International Pyrheliometer Comparison

IPC - X

26.9. – 14.10.2005
Davos, Switzerland

IOM report No. 91

WMO/TD No. 1320

2006

FOREWORD

The organiziation and hosting of the WMO International Pyrheliometer Comparisons (IPCs) is a long-standing tradition at the Physikalisch-Meteorologisches Observatorium Davos (PMOD). The first IPC was held in 1959, long before the WMO designated PMOD to act as the World Radiation Centre (WRC) in 1971. The concept of periodical IPCs is now laid down in the WMO *Guide to Meteorological Instruments and Methods of Observation*, WMO-No. 8, (CIMO Guide) as the key process to ensure the world-wide homogeneity of solar irradiance measurements as well as to monitor and maintain the stability of the World Radiometric Reference (WRR).

The tenth holding of the IPC in autumn 2005 was favoured by extraordinarily good weather conditions. An exceptionally large number of clear sky days allowed to collect an unprecedented amount of solar irradiance data. Because of the large data volume, statistics allowed to lower the uncertainty of the comparisons and statistically significant discrepancies have been found in the long-term behaviour of different types of instruments and the WRR. While the WRR clearly meets the stability criteria required by the CIMO Guide, the discrepancies are larger than what was observed in the past. The search for the source of the discrepancies is an ongoing process. The fact that possible trends are detected and are investigated shows that the concept of the IPC to ensure the stability of the WRR is functioning.

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Director of the PMOD/WRC

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Acting President of the Commission for Instruments and Methods of Observations

WMO International Pyrheliometer Comparison
IPC-X
26 September - 14 October 2005
Davos, Switzerland

Final Report

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IOM report No. 91
WMO/TD No. 1320
PMOD/WRC Internal Report, Davos, May 2006

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Chapter 1 Organization and Procedures

1.1 Introduction

Under the auspices of the Commission for Instruments and Methods of Observation (CIMO), the Tenth International Pyrheliometer Comparison (IPC-X) was held together with the Regional Pyrheliometer Comparisons of all WMO Regions from 26 September through 14 October 2005 at the Physikalisch-Meteorologisches Observatorium Davos/World Radiation Centre (PMOD/WRC) in Davos, Switzerland.

The results presented in this report are based on the measurements carried out during the three weeks assigned to the IPC-X. The favorable weather conditions allowed to acquire a record number of calibration points for most participating instruments. Cloudy and overcast days were used for technical preparations and training of participants as well as for a the IPC-X symposium.

1.2 Participation

Seventy-three participants from 16 Regional and 23 National Radiation Centers as well as the World Radiation Data Center and eleven institutions and manufacturers took part in the comparison. They operated a total number of 89 pyrheliometers. The six World Standard Group (WSG) instruments were operated by the WRC staff. Two representatives of WMO were attending the IPC-X during the first couple of days.

Table 1.1: IPC-X Participation: *World, Regional and National Radiation Centers*

Country	*Type*	*Institution*	*Participant(s)*	*Instrument(s)*
World Radiation Center				
Switzerland	WRC	Physikalisch-Meteorologisches Observatorium Davos/ World Radiation Center, Davos	W. Finsterle J. Gröbner H. Roth W. Schmutz C. Wehrli	**PMO2** **PMO5** **CROM2L** **PAC3** **HF18748** **MK67814** EPAC 11402 PMO609 PMO611 PMO6-0101 PMO6-0304 PMO6-0401 PMO6-79-122 PMO6-80022 AHF32455
RA I				
Algeria	RRC	Office National de Météorologie, Tamanrasset	B. Ouchene	HF 29225
Egypt	RRC	Egyptian Meteorol. Authority, Cairo	M. H. Korany	HF 31103
Guinea-Bissau	NRC	Direccad-Geral da Meteorologia, Bissau	L. Ca	–
Morocco	NRC	Meteo Maroc, Casablanca	S. Noureddine	Å8421
Nigeria	RRC	Nigerian Meteorol. Agency, Garki Abuja	I. D. Nnodu L. E. Akeh S. K. Muyiolu	Å 576
Sudan	NRC	Sudan Meteorological Authority, Karthoum	A.& A. Shibaika	NIP 28330
Uganda	NRC	Meteorology Department, Kampala	S. Ochoto	Å6549
RA II				
China	NRC	CMA Atmo. Ods. Technology Center, Beijing	Y. Yang M. Yueqin L. Maosheng	HF 19743 PMO6-850406
India	RRC	Central Radiation Laboratory, Pune	M. K. Gupta	HF 18742

Table 1.1: (continued)

Country	*Type*	*Institution*	*Participant(s)*	*Instrument(s)*
Japan	RRC	JMA, Tokyo	K. Honda	PMO6-811107 HF 32446
Philippines	NRC	Philippine Atmospheric, Geophys. and Astron. Services PAGASA, Quezon City	A. Griarte	Å12578
Thailand	NRC	Thai Meteorological Department, Bangkok	W. Subwat S. Rachupimol	HF 27796
RA III				
Chile	RRC	Dirección Meteorológica Chile, Santiago	P. A. Mostraj Aguilera	PMO6-850410
Colombia	NRC	IDEAM, Bogotá	L. Fajardo Sierra	PMO6-79-123
Peru	RRC	SENAMHI, Lima	E. Villegas	Å18020
RA IV				
Canada	RRC	Experimental Studies Division ARQX, Meteorological Service of Canada, Downsview	O. Niebergall D. Halliwell I. Abboud	HF 18747 HF 20406
Cuba	NRC	Instituto de Meteorologia, Habana	J. C. Pelaez	Å18587
El Salvador	NRC	SNET, San Salvador	O. Ramírez Ramírez	CH1 94046E6
Mexico	RRC	Instituto de Geofísica, UNAM México	A. Muhlia	HF 29223
USA	RRC	NOAA/CMDL, Boulder	D. W. Nelson	HF 28553 AHF 32448 AHF 30710 AHF 28553 TMI 67502
RA V				
Australia	RRC	Bureau of Meteorology, Melbourne	B. Forgan D. Anderson	 HF 27160 TMI 69137
RA VI				
Austria	NRC	ZAMG, Vienna	M. Mair	Å15192 TMI 68025

Table 1.1: (continued)

Country	*Type*	*Institution*	*Participant(s)*	*Instrument(s)*
Belgium	RRC	Royal Meteorological Institute, Brussels	S. Ginion S. Guilmot G. Preuveneers	CR09R
Croatia	NRC	Meteorological Service, Zagreb	K. Premec	CH1 940072
Czech Republic	NRC	Czech. Hydromet. Institute, Hradec Kralove	J. Pokorny	HF 30497
Estonia	NRC	Estonian Met & Hydr Inst, Tartu	A. Kallis	PMO6-850405
France	RRC	Météo-France-Centre Radiométrique, Carpentras-Serres	J.-P. Morel	TMI 68016 Å7636
Germany	RRC	DWD, Met. Obs. Lindenberg, Tauche -OT Lindenberg	K. Behrens	HF 27157 PMO6-5 PMO6-811103
Hungary	RRC	Hungarian Meteorological Service, Budapest	Z. Nagy	HF 19746
Israel	NRC	Meteorological Service, Bet-Dagan	A. Baskis	HF 27162
Lithuania	NRC	Lithuanian Hydrometeor. Service, Vilnius	D. Mikalajunas	Å567
Poland	NRC	Institute of Meteorology and Water Management, Warsaw	B. Bogdanska	HF 30716
Portugal	NRC	Instituto de Meteorologia, Ponta Delgada	F. Carvalho	HF 23737
Romania	NRC	National Meteo Administration, Bucharest	C. Oprea	Å702
Russian Federation	WRDC	Voeikov MGO, St. Petersburg	A. Pavlov	Å212
Slovakia	NRC	Slovak Hydrometeorol. Institute, Bratislava	V. Horecká	Å13439
Sweden	RRC	SMHI, Norrköping	T. Carlund	PMO6-811108
Switzerland	NRC	MeteoSwiss, Payerne	–	PMO6-79-121
The Netherlands	NRC	KNMI, De Bilt	W. Knap A. Los E. Worell	HF 27159
United Kingdom	NRC	Met Office, Exeter	P. Fishwick D. Moore	TMI 67604 HF 31110

Table 1.2: IPC-IX Participation: *Various Institutions and Manufacturers*

Country	*Institution*	*Participant(s)*	*Instrument(s)*
China	CIOMP, Changchun	W. Fang Y. Wang P. Dong	SIAR-1 SIAR-2c
Italy	European Commission DG-JRC, Ispra	W. J. Zaaiman H. Muellejans	PMO6-81109 PMO6-911204
Russia	FGUP VNIIO, Moscow	S. Morozova M. Pavlovitch	MAR-1-1 MAR-1-2
Sweden	SP Swedish National Testing and Research Institute, Borås	S. Källberg A. Andersson	HF 15744
Thailand	Silpakorn University, Nakhon Pathom	S. Janjai Y. Sawatdisawanee P. Pankaew K. Tohsing	AHF 32454
The Netherlands	Kipp & Zonen BV, Delft	M. Veenstra	PMO6-cc 103 CH1 980174 CHP1
USA	ARM/SGP, Billings OK	C. Webb	–
USA	AS & M, NASA Langley, Hampton VA	F. Denn	HF 31041 HF 31105
USA	ATLAS-DSET Laboratories, Phoenix AZ	E. Naranen D. Maciver	HF 17142
USA	National Renewable Energy Lab., Golden CO	I. Reda T. Stoffel	HF 28968 HF 29220 HF 30713 HF 68018
USA	The Eppley Laboratory Inc., Newport RI	J. R. Hickey	HF 14915 HF 27798 HF 28965 HF 33396

1.3 Data Acquisition and Evaluation

The signals from the WSG instruments and additional radiometers of the WRC as well as auxiliary parameters were acquired by an analog data acquisition system based on eight HP3478A voltmeters with relay scanners that are controlled by a data acquisition computer.

The participating instruments were operated with their standard equipment, either manual or automated, in order to avoid interface problems and mutual interferences. The data from the manually operated instruments were transmitted to the data acquisition computer via a number of micro-terminals operated by the participants. Each terminal could accept up to 3 different parameters from two instruments. After each series, a print-out of the values entered by micro-terminal was distributed to be checked by the participants. If necessary, the raw data could be edited manually to correct typing errors.

The participants having their own computer controlled systems (synchronized to the timing of the IPC's measurement series) had the possibility to up-load their data to a dedicated directory on the IPC-X FTP site. LAN/WLAN, floppy disks, or USB memory sticks were accepted means of data transfer. All data on the FTP site were ingested into the data acquisition and evaluation system at the end of each day.

1.3.1 Timing of the Measurements

The measurements were taken in series of 21 minutes with a basic cadence of 90 seconds. Voice announcements and buzzer signals were used to inform the participants about the sequence of operations. All automated data acquisition systems were synchronized to Central European Time (CET). A network time server and a large reference clock on the measuring field were set up for this purpose. The timing for the different types of instrument was as follows:

- Ångström pyrheliometers: Before the start and after the end of the run the zero of the instrument was established. Alternating right and left strip readings were performed, starting with the right hand strip exposed to the sun. The following readings were paired as L-R, R-L, etc., yielding a total of 12 irradiance values per run.

- PACRAD: the run started with the shutter closed, after 60 s the heater was turned on for 40 s (this was introduced after IPC-III in order to have a well defined thermal state of the instrument independent of the operation sequence before the run). At 270 s the zero of the thermopile was read and the heater switched on again. At 450 s the heater voltage, current and thermopile was read, the heater turned off and the shutter opened. From 540 s on readings were taken every 90 s yielding 8 irradiance values per run. After the last reading the shutter was closed.

- HF type pyrheliometers: the run started with the shutter closed, after 90 s the zero was read and the heater turned on until at 180 s the voltage, current and thermopile were read. The heater was then turned off and the shutter opened. From 270 s onward the instrument was read every 90 s yielding 11 irradiance values per run. Some instruments which were providing their data with diskettes performed the calibration between the series and consequently measured 13 irradiance values per run.

- TMI type pyrheliometers: the run started with the shutter closed and the calibration procedure was performed until the end of the first 90 s. Starting at 180 s readings were taken every 90 s yielding 12 irradiance values per run.

- Active cavity type pyrheliometers: the run started with a reference phase (shutter closed) of 90 s, followed by a measurement phase (shutter open) of 90 s. This was repeated for the next 18 minutes. A total of 6 open and 7 closed readings were taken yielding a total of 6 irradiance values during a run. PMO2 was read at twice that pace, with a reference phase of 32 s and a measurement phase of 58 s, producing 13 irradiance values per run so that for all readings of the basic sequence a PMO2 irradiance was available.

- Normal Incidence Pyrheliometers (NIP): it took 12 irradiance values every 90 s after an initial zero reading at 90 seconds.

1.3.2 Data Evaluation

For each instrument the irradiance was obtained with the appropriate evaluation procedure as listed below. After each day a summary of the computed irradiances was printed and distributed to be checked by the participants. As an indication the mean and standard deviation of the ratios to PMO2 were also given for each series. In all further steps of the data evaluation procedures none of the WSG instruments played a specific role.

The procedure used to calculate the irradiance *S* of each instrument type is described below. The notations are:

V_{th}	output of the thermopile
U_h, U_i	voltage across the heater (h) or across the standard resistor (i)
R_n	standard resistor
C	calibration factor
C_2	correction factor for lead heating
P	electrical power in the active cavities

- Ångström-pyrheliometers: the current through the right or left strip was measured as voltage drop across a standard resistor and the irradiance was obtained as:

$$S = C\frac{U_i(\text{left})U_i(\text{right})}{R_n^2}$$

  This corresponds to the geometric mean of the irradiances at the time of right and left readings. Thus, the ratio to WRR was calculated using the geometric mean of the WSG irradiances at the corresponding instances.

- PACRAD and HF type pyrheliometers: the irradiance was calculated from the thermopile output V_{th}(irrad) when the receiver was irradiated. The sensitivity was determined by the calibration during which the cavity was shaded and electrically heated and U_h and U_i were measured together with the corresponding thermopile output V_{th}(cal). Furthermore, the zero of the thermopile V_{th}(zero) was measured and subtracted.

$$S = C\frac{V_{th}(\text{irrad}) - V_{th}(\text{zero})}{V_{th}(\text{cal}) - V_{th}(\text{zero})}\frac{U_i}{R_n}\left(U_h - \frac{U_i}{R_n}C_2\right)$$

- TMI type pyrheliometers: most were operated in the "normal" way, that is by calibrating the readout directly in units of mW cm^{-2}. The values were entered in Wm^{-2} and no irradiance calculation was needed. Others were operated and evaluated like HF pyrheliometers.

- Active cavity pyrheliometers: the irradiance was obtained from P(closed) averaged from the closed values before and after the open reading P(open).

$$S = C(P(\text{closed}) - P(\text{open}))$$

  The power calculation was done according to the prescription of the instrument type with

$$P = U_h^2 \qquad \text{or} \qquad P = U_h U_i \qquad \text{or} \qquad P = U_h\frac{U_i}{R_n}$$

- Normal Incidence Pyrheliometer (NIP): the thermopile reading was divided by the calibration factor after subtraction of the zero point reading[1].

[1] Some NIP operators assumed a vanishing zero signal. They did not perform zero readings.

- PMO2: As during preceding IPCs, PMO2 was used as the reference instrument for the daily summaries because it can be operated fast enough to provide an irradiance value every 90 seconds. The values of PMO2 were obtained with the algorithm for active cavity radiometers. At the end of the open phase, 8 readings were taken in rapid succession of about one reading per second. For the on-line calculations the first reading was used as reference for the values entered by the terminals. The standard deviation of the 8 readings was used during the final evaluation as a quality control parameter to assess the atmospheric stability during each acquisition sequence (see Sect. 2.1).

1.3.3 Auxiliary Data

The meteorological parameters (air temperature, relative humidity, atmospheric pressure) were obtained from the automated weather station ASTA of MeteoSwiss located at PMOD/WRC (see Sect. 3.2.2). The ASTA values are 10-minute averages.

A cloud sensor flagged all data points when clouds were within 15 degrees of the Sun. The flagged points were not used to evaluate Ångstrom type pyrheliometers.

Precision Filter Radiometers (PFR) were used to determine Aerosol Optical Depth (AOD) at four wavelengths (367.6 nm, 412.0 nm, 501.2 nm, and 862.4 nm, see Sect. 3.2.3).

1.4 Approvement and Dissemination of the Results

According to Resolution 1 of CIMO-XI an Ad-hoc Group was established to discuss the preliminary results of the IPC-X, based upon criteria defined by the WRC, evaluate the above reference and recommend the updating of the calibration factors of the participating instruments. It was chaired by the Bruce W. Forgan, (Australia, RA V) and composed as follows: Mohamed Hussein Korany (Egypt, RA I), Kohei Honda (Japan, RA II), Pedro Mostraj Aquilera (Chile, RA III), Augustin Muhlia (Mexico, RA IV), Don Nelson (USA, RA IV), Zlotan Nagy (Hungary, RA VI), Klaus Behrens (Germany, CIMO Expert Team). The WRC was represented by Wolfgang Finsterle and Werner Schmutz.

The procedures used to compute the new WRR factors of the WSG and participating instruments are explained in Section 2.2.

Chapter 2 Measurements and Results

Measurements were taken on eleven days (2005 September 26, 28, and 30, October 4, 8, 9, 10, 11, 12, 13, and 14). October 10^{th} was the most productive day, yielding 18 series' of 21 minutes duration. On all days 113 series' were acquired. All data points that satisfy the following data selection criteria were considered in the final evaluation.

2.1 Data Selection Criteria for the Final Evaluation

At the beginning of IPC-X, the Ad-hoc Group responsible for the approval of the final evaluation procedure (c.f. Sect. 1.4) met and set the following criteria for the acceptance of IPC-X data:

1. Only observations falling within the appropriate measurement periods be accepted and that the last series for any group of instruments stop before the end of the period is reached (based on calculations associated with the instrument field of view).
2. That no measurements be used for Ångstrom pyrheliometers if a cloud is within 15 degrees of the sun. No measurements will be used for the absolute cavity radiometers (field-of-view = 5°) if a cloud is within 8 degrees of the sun.
3. That no data be used if the 500 nm AOD is greater than 0.12.
4. That an individual point be excluded from a series if the variation of the 8 fast PMO2 measurements is greater than $0.5\,\mathrm{Wm}^{-2}$.
5. That the minimum number of acceptable data points be 150 for the PMO2 taken over a minimum of three days during the comparison period.

2.2 Computation of the New WRR Factors

2.2.1 WSG Instruments

The WRR factor $WRR_{i,IPC}$ for the WSG instrument i, $i \in \{$PMO2, CROM2L, MK67814, HF18748, PAC3, PMO5$\}$, by definition is the ratio of the WRR to the WSG instrument i averaged over the duration of the IPC:

$$WRR_{i,IPC-X} = \left\langle \frac{WRR(t)}{WSG_i(t)} \right\rangle_t ,$$

where $WRR(t)$ and $WSG_i(t)$ are the reference irradiance and the irradiance measured by WSG instrument i at the time t, and $\langle x(t) \rangle_t$ denotes the temporal average of $x(t)$. The reference irradiance (WRR) is defined as the mean value of the simultaneous readings of at least three WSG instruments, multiplied by their corresponding WRR factors from the previous IPC

$$WRR(t) = \langle WSG_i(t) * WRR_{i,IPC-IX} \rangle_i .$$

We thus get

$$WRR_{i,IPC-X} = \left\langle \frac{\langle WSG_i(t) * WRR_{i,IPC-IX} \rangle_i}{WSG_i(t)} \right\rangle_t .$$

The new WRR factors for WSG instruments are given in Table 2.1.

2.2.2 Participating Instruments

For each participating instrument j the new WRR factor is calculated according to

$$WRR_{j,IPC-X} = \left\langle \frac{WRR(t)}{Irr_j(t)} \right\rangle_t ,$$

where $Irr_j(t)$ is the irradiance measured by the instrument j at the time t and $WRR(t)$ the coinstantaneous reference irradiance.

Temporal averaging is done by fitting a gaussian to the distribution of WRR-to-instrument ratios. Outliers are sucessively removed until the ratios are normally distributed with a probability higher than 90%, or until all ratios are within a certain range of their arithmetic mean value[1]. The new WRR factors for all participating instruments are listed in Table 2.2.

2.3 Status of the WSG

The main objective of the periodic IPC's is the dissemination of the World Radiometric Reference (WRR) in order to ensure worldwide homogeneity of meteorological radiation measurements. The WRR is realized by the WSG which is frequently inter-compared at PMOD/WRC to detect possible deviations of individual members of the group and to ensure the stability of the WRR. Independently, the stability of the WRR can be checked by instruments that have participated in previous IPC's.

Since IPC-IX, which was held in 2000, three member instruments of the WSG suffered from drifts of their WRR factors of -186 ppm/yr (PMO2), +120 ppm/yr (HF18748), and +93 ppm/yr (PAC3), respectively. The WRR factors of the remaining three WSG instruments (PMO5, CROM2L, MK67814) changed by less than 10 ppm/yr. These instruments are considered as stable over the past five years. The drift in PMO2 was first suspected to be caused by degradation of the signal amplifiers[2]. The instrument therfore underwent thorough testing, including the re-determination of the amplification factors and the standard resistor, but all parameters were consistent with the original characterization of the instrument. Because the lack of any plausible technical reason for the observed drift the measurements by PMO2 are still considered as trustworthy as any other WSG instrument.

In the case of HF18748 the manufacturer suggested to check and clean all cable connections. To avoid changing more than one WSG instrument at a time these tests were postponed until after PMO2 was fully operational again. At the time of writing no results were available.

The apparent drift in PAC3 can be attributed to its well known sensitivity to ambient temperature. Because of the poor weather conditions in 2000 additional data had been acquired after the IPC-IX and was used to determine the WRR factors. Some of these data were acquired as late as December 2000, when temperatures were consideralby lower than during the IPC-IX. Therefore the old WRR factor for PAC3 was not representative for the conditions during September/October.

At this point it should be mentioned that the WMO-CIMO guide requires the WSG instruments to perform better than 0.2% in terms of long-term stability. For this and the above mentioned reasons it seems reasonable to keep all six members in the WSG and to use all of them to transfer the WRR.

[1] This threshold range ususally is ± 0.002 for cavity pyrheliometers. However, for most Ångströms, NIP's and some cavities a different range had to be chosen manually in order to make the most plausible selection of data points.

[2] An almost identical drift occured in PMO5 five years ago and could be corrected by removing the signal amplifiers.

2.4 Transfer of the WRR

Since the instrumental drifts described in Sect. 2.3 nearly compensate each other all six WSG member instruments (i.e. PMO2, PMO5, CROM2L, PAC3, MK67814, HF18748) were included in the transfer of the WRR. This can also be justified by the fact that the WRR factors of the three stable instruments (PMO5, CROM2L, and MK67814) are unchanged by including or rejecting the remaining three instruments PMO2, HF18748, and PAC3.

Table 2.1: New WRR-factors for the WSG instruments computed using PMO2, PMO5, CROM2L, PAC3, HF18748 and MK67814 and the IPC-IX WRR-factors.

Instrument	*WRR factors IPC-IX*	*WRR factors IPC-X*	*Standard Uncertainty* $\sqrt{\frac{\sigma}{(N-1)}}$ *[ppm]*	*N*	*Change [ppm] IPC-X - IPC-IX*
PMO2	0.999548	0.998618	11	1026	-930
CROM2L	1.00301	1.002998	36	500	-12
MK67814	1.00066	1.000708	11	945	48
HF18748	0.995675	0.996274	14	938	599
PAC3	1.00065	1.001116	12	641	466
PMO5	0.998974	0.998982	24	520	8

Table 2.2: The new WRR factors for the participating instruments

Instrument	C_1	C_2	C_3	**WRR Factor**	σ [ppm]	*N used*	*N tot*	*Country/ Owner*
Å12578	4465.9	1000.		**1.006552**	4295	612	906	Philippines
Å13439	4411.8	1000.		**1.003292**	1491	709	953	Slovakia
Å15192	4494.95	1000.		**1.002164**	1722	274	763	Austria
Å18020	4624.49	1000.		**1.004923**	1822	636	852	Peru
Å18587	4576.77	1000.		**0.997654**	2452	693	849	Cuba
Å212	10535.0	1.		**1.003384**	1737	623	769	Russia
Å567	5777.02	1.		**1.000247**	2901	649	824	Lithuaniy
Å576	5885.13	1000.		**1.000059**	3256	702	973	Nigeria
Å6549[3]	4603.34	2.		********	*****	0	954	Uganda
Å702	6141.14	200.		**1.005977**	3983	712	938	Romania
Å7636	4328.5	10000.		**1.001120**	1492	762	982	France
Å8421[4]	47880.0	1.		**0.097869**	19006	567	1040	Morocco
AHF14915	20010.0	0.066		**0.999641**	893	680	898	EPLAB
HF15744	20020.0	0.066		**0.998038**	740	770	1015	Sweden
AHF17142	19959.0	0.066		**0.999146**	779	813	1091	ATLAS-DSET
AHF18742	20089.26	0.066	10000.	**1.003773**	2679	735	996	India
HF18747	20014.0	0.066		**1.002680**	618	763	983	Canada

[3] This instrument is broken. It yields constant readings. Unfortunately, this behaviour could not be discovered in the daily summary data.

[4] This instrument was operated in "NIP mode", i.e. without heating of the shaded strip. Instead the voltage across the thermo-couple was directly evaluated using the same procedure as for NIP. We recommend to not use this instrument as a reference instrument.

Table 2.2: (continued)

Instrument	C_1	C_2	C_3	**WRR Factor**	σ [ppm]	*N used*	*N tot*	*Country/ Owner*
HF19743	20041.8	0.066	10000.	**0.999495**	1796	741	950	China
HF19746	20013.8	0.066	10000.	**0.998778**	677	810	1046	Hungary
HF20406	20038.0	0.066		**1.004065**	672	761	1055	Canada
HF23737	20030.0	0.066	10000.	**0.993700**	1961	719	943	Portugal
HF27157	20037.6	0.066	10000.	**0.998723**	1441	563	875	Germany
HF27159	20030.01	0.066		**0.998007**	827	844	1083	The Netherlands
AHF27160	20030.0	0.066	10.	**0.996911**	686	785	1025	Australia
HF27162	20020.0	0.066	1000.	**1.000185**	999	583	767	Israel
HF27796	19986.1	0.066	1000.	**0.996979**	1007	679	828	Thailand
AHF27798	20020.0	0.066		**0.999413**	1063	676	897	EPLAB
AHF28553	19989.0	0.066		**0.996109**	711	737	862	USA/NOAA
AHF28965	19986.0	0.066		**0.997271**	721	717	839	EPLAB(M)
AHF28968	19980.2	0.066		**0.997766**	751	911	1146	NREL
AHF29220	19999.0	0.066		**0.997560**	735	922	1158	NREL
HF29223	1.9998	0.066		**0.996765**	1090	359	849	Mexico
AHF29225	20042.0	0.066		**0.996107**	721	653	831	Algeria
AHF30497	19943.8	0.066		**0.999346**	540	788	1025	Czech Republic
AHF30710	19999.0	0.066		**1.002511**	827	733	857	USA/NOAA
AHF30713	19989.0	0.066		**0.997512**	666	911	1147	NREL
AHF30716	20009.2	0.066	10000.	**0.997157**	659	718	946	Poland
AHF31041	19999.2	0.066		**0.996294**	746	917	1188	NASA
AHF31103	19989.0	0.066	10000.	**0.999636**	674	755	1015	Egypt
AHF31105	1.0	0.066		**1.001649**	925	915	1188	NASA
AHF31110	19989.0	0.066		**0.997211**	787	722	987	United Kingdom
AHF32446	19986.9	0.066		**0.998873**	611	848	1104	Japan
AHF32448	19992.0	0.066		**0.999874**	859	706	839	USA/NOAA
AHF32454	1.0			**0.999045**	691	706	815	Thailand
AHF32455	20009.2	0.066	10.	**0.999090**	544	943	1201	WRC
AWX33393	2.0009	0.066		**0.997281**	751	804	1032	Sweden
AHF33396	1.0	0.066		**0.997951**	893	673	897	EPLAB(J)
0501657	7.46			**1.008130**	11774	759	938	WRC
28335	8330.0			**1.012882**	5869	904	1166	Sudan
31144E6	8.04			**0.997155**	3481	929	1204	WRC
CHP1	8.75			**1.002837**	673	306	369	The Netherlands
CH1940072	10330.0			**1.005958**	1412	855	1105	Croatia
CH1980174	10.28			**1.001401**	1418	307	369	The Netherlands
CH19046E6	7970.0			**1.012451**	3274	770	1108	El Salvador
CH1930018	10.85			**0.996200**	2337	797	1056	JRC Italy
CR09L	12780.9			**0.999108**	1256	353	418	Belgium
EPAC 11402	10024.0	0.066	50.	**1.000563**	841	865	1204	WRC
MAR-1-2	1.0			**0.998704**	1257	289	329	Russia
MAR-1-1	1.0			**0.998684**	798	342	423	Russia
PMO6-79-121	132.551			**1.000388**	571	521	661	Switzerland
PMO6-79-122	600.0			**0.999148**	459	522	661	WRC

Table 2.2: (continued)

Instrument	C_1	C_2	C_3	**WRR Factor**	σ [ppm]	*N used*	*N tot*	*Country/ Owner*
PMO6-80022	597.875			**0.997948**	518	520	661	WRC
PMO6-81109	23.9995			**0.998413**	703	921	1199	JRC Italy
PMO6-811107	24.0323			**0.999052**	1516	404	551	Japan
PMO6-811103	23.94			**0.999205**	815	317	463	Germany
PMO6-850405	24.194			**0.999194**	388	367	492	Estonia
PMO6-850405P	0.1209			**0.999033**	434	382	487	Estonia
PMO6-850406	24.0008			**0.999445**	621	384	530	China
PMO6-850410	609.17			**0.987027**	854	406	552	Chile
PMO6-911204	24.104			**0.999011**	888	848	1117	JRC Italy
PMO6-0101d	50000.0			**1.030197**	403	508	636	WRC
PMO6-0304d	50000.0			**1.042035**	599	442	619	WRC
PMO6-0401d	50000.0			**1.021527**	382	517	649	WRC
PMO6-5	50865.1			**0.999959**	477	443	561	Germany
PMO6-cc103	51183.3			**0.999424**	638	762	1035	The Netherlands
PMO609	24.0392			**1.003793**	655	514	661	WRC
PMO611	23.9442			**1.003386**	643	518	661	WRC
PMO679-123	601.61			**1.000515**	2776	399	555	Colombia
PMO811108	24.0887			**0.998116**	602	775	1025	Sweden
SIAR-1	1.0			**1.001928**	815	753	945	CIOMP/China
SIAR-2a	1.0			**1.000623**	490	906	1210	WRC
SIAR-2b	1.0			**0.998620**	507	979	1318	WRC
SIAR-2c	1.0			**1.000016**	933	761	956	CIOMP/China
TMI67502	1.0039			**0.999483**	899	553	660	USA/NOAA
TMI67604	1.0052			**0.998793**	716	806	1014	United Kingdom
TMI68016	10031.5			**1.000087**	694	73	82	France
TMI68018	10046.0		1.	**0.997134**	671	897	1147	NREL
TMI68025	1.0			**0.998135**	1310	746	1103	Austria
TMI69137	10020.0		10.	**1.001704**	731	786	1023	Australia

2.5 Stability of the WSG

In Section 2.3 the stability of the WSG was checked by analyzing the trends of individual members of the WSG with respect to the group's average. The stability of the WSG can also be checked with respect to the WRR factors of those participating instruments that have also participated in IPC-IX (58 instruments, not counting the WSG). This analysis yields a conflicting results which we will discuss here in detail:

For the stability analysis only instruments whose WRR factors had changed by less than 0.2% over the past five years were considered. Also all instruments that showed unexplained or inconsistent behaviour during either IPC-IX or IPC-X were excluded. On average the WRR factors of the remaining 46 instruments changed by -471 ppm with a standard uncertainty of 206 ppm (95% confidence). In other words the probability that WSG was stable over the past five years is less than 5%. However, we found substantial differences between the different types of pyrheliometers, indicating that the

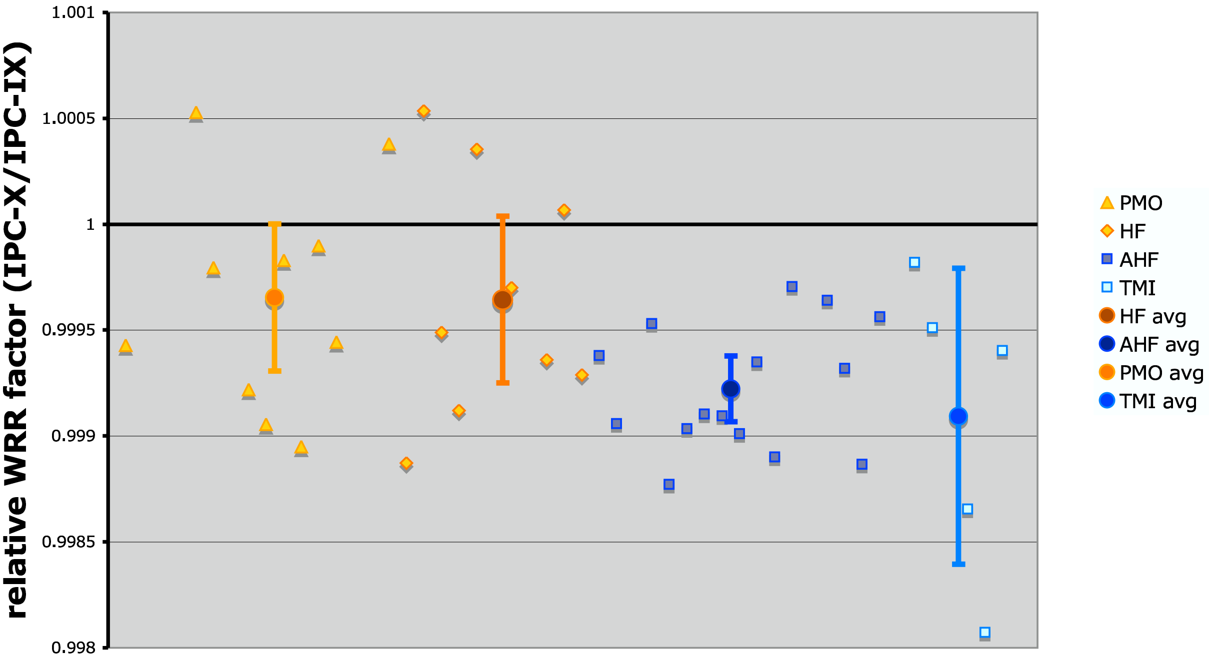


Figure 2.1: The relative WRR factors sorted by type of instrument. The filled circles are the respective averages with 2-σ error bars (95% confidence).

observed changes of WRR factors might not be of purely stochastical nature but depend on the type of instrument. The WRR factors of HF and PMO type instruments consistently changed by -346 ± 347 ppm and -356 ± 393 ppm, respectively. On the 95% confidece level these changes are just consistent with the assumption of the WSG being stable, while the WRR factors of AHF's changed by -778 ± 156 ppm and therefore are inconsistent with the stability assumption. Chances are low that the differences between HF's and PMO's on one side and AHF's on the other side occur randomly[5] The groups of TMI, CROM, MAR, and SIAR type pyrheliometers are too small to draw any meaningful statistical conclusion from these types of instrument (cf. Fig. 2.1).

No Ångström type pyrheliometer were included in the WSG stability analysis because only two of them changed by less than 0.2% since the previous IPC. The WRR factors for all Ångström pyrheliometers increased since IPC-IX, which can easily be explained by the different weather conditions prevailing during IPC-X and IPC-IX. In 2000 many data points were affected by clouds in the Ångström's field-of-view, resulting in an over-estimation of the solar irradiance due to scattered light. In 2005, there were much more clear sky periods than in 2000. Moreover, a cloud detector was used in 2005 to eliminated all data points where clouds were closer than 15 degrees of the Sun.

2.6 Conclusions and Recommendations

Despite the above mentioned difficulties with some instruments or groups of instruments (c.f. Sect. 2.5) the WRR is considered stable within the limits required by the WMO-CIMO guide. The reported drifts in the WRR factors of most AHF's over the past five years (Fig. 2.1) are based purely phenomenological observations at this point. There is no know reason that could cause these dirfts and all tests to attribute them to any instrument-specific procedures were negative. While the average drift of the AHF's is statistically significant it still depends on the selection criteria and also on the choice of the statistical samples, i.e. the way of pooling the instruments for the statistical analysis.

[5] On average HF's and AHF's differ by 427 ± 149 ppm (1-σ level). This means that there is only a 0.5% probability (2.8-σ) that the observed differences are random.

We therefore cannot conclude that any of the participating types of cavities is less fit than the others to represent the WRR. The recommended WRR factors are listed in Table 2.2.

The large amount of data collected during IPC-X allowed us to find subtle differences in the behaviour of the various types of instruments. The quest for explanations of the observed differences is still an on-going process to which we invite the whole communitiy to contribute.

Chapter 3 Graphical Representation of the Results

3.1 WSG and Participating Instruments

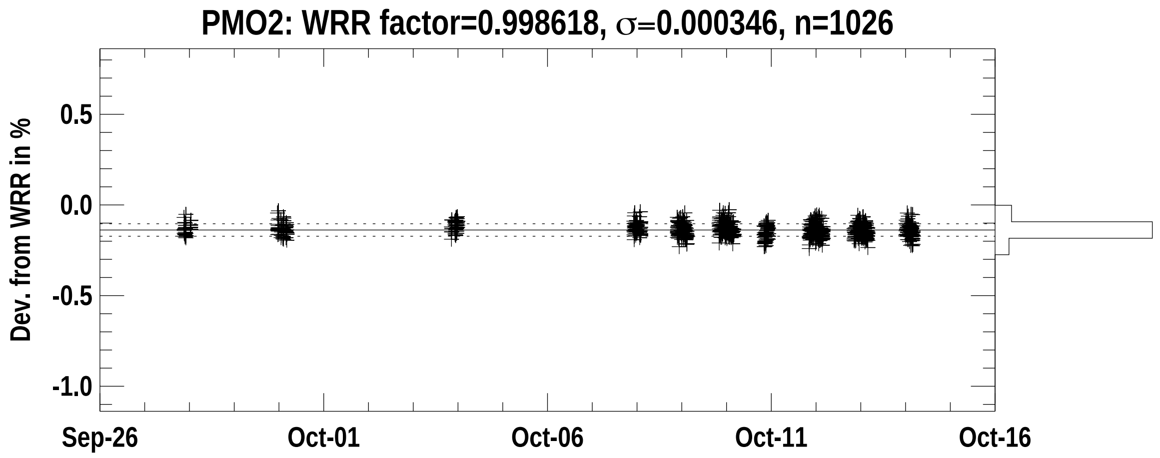
The following figures show the performances of the instruments. The deviation from WRR is plotted. All the points which were used for the analysis (i.e. the points fulfilling the selection criteria listed in Sect. 2.1) have been plotted with a corresponding histogram on the side. The horizontal solid line represents the derived new WRR factor and the dashed lines its 1-σ standard deviation. The new WRR factor and its standard deviation is printed on top of each plot with the number of points used to determine this value. The number in parentheses corresponds to the total number of points available for the analysis.

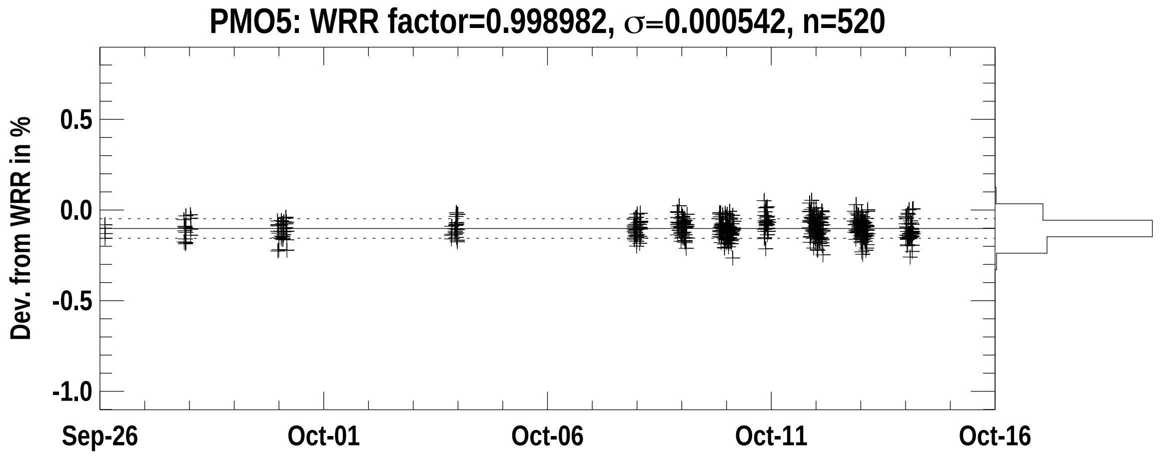
Note: Two participating Ångström type instruments exhibited serious problems. Å8412 (Morocco) was operated in an "actinometric"-type mode, i.e. with no heating power applied to the shaded strip. The reading of the thermocouple was submitted instead of the heater current. These data were analyzed using the standard procedure for NIP's without zero reading. The uncertainty of the resulting WRR factor therefore is quite high and we do not recommend to use this instrument as a calibration standard.

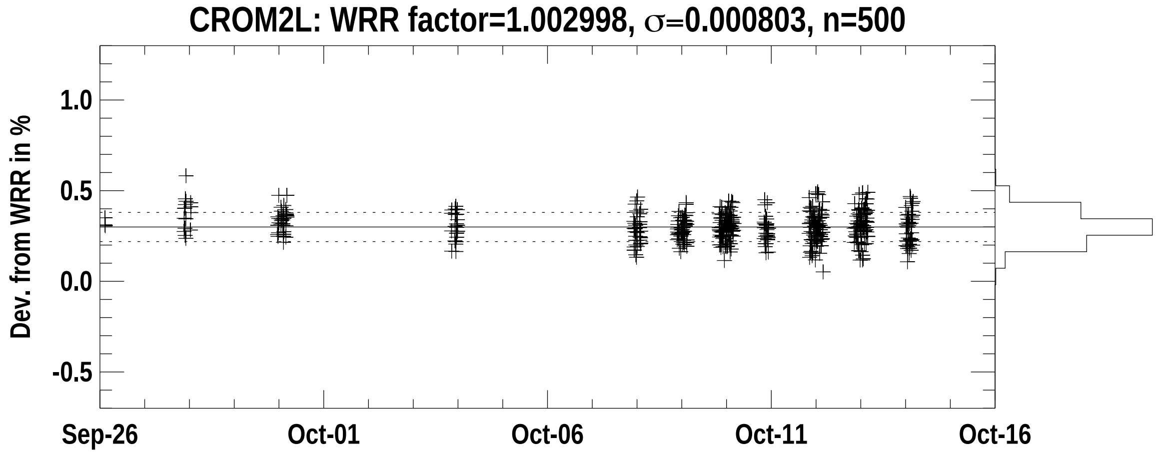
Å6549 (Uganda) submitted an almost constant reading corresponding to $\sim 830Wm^{-2}$. The same happened already during IPC-IX and was then attributed to an faulty operation of the instrument. However, since the instrument was now operated by a different person but still having the same problem it is unlikely that this was the cause. The instrument most likely is broken. Unfortunately, the daily summary data for this instrument did not look too suspicious so the problem went unnoticed. Data from this instrument could not be evaluated and no WRR factor could be calculated.

Several other instruments were affected by technical problems which could be fixed by the technical staff at PMOD/WRC.

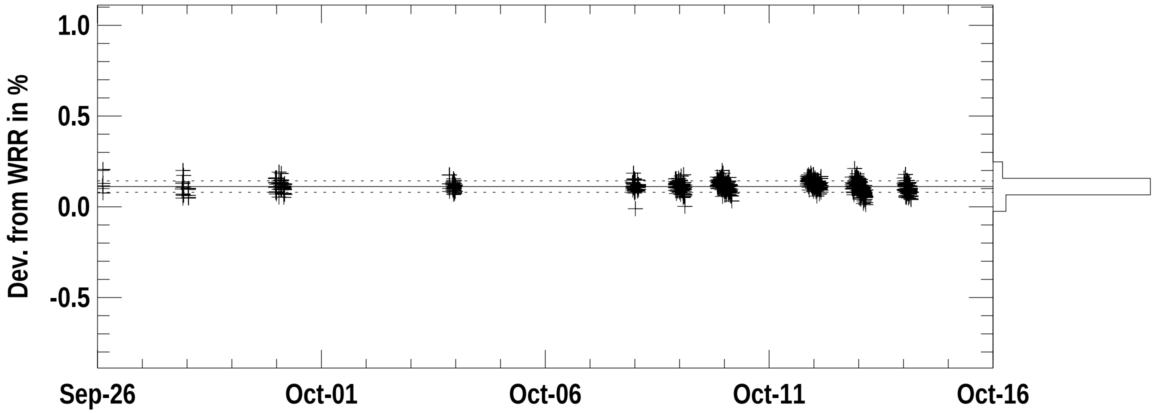
3.1.1 WSG Instruments



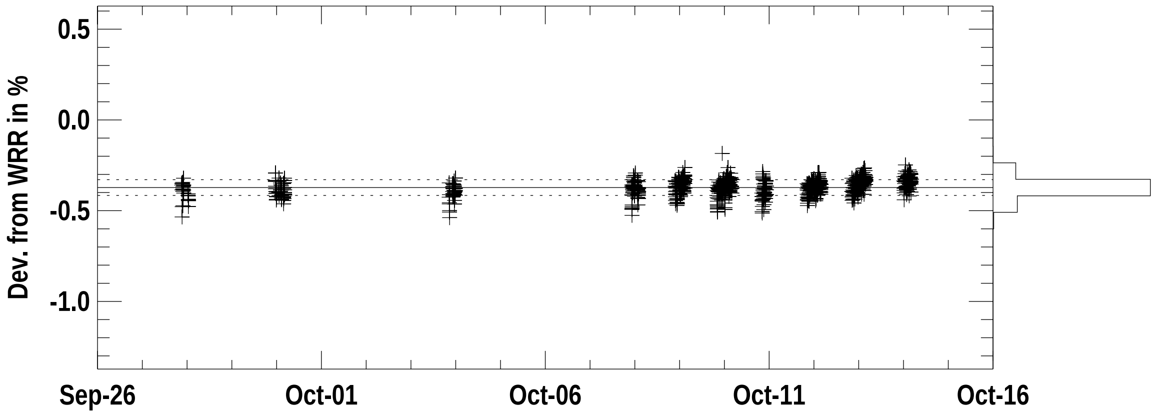




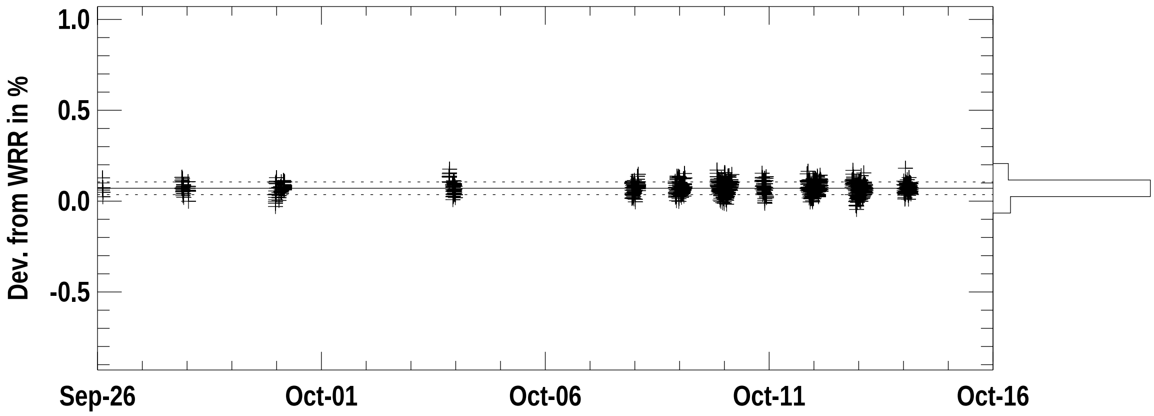
PAC3: WRR factor=1.001116, σ=0.000313, n=641



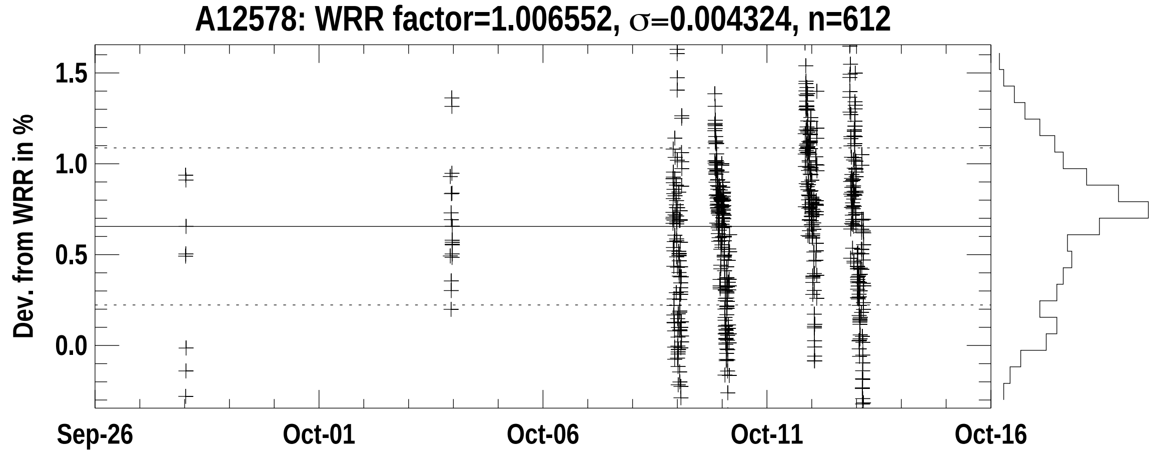
HF18748: WRR factor=0.996274, σ=0.000433, n=938

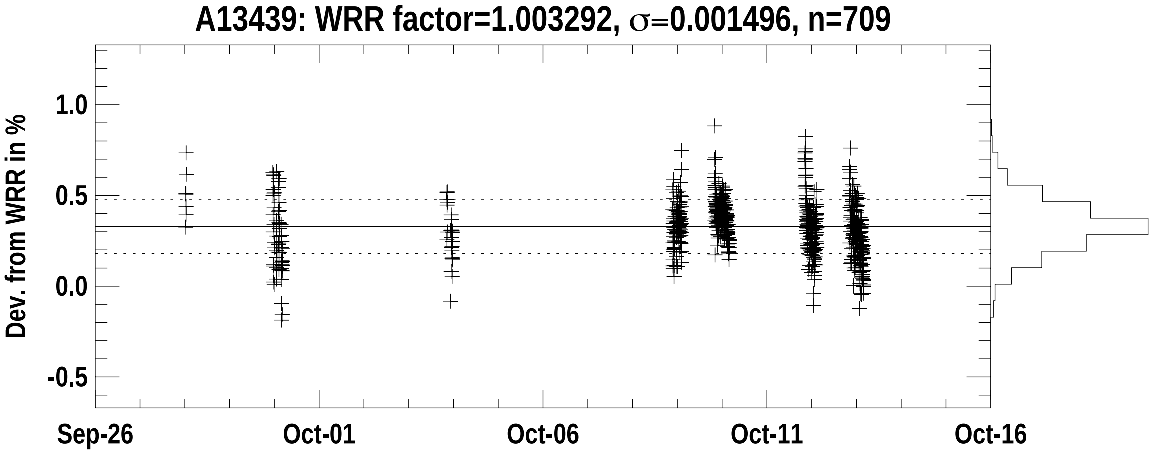


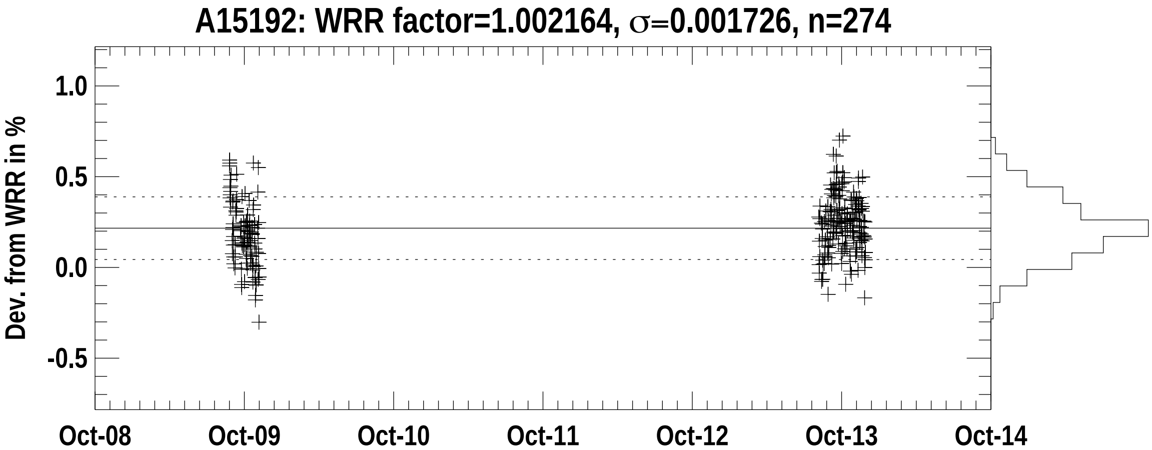
MK67814: WRR factor=1.000708, σ=0.000347, n=945

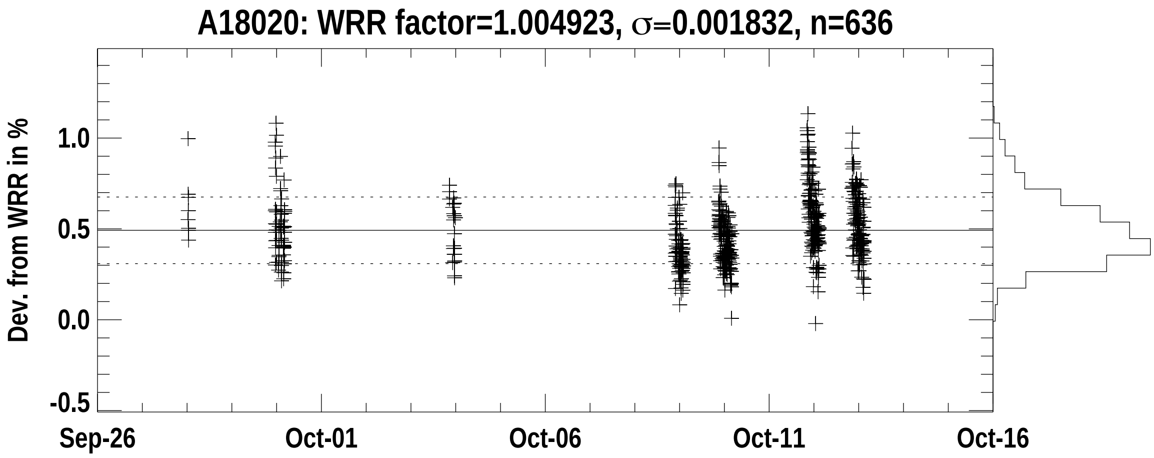


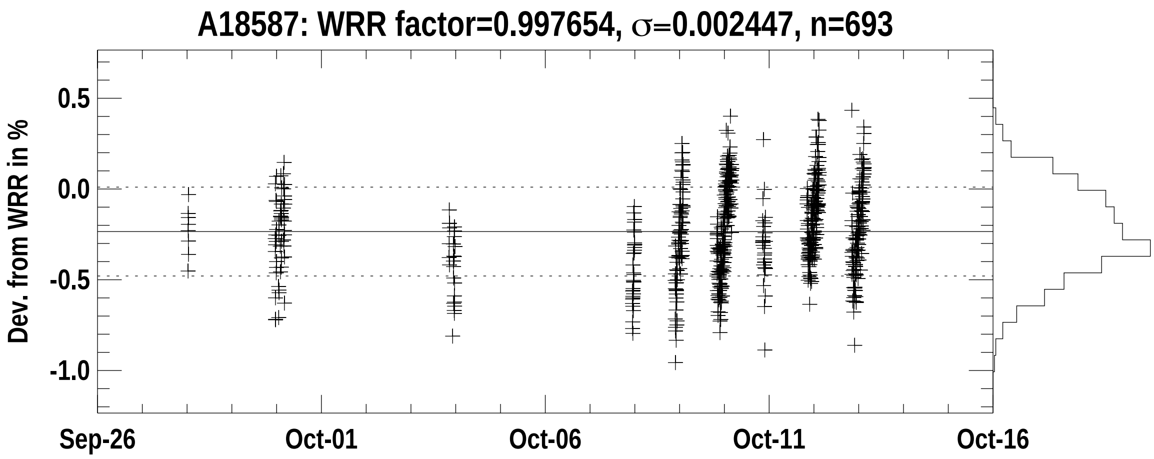
3.1.2 Participating Instruments

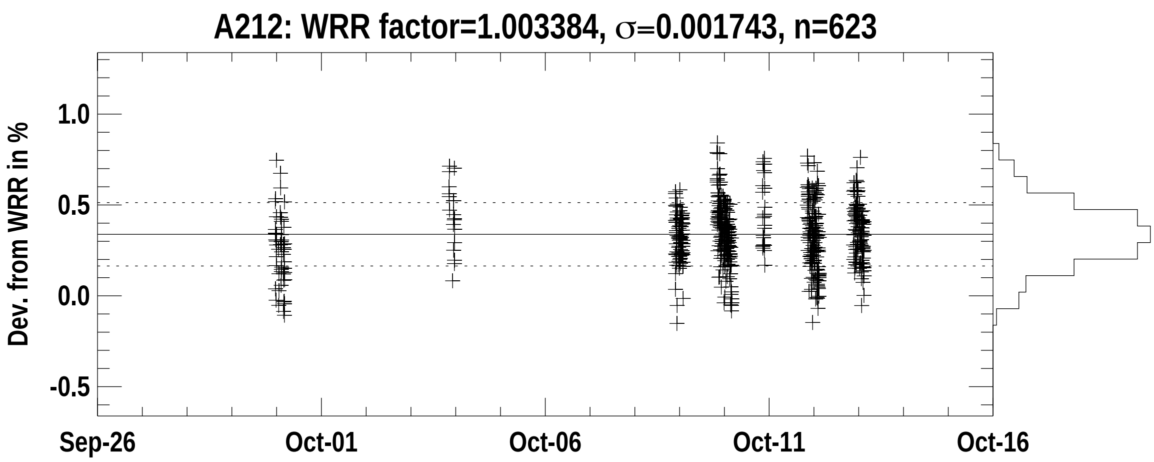


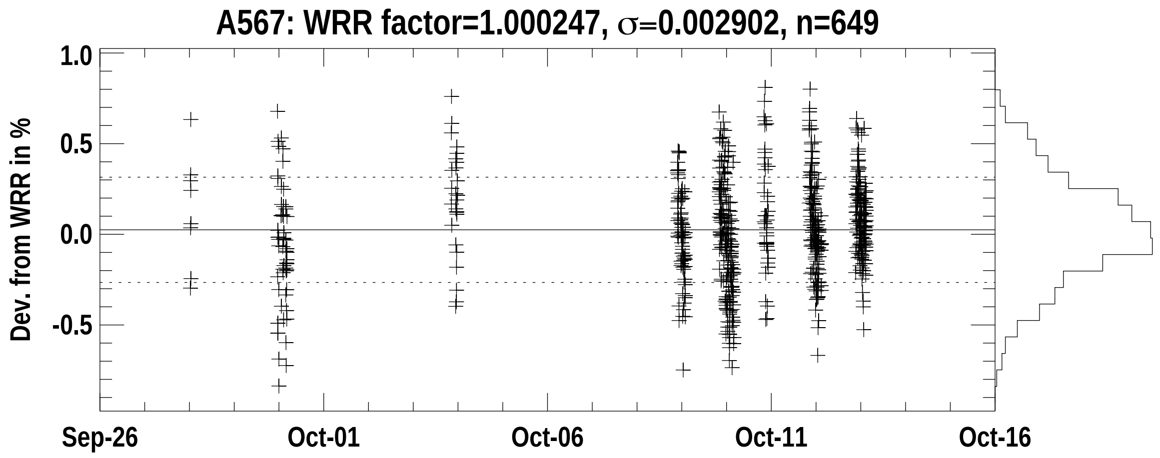


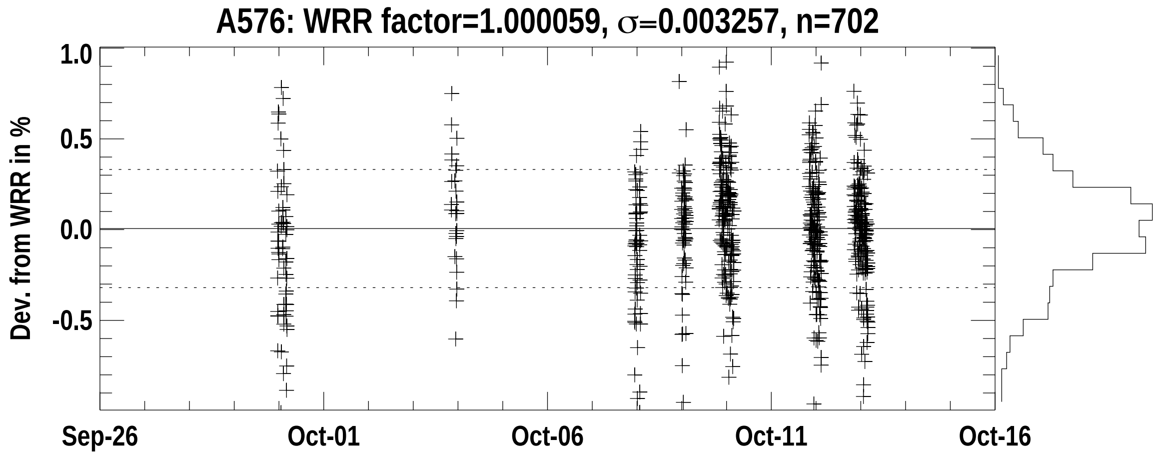


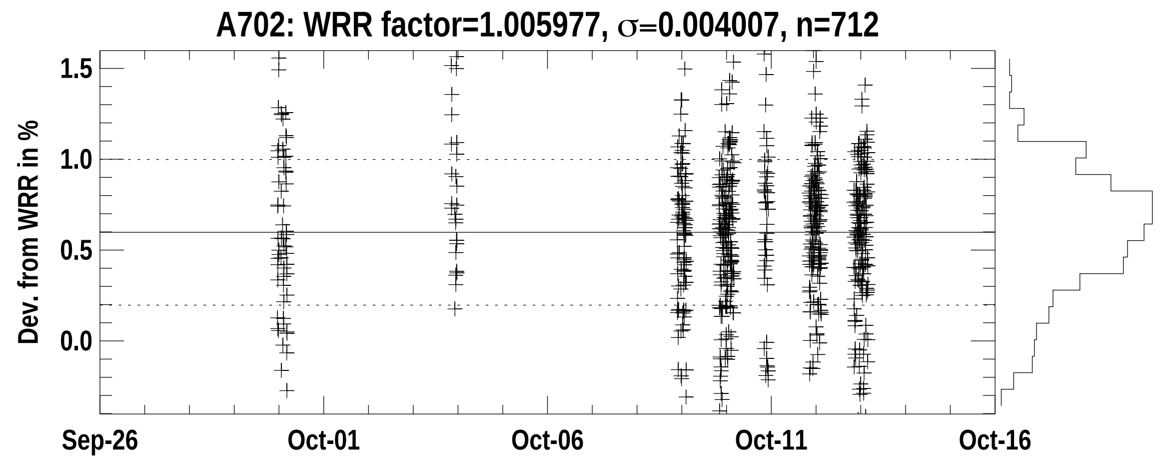

A18020: WRR factor=1.004923, σ=0.001832, n=636
Dev. from WRR in %
1.0
0.5
0.0
-0.5
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

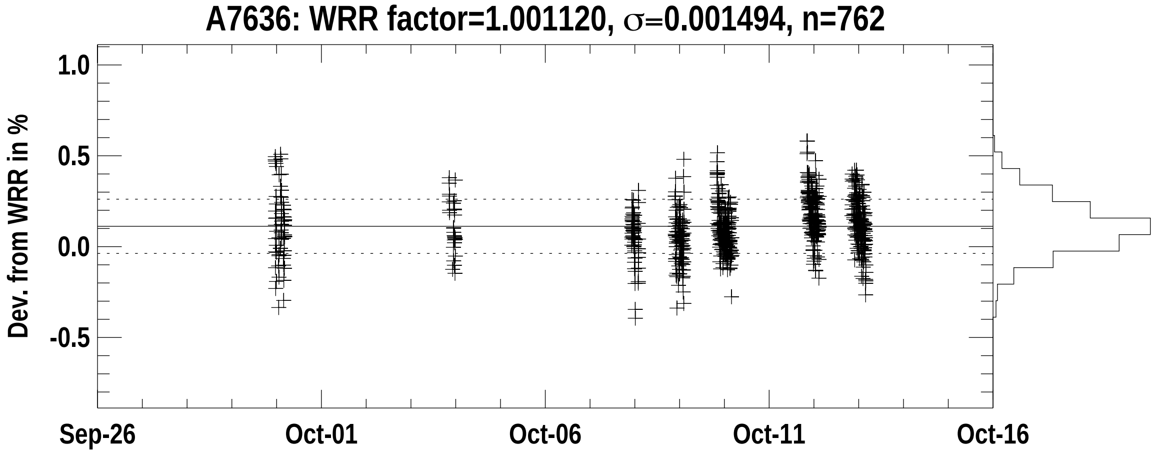

A18587: WRR factor=0.997654, σ=0.002447, n=693
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

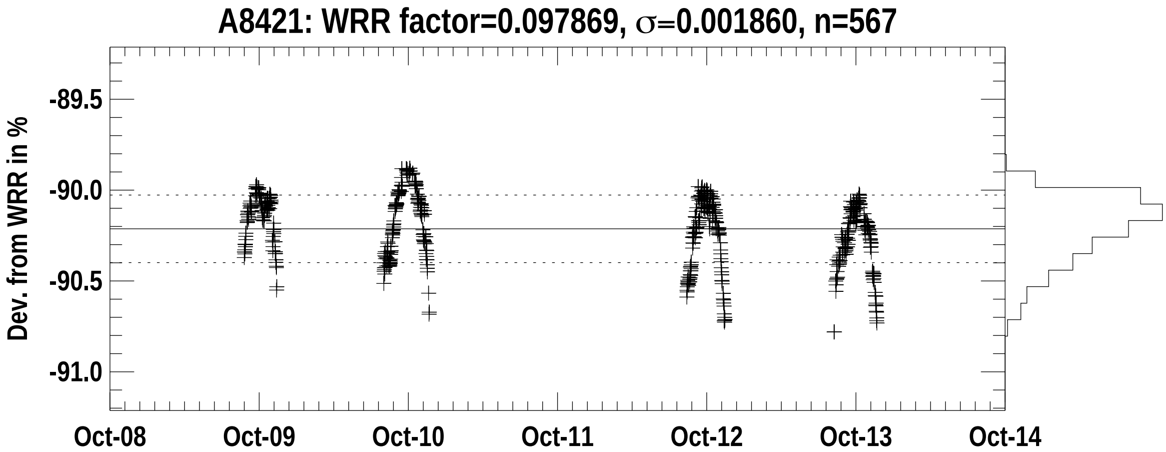

A212: WRR factor=1.003384, σ=0.001743, n=623
Dev. from WRR in %
1.0
0.5
0.0
-0.5
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

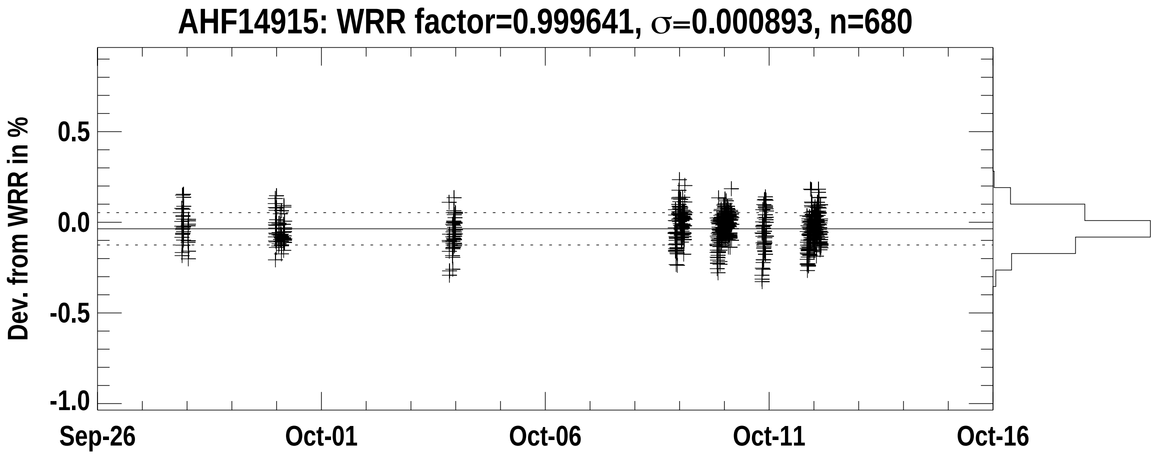

A567: WRR factor=1.000247, σ=0.002902, n=649
Dev. from WRR in %
1.0
0.5
0.0
-0.5
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16


A576: WRR factor=1.000059, σ=0.003257, n=702
Dev. from WRR in %
1.0
0.5
0.0
-0.5
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

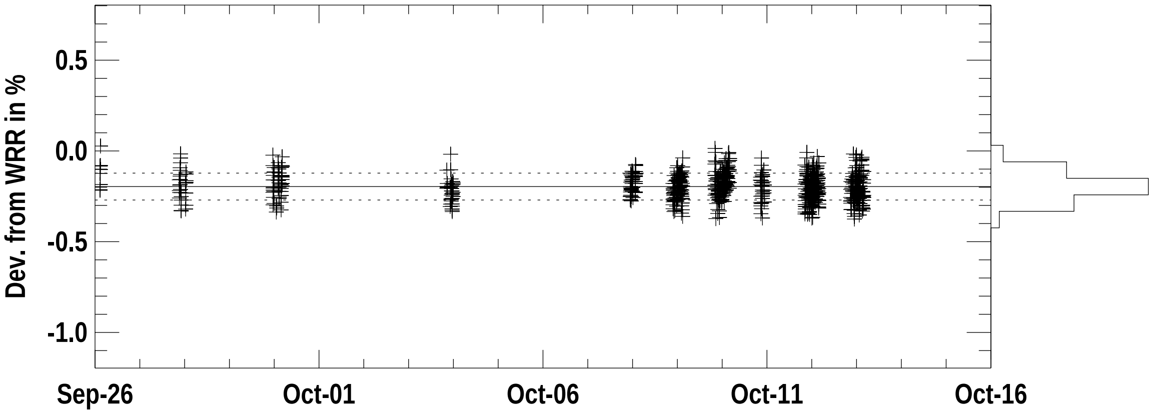

A702: WRR factor=1.005977, σ=0.004007, n=712
Dev. from WRR in %
1.5
1.0
0.5
0.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16


A7636: WRR factor=1.001120, σ=0.001494, n=762
Dev. from WRR in %
1.0
0.5
0.0
-0.5
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

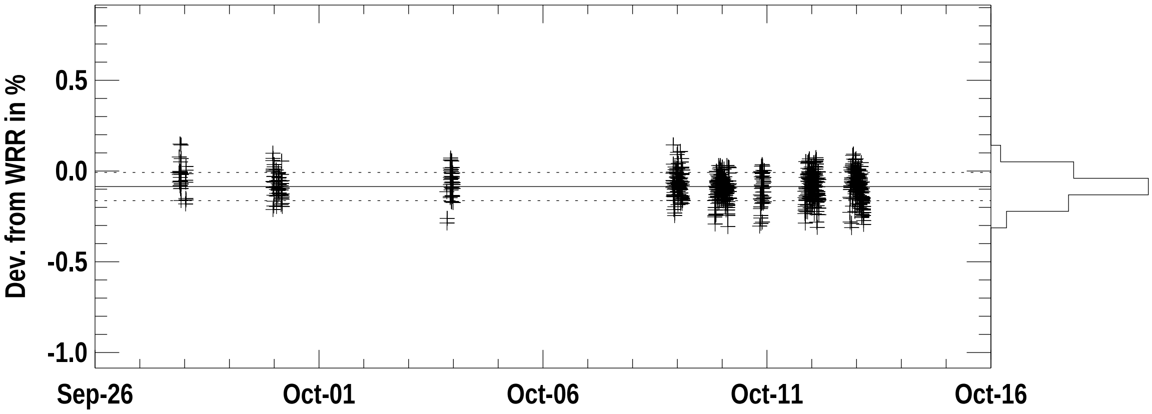

A8421: WRR factor=0.097869, σ=0.001860, n=567
Dev. from WRR in %
-89.5
-90.0
-90.5
-91.0
Oct-08
Oct-09
Oct-10
Oct-11
Oct-12
Oct-13
Oct-14


AHF14915: WRR factor=0.999641, σ=0.000893, n=680
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

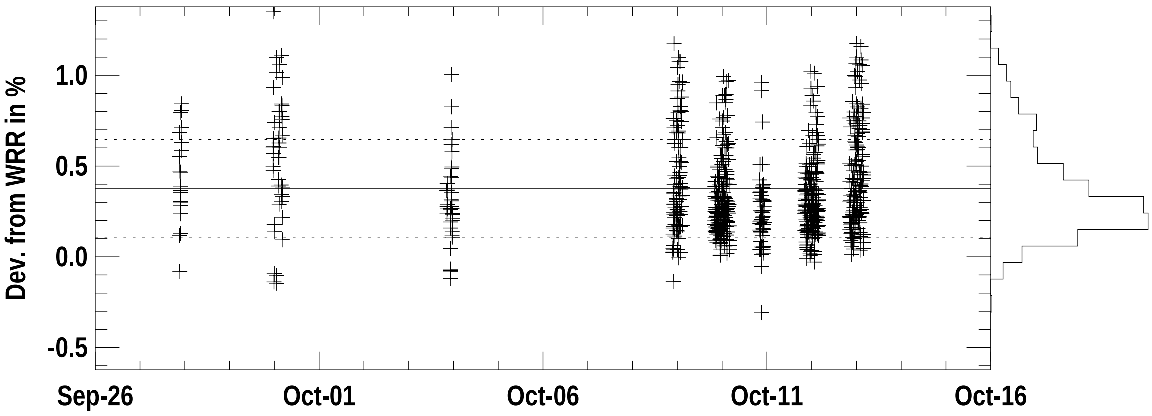
HF15744: WRR factor=0.998038, σ=0.000739, n=770



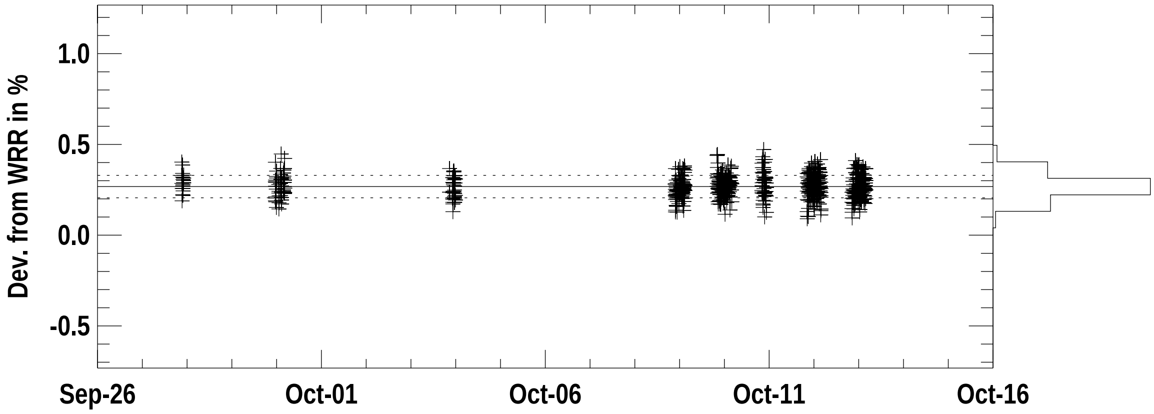
AHF17142: WRR factor=0.999146, σ=0.000778, n=813



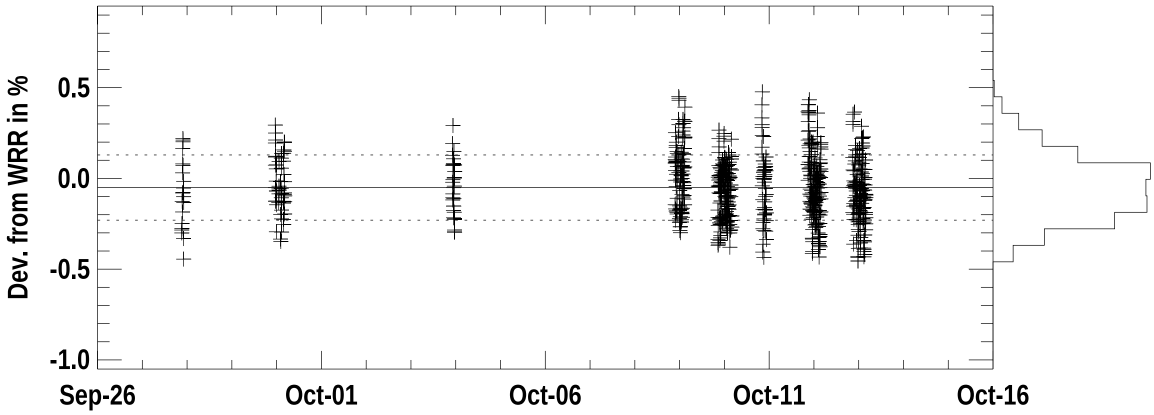
AHF18742: WRR factor=1.003773, σ=0.002690, n=735



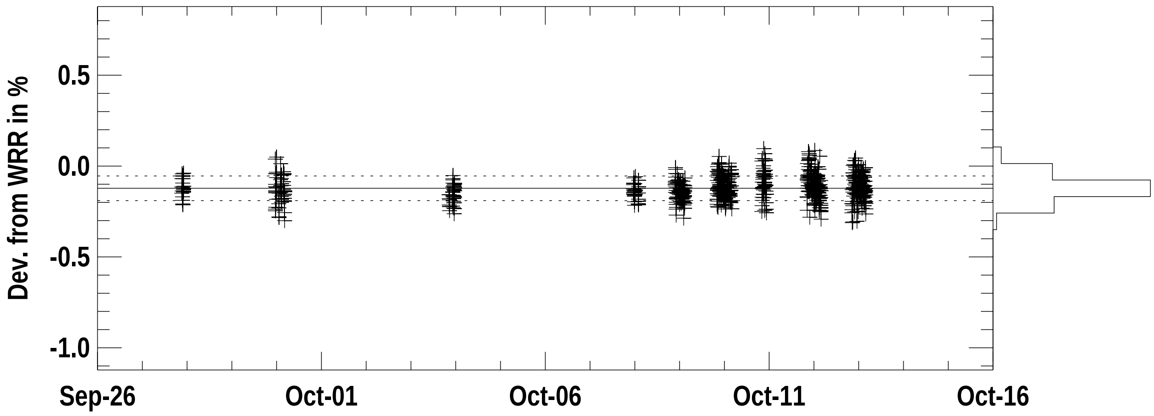
HF18747: WRR factor=1.002680, σ=0.000620, n=763

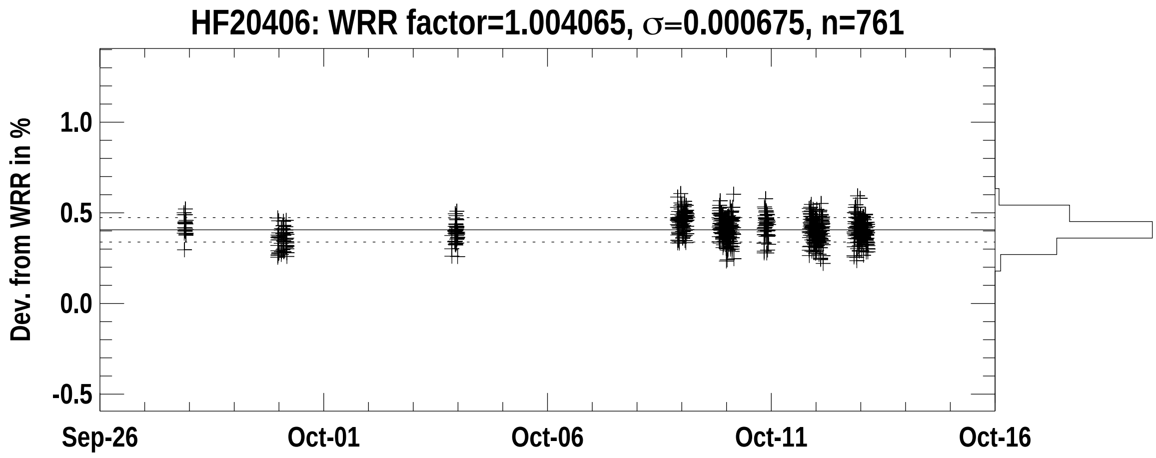


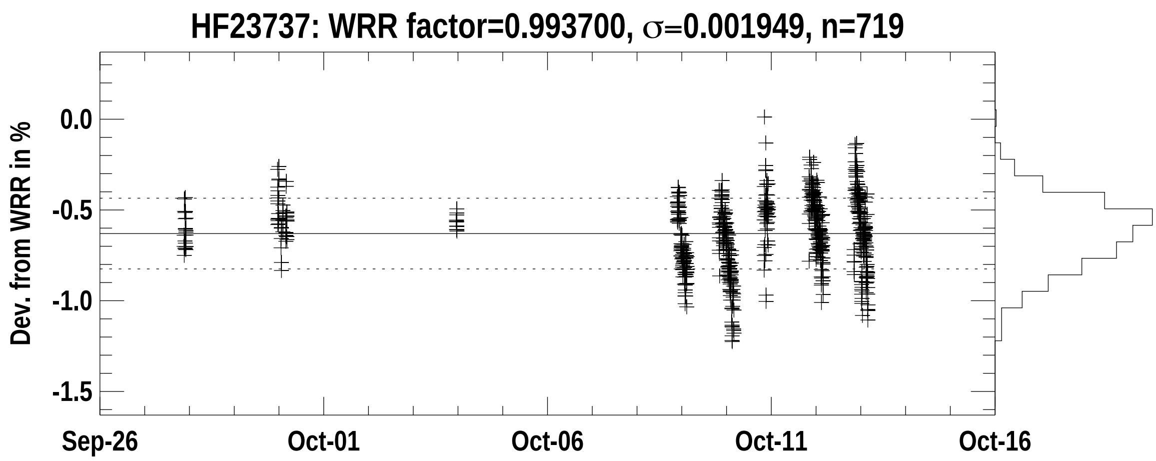
HF19743: WRR factor=0.999495, σ=0.001795, n=741

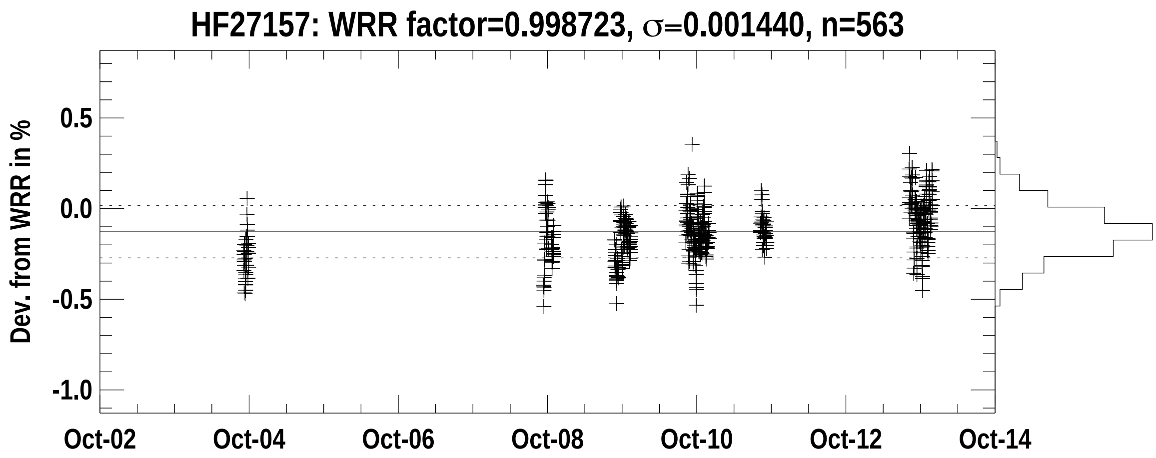


HF19746: WRR factor=0.998778, σ=0.000676, n=810

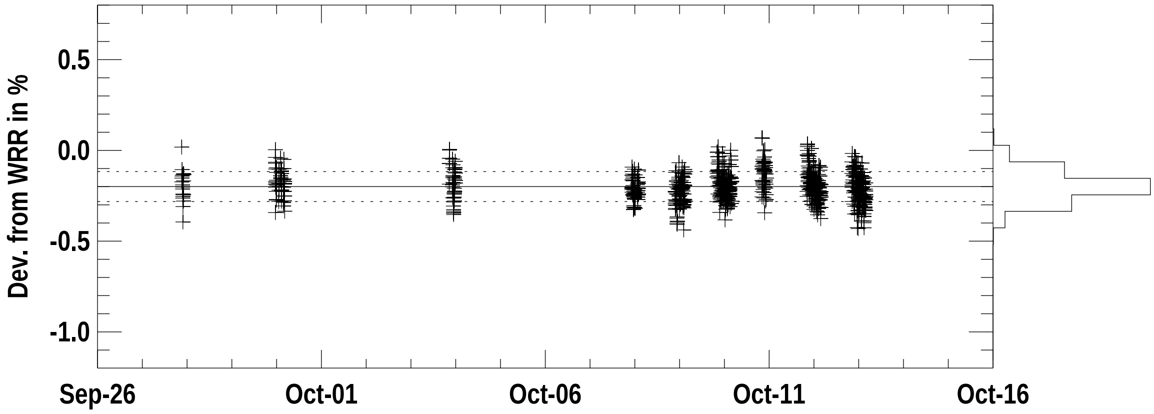



HF20406: WRR factor=1.004065, σ=0.000675, n=761
Dev. from WRR in %
1.0
0.5
0.0
-0.5
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

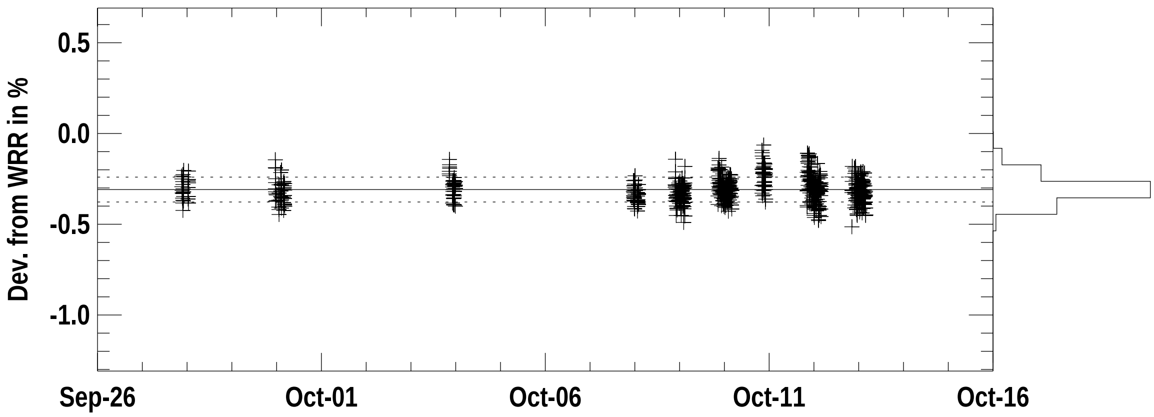

HF23737: WRR factor=0.993700, σ=0.001949, n=719
Dev. from WRR in %
0.0
-0.5
-1.0
-1.5
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16


HF27157: WRR factor=0.998723, σ=0.001440, n=563
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Oct-02
Oct-04
Oct-06
Oct-08
Oct-10
Oct-12
Oct-14

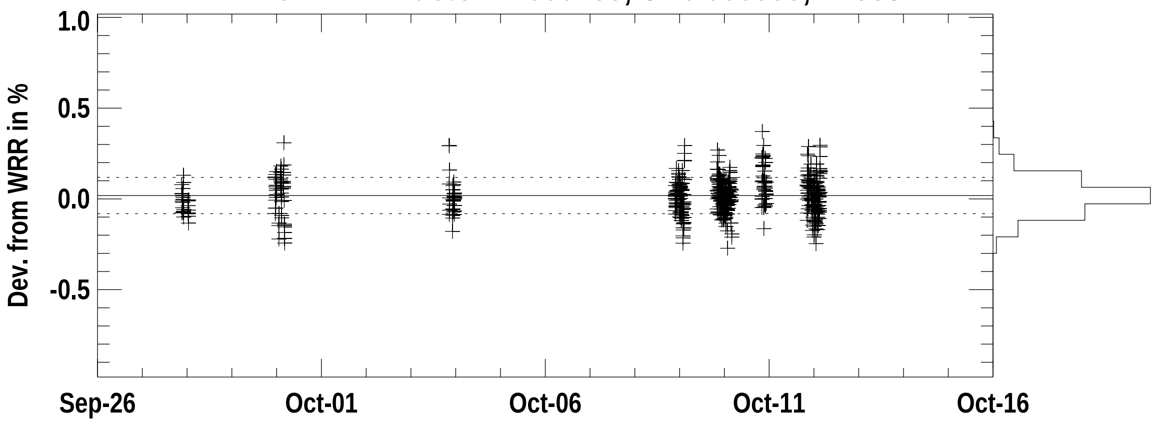
HF27159: WRR factor=0.998007, σ=0.000826, n=844

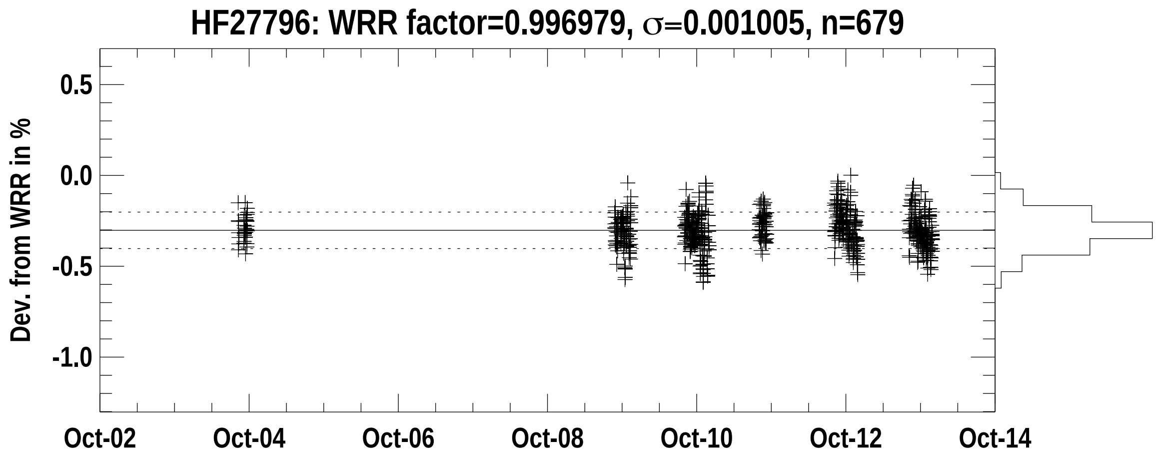


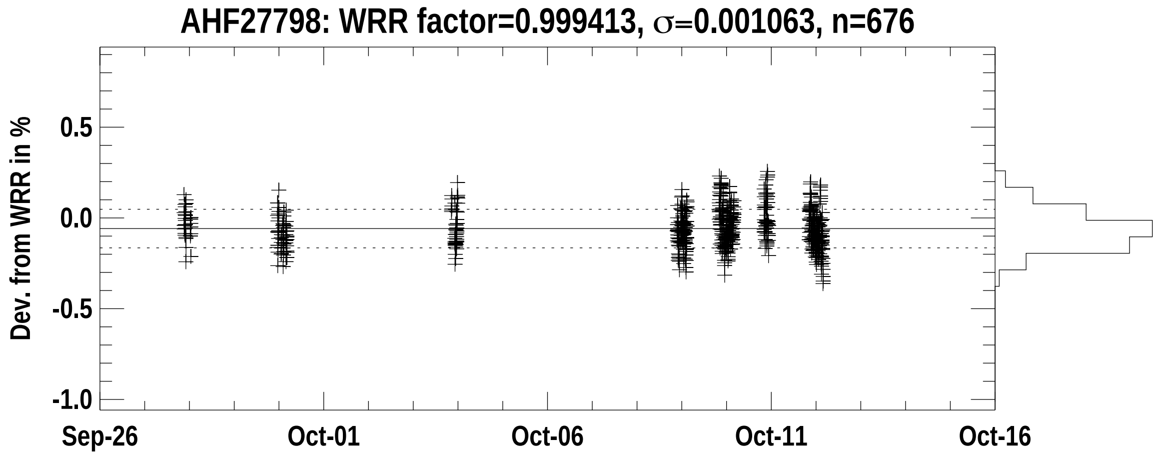
AHF27160: WRR factor=0.996911, σ=0.000684, n=785

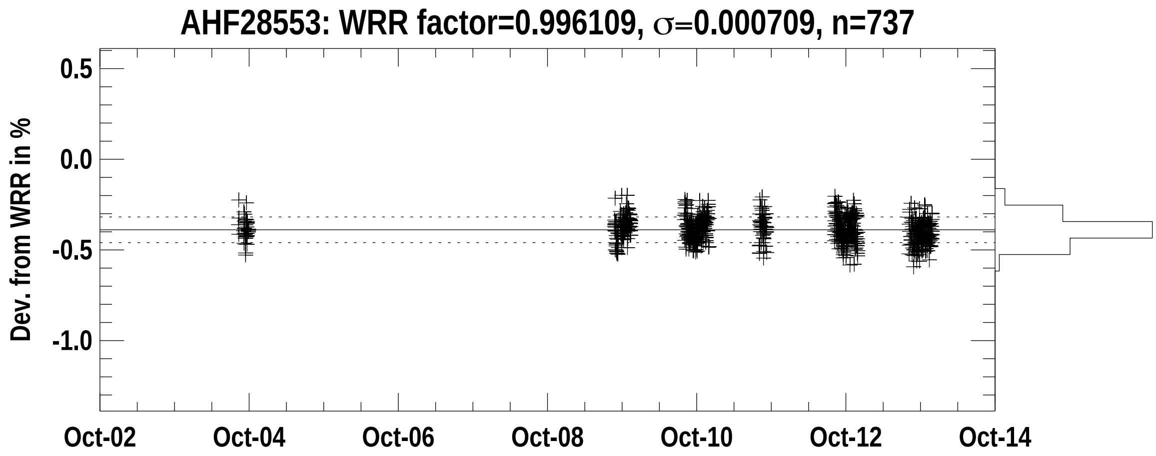


HF27162: WRR factor=1.000185, σ=0.000999, n=583

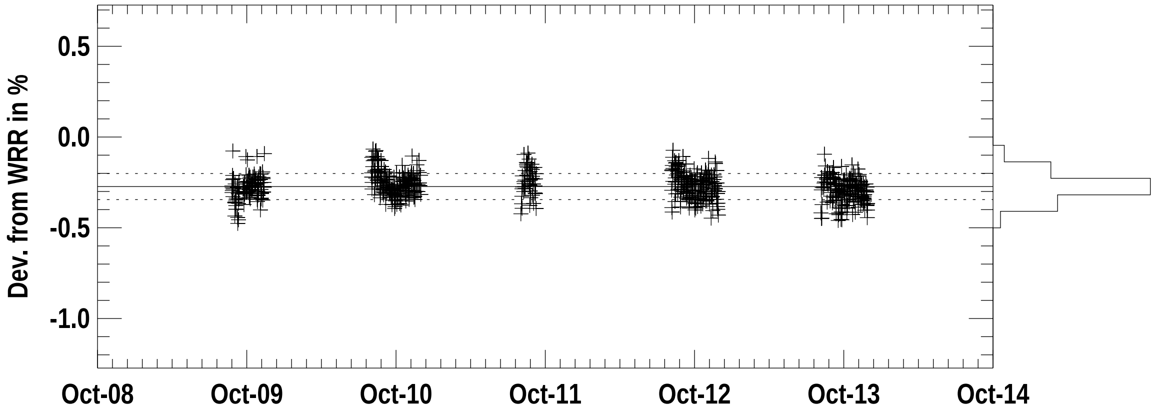



HF27796: WRR factor=0.996979, σ=0.001005, n=679
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Oct-02
Oct-04
Oct-06
Oct-08
Oct-10
Oct-12
Oct-14

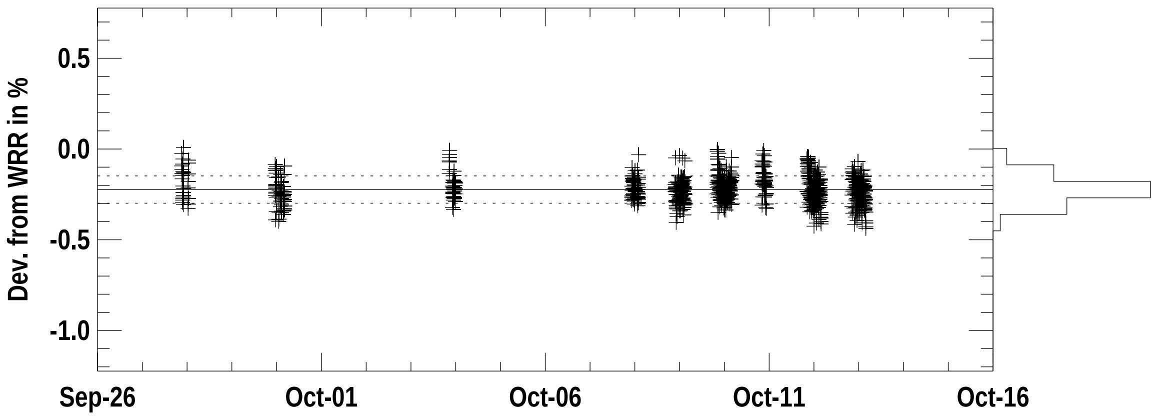

AHF27798: WRR factor=0.999413, σ=0.001063, n=676
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16


AHF28553: WRR factor=0.996109, σ=0.000709, n=737
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Oct-02
Oct-04
Oct-06
Oct-08
Oct-10
Oct-12
Oct-14

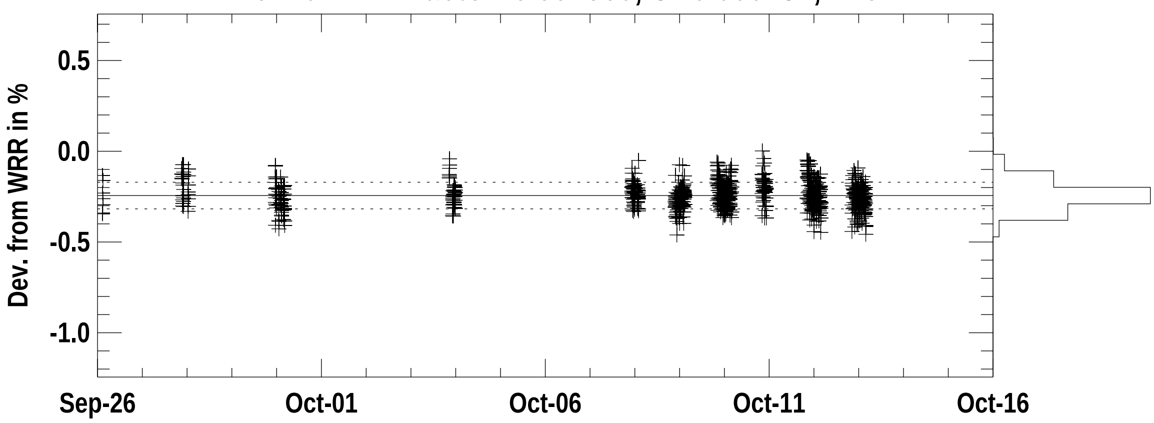
AHF28965: WRR factor=0.997271, σ=0.000719, n=717



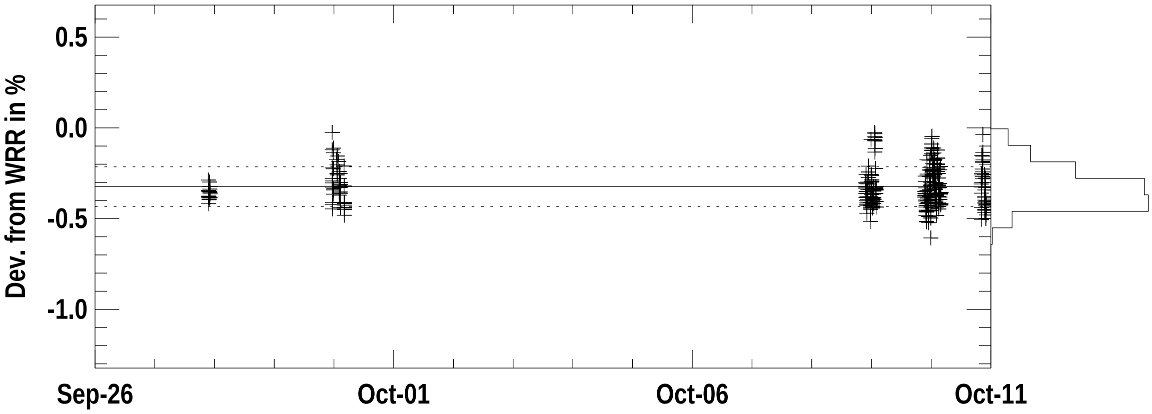
AHF28968: WRR factor=0.997766, σ=0.000750, n=911



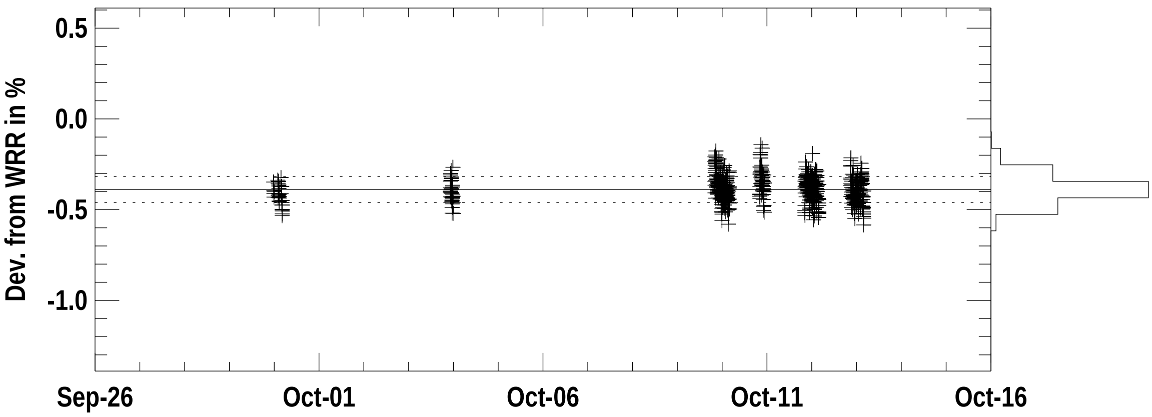
AHF29220: WRR factor=0.997560, σ=0.000734, n=922



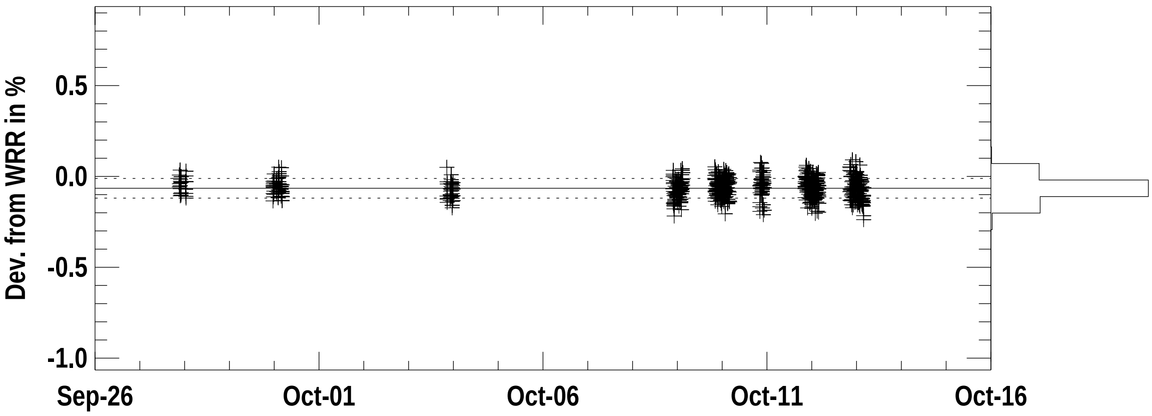
HF29223: WRR factor=0.996765, σ=0.001087, n=359

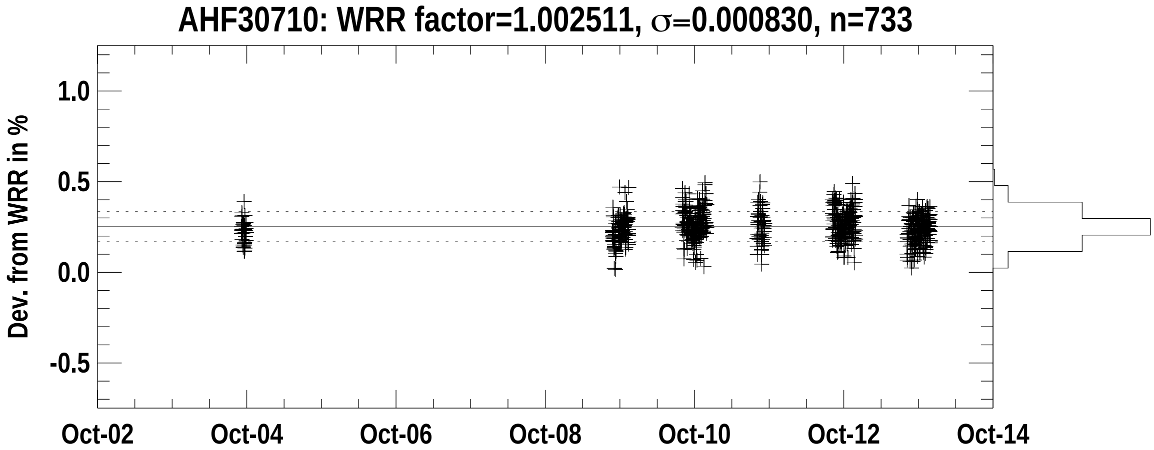


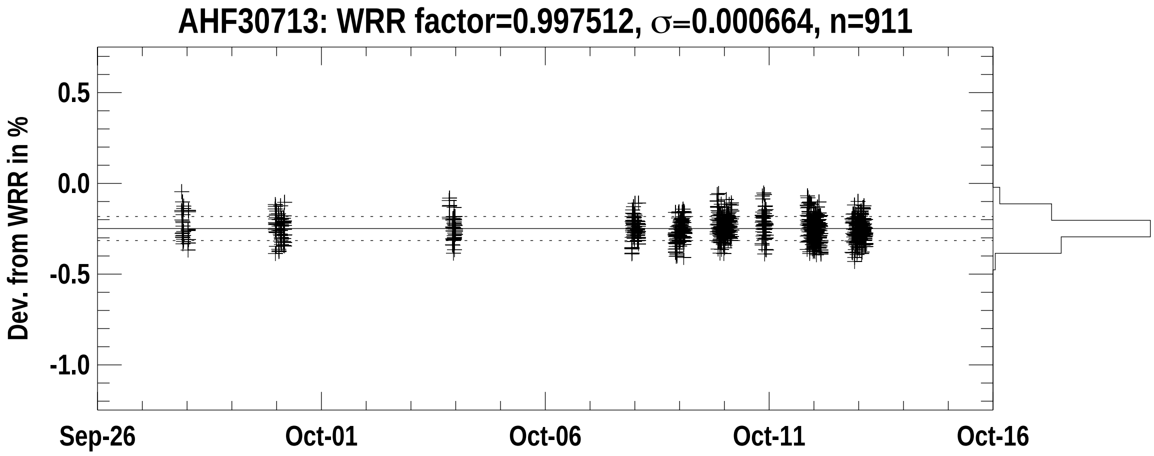
AHF29225: WRR factor=0.996107, σ=0.000718, n=653

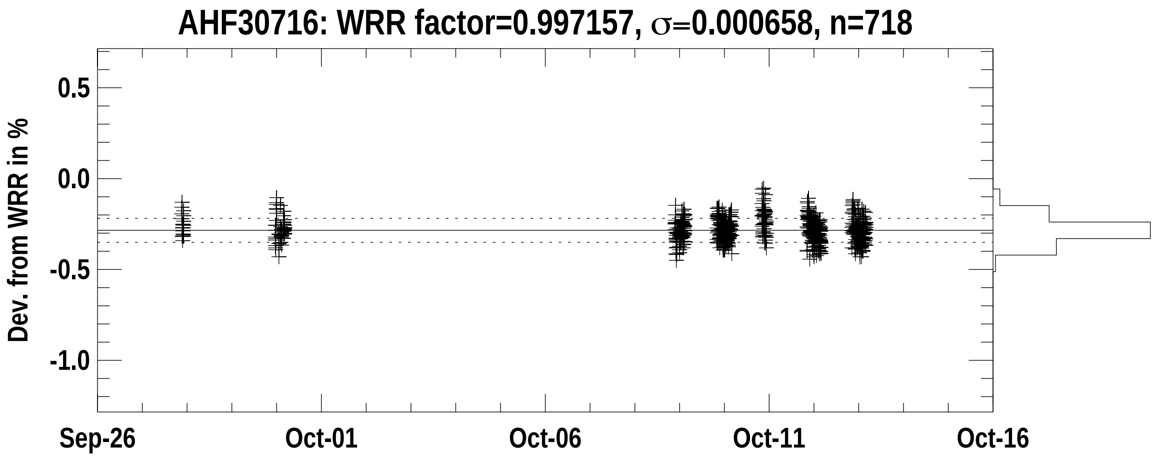


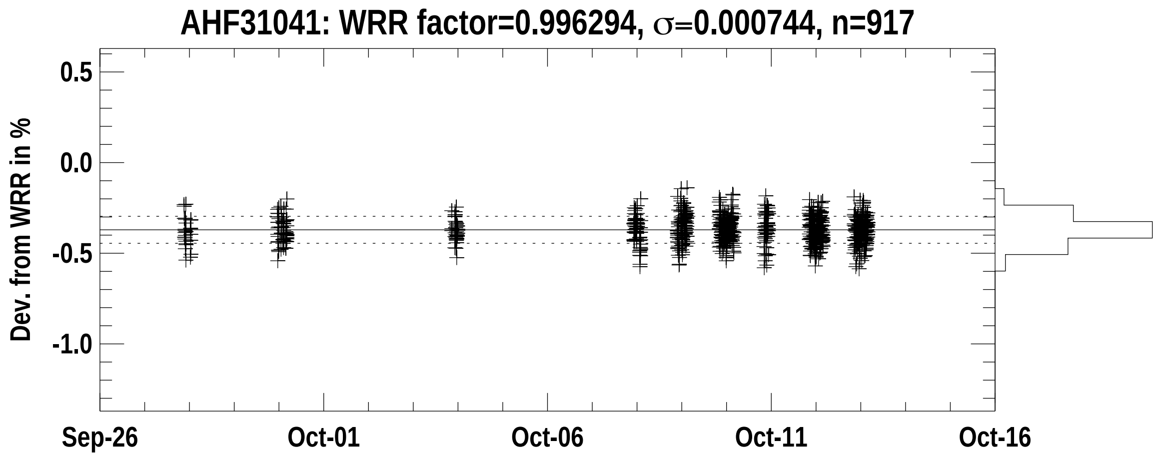
AHF30497: WRR factor=0.999346, σ=0.000540, n=788

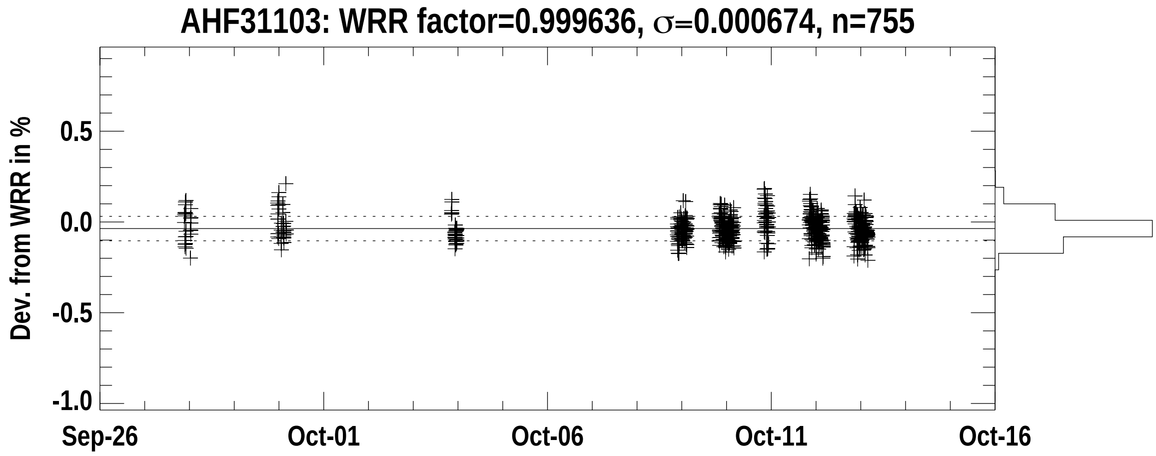


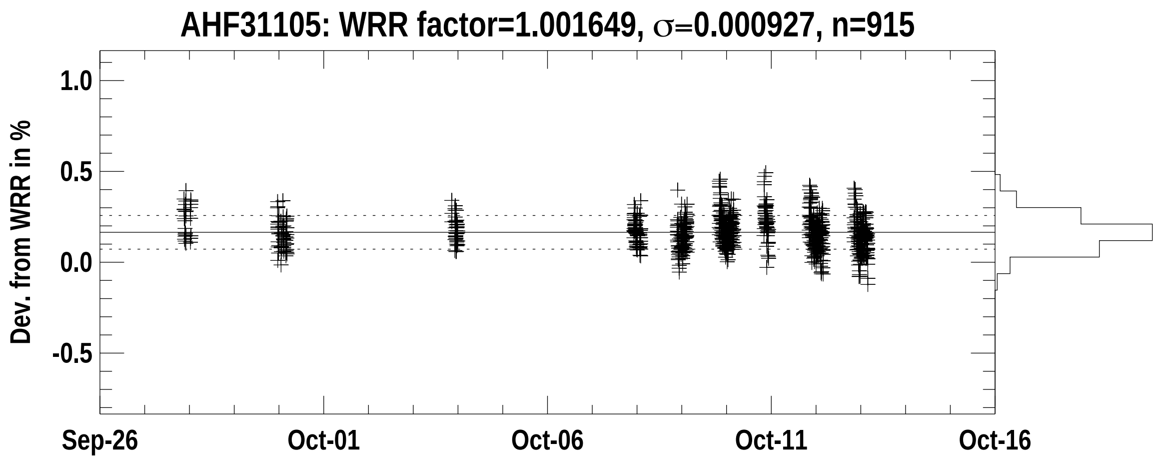

AHF30710: WRR factor=1.002511, σ=0.000830, n=733
Dev. from WRR in %
1.0
0.5
0.0
-0.5
Oct-02
Oct-04
Oct-06
Oct-08
Oct-10
Oct-12
Oct-14

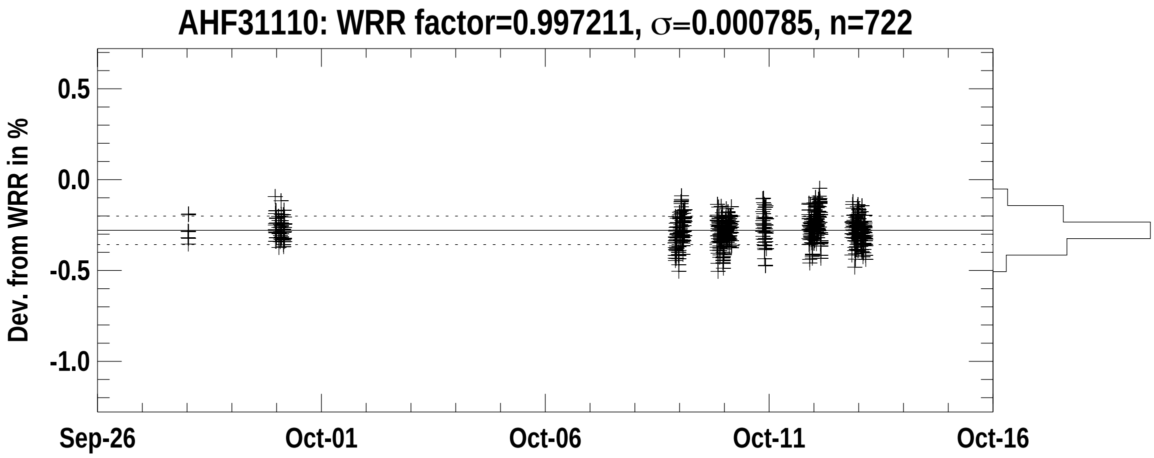

AHF30713: WRR factor=0.997512, σ=0.000664, n=911
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

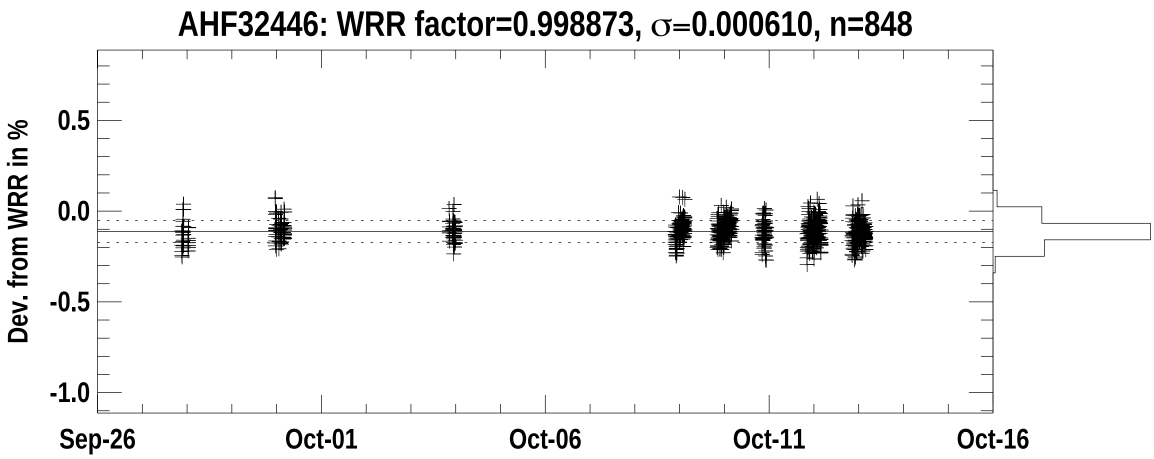

AHF30716: WRR factor=0.997157, σ=0.000658, n=718
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

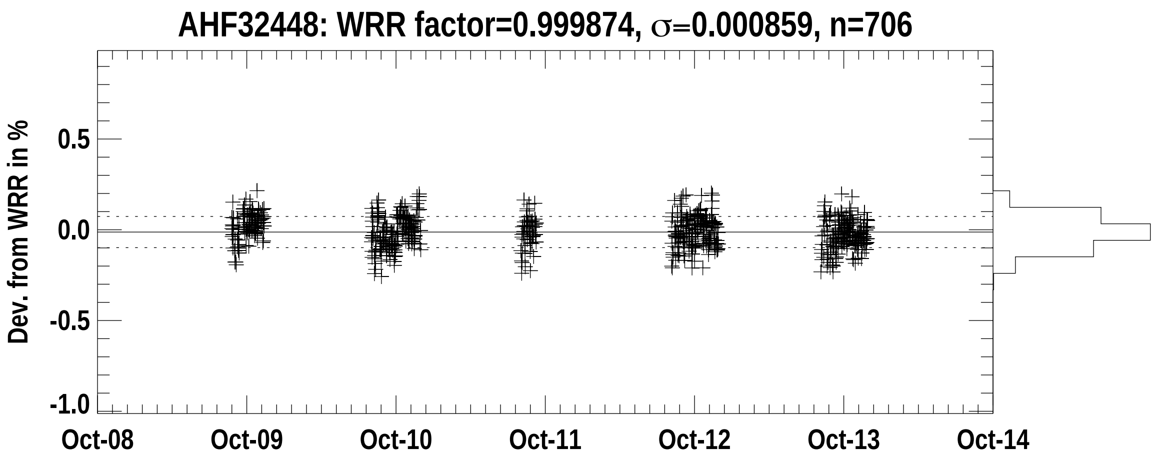

AHF31041: WRR factor=0.996294, σ=0.000744, n=917
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

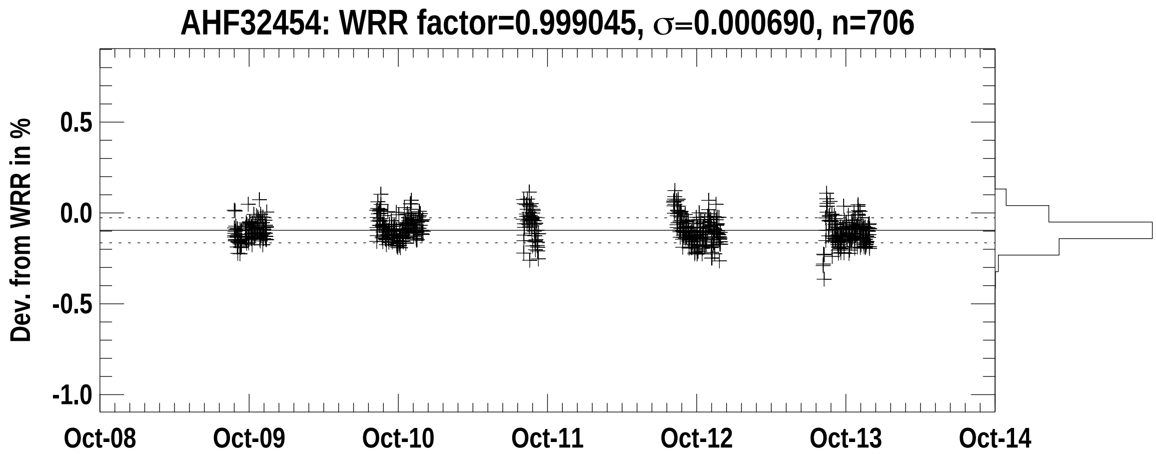

AHF31103: WRR factor=0.999636, σ=0.000674, n=755
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

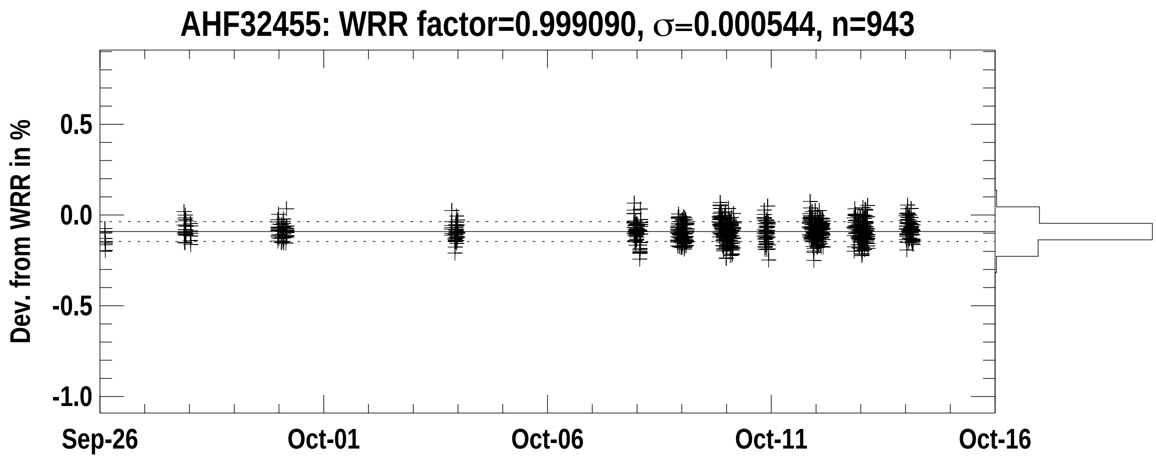

AHF31105: WRR factor=1.001649, σ=0.000927, n=915
Dev. from WRR in %
1.0
0.5
0.0
-0.5
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

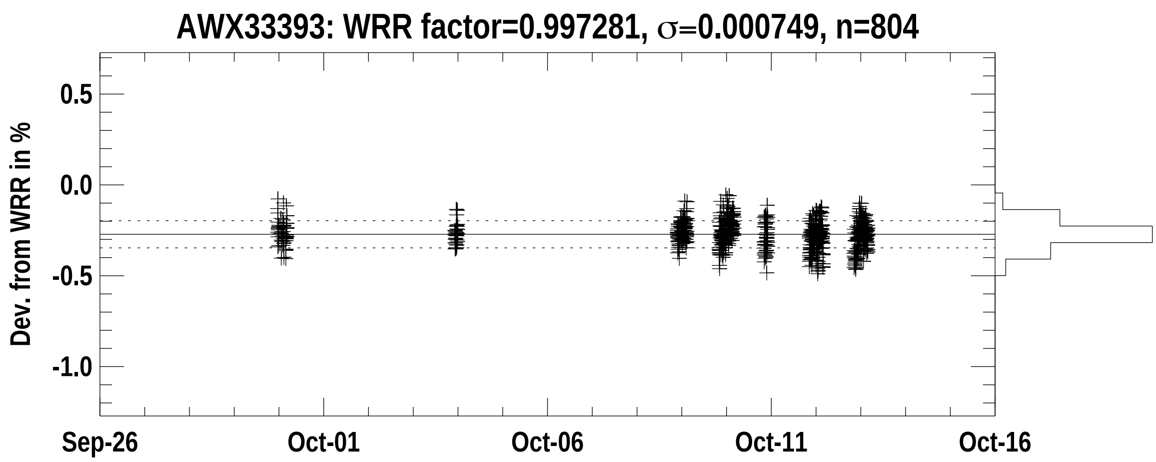

AHF31110: WRR factor=0.997211, σ=0.000785, n=722
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

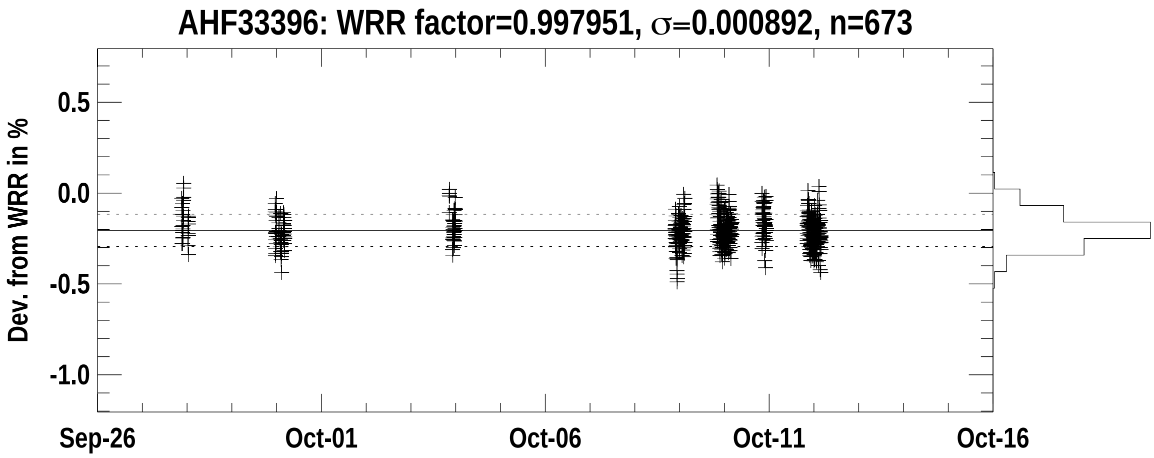

AHF32446: WRR factor=0.998873, σ=0.000610, n=848
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

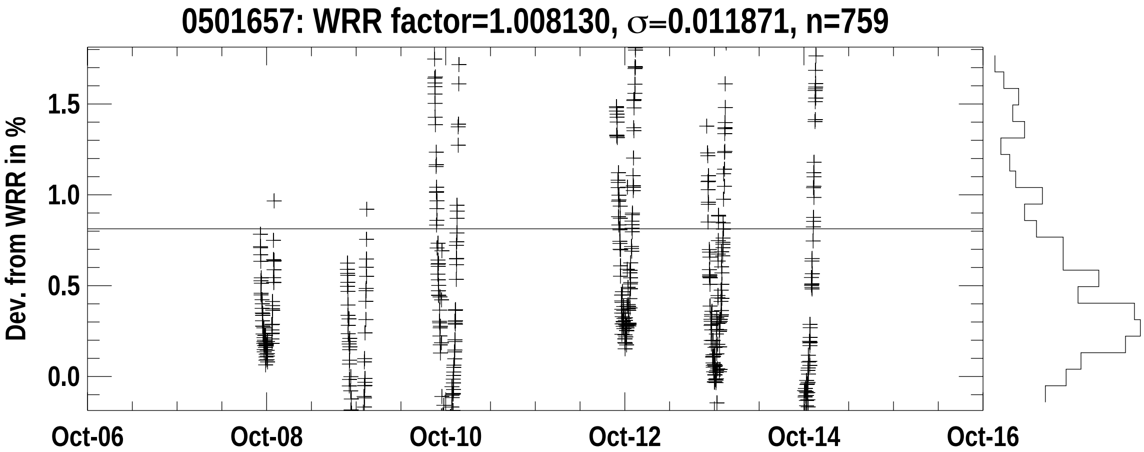

AHF32448: WRR factor=0.999874, σ=0.000859, n=706
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Oct-08
Oct-09
Oct-10
Oct-11
Oct-12
Oct-13
Oct-14

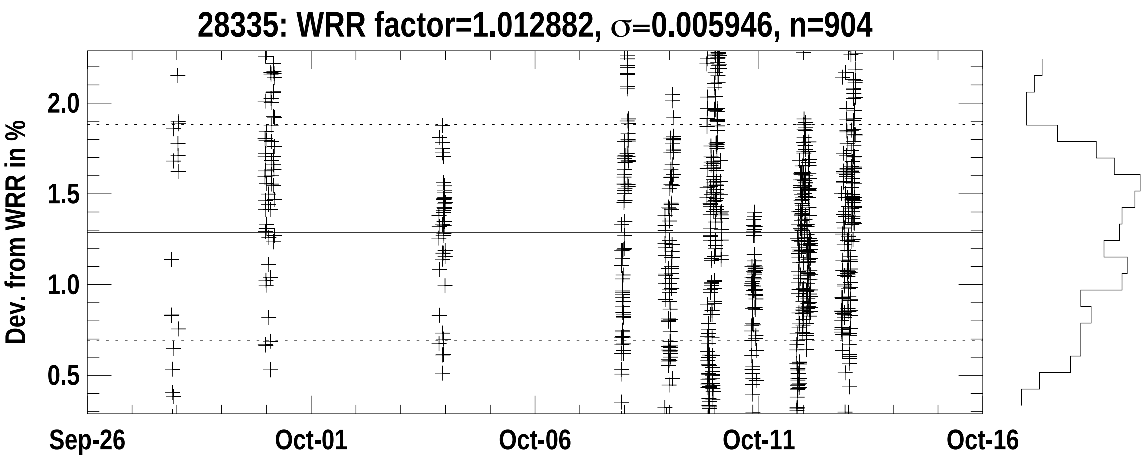

AHF32454: WRR factor=0.999045, σ=0.000690, n=706
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Oct-08
Oct-09
Oct-10
Oct-11
Oct-12
Oct-13
Oct-14

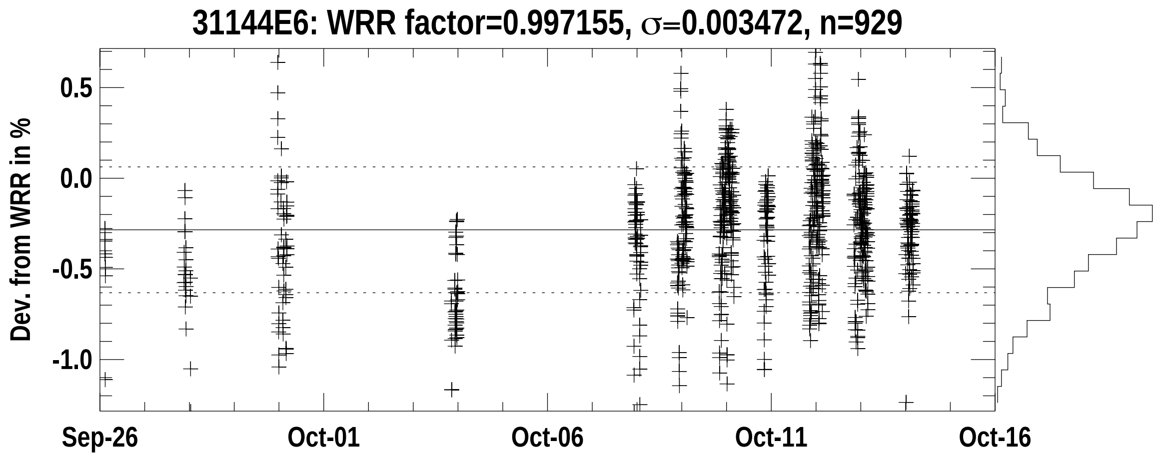

AHF32455: WRR factor=0.999090, σ=0.000544, n=943
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

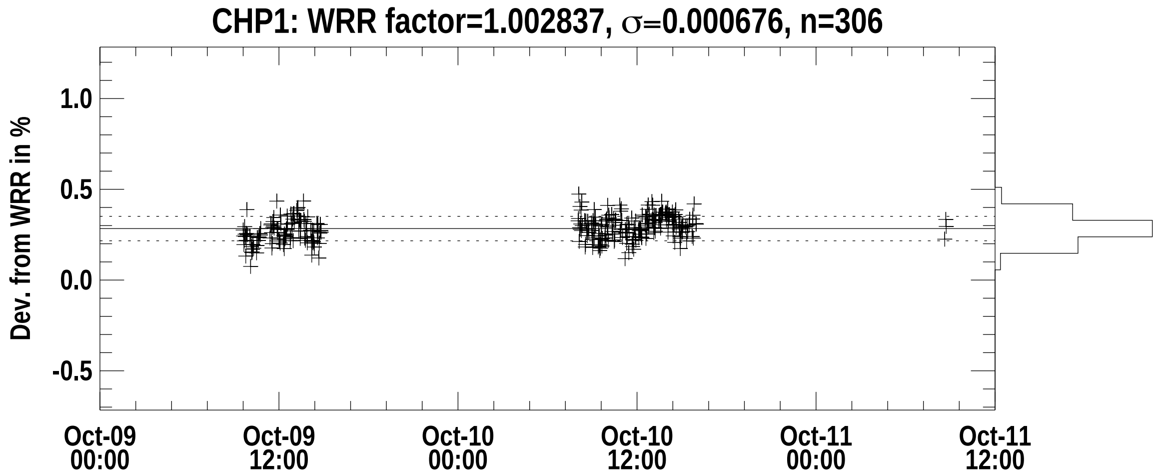

AWX33393: WRR factor=0.997281, σ=0.000749, n=804
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

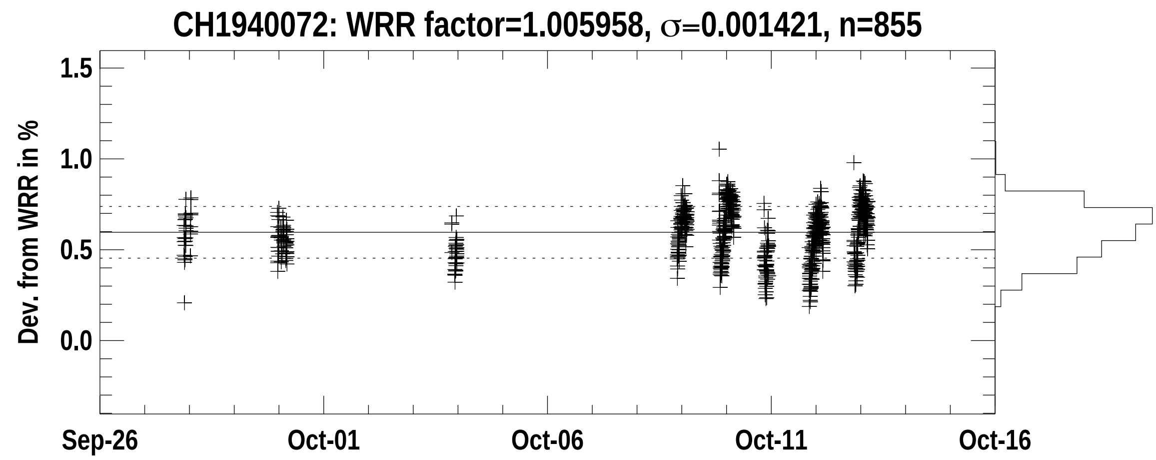

AHF33396: WRR factor=0.997951, σ=0.000892, n=673
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

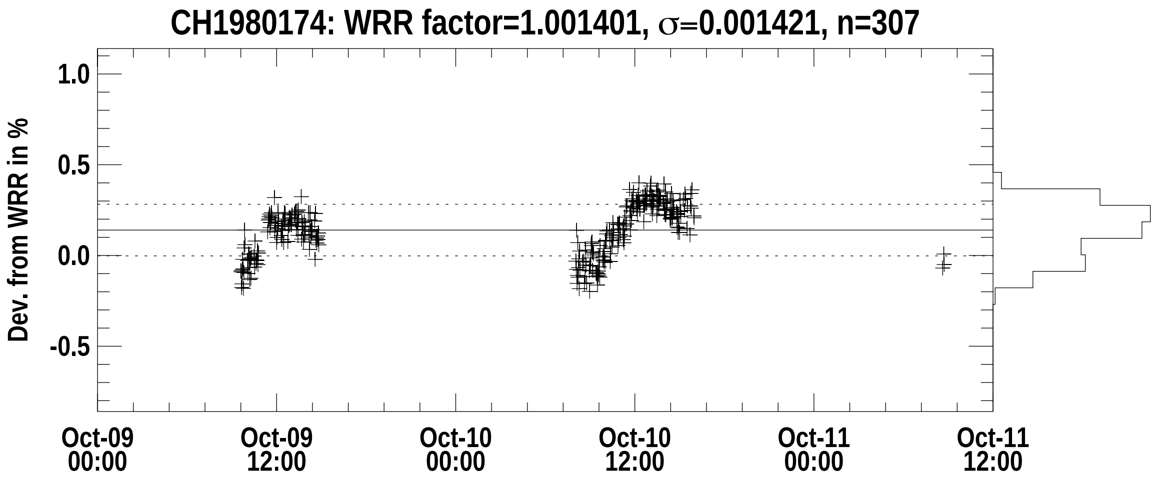

0501657: WRR factor=1.008130, σ=0.011871, n=759
Dev. from WRR in %
1.5
1.0
0.5
0.0
Oct-06
Oct-08
Oct-10
Oct-12
Oct-14
Oct-16

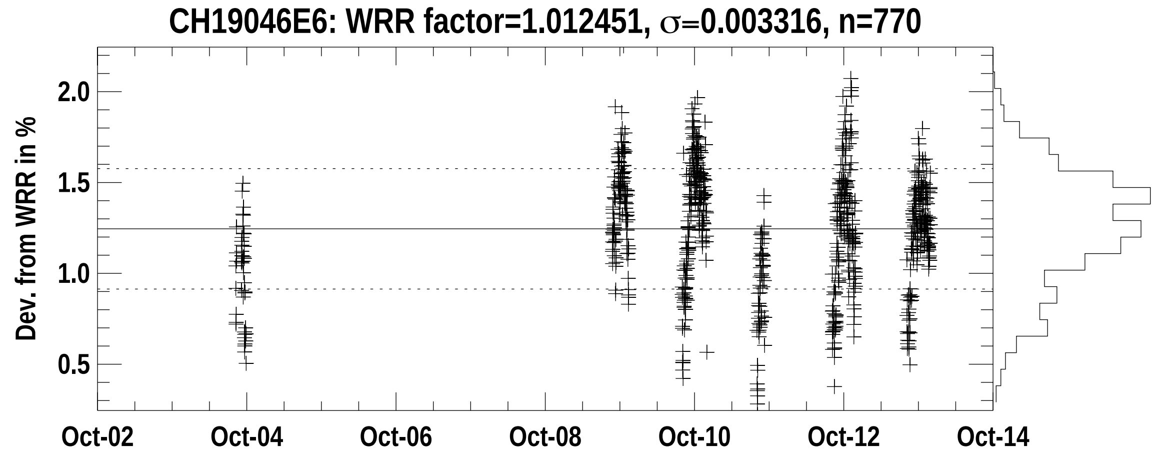

28335: WRR factor=1.012882, σ=0.005946, n=904
Dev. from WRR in %
2.0
1.5
1.0
0.5
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

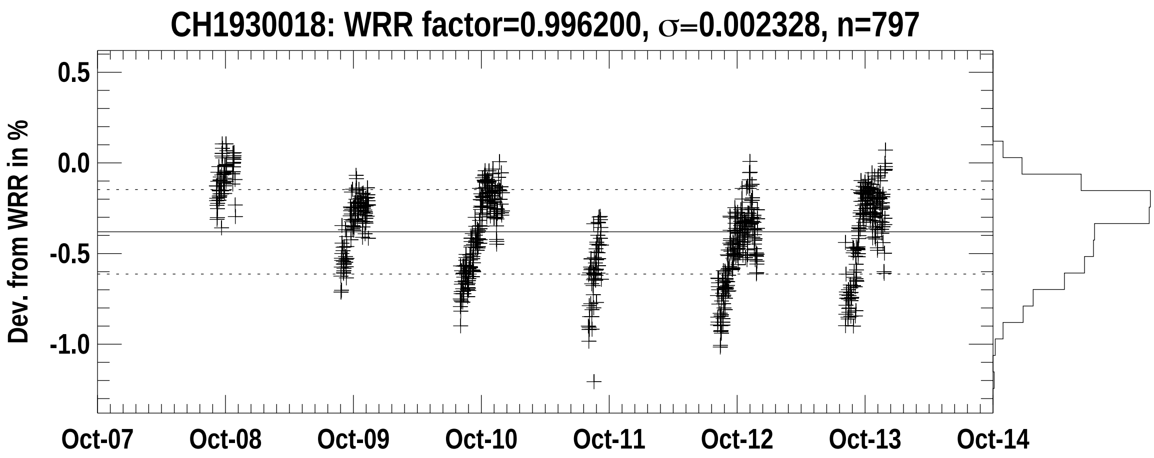

31144E6: WRR factor=0.997155, σ=0.003472, n=929
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

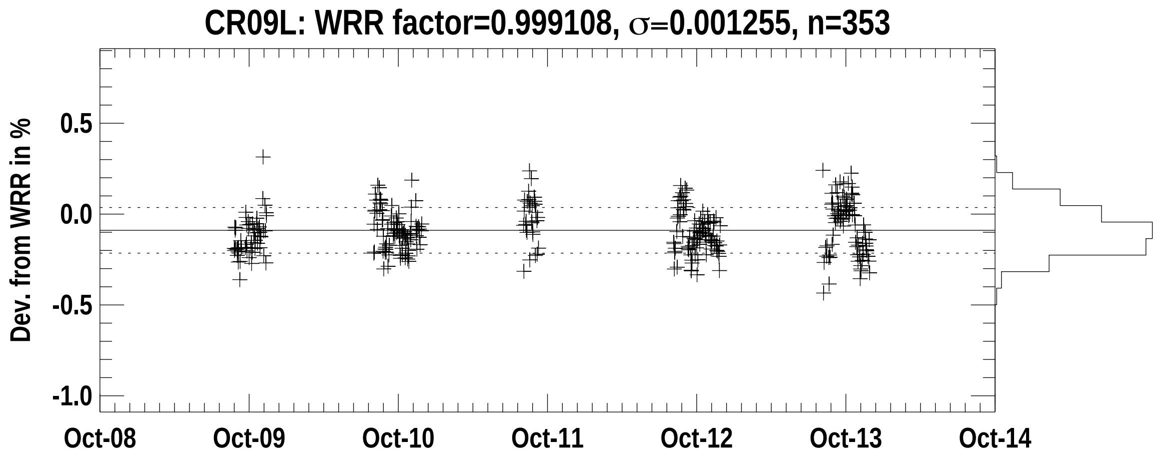

CHP1: WRR factor=1.002837, σ=0.000676, n=306
Dev. from WRR in %
1.0
0.5
0.0
-0.5
Oct-09 00:00
Oct-09 12:00
Oct-10 00:00
Oct-10 12:00
Oct-11 00:00
Oct-11 12:00

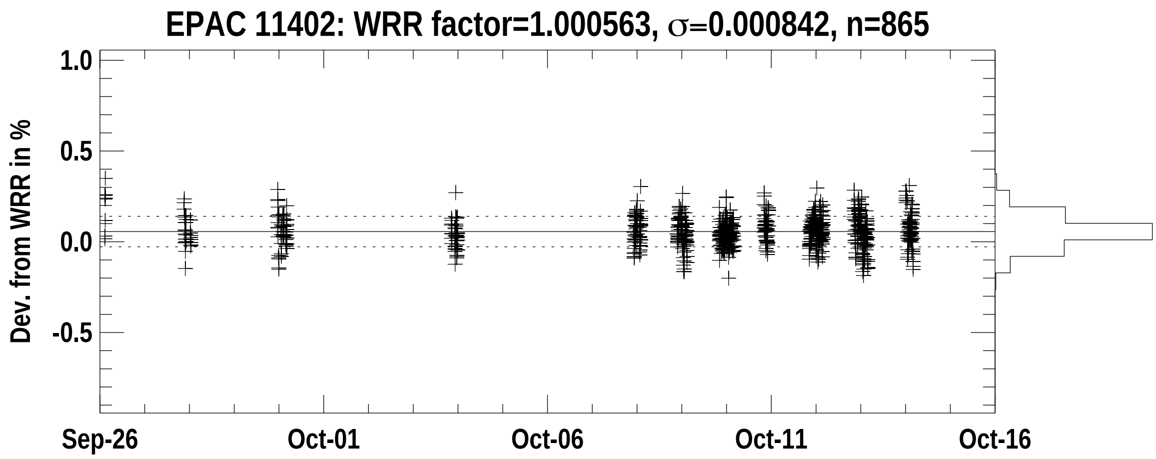

CH1940072: WRR factor=1.005958, σ=0.001421, n=855
Dev. from WRR in %
1.5
1.0
0.5
0.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

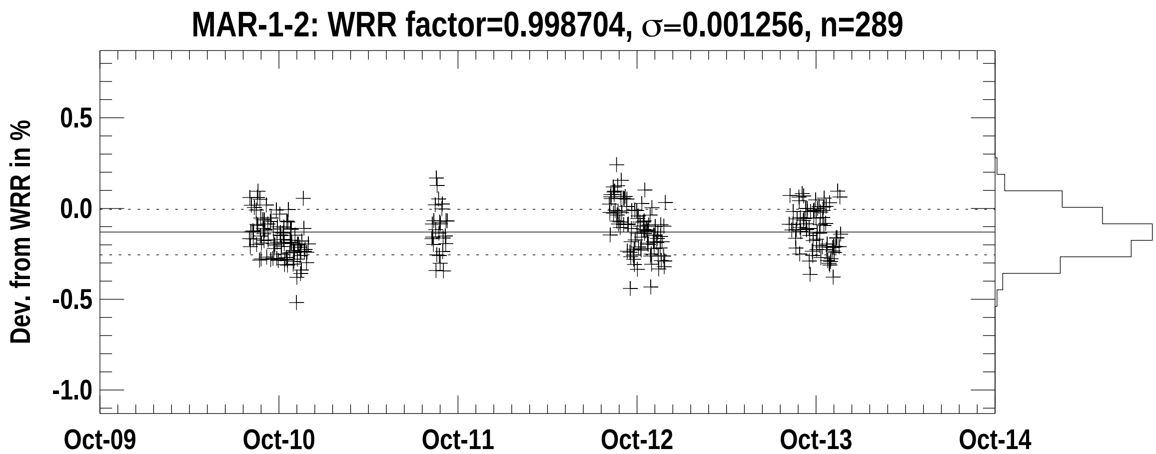

CH1980174: WRR factor=1.001401, σ=0.001421, n=307
Dev. from WRR in %
1.0
0.5
0.0
-0.5
Oct-09 00:00
Oct-09 12:00
Oct-10 00:00
Oct-10 12:00
Oct-11 00:00
Oct-11 12:00

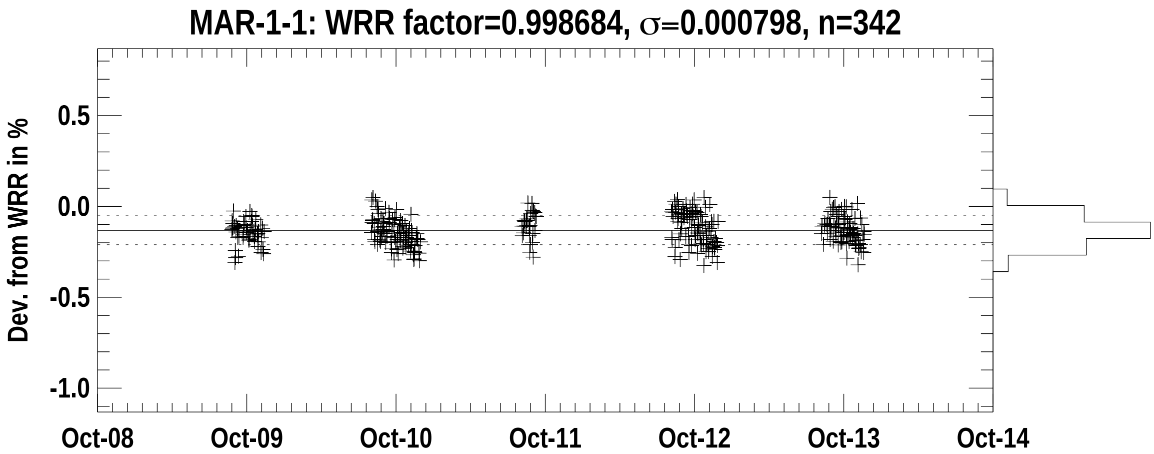

CH19046E6: WRR factor=1.012451, σ=0.003316, n=770
Dev. from WRR in %
2.0
1.5
1.0
0.5
Oct-02
Oct-04
Oct-06
Oct-08
Oct-10
Oct-12
Oct-14

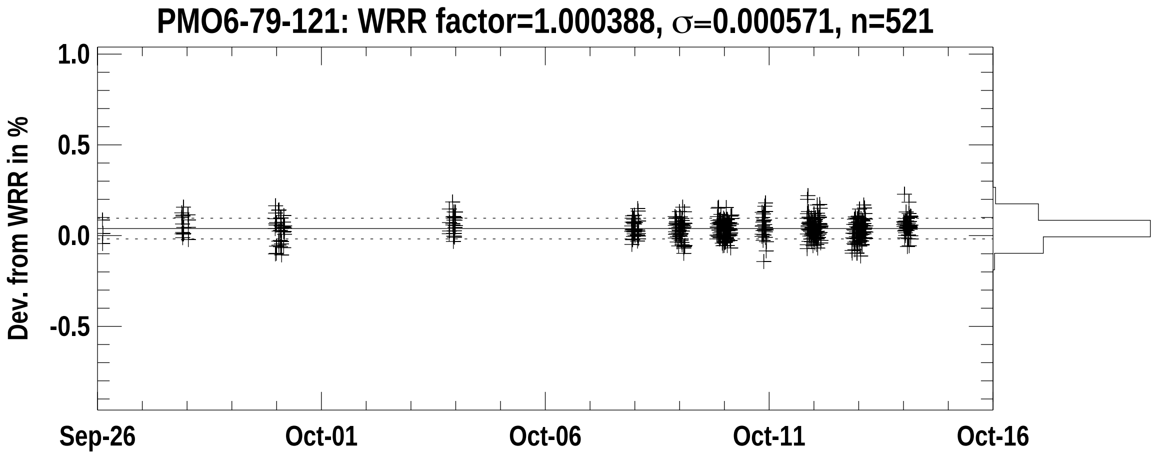

CH1930018: WRR factor=0.996200, σ=0.002328, n=797
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Oct-07
Oct-08
Oct-09
Oct-10
Oct-11
Oct-12
Oct-13
Oct-14

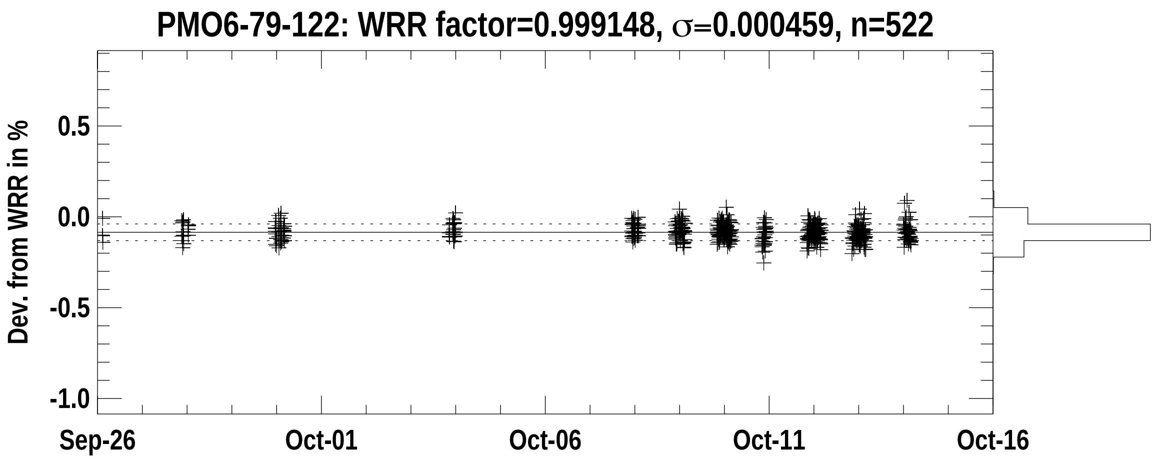

CR09L: WRR factor=0.999108, σ=0.001255, n=353
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Oct-08
Oct-09
Oct-10
Oct-11
Oct-12
Oct-13
Oct-14

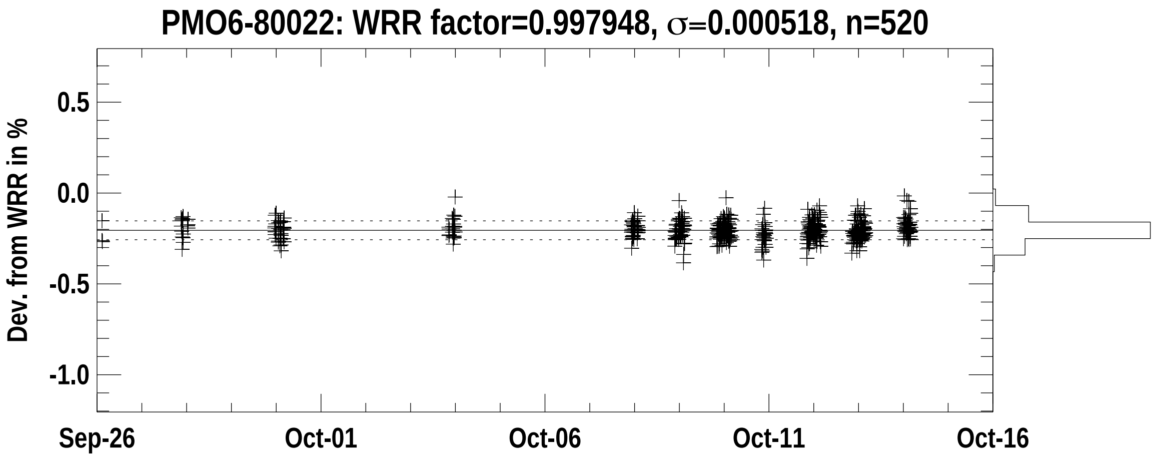

EPAC 11402: WRR factor=1.000563, σ=0.000842, n=865
Dev. from WRR in %
1.0
0.5
0.0
-0.5
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

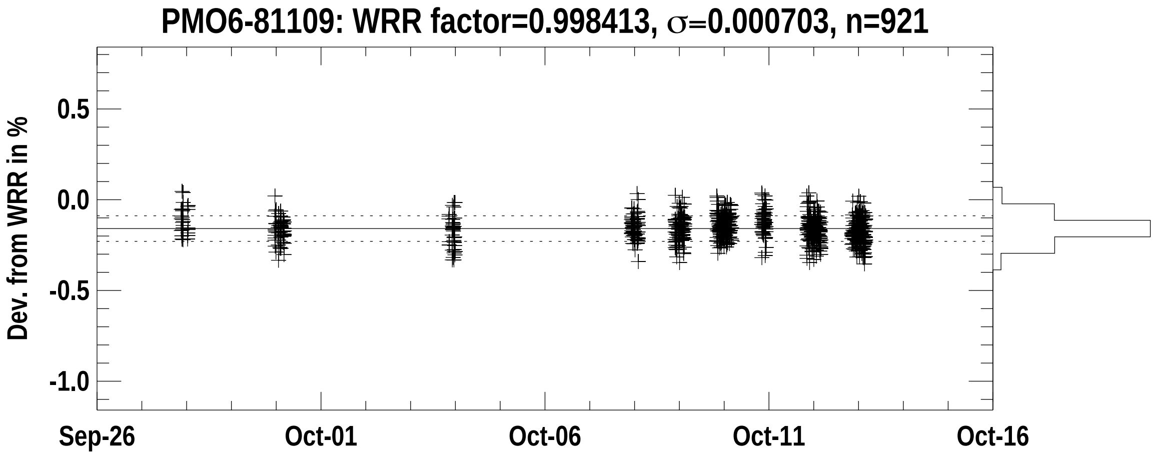

MAR-1-2: WRR factor=0.998704, σ=0.001256, n=289
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Oct-09
Oct-10
Oct-11
Oct-12
Oct-13
Oct-14

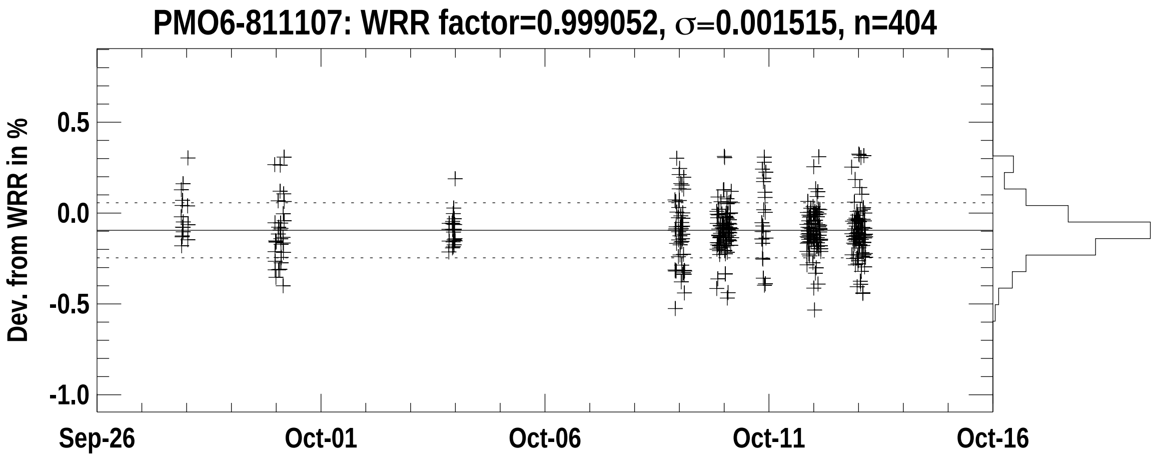

MAR-1-1: WRR factor=0.998684, σ=0.000798, n=342
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Oct-08
Oct-09
Oct-10
Oct-11
Oct-12
Oct-13
Oct-14

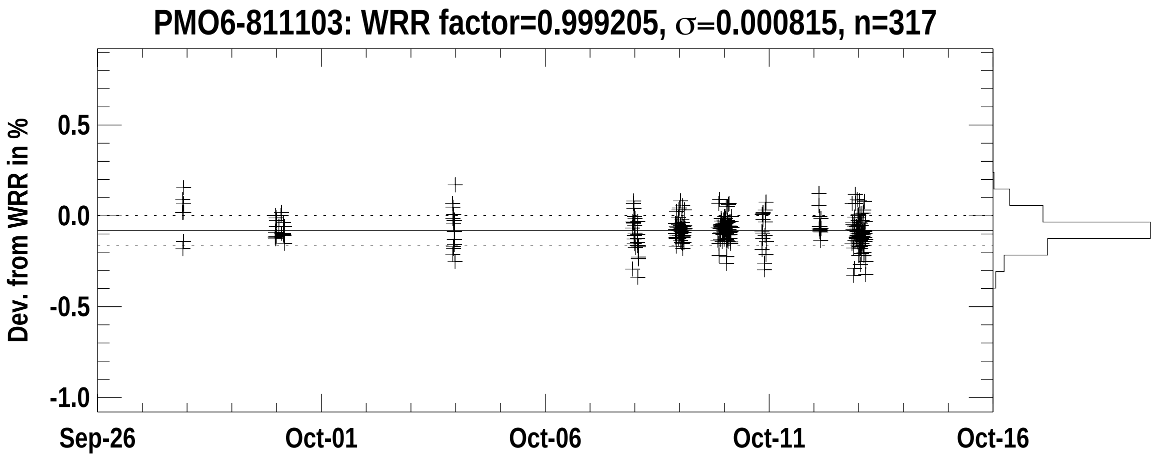

PMO6-79-121: WRR factor=1.000388, σ=0.000571, n=521
Dev. from WRR in %
1.0
0.5
0.0
-0.5
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

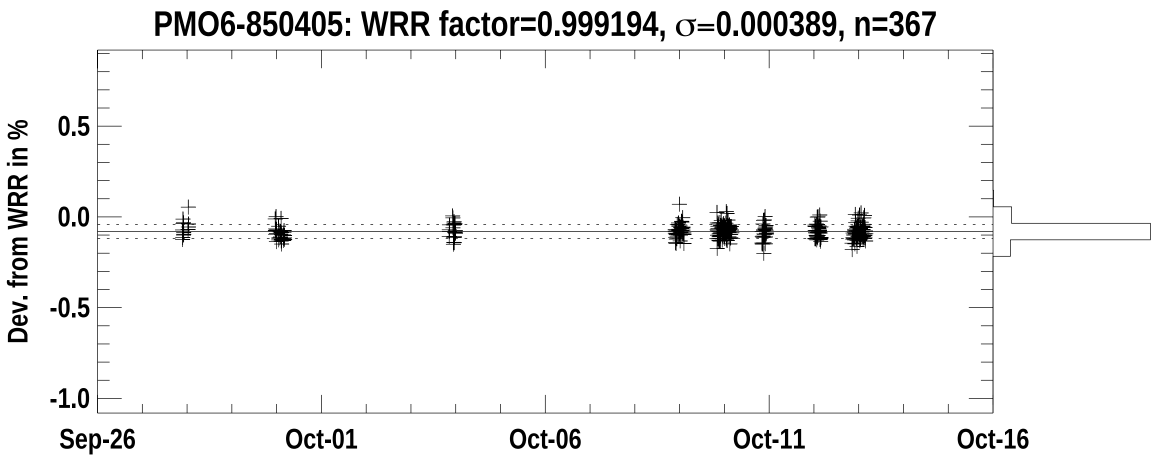

PMO6-79-122: WRR factor=0.999148, σ=0.000459, n=522
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

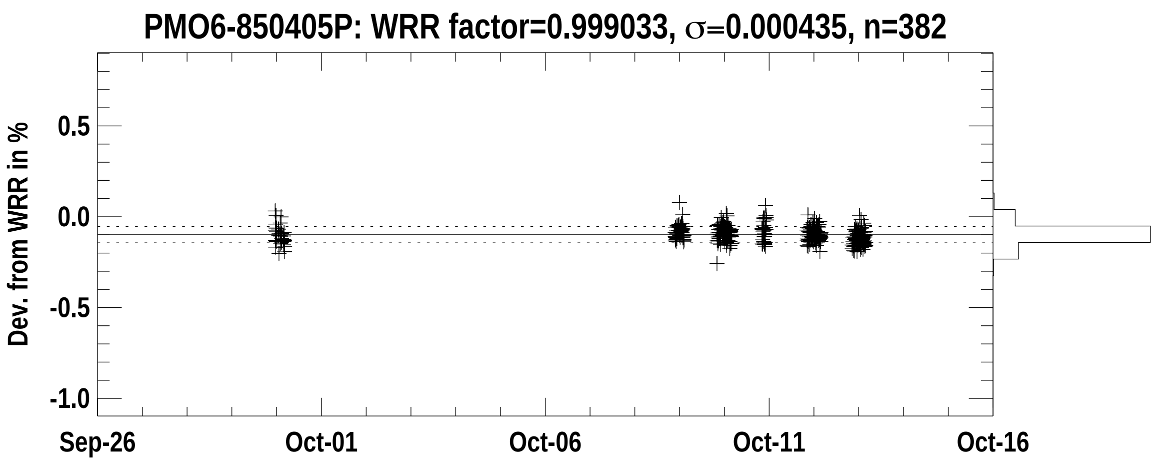

PMO6-80022: WRR factor=0.997948, σ=0.000518, n=520
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

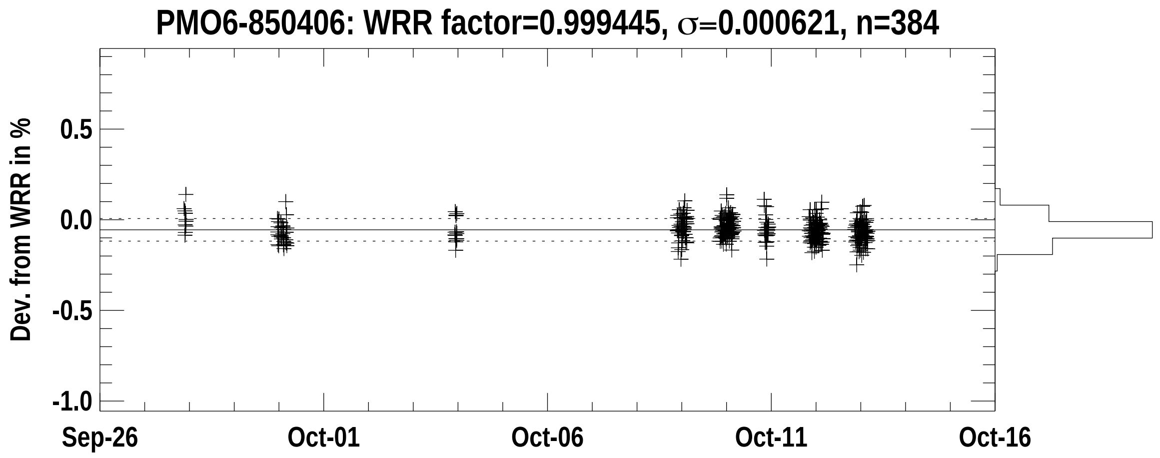

PMO6-81109: WRR factor=0.998413, σ=0.000703, n=921
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

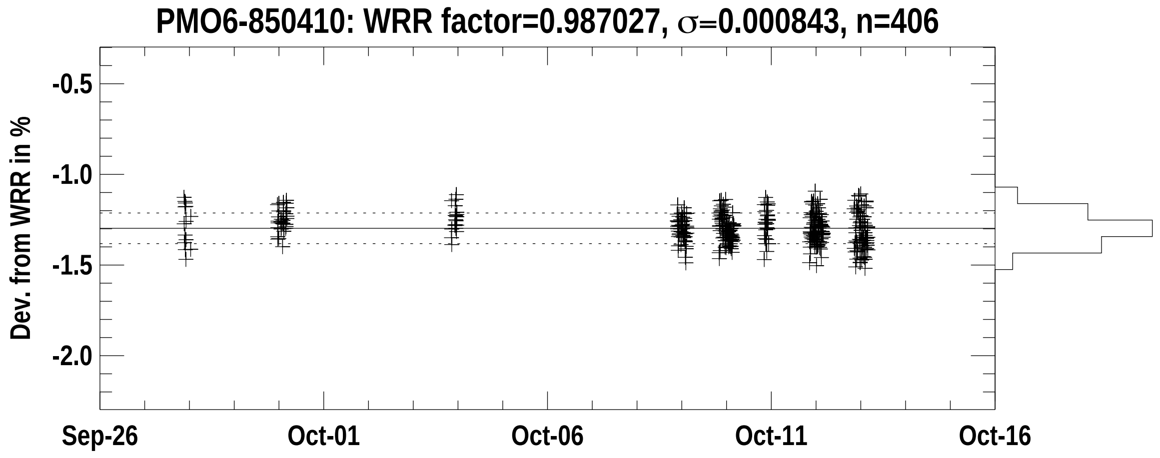

PMO6-811107: WRR factor=0.999052, σ=0.001515, n=404
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

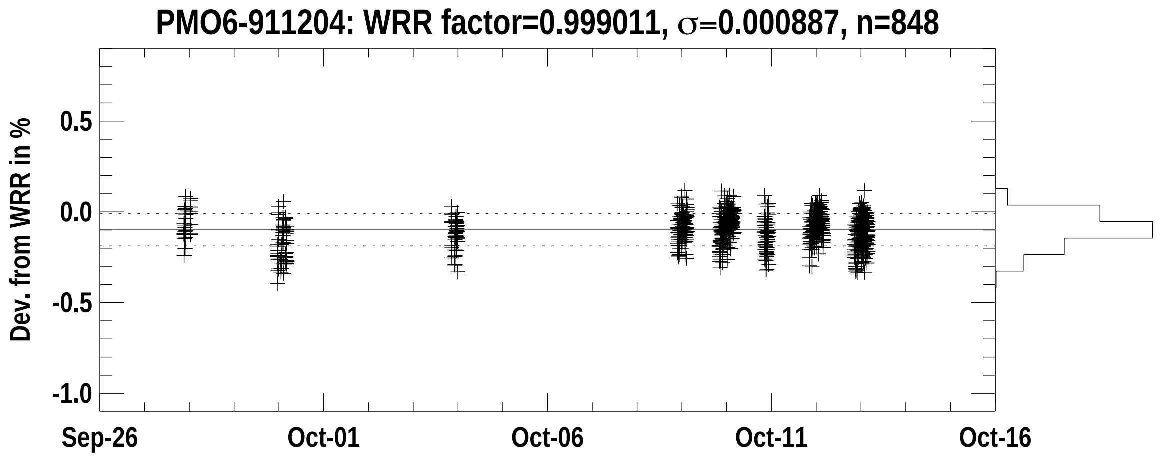

PMO6-811103: WRR factor=0.999205, σ=0.000815, n=317
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

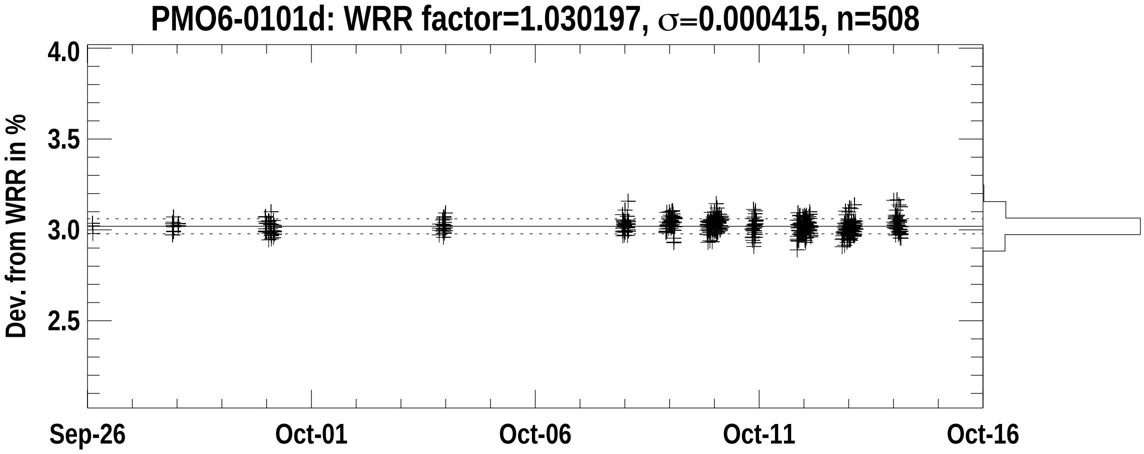

PMO6-850405: WRR factor=0.999194, σ=0.000389, n=367
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

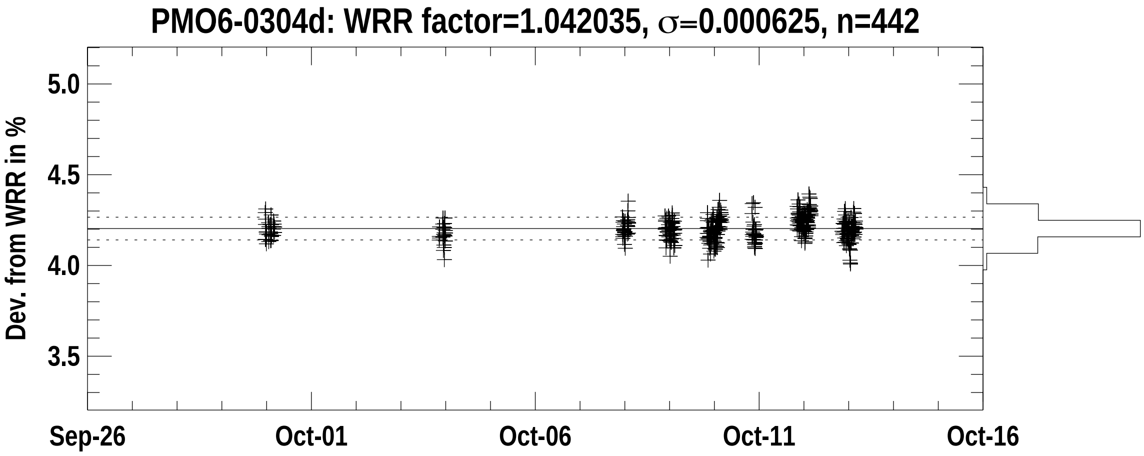

PMO6-850405P: WRR factor=0.999033, σ=0.000435, n=382
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

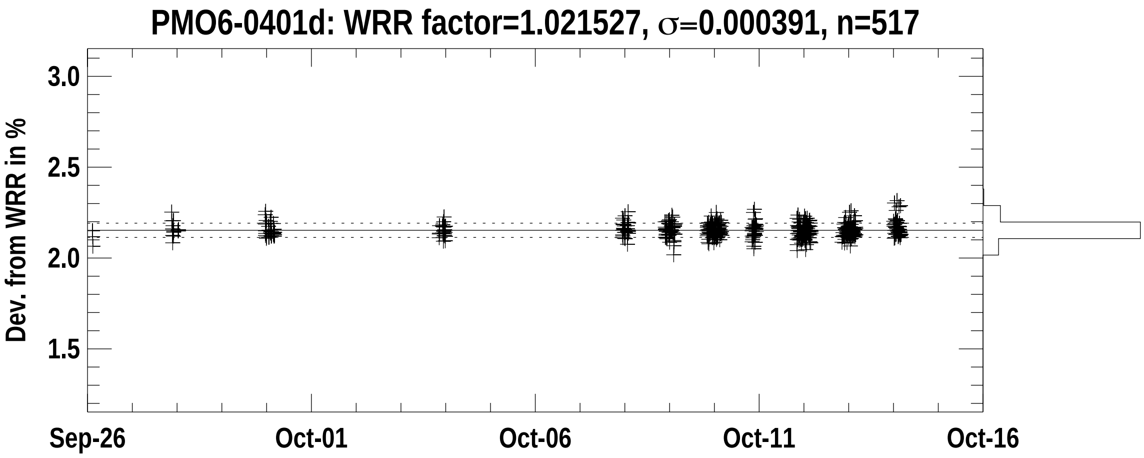

PMO6-850406: WRR factor=0.999445, σ=0.000621, n=384
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16


PMO6-850410: WRR factor=0.987027, σ=0.000843, n=406
Dev. from WRR in %
-0.5
-1.0
-1.5
-2.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

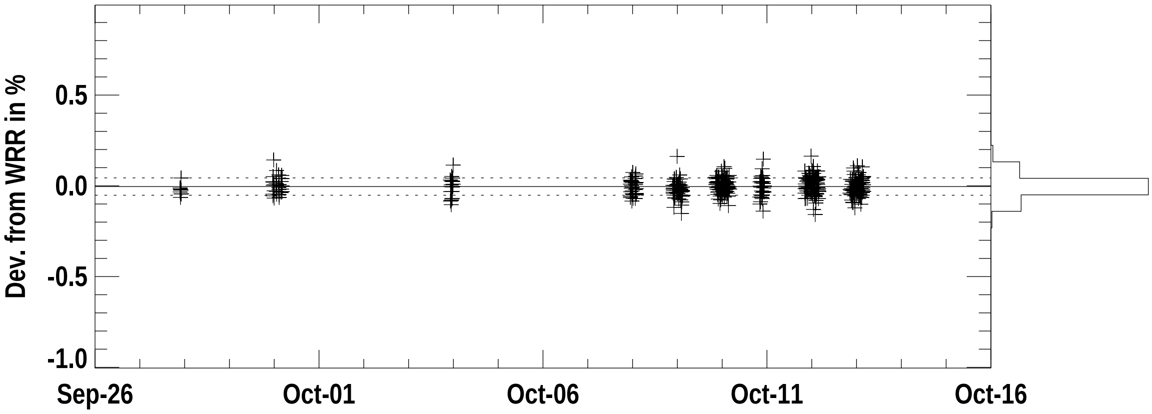

PMO6-911204: WRR factor=0.999011, σ=0.000887, n=848
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16


PMO6-0101d: WRR factor=1.030197, σ=0.000415, n=508
Dev. from WRR in %
4.0
3.5
3.0
2.5
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

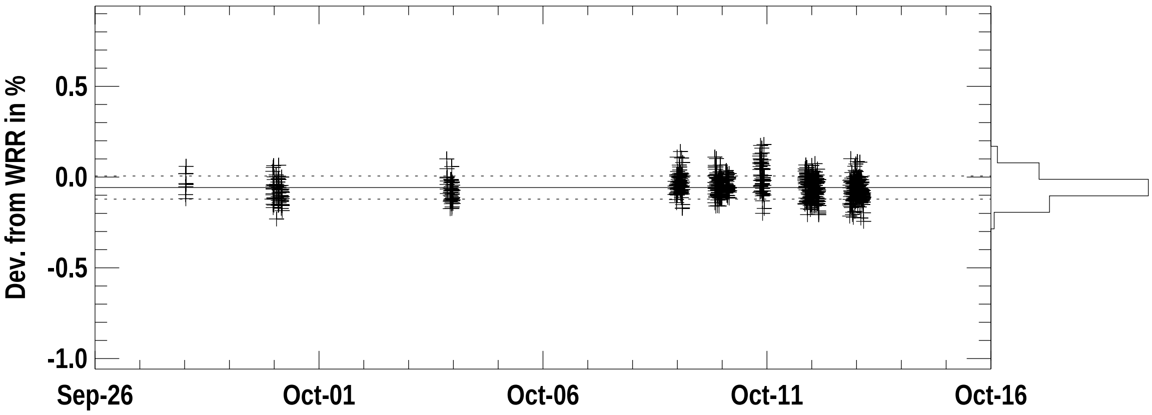

PMO6-0304d: WRR factor=1.042035, σ=0.000625, n=442
Dev. from WRR in %
5.0
4.5
4.0
3.5
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16


PMO6-0401d: WRR factor=1.021527, σ=0.000391, n=517
Dev. from WRR in %
3.0
2.5
2.0
1.5
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

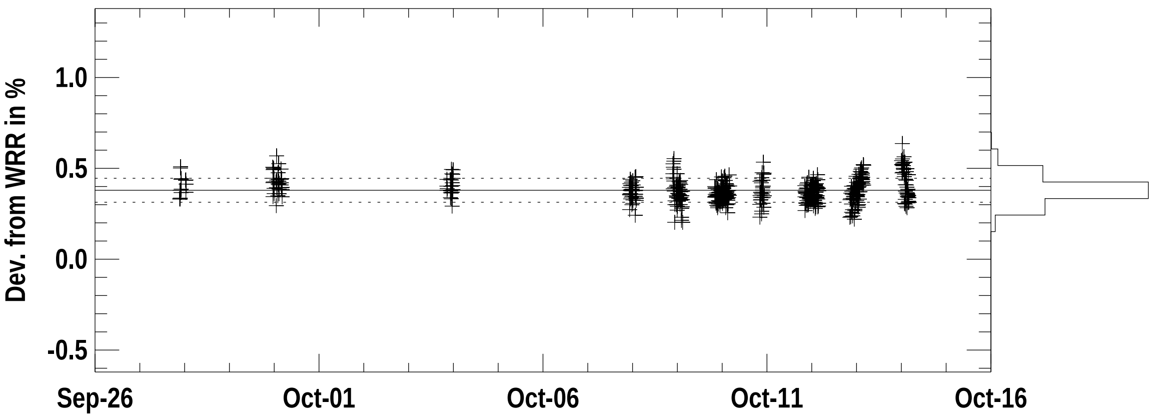
PMO6-5: WRR factor=0.999959, σ=0.000477, n=443

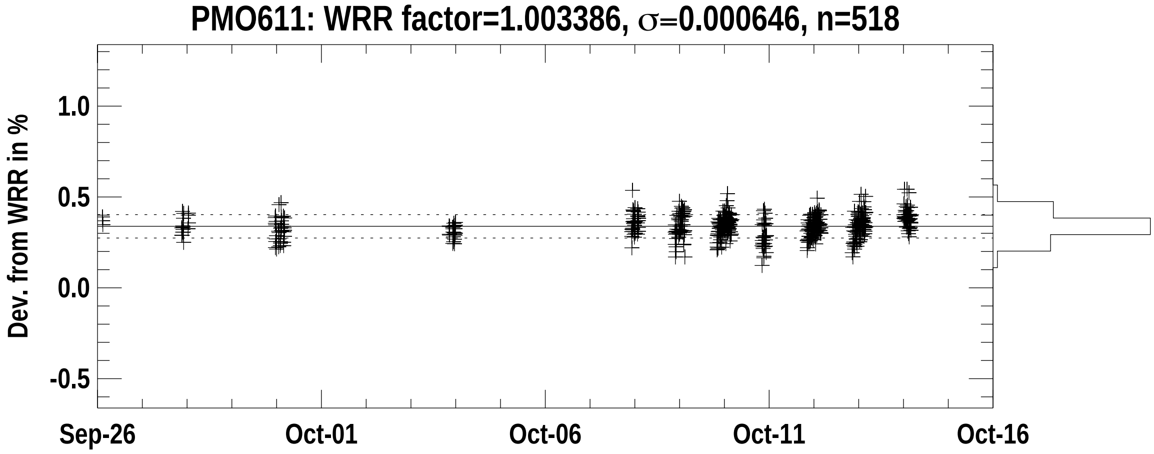


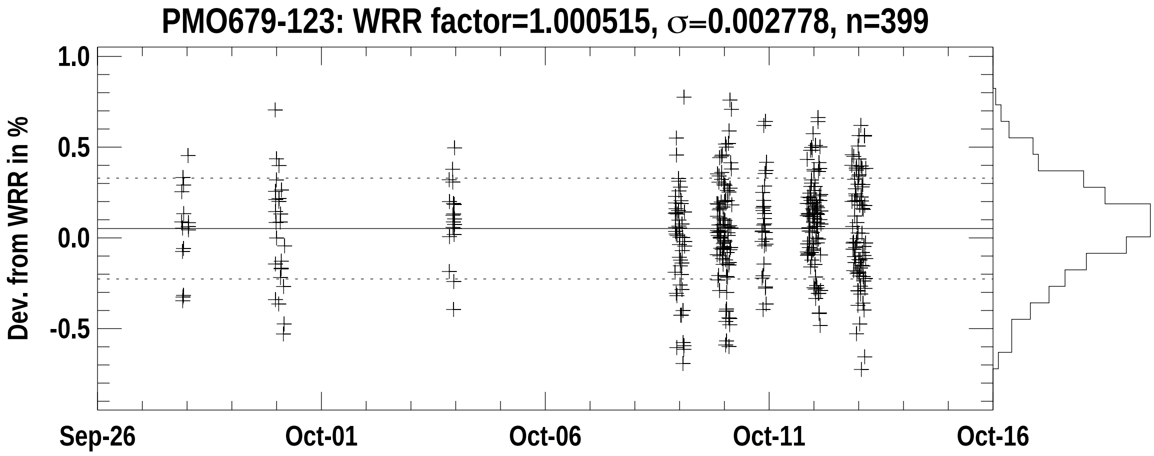
PMO6-cc103: WRR factor=0.999424, σ=0.000638, n=762

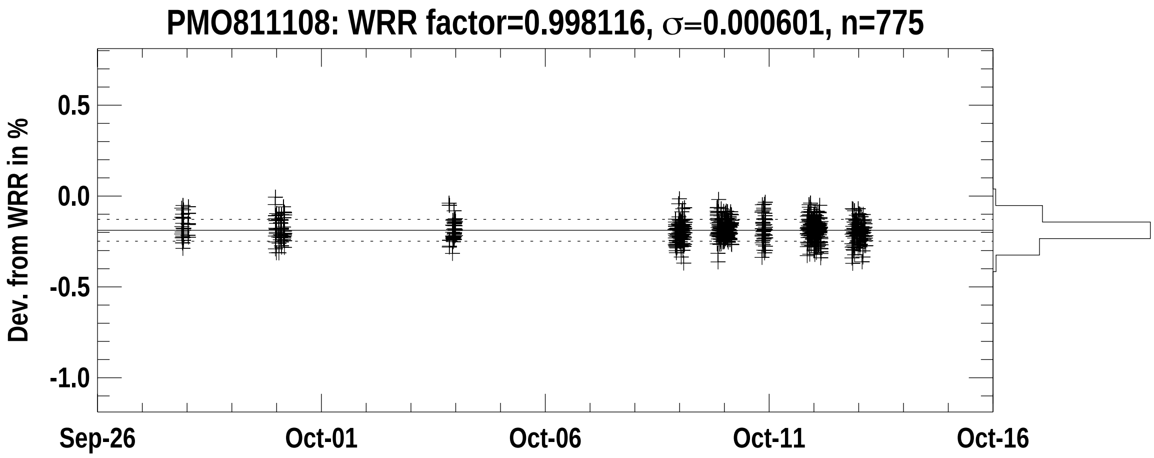


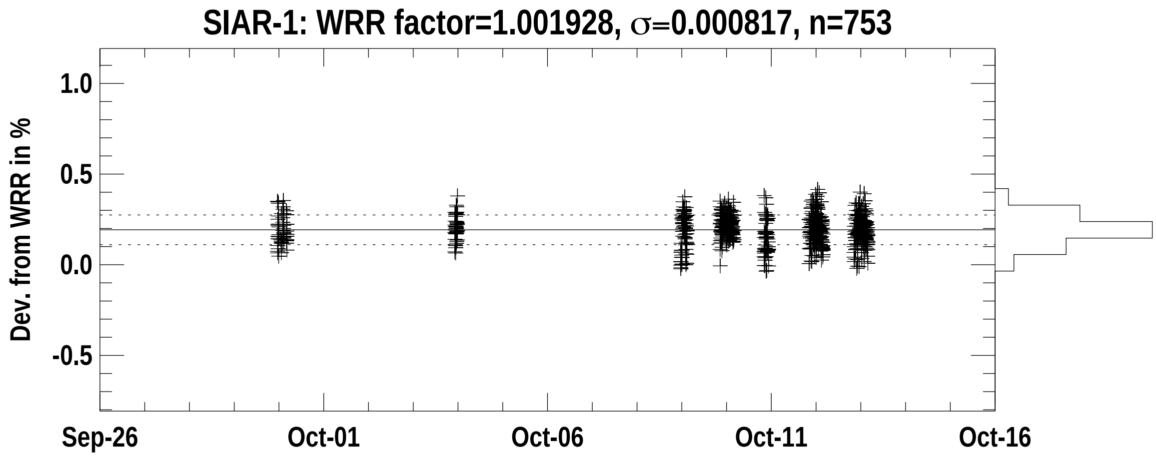
PMO609: WRR factor=1.003793, σ=0.000658, n=514

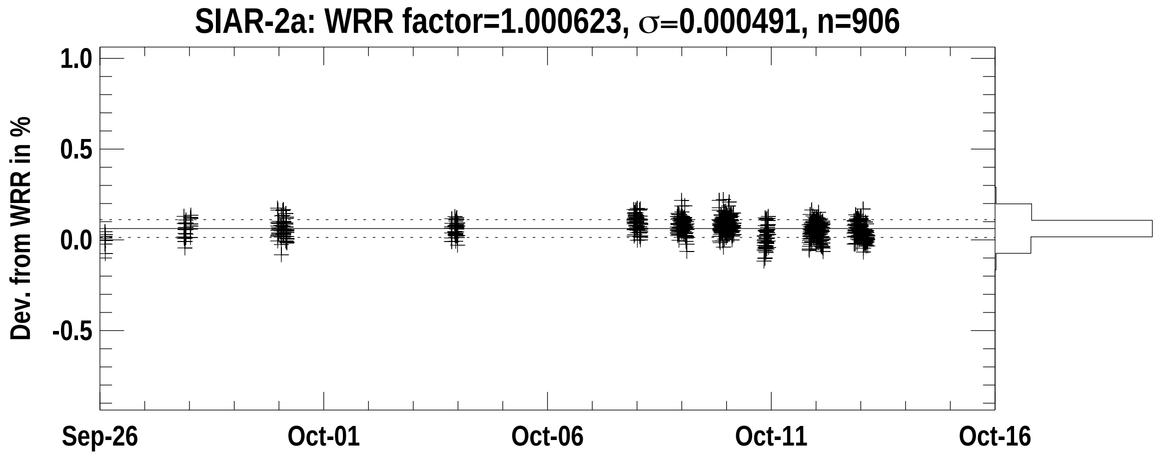


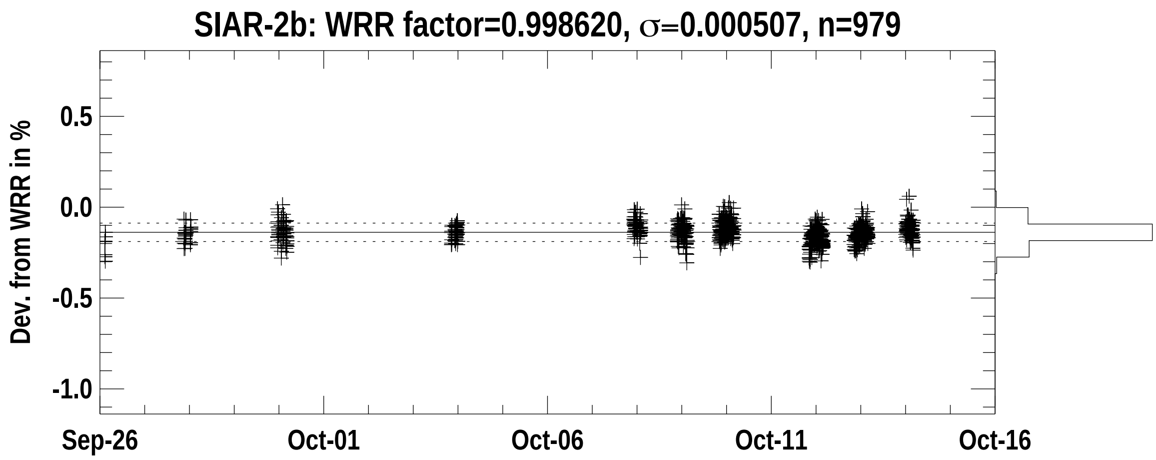

PMO611: WRR factor=1.003386, σ=0.000646, n=518
Dev. from WRR in %
1.0
0.5
0.0
-0.5
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

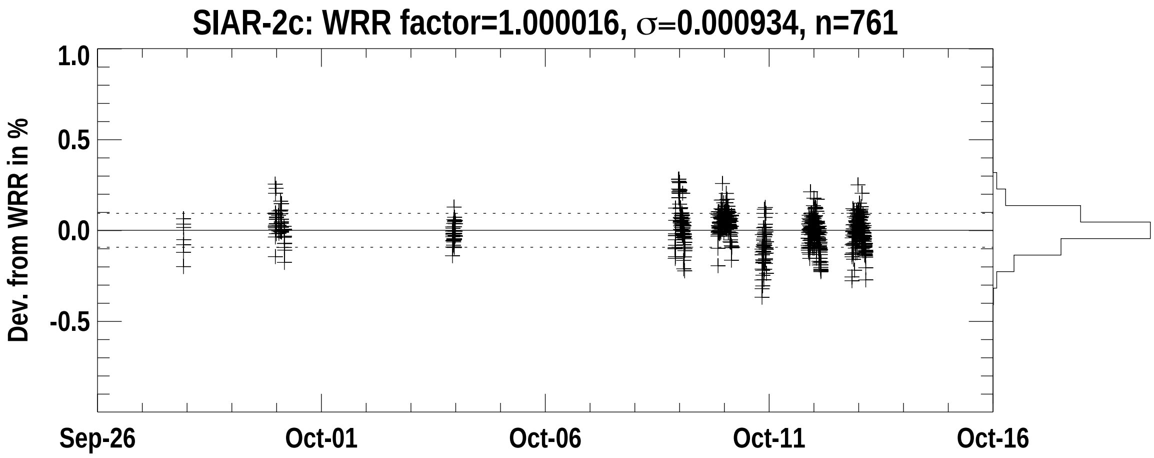

PMO679-123: WRR factor=1.000515, σ=0.002778, n=399
Dev. from WRR in %
1.0
0.5
0.0
-0.5
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

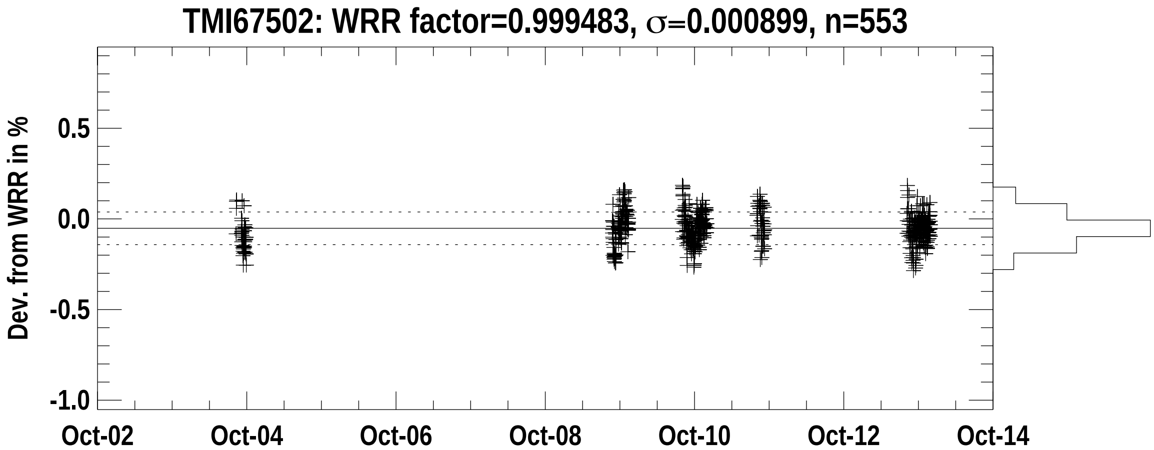

PMO811108: WRR factor=0.998116, σ=0.000601, n=775
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

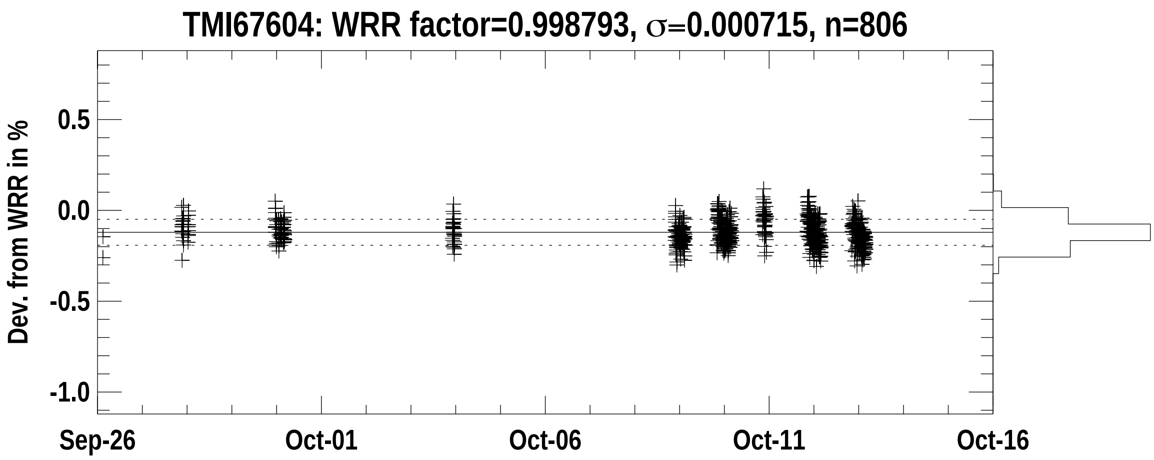

SIAR-1: WRR factor=1.001928, σ=0.000817, n=753
Dev. from WRR in %
1.0
0.5
0.0
-0.5
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

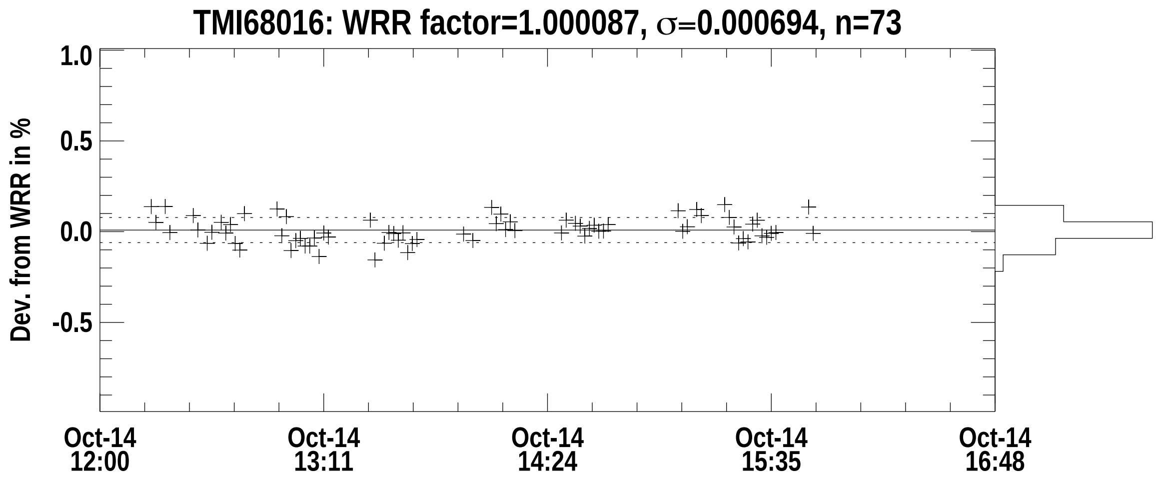

SIAR-2a: WRR factor=1.000623, σ=0.000491, n=906
Dev. from WRR in %
1.0
0.5
0.0
-0.5
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

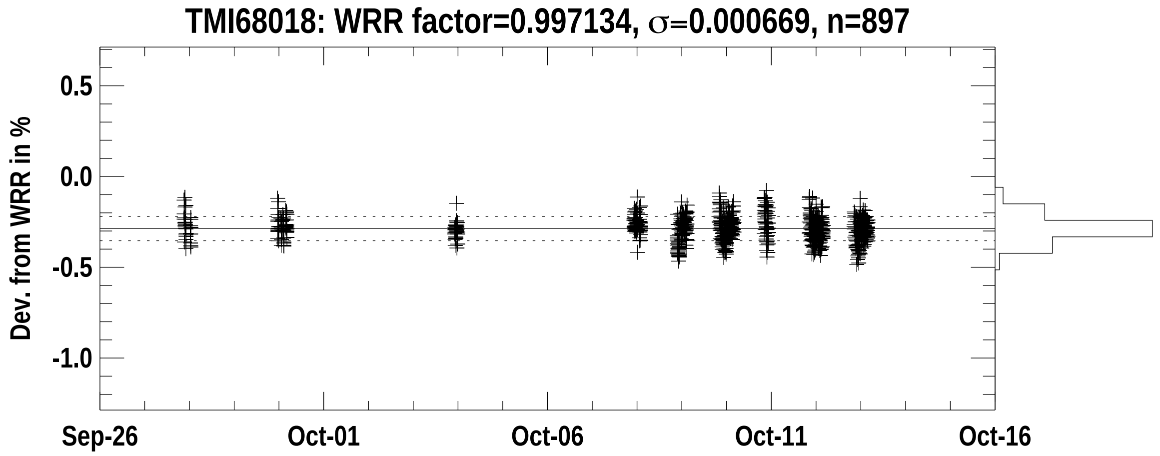

SIAR-2b: WRR factor=0.998620, σ=0.000507, n=979
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16


SIAR-2c: WRR factor=1.000016, σ=0.000934, n=761
Dev. from WRR in %
1.0
0.5
0.0
-0.5
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16


TMI67502: WRR factor=0.999483, σ=0.000899, n=553
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Oct-02
Oct-04
Oct-06
Oct-08
Oct-10
Oct-12
Oct-14


TMI67604: WRR factor=0.998793, σ=0.000715, n=806
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16


TMI68016: WRR factor=1.000087, σ=0.000694, n=73
Dev. from WRR in %
1.0
0.5
0.0
-0.5
Oct-14 12:00
Oct-14 13:11
Oct-14 14:24
Oct-14 15:35
Oct-14 16:48


TMI68018: WRR factor=0.997134, σ=0.000669, n=897
Dev. from WRR in %
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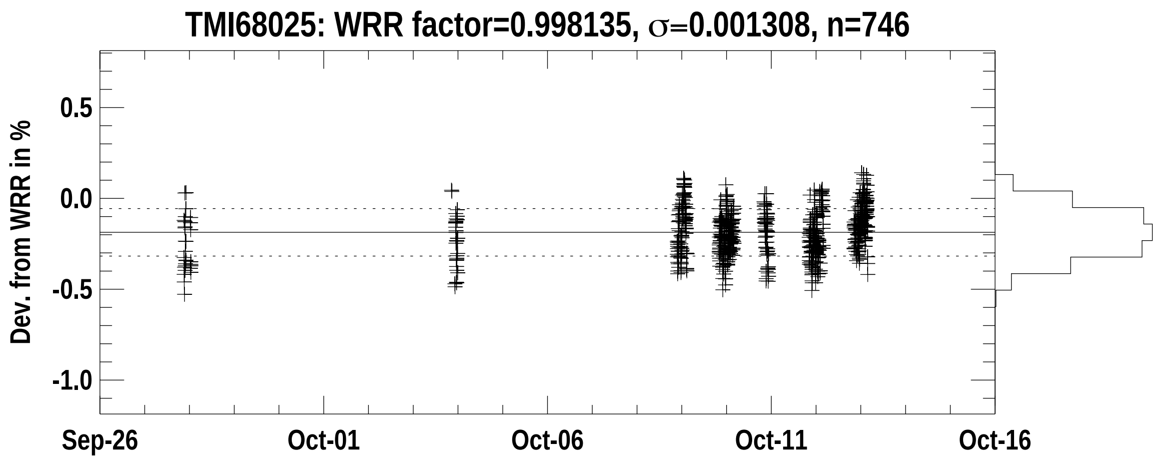
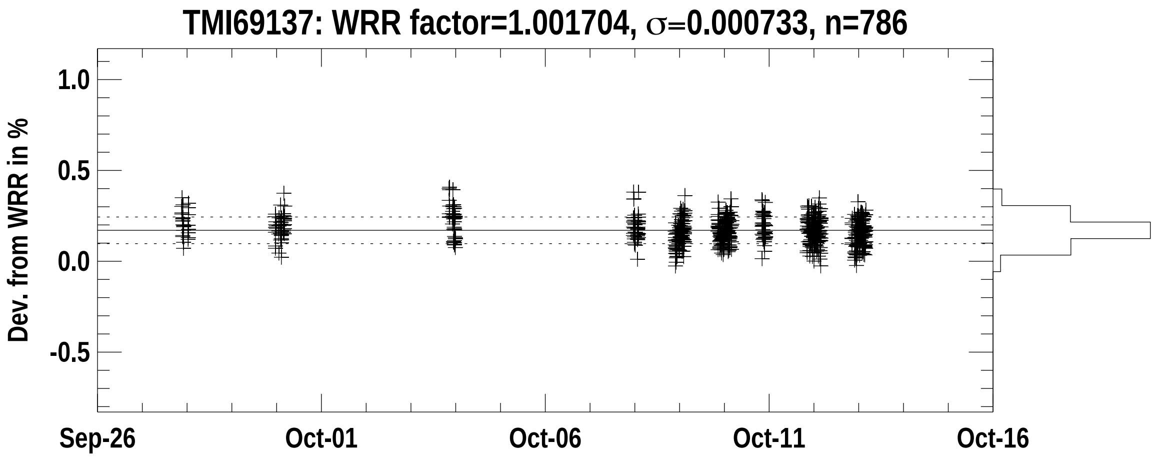
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16


TMI68025: WRR factor=0.998135, σ=0.001308, n=746
Dev. from WRR in %
0.5
0.0
-0.5
-1.0
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16


TMI69137: WRR factor=1.001704, σ=0.000733, n=786
Dev. from WRR in %
1.0
0.5
0.0
-0.5
Sep-26
Oct-01
Oct-06
Oct-11
Oct-16

3.2 Auxiliary Data

3.2.1 Direct and Diffuse Irradiance

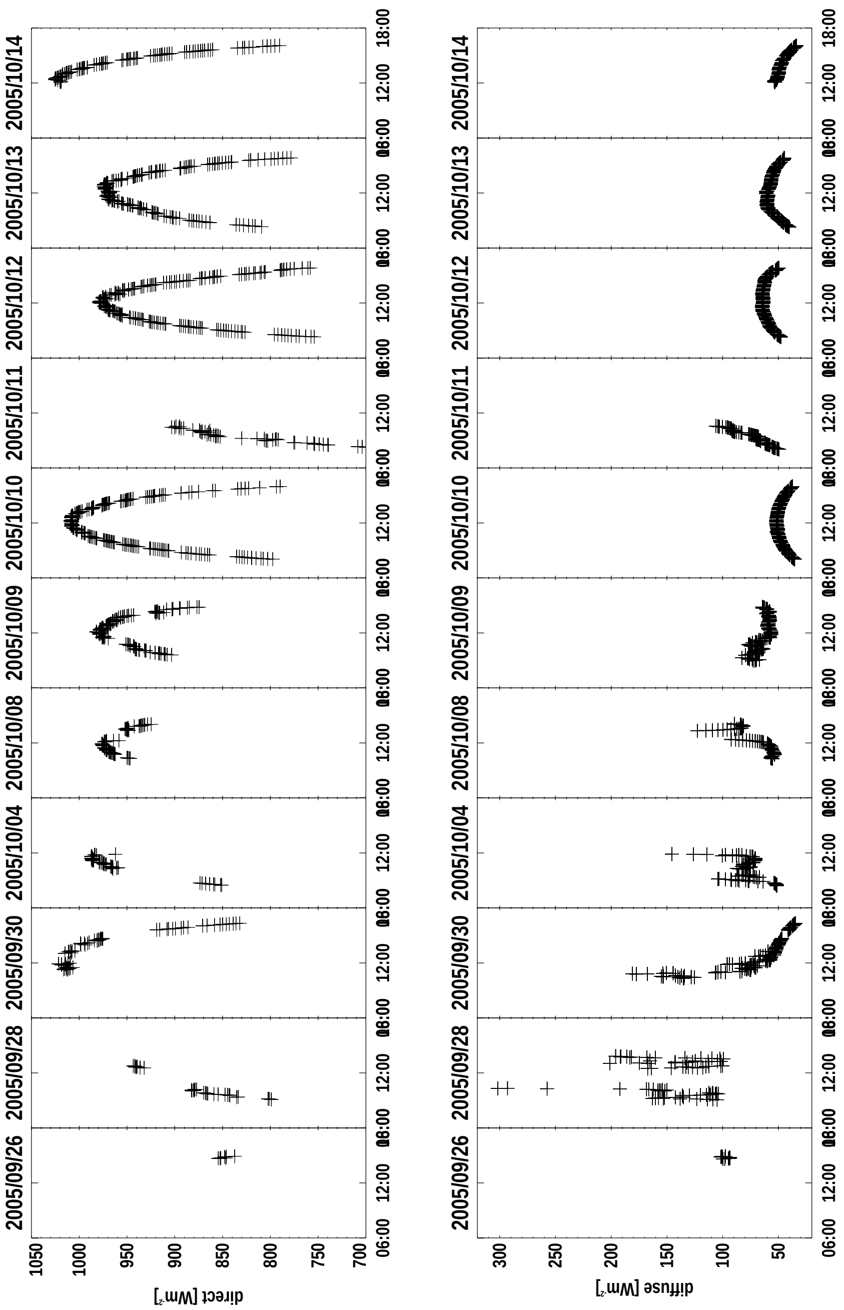


Figure 3.1: Direct (WRR) and diffuse irradiance measured by a shaded Kipp & Zonen CM22 pyranometer.

3.2.2 Meteorological Data

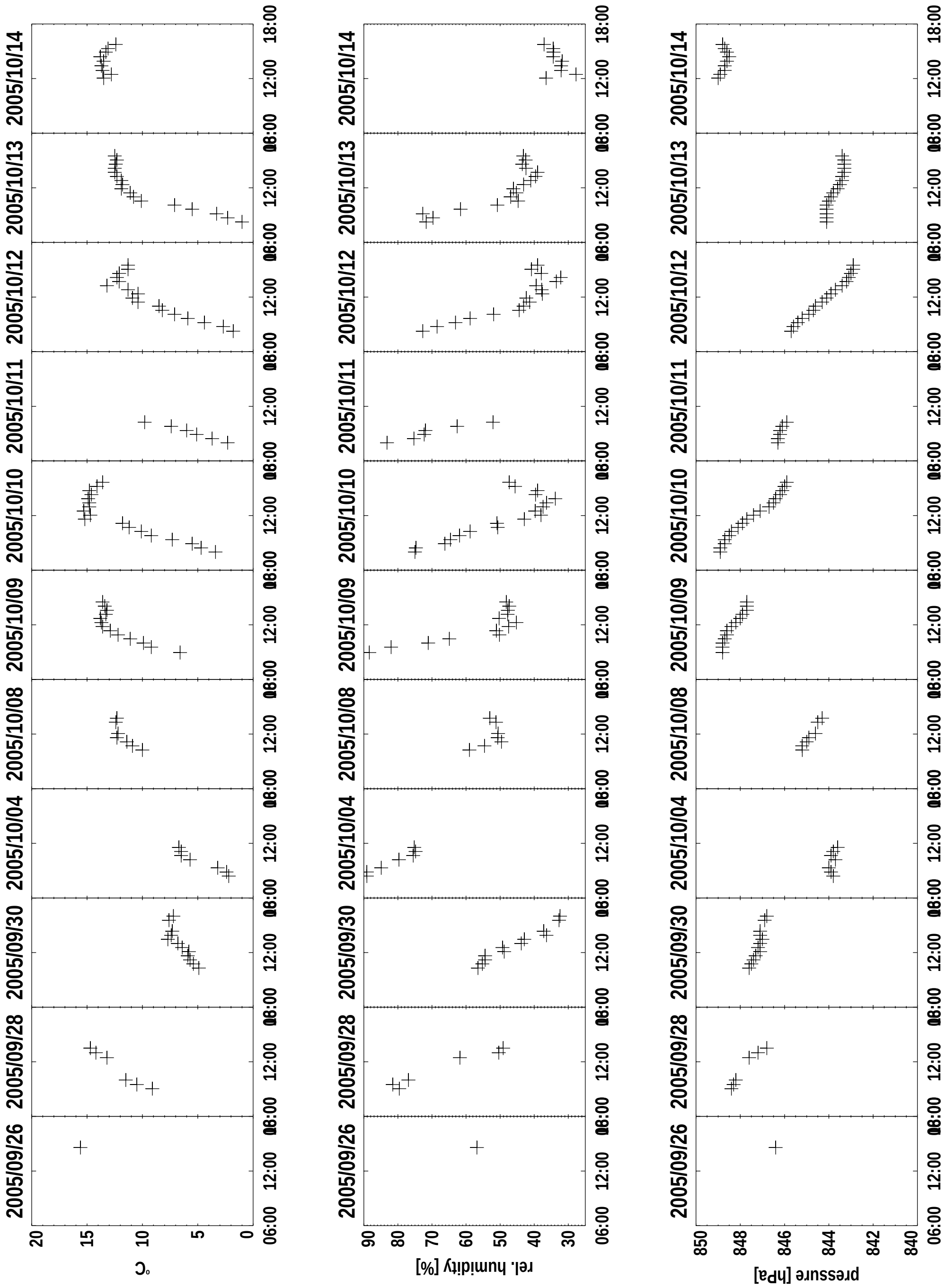


Figure 3.2: Meteorological parameters measured by the ASTA station of MeteoSwiss at Davos.

3.2.3 Airmass and Aerosol Optical Depth (AOD)

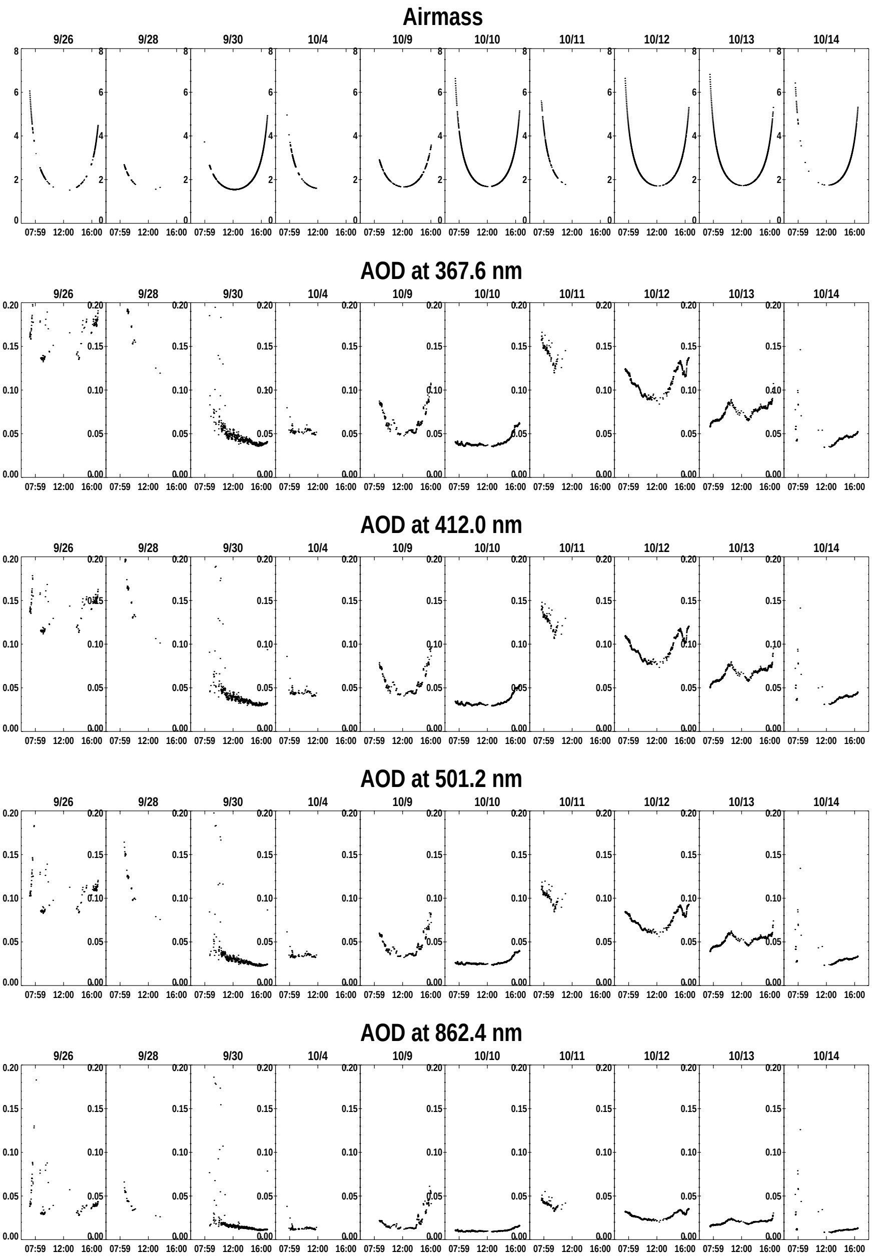


Figure 3.3: A four-channel Precision Filter Radiomtere (PFR) was used to determine AOD.

Chapter 4 Symposium

4.1 To Build and Share Knowledge

On cloudy, overcast, or rainy (snowy!) days when no measurements were possible the IPC-X symposium was held. Radiation experts from PMOD/WRC as well as other IPC-X participants presented their work and/or national radiation infrastructure in order to share and build knowledge. Guest speaker Prof. A. Ohmura of ETH Zurich emphasized the importance of accurately calibrated radiation measurements climatologic research.

Over the three weeks, more than 30 talks and presentations were given, most of which are available for download on the IPC-X ftp site ftp://ftp.pmodwrc.ch/stealth/ipc-x/Symposium/.

Chapter 5 Supplementary Information

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