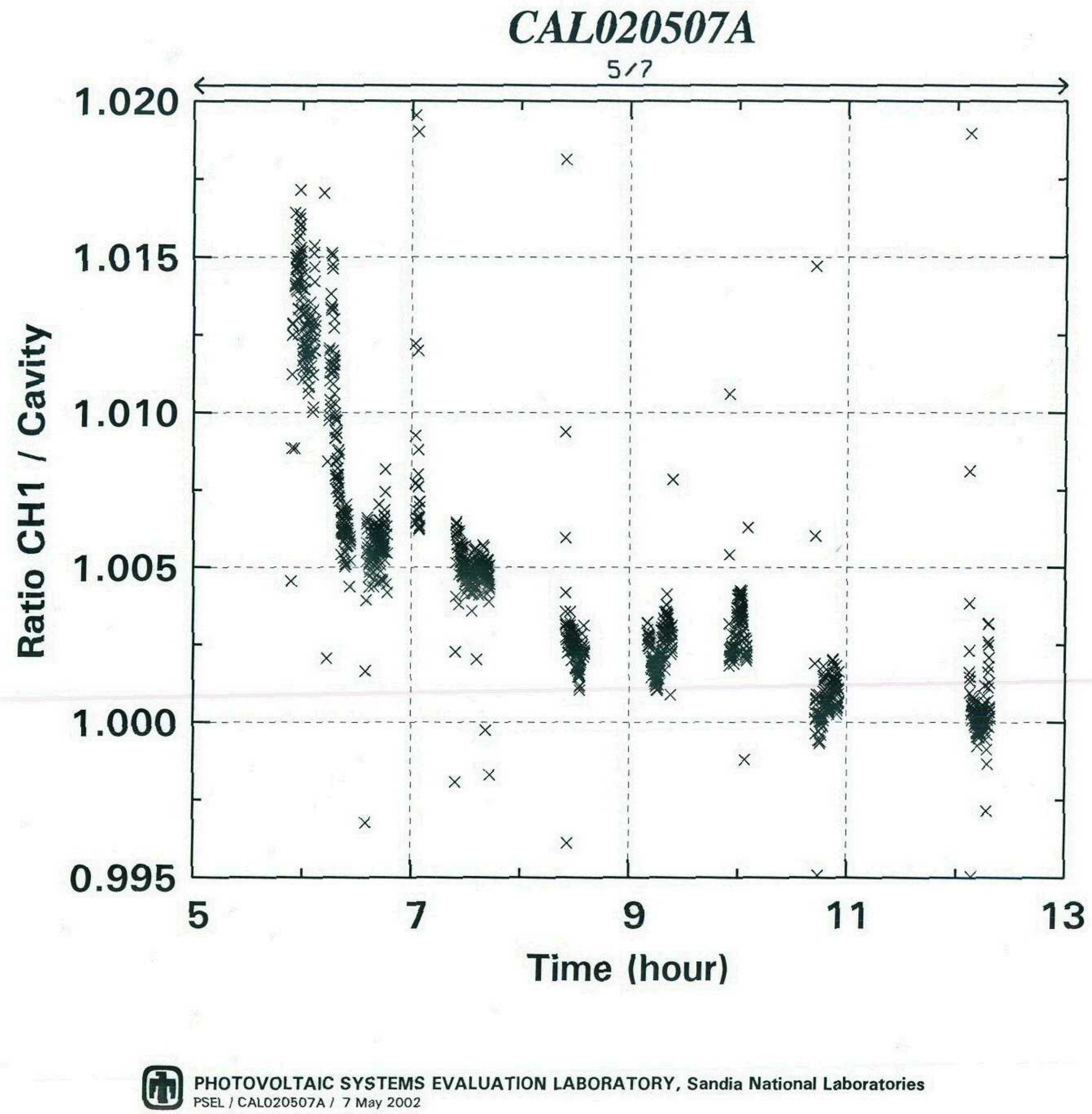

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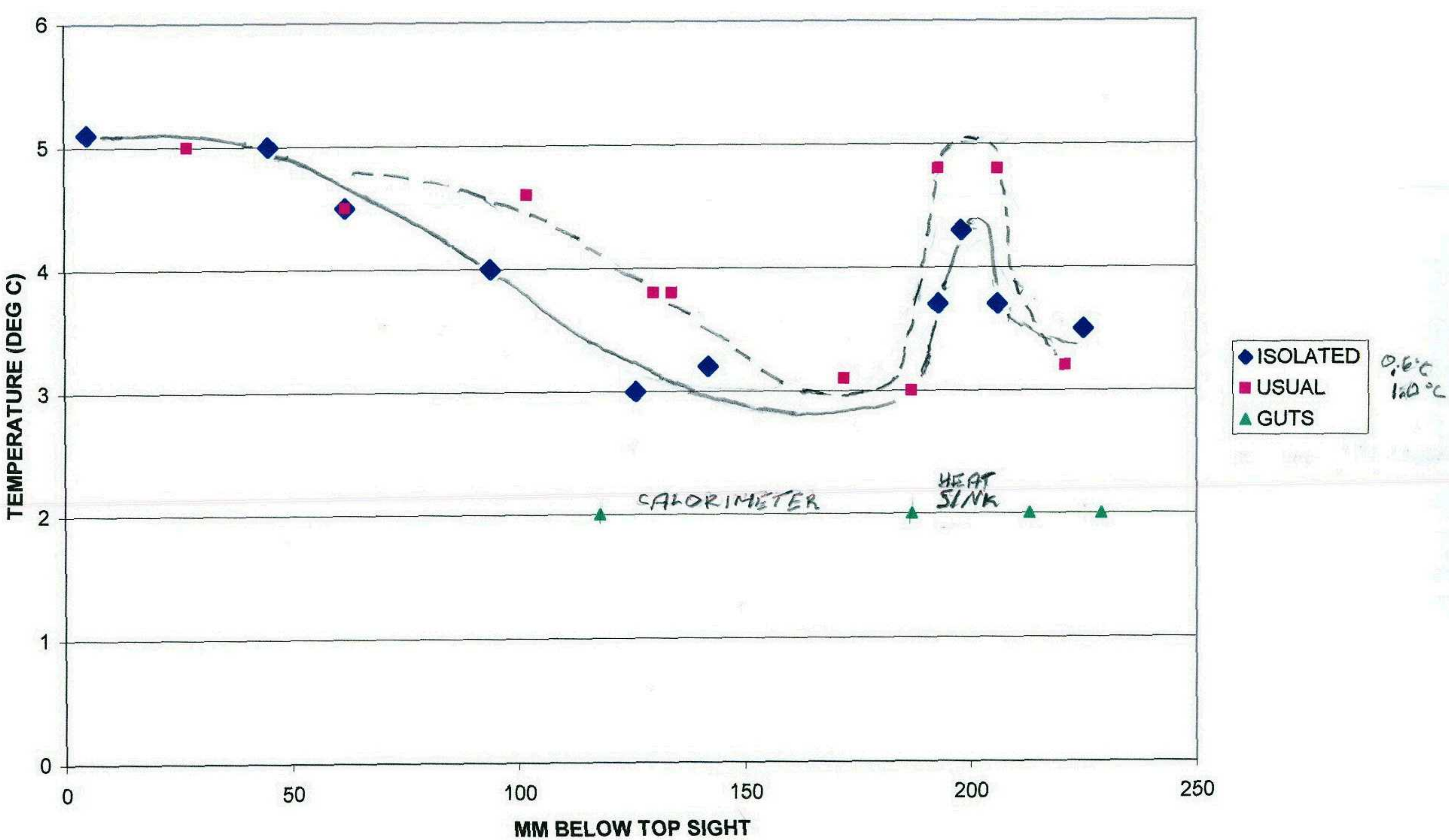
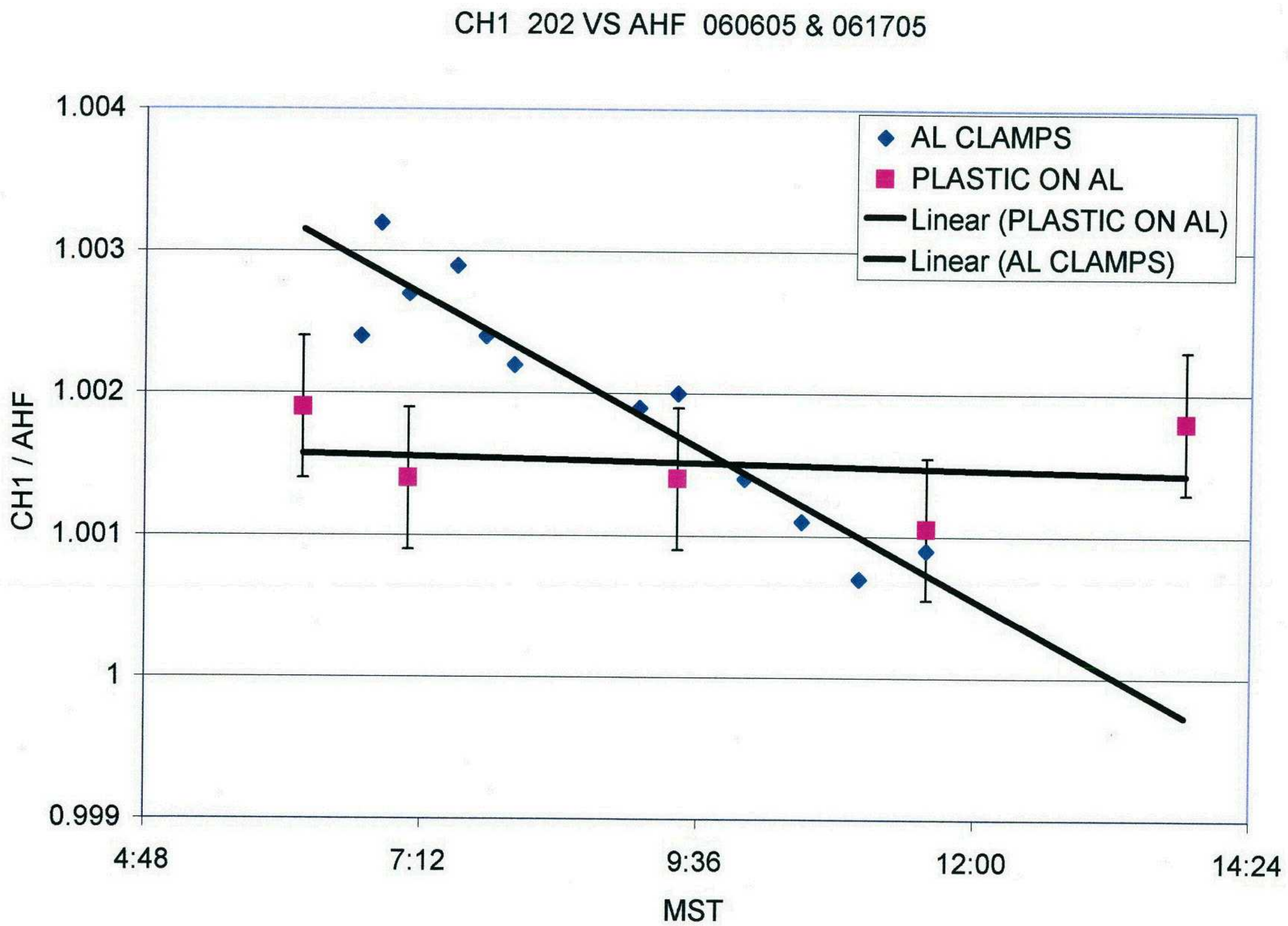
- **Figs. 15 – 16. Pyrheliometer Response in the Morning.**
- **The cause of the morning drop was eventually traced to a longitudinal heat flow in the pyrheliometer in which the sun warms the front of the device and the heat flows down the barrel being lost by radiation to the cold sky. Special tests then indicate how the morning drop might occur. First, the external temperature of the barrel was measured by an infrared camera [Ref. 7] with the pyrheliometer mounted is its usual fashion. Then the pyrheliometer was isolated as much as possible: a piece of thick felt (removed for the photo) blocked the sky; thinner felt blocked conduction through the tracker clamps; and a mirror with a center hole (made from a piece of shiny aluminum with a hole punched out the size of the field stop) which prevented all but the required solar heating of the pyrheliometer. Results are shown in Fig. 17.**

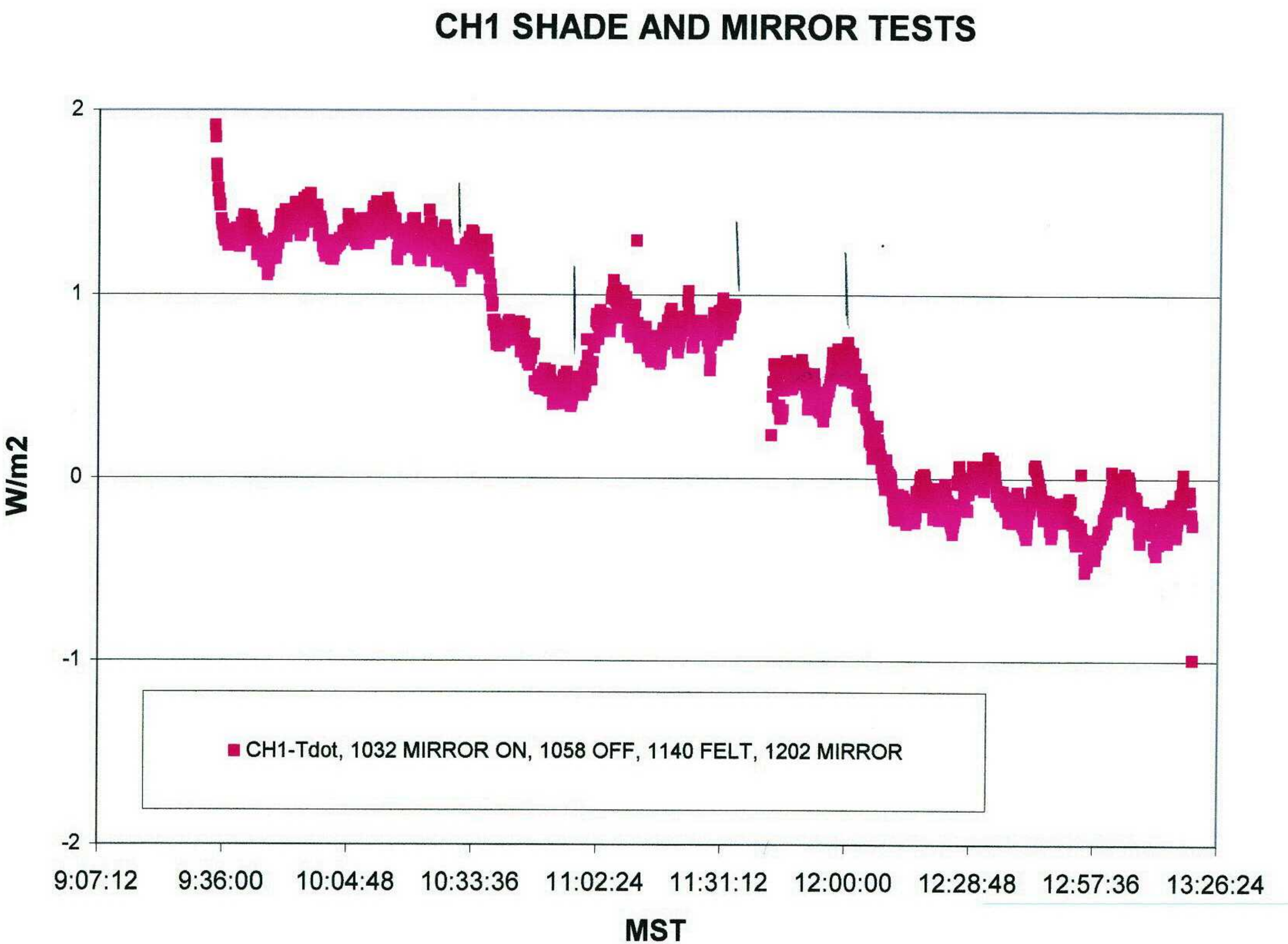
CH1 TEMPERATURE DISTRIBUTION WHEN THERMALLY ISOLATED



- **FIG. 17. CH 1 Surface Temperature Distribution.**
- **CH1 when the device is thermally isolated and when it has its usual mounting. The interior position ("guts") of the calorimeter and the heat sink are marked off by triangles.**
- **With the calorimeter isolated, the gradient across the calorimeter is about 0.5 deg C; and with the usual setup, the gradient is 1 deg C. Interior measurements must be made before drawing firm conclusions. Measurements that have been made are shown in Figs. 18 & 19. Figure 18 shows the cancellation of the morning drop in k brought about by putting foam under the tracker clamps. Figure 19 shows data analyzed using Eq.1 to bring out the effects of reflecting sunlight from the pyrheliometer top plate and of using felt cloth to isolate the pyrheliometer from the tracker.**


CH1 202 VS AHF 060605 & 061705
AL CLAMPS
PLASTIC ON AL
Linear (PLASTIC ON AL)
Linear (AL CLAMPS)
CH1 / AHF
1.004
1.003
1.002
1.001
1
0.999
4:48
7:12
9:36
12:00
14:24
MST

- **FIG. 18. CH 1 with and without Plastic Foam isolating the Pyrheliometer from the Tracker.**


CH1 SHADE AND MIRROR TESTS
2
1
0
-1
-2
W/m2
CH1-Tdot, 1032 MIRROR ON, 1058 OFF, 1140 FELT, 1202 MIRROR
9:07:12
9:36:00
10:04:48
10:33:36
11:02:24
11:31:12
12:00:00
12:28:48
12:57:36
13:26:24
MST

- **FIG. 19.   CH 1 with and without a Sunlight Reflector and with and without Felt Cloth to isolate Pyrheliometer from Tracker.**

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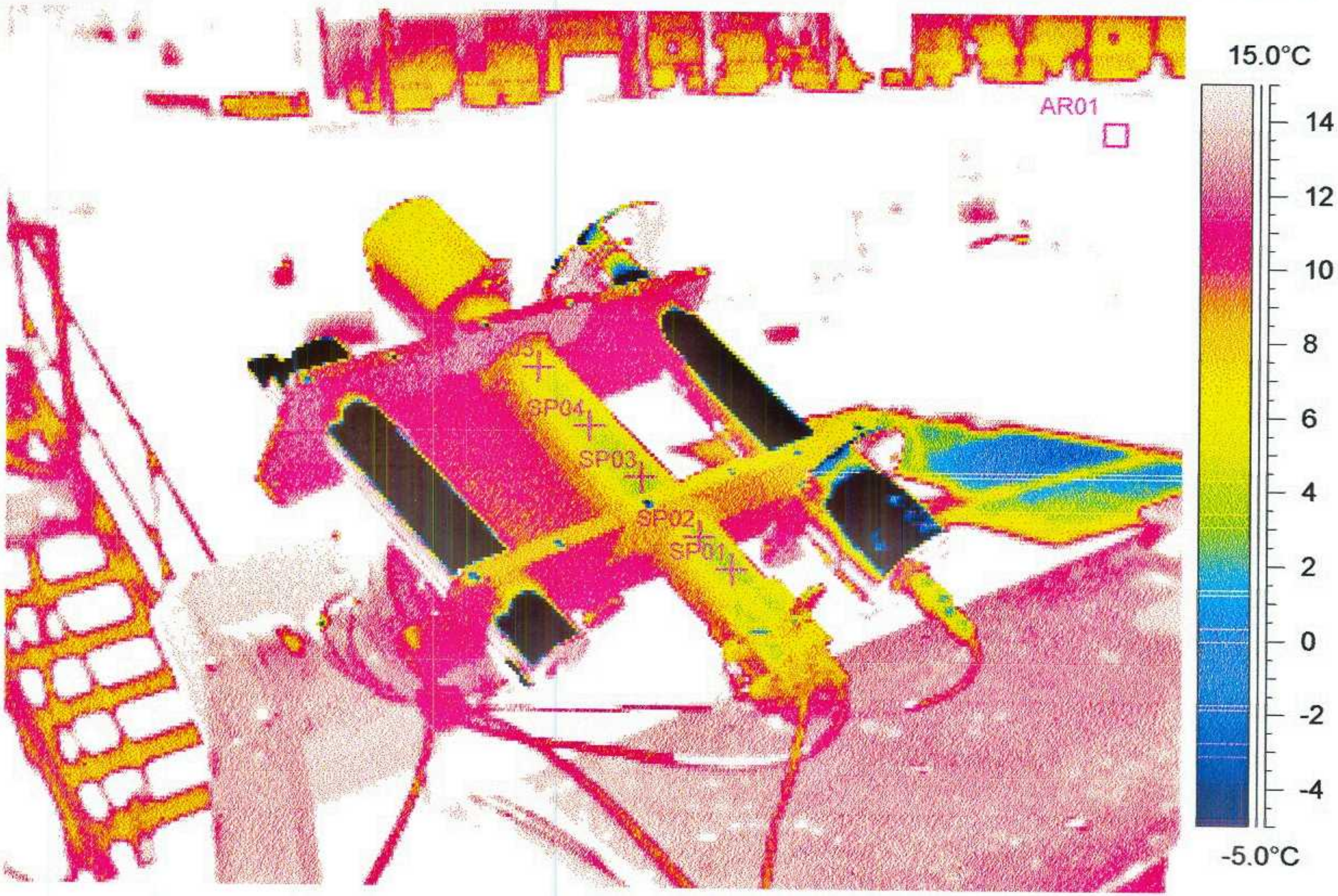
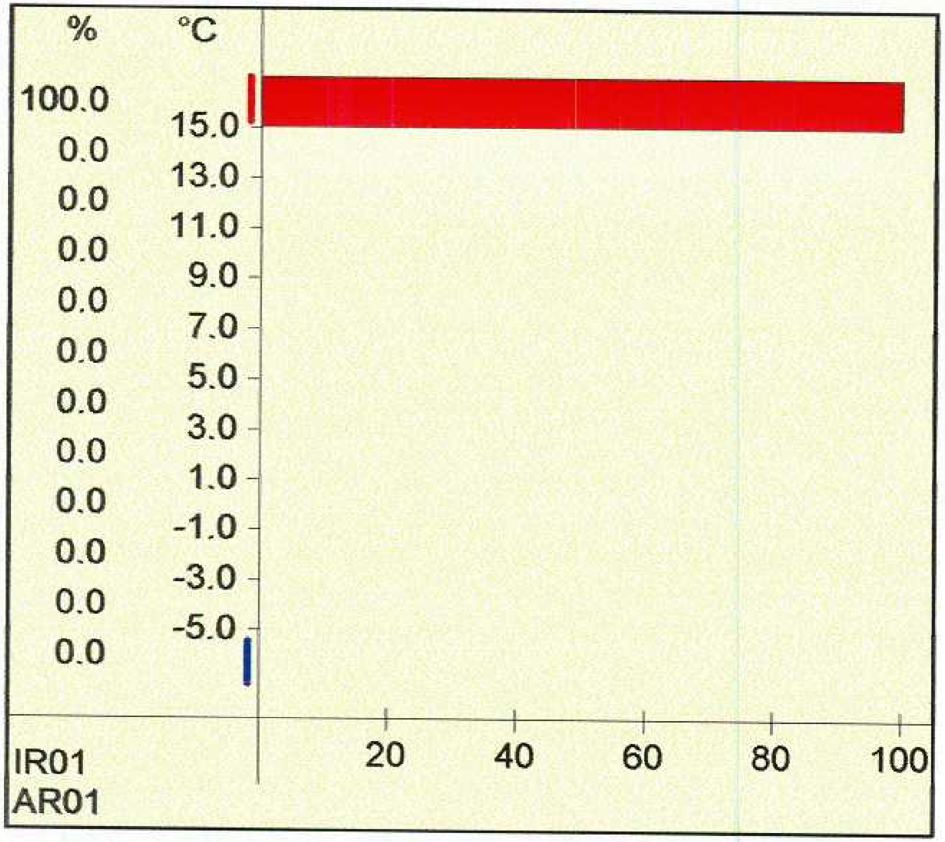
Infrared (IR) Image

Kipp & Zonen CH1 #990202 with felt spacers.
Second Image taken ~ 12:00 p.m.

capped, no mirror

01/15/2003
12:55:34 PM





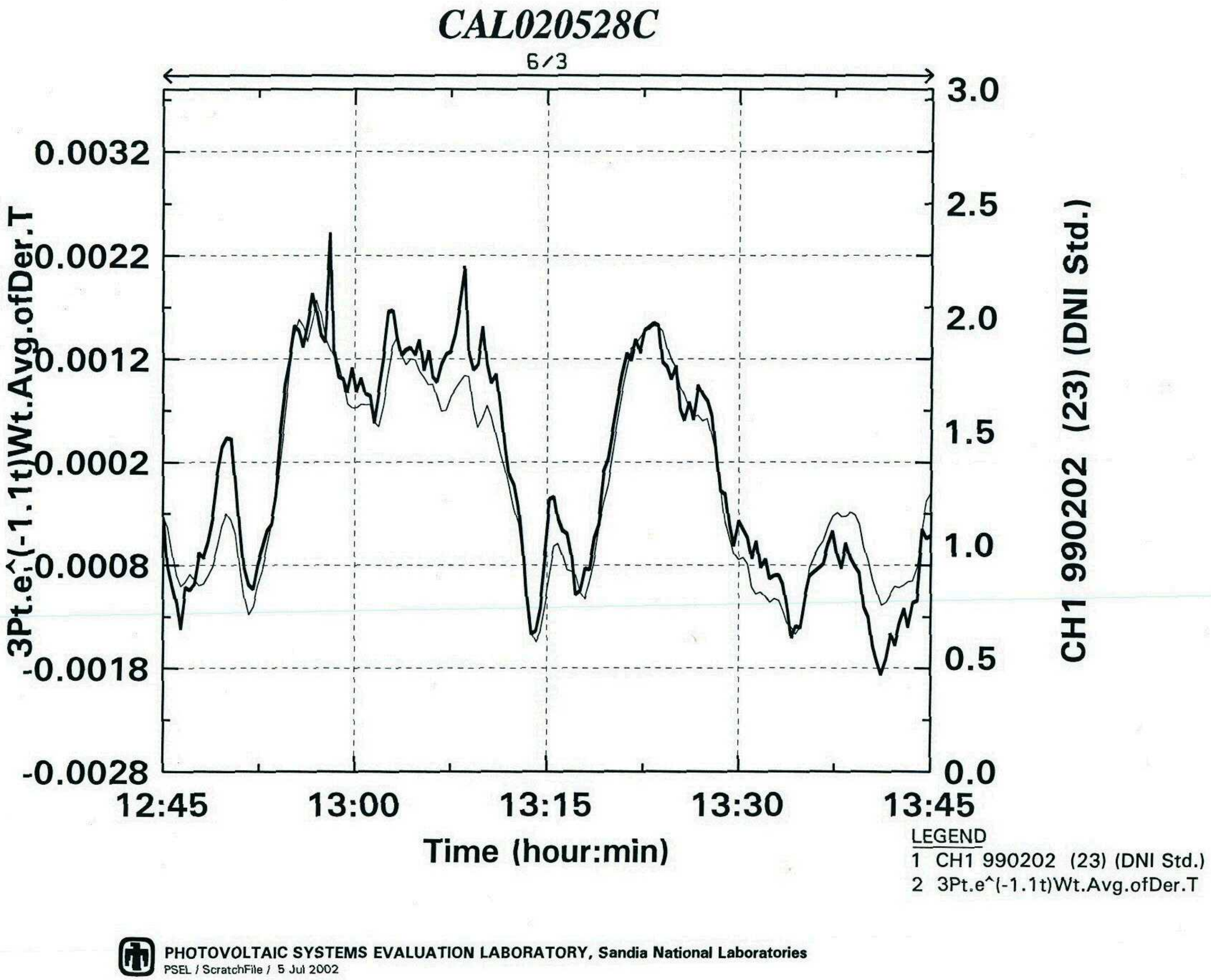
Camera Type	Flir Prism DS
Serial No.	760059
Wavelength	3.6 to 5.0 micron
Range (min to max)	-9.8 to 70.0 C

Label	**Value**
SP01	3.6°C
SP02	3.9°C
SP03	4.3°C
SP04	5.1°C
SP05	6.2°C
AR01 : max	22.0°C
AR01 : min	16.6°C
AR01 : avg	19.7°C
AR01: stdev	2.0°C

Object parameter	**Value**
Emissivity	1.00
Ambient temperature	23.0°C

Test4.ana

- **SUPPLEMENTAL:**
- **IR camera view.**
- **2 ea zero fits.**



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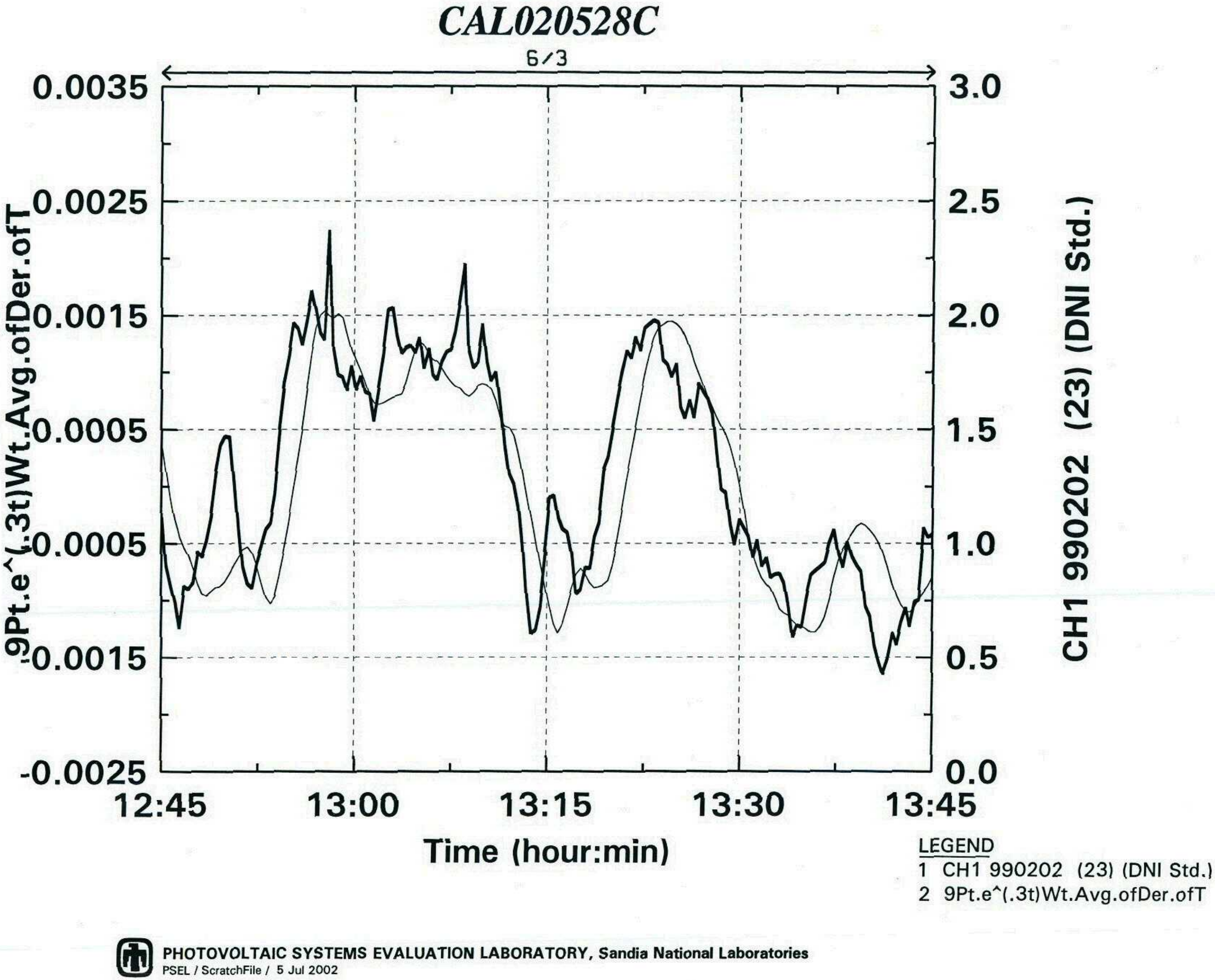
CAL020528C
6/3
0.0035
0.0025
0.0015
0.0005
-0.0005
-0.0015
-0.0025
3.0
2.5
2.0
1.5
1.0
0.5
0.0
12:45
13:00
13:15
13:30
13:45
Time (hour:min)
9Pt.e^(.3t)Wt.Avg.ofDer.ofT
CH1 990202 (23) (DNI Std.)
LEGEND
1 CH1 990202 (23) (DNI Std.)
2 9Pt.e^(.3t)Wt.Avg.ofDer.ofT
PHOTOVOLTAIC SYSTEMS EVALUATION LABORATORY, Sandia National Laboratories
PSEL / ScratchFile / 5 Jul 2002

- **Items still to be investigated:**
- **Wind effect on pyrheliometers.**
- **Aureole contributions to the insolation..**
- **Times to reach thermal equilibrium.**
- **Alignment**
- **Correction for longitudinal heat flow.**
- **Heat-flow design in calorimeters**

- **UNCERTAINTY ANALYSIS**
- **Uncertainty component (Very) Approximate 2-Sigma Value**
- **(%)**

Uncertainty component	(Very) Approximate 2-Sigma Value (%)	
Calibration	0.35	Ref. 6
Dirty optics	0.1	
Electrical Noise	0.1	
Spectral shift of window	0.15	
k(r) for CH1 tracker	0.05	
Al2O3 window	0.15	
RSS =	0.6	

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- REFERENCES
- Mention of a company product implies no endorsement by either Sandia National Laboratories or the National Renewable Energy Laboratory or lack of a suitable substitute.
- LOWTRAN (disk and manual) are available from ONTAR, sales@ontar.com , and technical support (978) 689-9622 x328.
- John Hickey, EPLAB, personal communication.
- Instruction manual CH 1, Kipp & Zonen.
- Anon., *Short-Wave and Long-Wave Radiation*, from the BSRN-Meeting ETHZ, 12.-16. September 1994, from file: CAWP51\BSRN_VG.064.
- P. D. Thacher, W. E. Boyson, E. J. T. Burns, and I. Reda, *Terrestrial Solar Radiometry of High Accuracy Using Electrically-Calibrated Pyrheliometers,* in preparation *(2009).*
- J. Kratochvil, Sandia, personal communication.

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