The new sun-sky-lunar Cimel CE318-T multiband photometer. A comprehensive performance evaluation.

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LIST OF TOPICS

1. Brief Introduction: Moon photometry. Why is so difficult?
   What we have done?
   ROLO model
2. CE318-T. New features
3. How to estimate the instrument's accuracy
4. Results (daytime and nighttime evaluation, AOD day/night coherence transition test, PWV validation and case studies at IZO)
5. Final uncertainty estimation for CE318-T

INTRODUCTION: WHY IS THE CALIBRATION OF LUNAR PHOTOMETERS SO DIFFICULT?

The three most important issues in lunar photometry are:

1) Moon’s illumination is changing at any time

As a consequence: $I_\lambda = I_{0,\lambda} e^{-\tau_\lambda \cdot m}$ → calculate each night!!!!

It’s required to introduce a new methodology for nocturnal absolute calibration

INTRODUCTION: WHY IS THE CALIBRATION OF LUNAR PHOTOMETERS SO DIFFICULT?

The three most important issues in lunar photometry are:

1) Moon's illumination is changing at any time

2) We need to have a reference for the Moon's irradiance at TOA

It's necessary to find an accurate estimation for Moon's spectral extraterrestrial irradiance

INTRODUCTION: WHY IS THE CALIBRATION OF LUNAR PHOTOMETERS SO DIFFICULT?

The three most important issues in lunar photometry are:

1) Moon's illumination is changing at any time

2) We need to have a reference for the Moon's irradiance at TOA

3) Nocturnal measurements only under relatively high illumination conditions (FI≥50%) → ≈ 50% lunar cycle

Our experience suggests nocturnal measurement above 50% Illumination

Improve instrument detectivity to extend the range????

We have to assume a "blind" period over the Moon cycle “blind” period over the Moon cycle: only **lunacy**

INTRODUCTION: WHAT WE HAVE DONE?

- Lunar Langley Method for absolute calibration (Illumination variability problem)

$$I_\lambda = I_{0,\lambda} e^{-\tau_\lambda \cdot m}$$

$$V_{0,j} = I_{0,j} \cdot \kappa_j$$

where

$$\kappa(\lambda) = \frac{1}{C_j(\lambda) \cdot \Omega(\lambda)}$$

New cal. coef. (strictly constant)

Assuming I_0 known

Linear regression analysis:

$$ln\left(\frac{V(\lambda)}{I_0(\lambda)}\right) + m_{atm}(\theta) \cdot \tau_{atm}(\lambda) = ln(\kappa(\lambda)) - m_a(\theta) \cdot \tau_a(\lambda)$$

INTRODUCTION: WHAT WE HAVE DONE?

- ✓ Lunar Langley Method for absolute calibration (Illumination variability problem)

- ✓ ROLO model* (Agreement with USGS, $u(I_0)\approx 1\%$)

$$V_{0,j} = I_{0,j} \cdot \kappa_j$$

where:

$$I_j = \frac{A_j \cdot \Omega_M \cdot E_j}{\pi}$$

(ROLO*, USGS Lunar Irradiance empirical model)

A_j: moon's disk-equivalent reflectances

Ω_M: moon's solid angle

E_j: sun's spectral irrad. 1AU (Wehrli)

$$ln(A_j) = \sum_{n=1}^{3} a_{i,j} g^i + \sum_{n=1}^{3} b_{n,j} \varphi^{2n-1} + c_1 \cdot \theta + c_2 \cdot \phi + c_3 \cdot \varphi \cdot \theta + c_4 \cdot \varphi \cdot \phi + d_{1,j} \cdot e^{\frac{-g}{p_1}} + d_{2,j} \cdot e^{\frac{-g}{p_2}} + d_{3,j} \cdot cos(\frac{g - p_3}{p_4})$$

g: moon's phase angle
θ and Φ: selenographic lat/lon observer
φ: selenographic sun's longitude

*Kieffer and Stone, 2005

New features and improvements over the standard model

THE NEW CE318-T

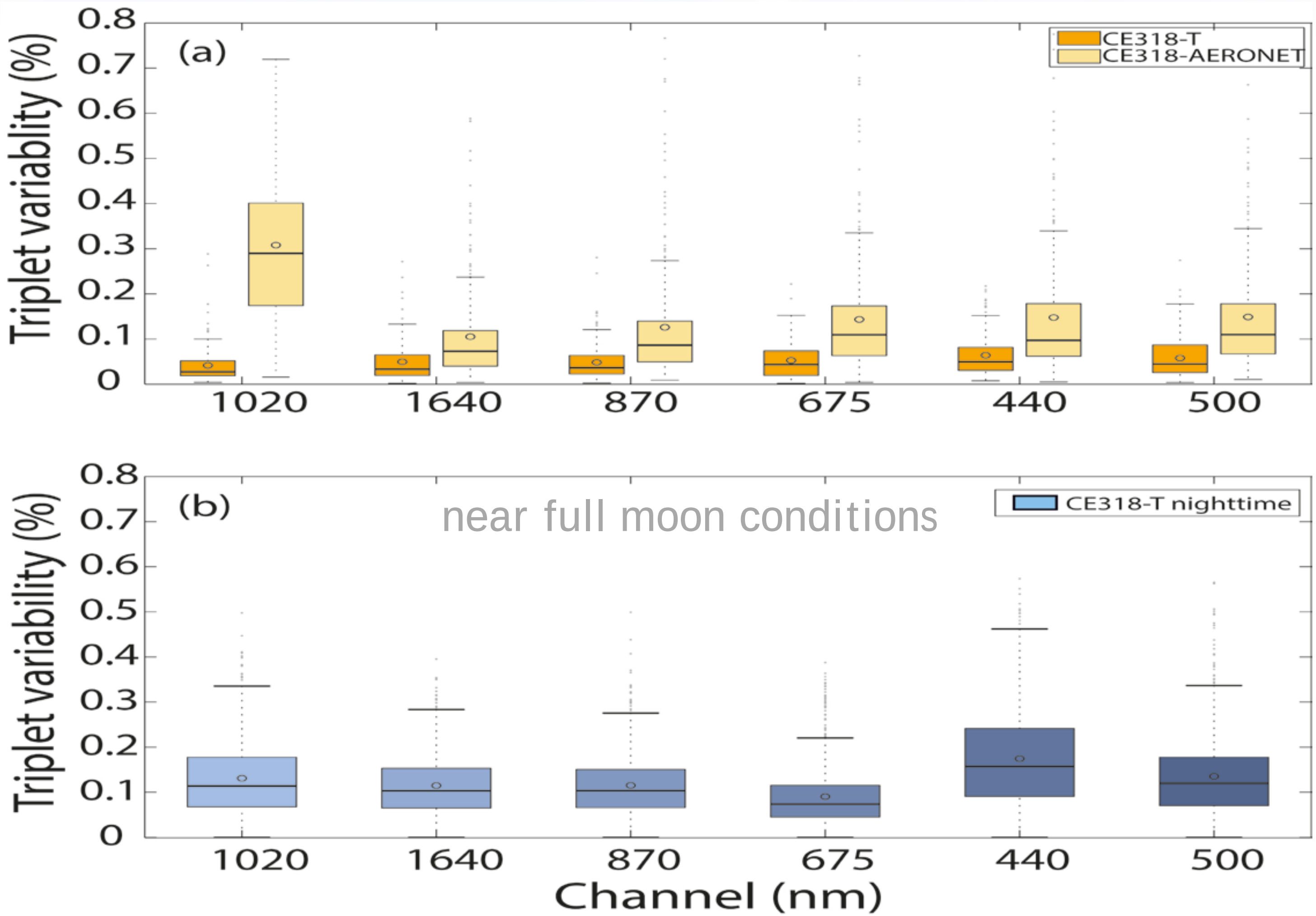
The new CE318-T

DAYTIME

NIGHTTIME

CE318-T. New features

New tracking system



CE318-T. New features

- New tracking system
- GPS positioning
- P measurements
- Robot controlled by micro-stepping
- ...

GAW REPORT

HOW TO ESTIMATE THE INSTRUMENT'S UNCERTAINTY

Instrument's uncertainty

WORLD METEOROLOGICAL ORGANIZATION
GLOBAL ATMOSPHERE WATCH

No. 162

WMO/GAW EXPERTS WORKSHOP ON A GLOBAL SURFACE-BASED NETWORK FOR LONG TERM OBSERVATIONS OF COLUMN AEROSOL OPTICAL PROPERTIES

Davos, Switzerland, 8-10 March 2004

2005

1. Standards

In most cases, the dominant uncertainty terms in AOD determination are the representative top-of-the–atmosphere signal and the measured transmission signal scaled by representative air mass. The calibration process for determination of either S_o or the top-of-atmosphere irradiance $E_o(\lambda_i)$ and a measured irradiance signal have not been standardized and are largely up to individual network operators. There is no world-community-acceptable and realisable method based on traceable physical quantities to determine these most fundamental of quantities for routine spectral solar observations to determine AOD.

The preferred methods of traceability are either inter-comparisons of network-representative reference instruments or co-location of representative network instruments with one or more instruments directly traceable to the WORCC standards.

As traceability is not currently possible based on physical measurement systems, the initial form of traceability will be based on difference criteria. That is, at an inter-comparison or co-location, traceability will be established if the difference between one network's AOD and another's is within specific limits. Those limits will be dependent on the derivation methodology as each measurement system has a different uncertainty profile.

(1) U_{95} <0.005 + 0.010/m_a for finite fov transmission measurements;
(2) U_{95} <0.025 for 2π instruments, and
(3) U_{95} <0.020 for non-linear scattered extinction methods.

$$U_{95} = \pm(0.005 + {}^{0.010}/_{m_a})$$

DAYTIME AOD EVALUATION AT IZAÑA

RESULTS

Daytime AOD evaluation at IZO

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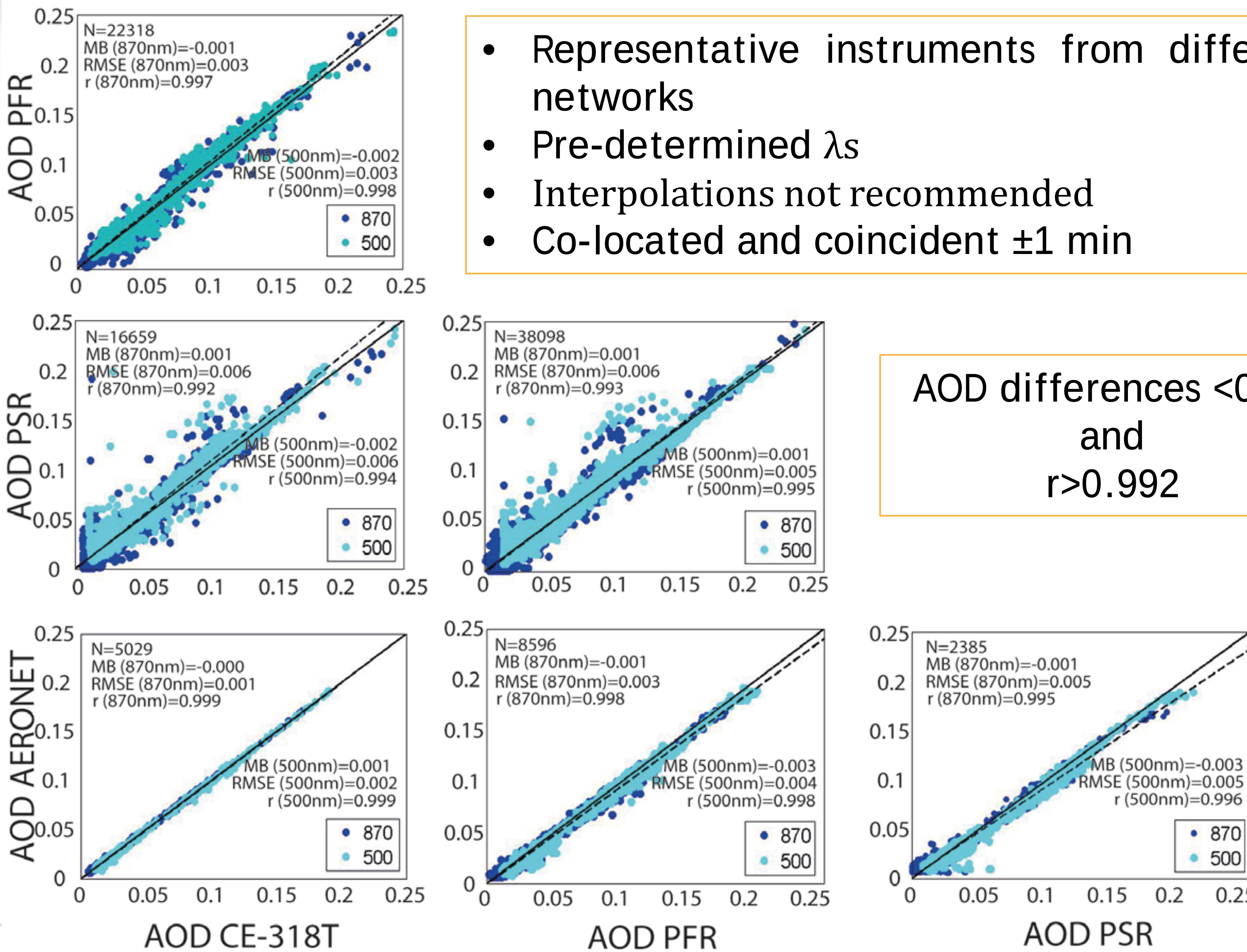
AOD accuracy ≈ 0.01

AOD accuracy < 0.01

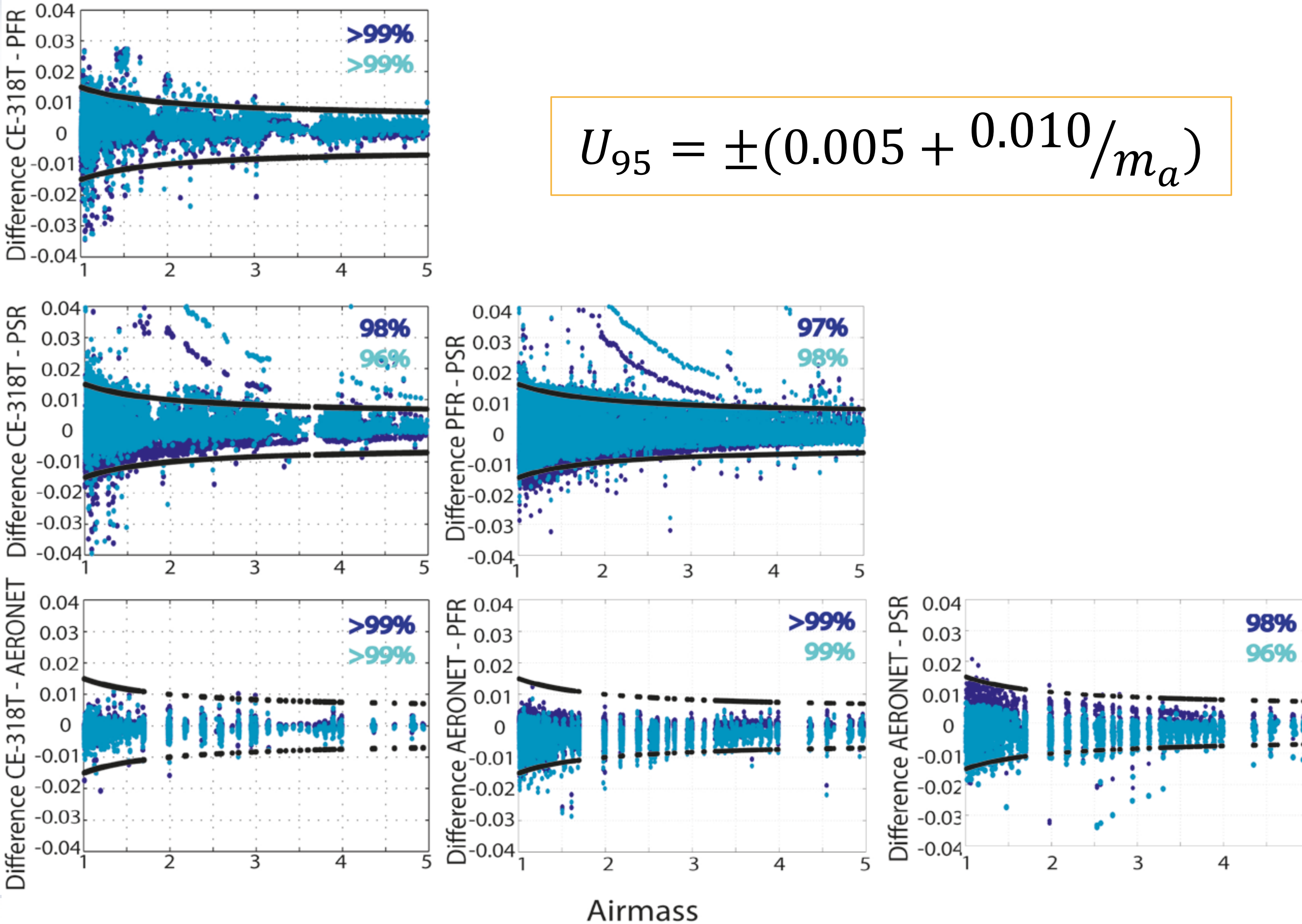
Daytime AOD evaluation at IZO



- Representative instruments from different networks
- Pre-determined λs
- Interpolations not recommended
- Co-located and coincident ±1 min

AOD differences <0.01
and
r>0.992

Daytime AOD evaluation at IZO



$$U_{95} = \pm(0.005 + {}^{0.010}/_{m_a})$$

Daytime AOD evaluation at IZO

- ❑ Good performance of CE318-T at daytime (ΔAOD<0.01)
- ❑ Also confirmed using WMO U95 criteria
- ❑ CE318-T accuracy at least similar than CE318-AERONET and PFR
- ❑ Expected better accuracy
  - Pressure measurements
  - Improved pointing accuracy
  - Syncronization by GPS
  - ...

NIGHTTIME AOD EVALUATION AT GRANADA

RESULTS

Nighttime AOD evaluation at GRA

Excalibur star-photometer
University of Granada, IISTA-CEAMA

CELESTRON CGR 1100

+

Filter wheel
380, 436, 500,670, 880, 940,1020

+

Atm. Extinction

Pointing

Accuracy (Pérez-Ramírez, 2011)
$\approx 0.02\ \lambda < 800\,\mathrm{nm}$
$\approx 0.01\ \lambda > 800\,\mathrm{nm}$

Cloud screening: Pérez-Ramírez, 2011

Nighttime AOD evaluation at GRA

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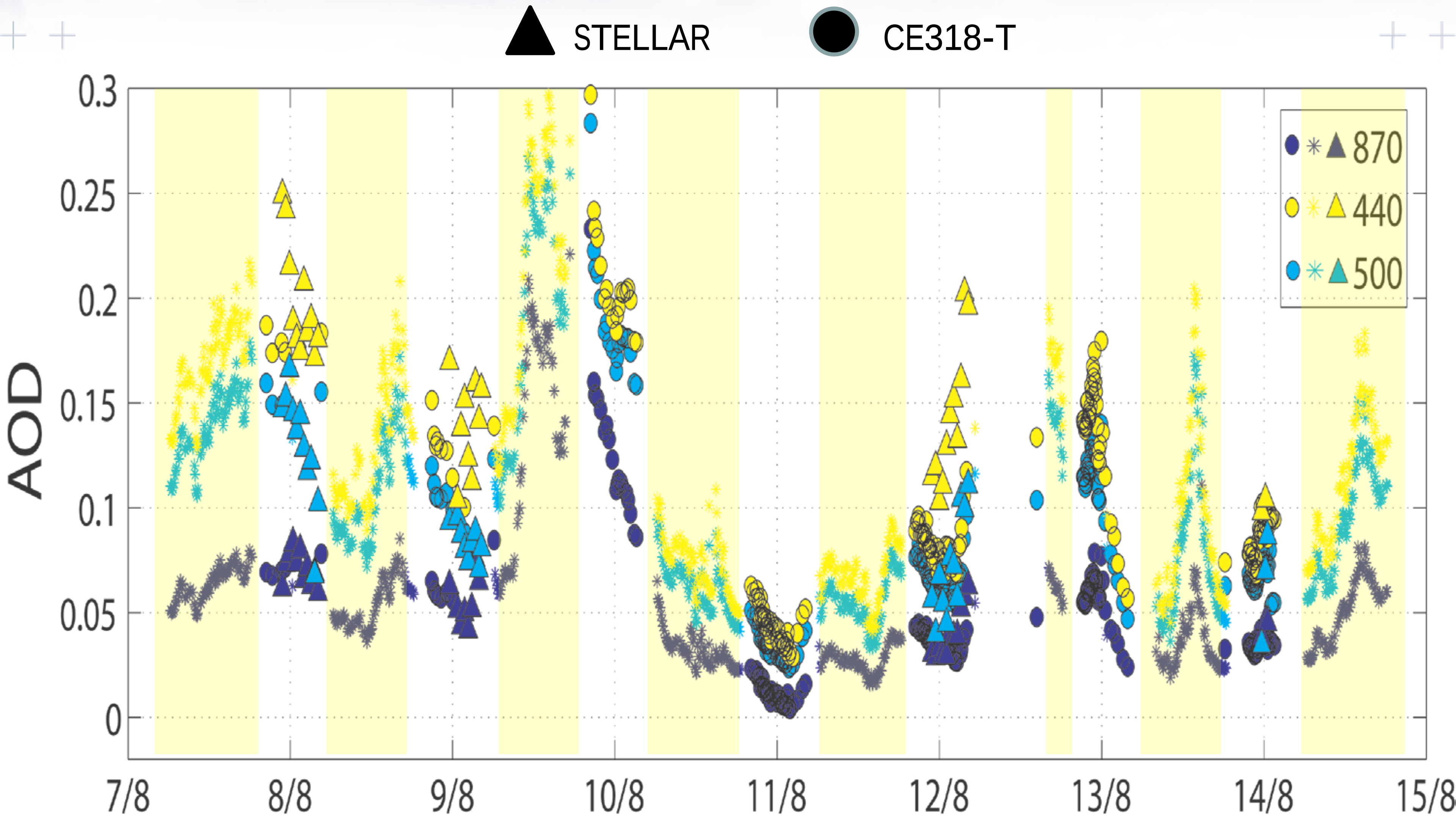
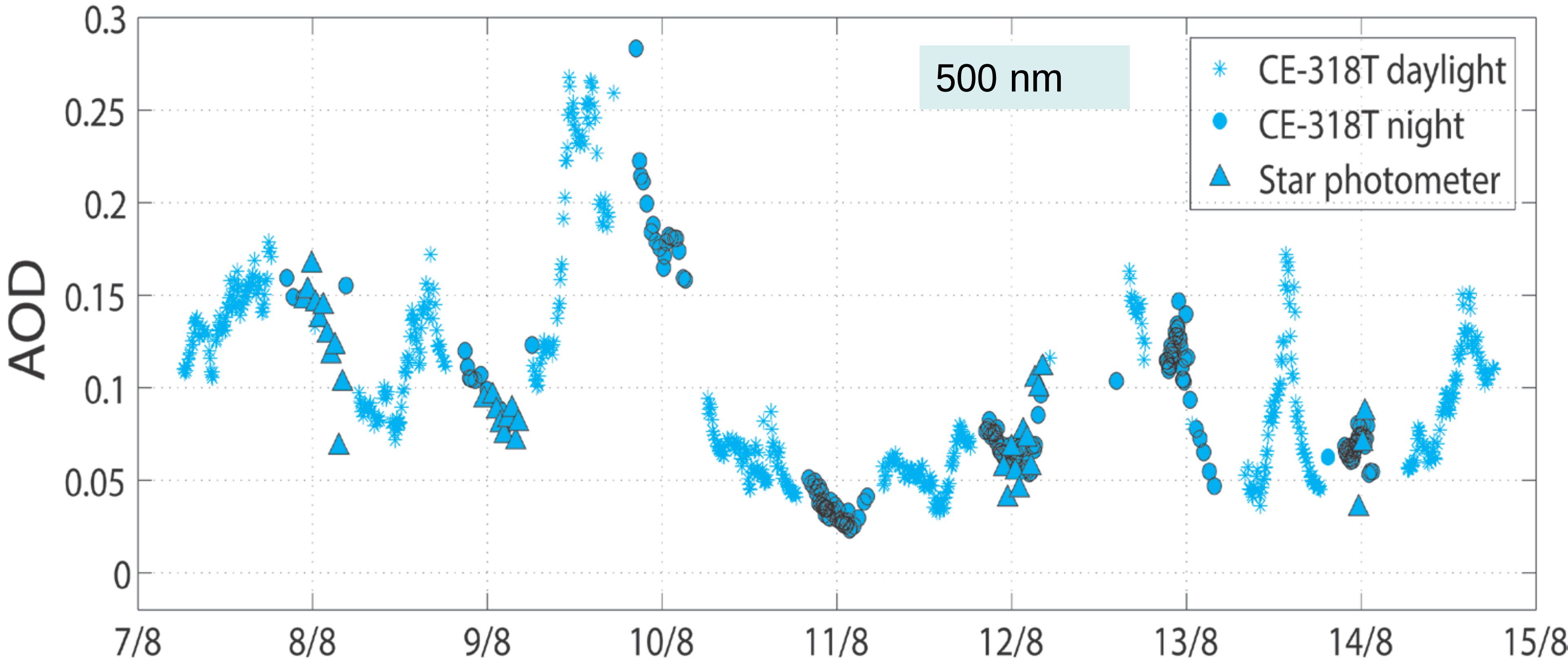


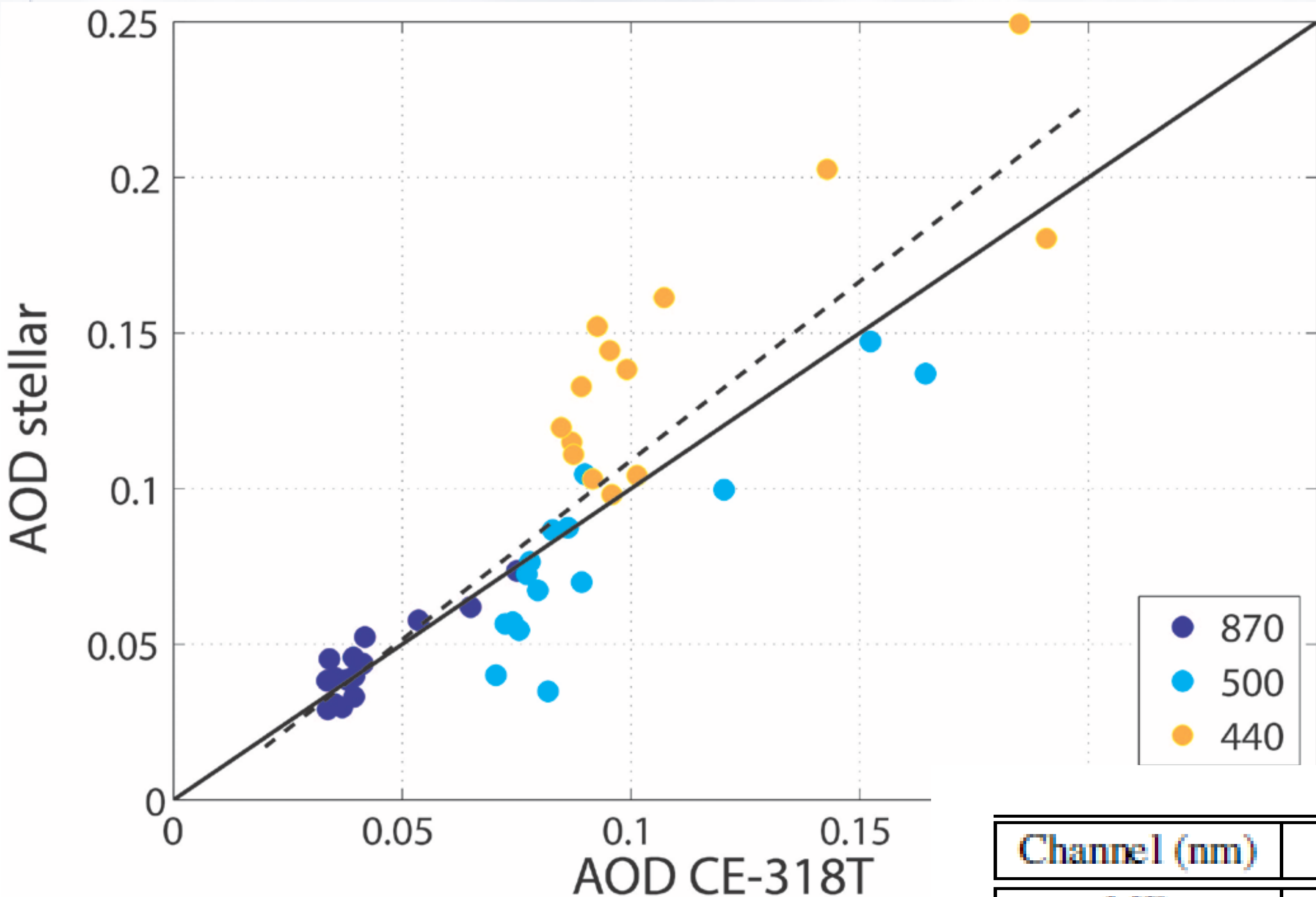
Nighttime AOD evaluation at GRA

Good agreement between the three measurements for 870 nm and 500 nm



Nighttime AOD evaluation at GRA

Scatterplots of AOD Stellar and AOD CE318-T



Channel (nm)	870	500	440
MB	-0.001	0.013	-0.033
RMSE	0.003	0.009	0.018
r	0.946	0.937	0.911
N	15	15	14

¿?

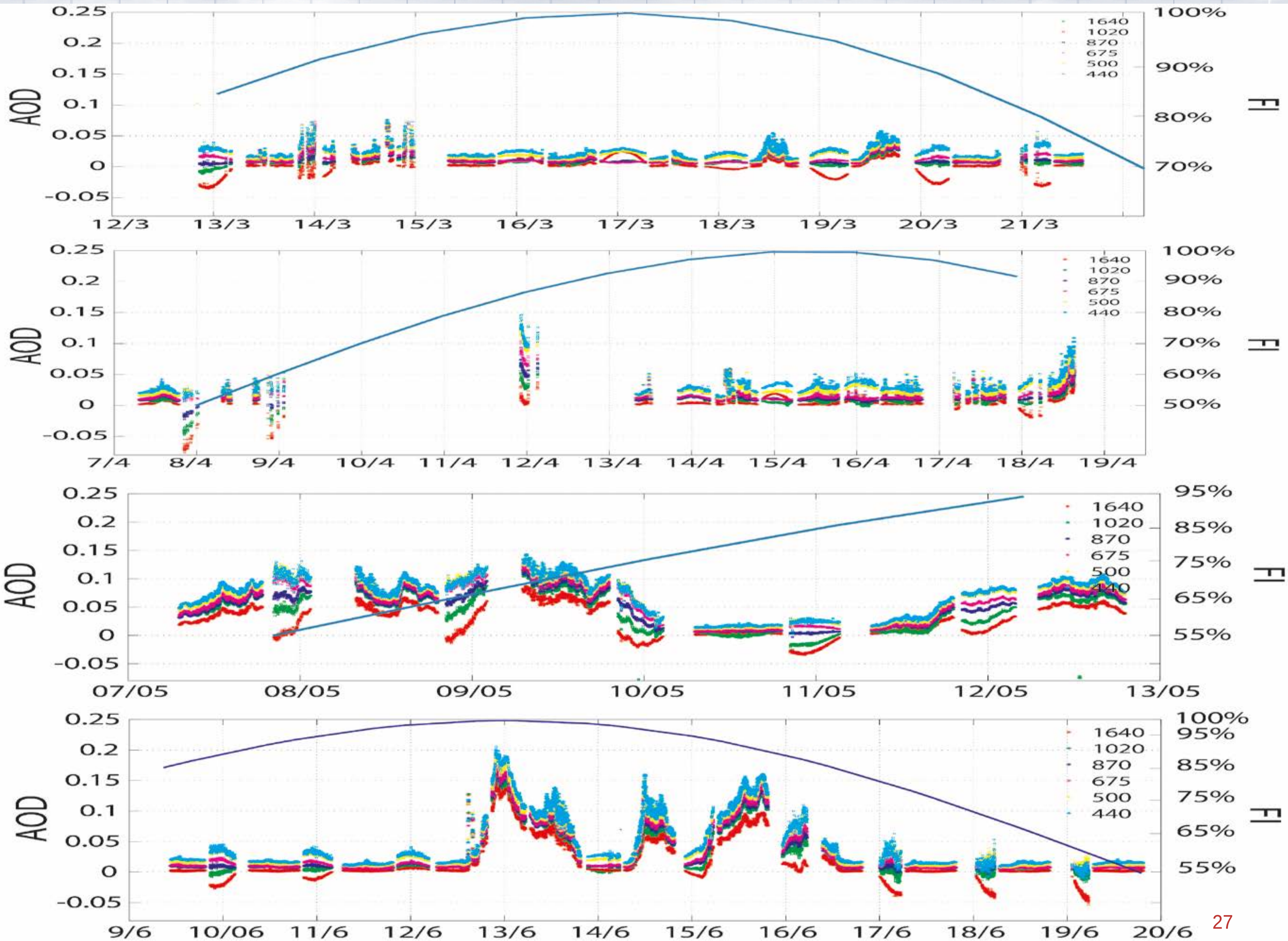
Nighttime AOD evaluation at GRA

- This is first attempt for CE318-T evaluation at nighttime.
- Different conditions and aerosols types than those in Izaña.
- Good agreement between techniques.
- Lower instrumental and calibration complexities of the CE318-T result in more information available for aerosol characterization. But ROLO…
- Promising results but is needed to extend them to wider aerosol conditions and to a greater number of instruments.

AOD DAY/NIGHT TRANSITION COHERENCE TEST AT IZAÑA

RESULTS

AOD coherence test at IZO



AOD coherence test at IZO

Only for stable AOD conditions

Table 4: MB and RMSE values for AOD differences extracted from AERONET daytime and CE318-T nighttime data during sunset-moonrise (SS-MR, defined as the last 1-h of daytime data versus the first 1-h of nocturnal data) as a function of the average moon's fraction of illumination (FI).

	SS-MR							
	# cases		1020	1640	870	675	500	440
60% ≥ FI > 50%	2	MB	0.035	0.061	0.012	-0.015	-0.008	-0.019
		RMSE	0.037	0.062	0.017	0.018	0.014	0.022
70% ≥ FI > 60%	2	MB	0.029	0.051	0.008	-0.014	-0.007	-0.015
		RMSE	0.029	0.051	0.009	0.014	0.008	0.016
80% ≥ FI > 70%	1	MB	0.048	0.056	0.024	0.008	0.016	0.006
		RMSE	— — —	— — —	— — —	— — —	— — —	— — —
90% ≥ FI > 80%	4	MB	0.016	0.027	0.001	-0.010	-0.012	-0.016
		RMSE	0.018	0.027	0.003	0.011	0.013	0.016
95% ≥ FI > 90%	3	MB	0.001	0.010	-0.004	-0.010	-0.016	-0.016
		RMSE	0.003	0.010	0.006	0.012	0.017	0.017
FI ≥ 95%	8	MB	0.015	0.009	0.014	0.013	0.010	0.012
		RMSE	0.008	0.006	0.008	0.008	0.008	0.008

λ≤870 nm ΔAOD≤0.020
1640 and 1020nm --- ΔAOD up to 0.06 at low FI

Before FM

Table 5: MB and RMSE values for AOD differences extracted from CE318-T between daytime and nighttime data during moonset-sunrise (MS-SR, as the first 1-h of daytime data versus the last 1-h of nocturnal data) as a function of the average moon's fraction of illumination (FI).

	MS-SR							
	# cases		1020	1640	870	675	500	440
50% ≥ FI > 60%	1	MB	0.012	0.046	0.003	-0.009	-0.008	-0.006
		RMSE	—	—	—	—	—	—
60% ≥ FI > 70%	1	MB	0.007	0.039	-0.002	-0.014	-0.005	-0.015
		RMSE	—	—	—	—	—	—
80% ≥ FI > 70%	2	MB	0.007	0.034	-0.001	-0.012	-0.012	-0.017
		RMSE	0.010	0.034	0.003	0.012	0.013	0.017
90% ≥ FI > 80%	4	MB	0.012	0.023	0.009	0.002	-0.001	-0.001
		RMSE	0.002	0.012	0.001	0.006	0.009	0.009
95% ≥ FI > 90%	4	MB	0.011	0.016	0.007	-0.002	-0.002	-0.001
		RMSE	0.015	0.018	0.011	0.009	0.011	0.010
FI ≥ 95%	11	MB	-0.001	-0.003	-0.002	-0.004	-0.009	-0.006
		RMSE	0.002	0.004	0.002	0.004	0.008	0.006

λ≤1020 nm ΔAOD≤0.015
1640 nm --- ΔAOD up to 0.05 at low FI

After FM

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PWV VALIDATION AT IZAÑA AND GRANADA STATIONS

RESULTS

PWV validation at IZO and GRA

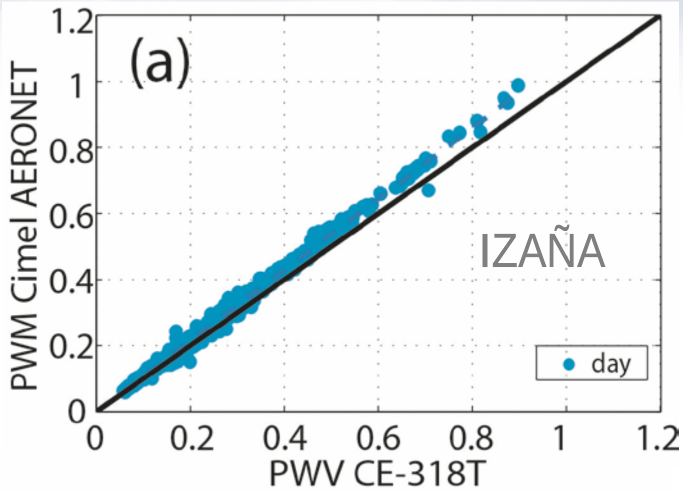
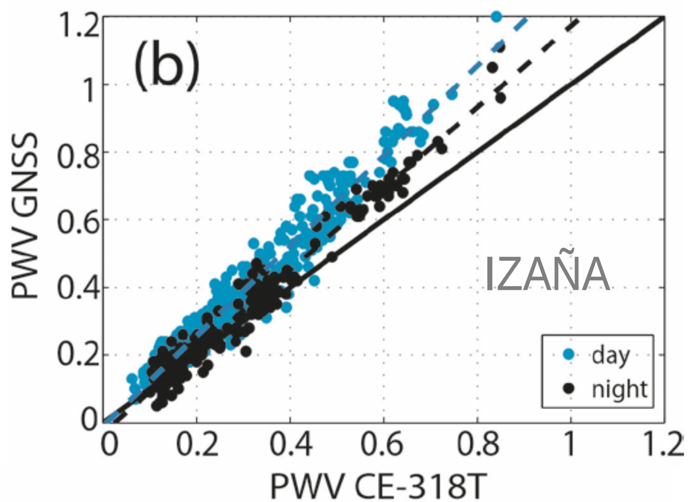
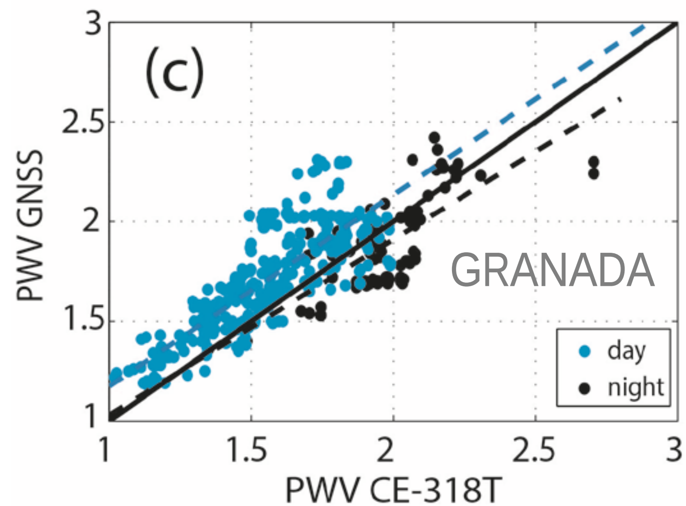


Table 6: Main statistics of the PWV comparison (in cm) extracted from CE318-T, AERONET and GNSS for daytime data, and from CE318-T and GNSS for nocturnal data. In case of nighttime information a comparison in function of the moon's fraction of illumination (FI, in %) is also included.

	DAY			
Instruments	MB	RMSE	r	N
CE318-T/Cimel AERONET	-0.02	0.02	0.99	1935
CE318-T/GNSS	-0.09	0.05	0.97	461
CE318-T/GNSS	NIGHT			
60% ≥ FI > 50%	-0.08	0.09	0.99	10
70% ≥ FI > 60%	-0.07	0.08	0.99	10
80% ≥ FI > 70%	-0.01	0.02	0.98	10
90% ≥ FI > 80%	-0.03	0.07	0.99	43
95% ≥ FI > 90%	-0.03	0.06	0.98	41
100% ≥ FI > 95%	-0.02	0.05	0.99	93
TOTAL				**207**





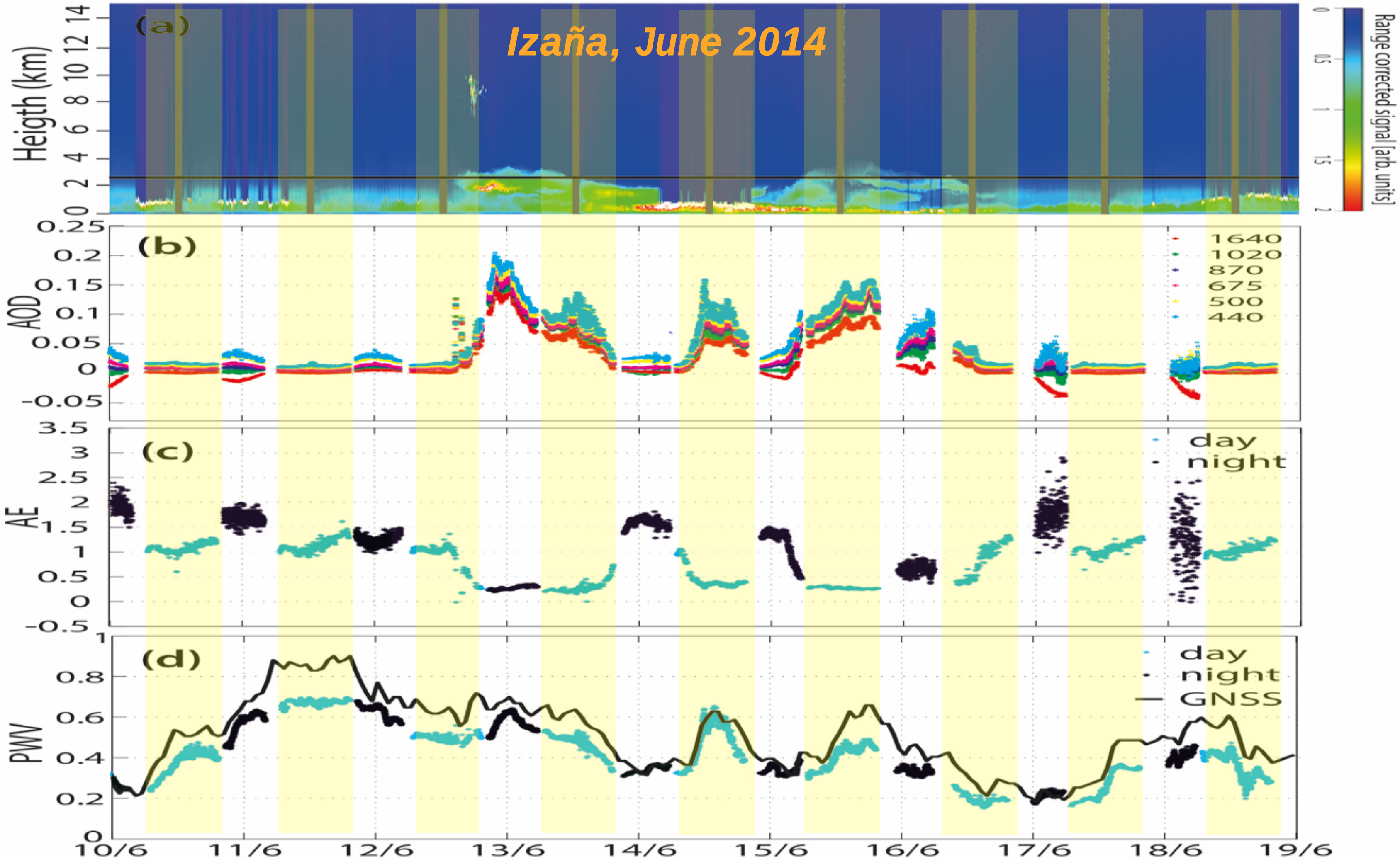
PWV precision*: Cimel 7% for PWV>0.7cm
25% for dry conditions
GPS <10% for PWV>0.35cm
20% for drier conditions

*(Schneider et al. 2010)

CASE STUDIES AT IZAÑA

RESULTS

Case studies at IZO



Case studies at IZO

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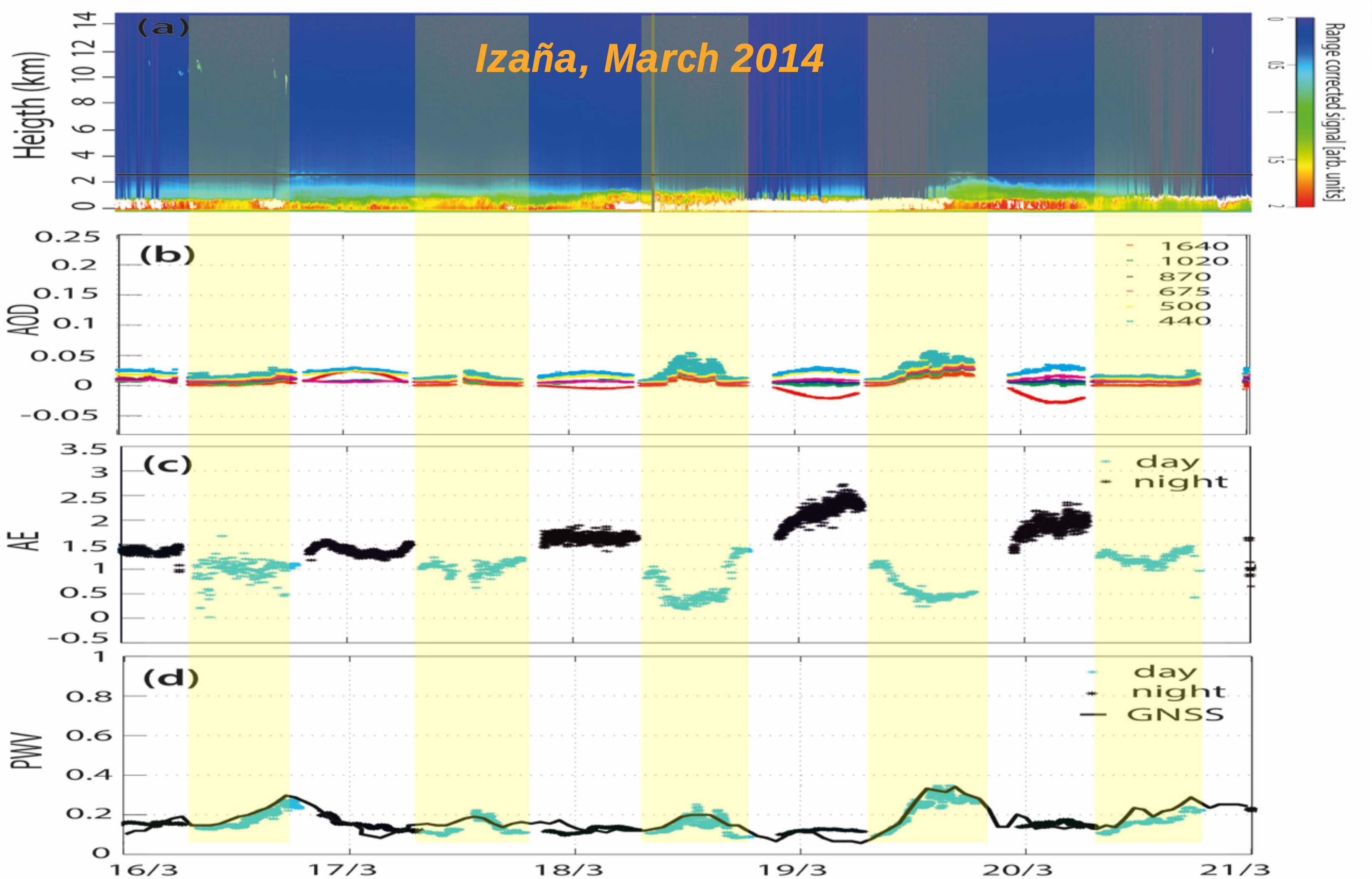


ERROR PROPAGATION THEORY

FINAL UNCERTAINTY ESTIMATION

TERMS INVOLVED:

$$AOD_j = \frac{\ln(V_j) - \ln(V_{0,j}) - m_{atm}(\theta) \cdot \tau_{atm,j}}{m_a(\theta)}$$

$$u_{AOD} = \sqrt{\frac{1}{m^2}\left[\cdot \left(\frac{\delta AOD}{\delta V_0}\right)^2 \cdot u^2(V_0) + \left(\frac{\delta AOD}{\delta V}\right)^2 \cdot u^2(V) + \left(\frac{\delta AOD}{\delta m}\right)^2 \cdot u^2(m)\right]}$$

Uncertainty in V_0 determination

Instrumental error

In air-mass calculation

DAYTIME

$$u^D_{AOD} = \frac{1}{m} \cdot \frac{u(V_0)}{V_0}$$

NIGHTTIME

$$V_{0,j} = I_{0,j} \cdot \kappa_j \longrightarrow AOD_j = \frac{\ln\left(\frac{V_j}{I_{0,j}}\right) - \ln(\kappa_j) - m_{atm}(\theta) \cdot \tau_{atm,j}}{m_a(\theta)}$$

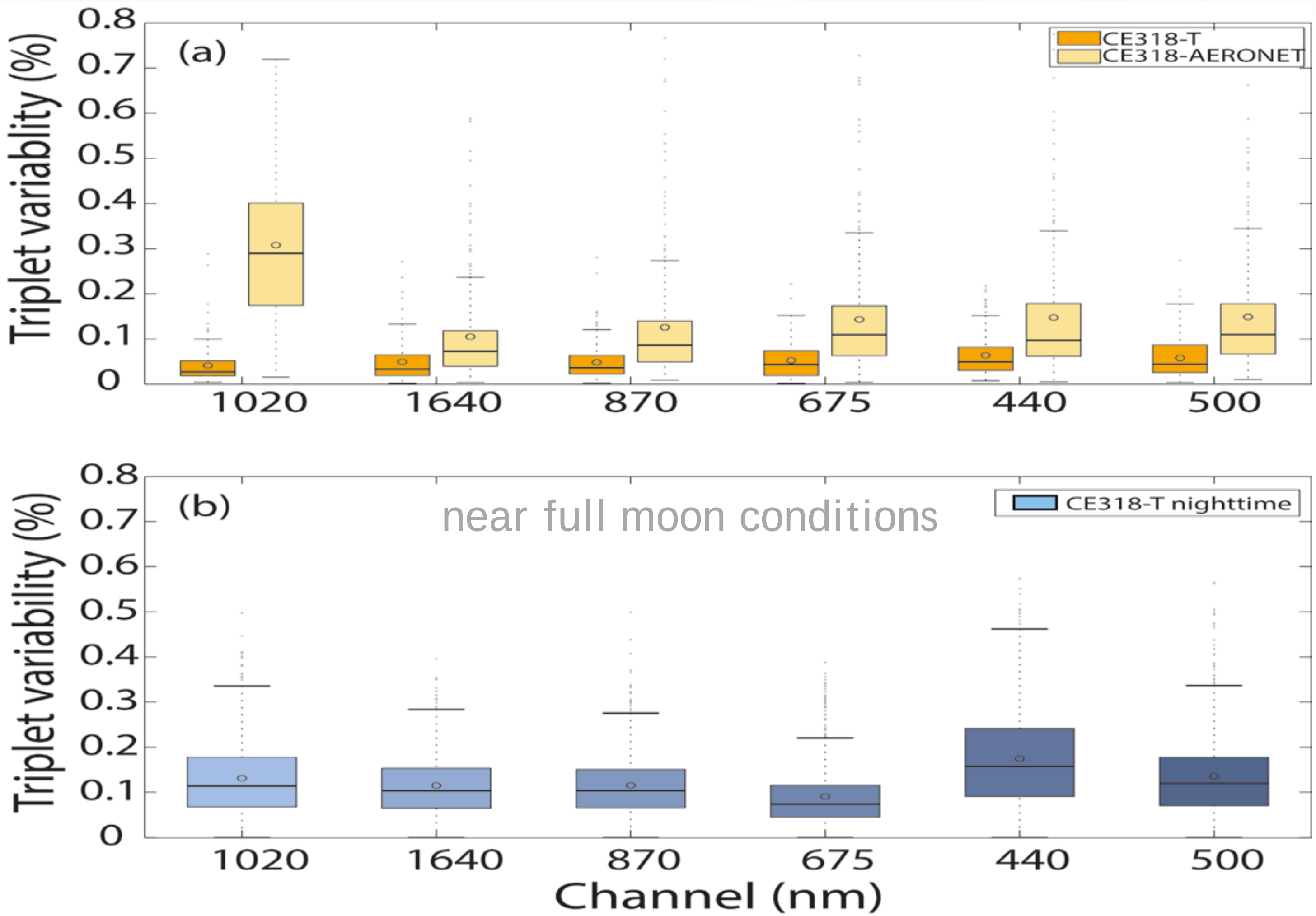
$$u_{AOD}^{N\,2} = \frac{1}{m^2}\left(\frac{u^2(\kappa)}{\kappa^2} + \frac{u^2(I_0)}{I_0^2} + \frac{u^2(V)}{V^2}\right) + \frac{2}{m^2} \cdot r_{\kappa,I_0} \cdot \left(\frac{\delta AOD}{\delta\kappa}\right) \cdot \left(\frac{\delta AOD}{\delta I_0}\right) \cdot u(\kappa) \cdot u(I_0) \sim \frac{1}{m^2}\left(\frac{u^2(\kappa)}{\kappa^2} + \frac{u^2(I_0)}{I_0^2} + \frac{u^2(V)}{V^2}\right)$$

$u(\kappa)$: Random error due to dispersion in the fitting analysis.
$u(I_0)$: Systematic error due to model's accuracy.
$u(V)$: Instrumental error (systematic).

$r(\kappa,I_0)$: covariance term due to κ and I_0 are correlated (expected – and ≈ 0).

$u(\kappa)$ REF. INSTR.: 0.004-0.014 using CV different Langleys
$u(I_0)$: Reported relative uncertainties ≤1%
$u(V)$: From triplets variability 0.2-1% (2% in 440nm)

Triplets variability (%)



NIGHTTIME

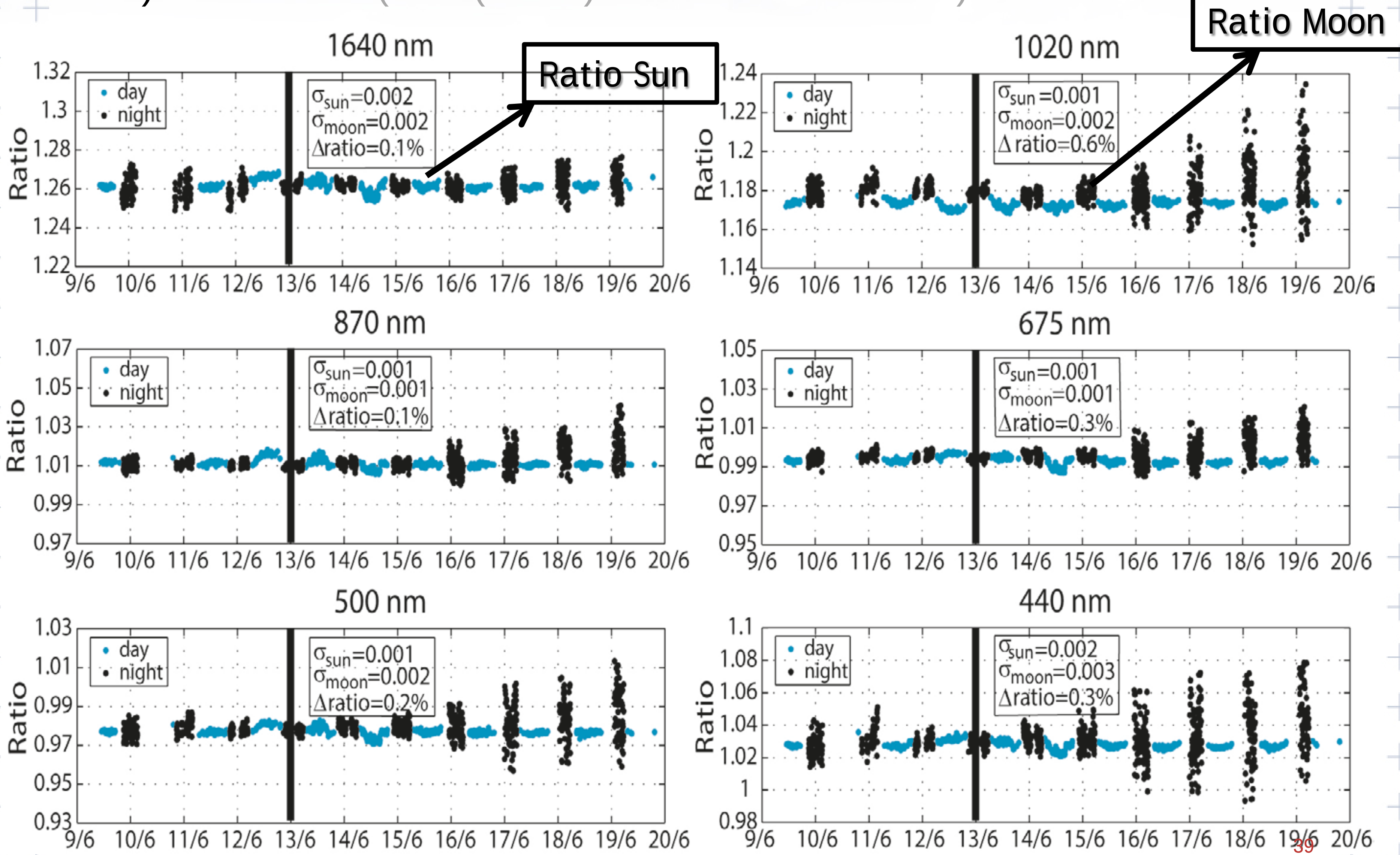
$$V_{0,j} = I_{0,j} \cdot \kappa_j \longrightarrow AOD_j = \frac{\ln\left(\frac{V_j}{I_{0,j}}\right) - \ln(\kappa_j) - m_{atm}(\theta) \cdot \tau_{atm,j}}{m_a(\theta)}$$

$$u_{AOD}^{N\,2} = \frac{1}{m^2}\left(\frac{u^2(\kappa)}{\kappa^2} + \frac{u^2(I_0)}{I_0^2} + \frac{u^2(V)}{V^2}\right) + \frac{2}{m^2} \cdot r_{\kappa,I_0} \cdot \left(\frac{\delta AOD}{\delta \kappa}\right) \cdot \left(\frac{\delta AOD}{\delta I_0}\right) \cdot u(\kappa) \cdot u(I_0) \sim \frac{1}{m^2}\left(\frac{u^2(\kappa)}{\kappa^2} + \frac{u^2(I_0)}{I_0^2} + \frac{u^2(V)}{V^2}\right)$$

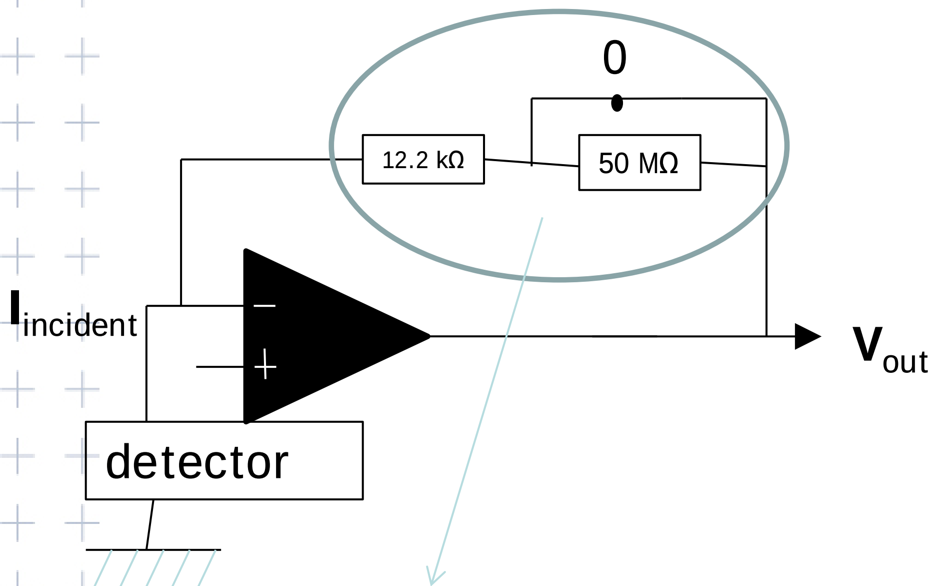
u(κ) REF. INSTR.: 0.004-0.014 using CV different Langleys
$u(I_0)$: Reported relative uncertainties ≤1%
u(V): From triplets variability 0.2-1% (2% in 440nm)

REF. INSTR: 0.011-0.016 (VIS)
0.012-0.020 (near IR)
0.023-0.024 (440 nm channel)

u(κ): 0.004-0.014 using CV different Langleys+0.003 (sigma ratio sun vs ratio moon-)+0.005-0.008 (SR –Δ(RS-RM) for 7 different heads-)



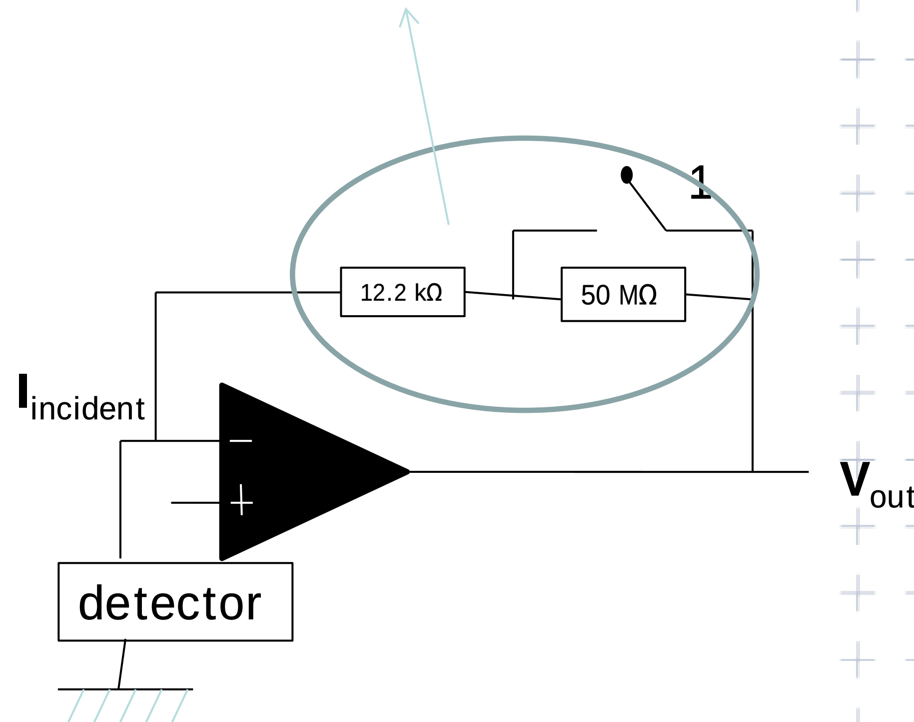
Direct SUN Mode



$$R_{eq} = \left[\frac{1}{12.2\ k\Omega} + \frac{1}{50\ M\Omega}\right] = 12197.02\ \Omega$$

Moon Sky Mode

$$R_{eq} = [12.2\ k\Omega + 50 M\Omega] = 50.0122\ M\Omega$$



u(R)<1%

SUN RATIO CAL. TECHNIQUE

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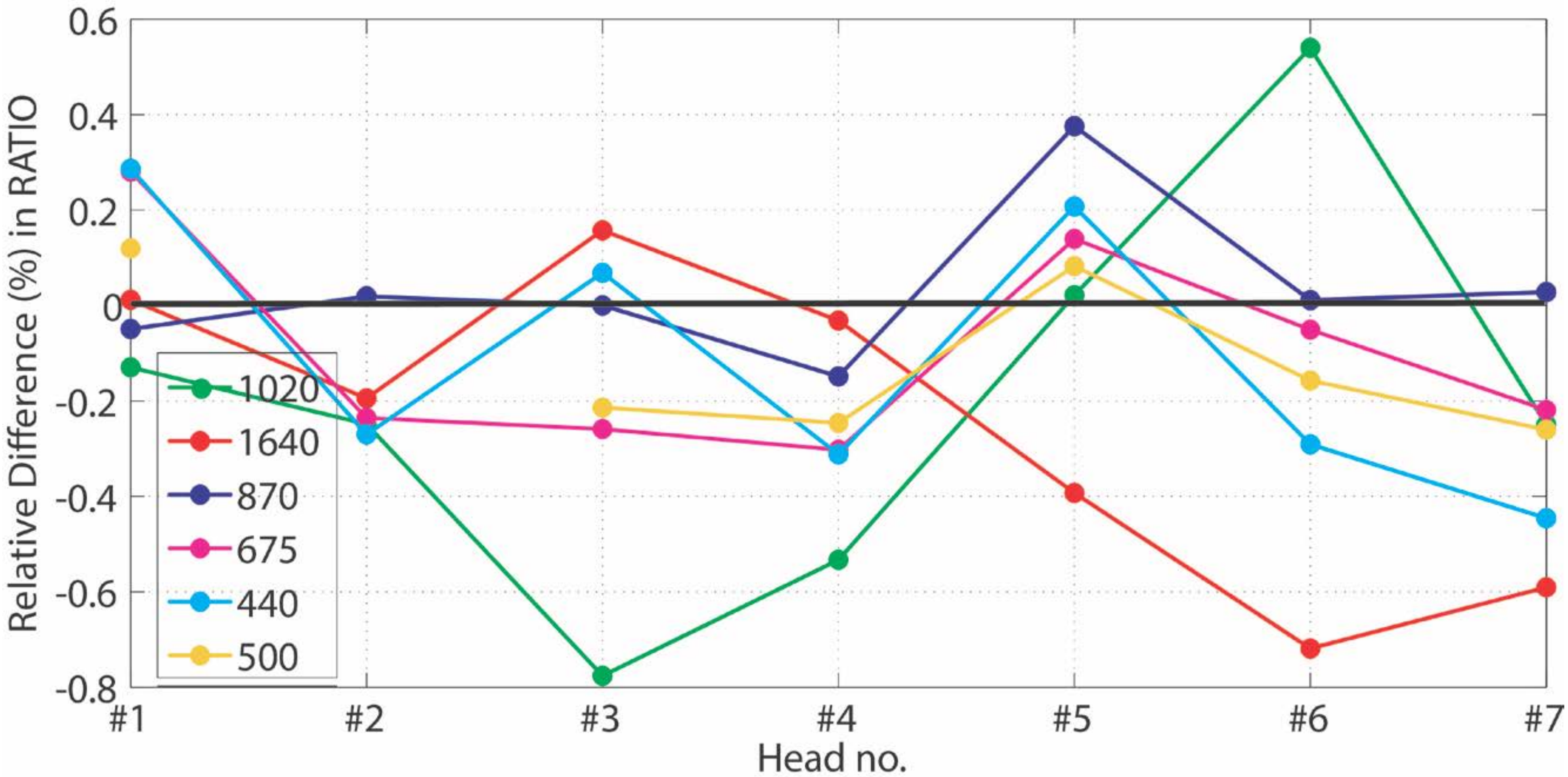
u(κ): 0.004-0.014 using CV different Langleys+0.003 (sigma ratio sun vs ratio moon-)+0.005-0.008 (RS –Δ(RS-RM) for 7 different heads-)



Final accuracy:

Reference instruments: VIS ≈ 0.011-0.016
440 nm ≈0.023-0.024
nIR ≈ 0.012-0.020

Field instruments (RM): VIS ≈ 0.011-0.017
440 nm ≈0.023-0.024
nIR ≈ 0.013-0.020

Field instruments (RS): VIS ≈ 0.012-0.017
440 nm ≈0.023-0.025
nIR ≈ 0.019-0.022

GRACIAS POR TODO!