Analysis and forecasting of weather conditions from satellite data and correlation with astronomical parameters for the E-ELT site

STEFANO CAVAZZANI
CTA Consortium
QUANTUM FUTURE Team

SERGIO ORTOLANI

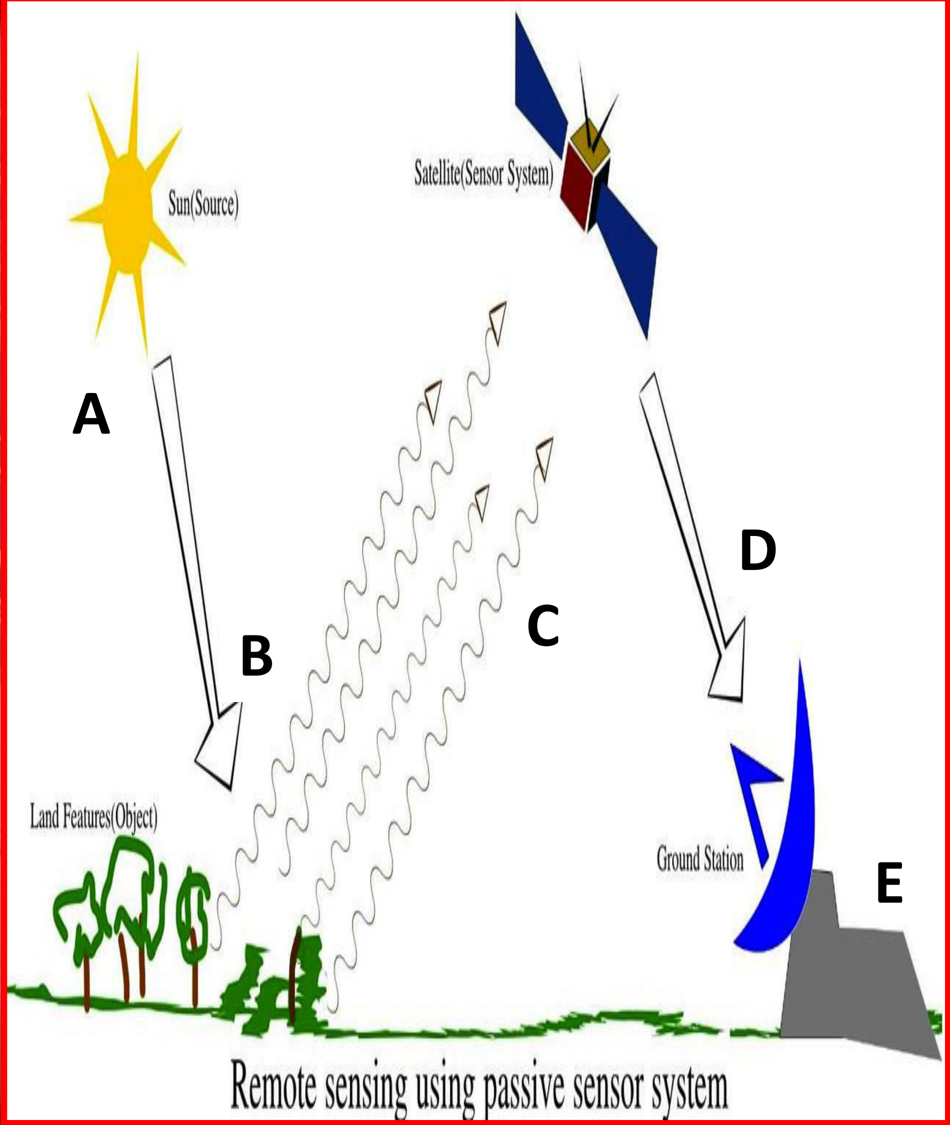
VALENTINA ZITELLI

THE OUTCOME OF THE T-REX PROJECT, the Italian Progetto premiale for E-ELT

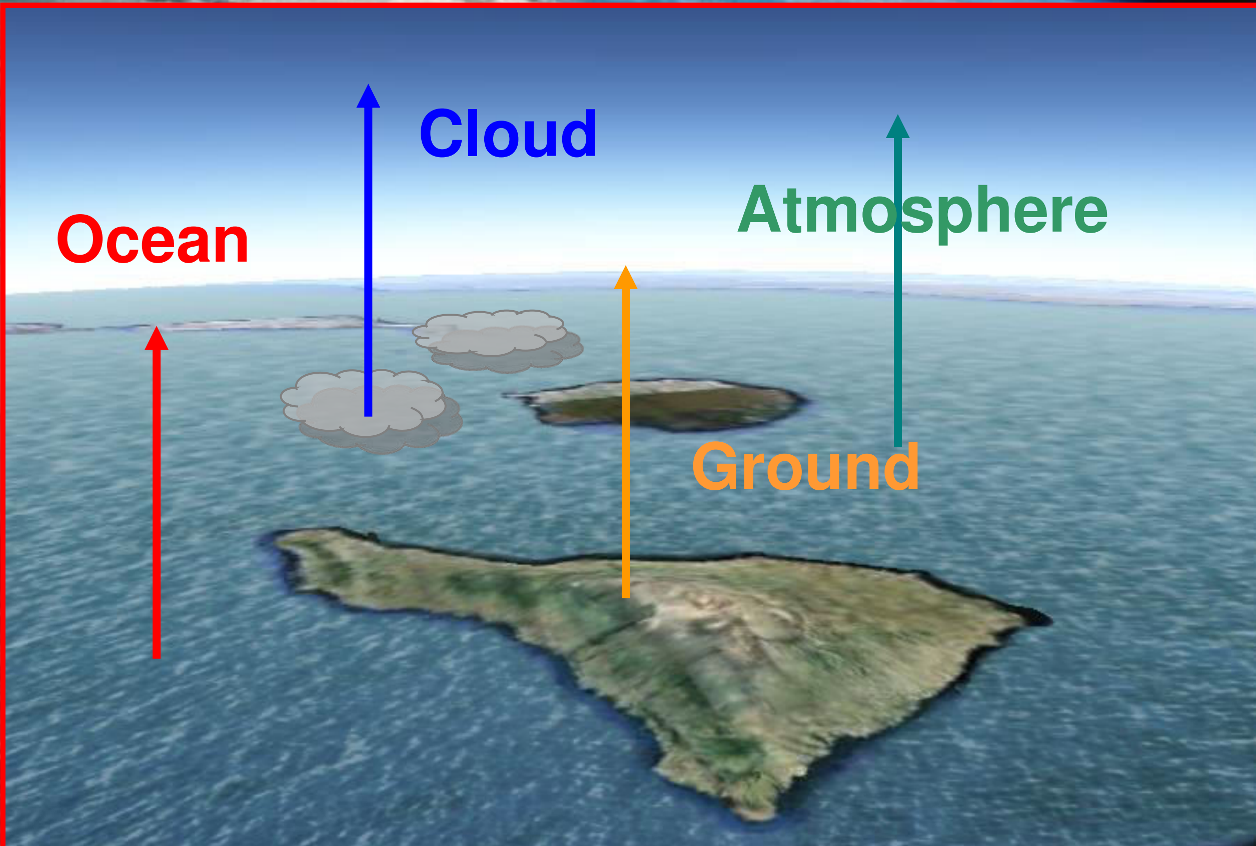
July 20-23 2015 Sexten

The Steps of Remote Sensing

A. The Sun provide electromagnetic energy
B. The energy reaches the target and interacts with it according to the target's properties
C. Energy emitted or scattered by the target is collected by the sensor
D. The sensor transmits the electronic information to a receiving and processing station and information is processed into an image
E. The processed image is than interpreted



Night Infrared Emission



During the night we observe the infrared emission and we have various components of this emission

There are no meteorological database on the night cloud cover at astronomical sites

It is very difficult to separate these components from satellite

Site Testing

- To give answer to the questions:
  - "Will the sky be clear?"
  - "Will the turbulence be strong, regular or quiet?"
- To optimize and tune the telescope instruments
- Atmospheric turbulence is one of the main limitations for ground based observations.
- Site test campaigns are limited to a short time interval and the local conditions can considerably change after the installation of new dome and buildings
- About 20% of the available science time

Great Importance of a model able to predict the atmospheric conditions

Satellite Data

- Geostationary satellites

Orbit: 36000km. They orbit always above the same point. Limited field of view.

Higher Time Resolution

- Polar satellites

Orbit: 800km. They pass over the same point about every 12 hours

Theoretical High Spatial Resolution

GOES 12

AQUA-MODIS

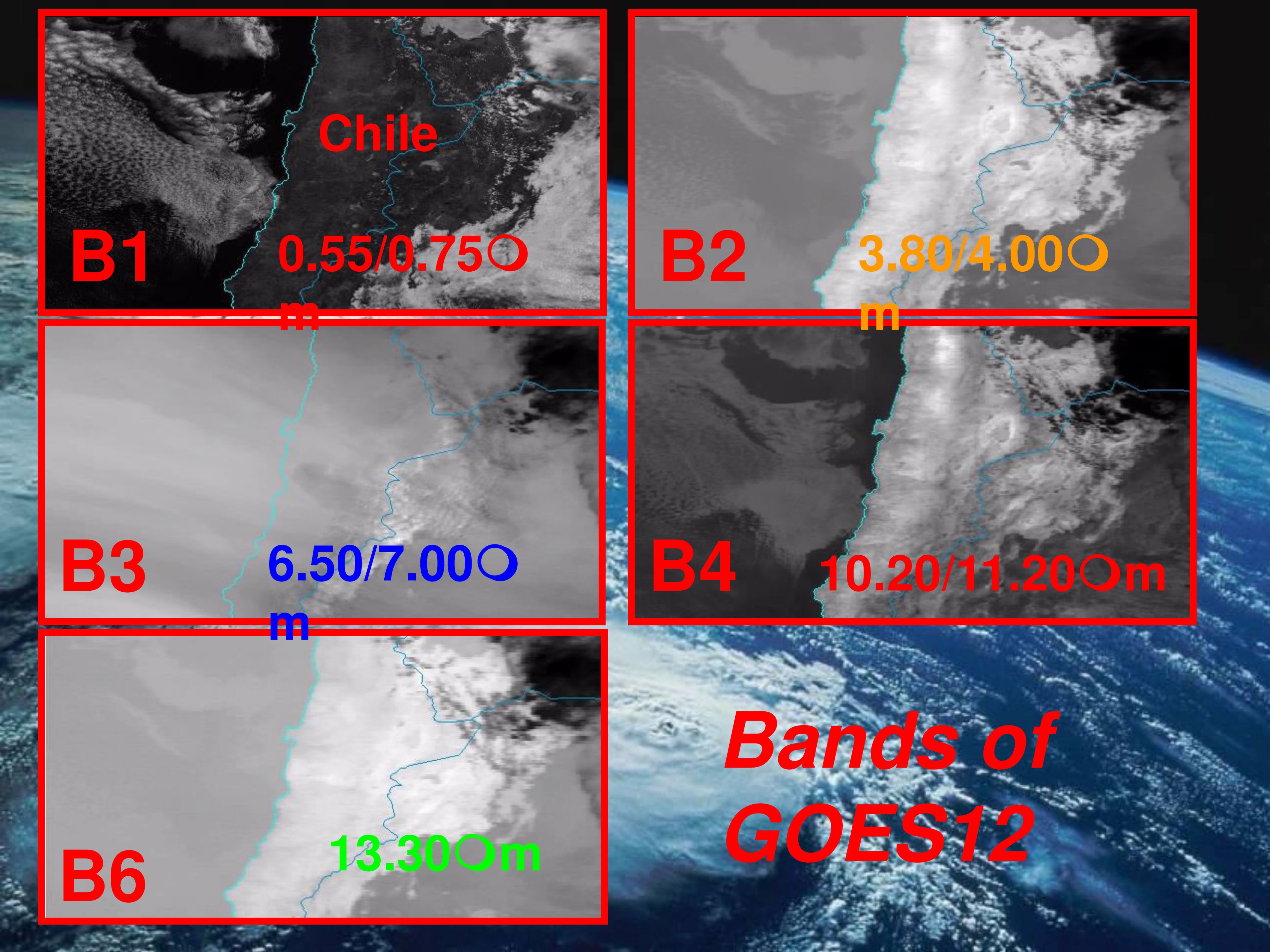
Orbit always above the same point. Limited field of view.
Higher Time Resolution.

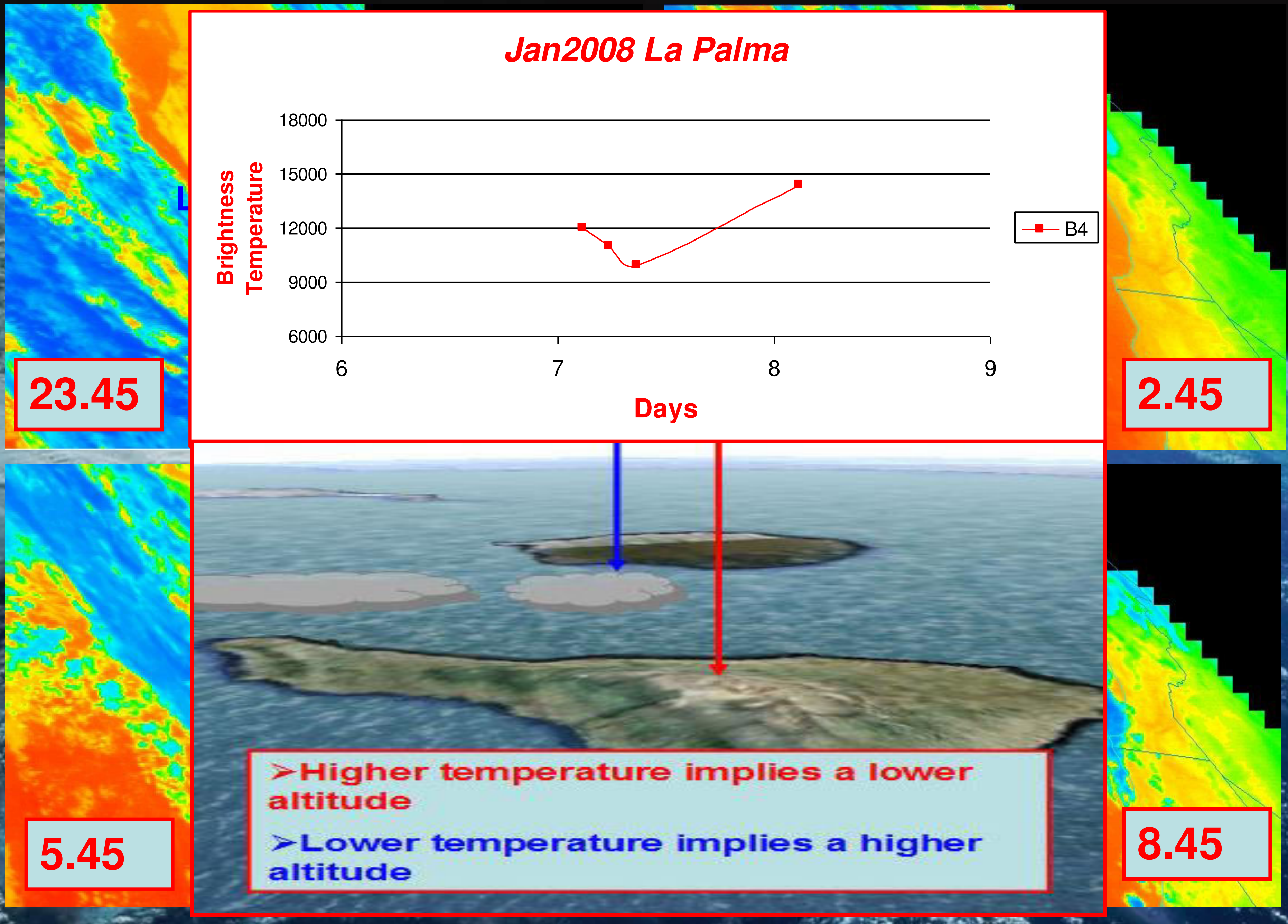
Pass over the same point about every 12 hours.
Covers the entire globe

Bands of GOES12

● Resolution

- BAND1: (Visible) 0.55/0.75μm (4Km)
- BAND2: (MW) 3.80/4.00μm (4Km)
- BAND3: (H_2O) 6.50/7.00μm (4Km)
- BAND4: (IR) 10.20/11.20μm (4Km)
- BAND6: (CO_2) 13.30μm (8Km)


Chile
B1
0.55/0.75❍m
B2
3.80/4.00❍m
B3
6.50/7.00❍m
B4
10.20/11.20❍m
B6
13.30❍m
Bands of GOES12


23.45
2.45
5.45
8.45
Jan2008 La Palma
Brightness Temperature
18000
15000
12000
9000
6000
6
7
8
9
Days
B4
➢Higher temperature implies a lower altitude
➢Lower temperature implies a higher altitude

David André Erasmus *(1955-2007)*

The pioneer of this type of analysis

- **He was member of American Meteorological Society and the American Geophysical Union**

- **Important member of ESO staff**

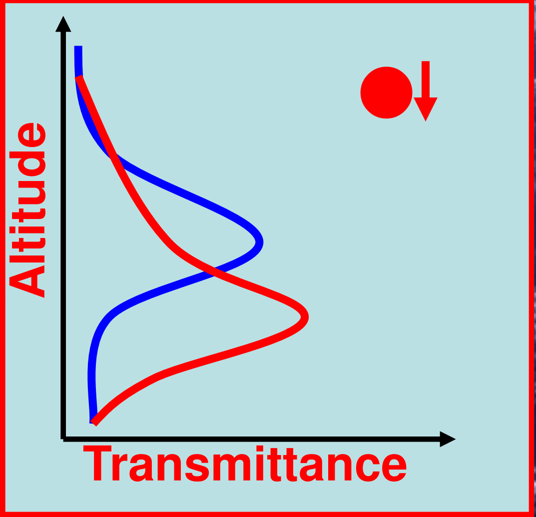
- **He was a consulting meteorologist who contributed to work on the siting of telescopes, inclusing the SALT and the ESO VLT.**

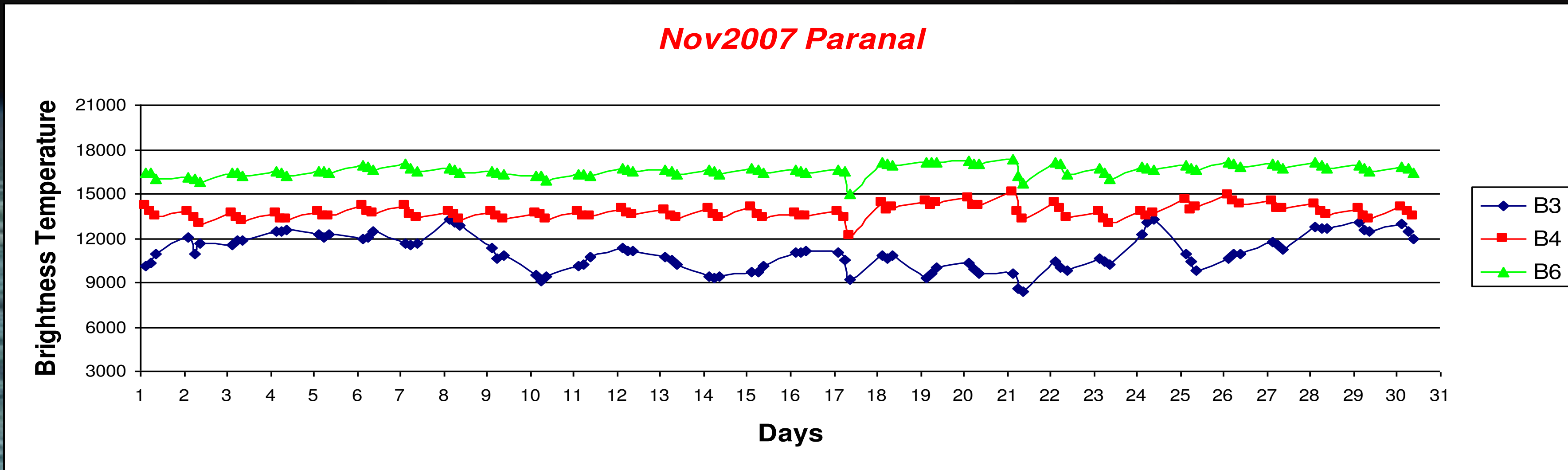
Inversion Data Method

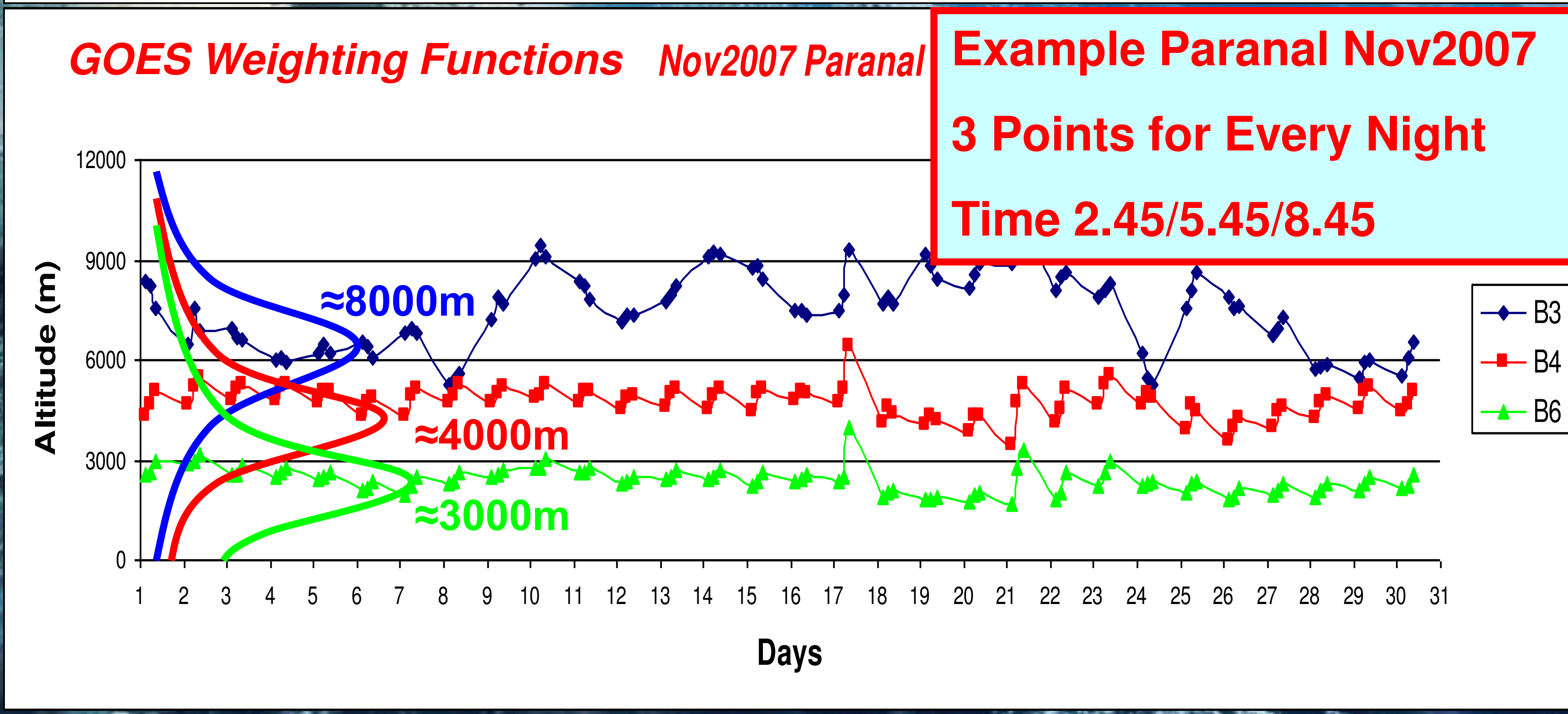
$$R_\lambda = (I_0)_\lambda \tau_\lambda(z_0) + \int_{z_0}^{\infty} B_\lambda[T(z)] K_\lambda(z)\,dz$$

- R_λ: The emitted monochromatic radiation intensity at a given ●
- $(I_0)_\lambda$: Emission from the earth surface at height z_0
- $\tau_\lambda(z_0)$: Vertical transmittance from height z to space
- $B_\lambda[T(z)]$: Planck function profile as function of vertical temperature profile T
- $K_\lambda(z)$: **Weighting Function (WF)** Specifies the layer from which the radiation emitted, determines the region of the atmosphere which can be sensed from space at fixed ●

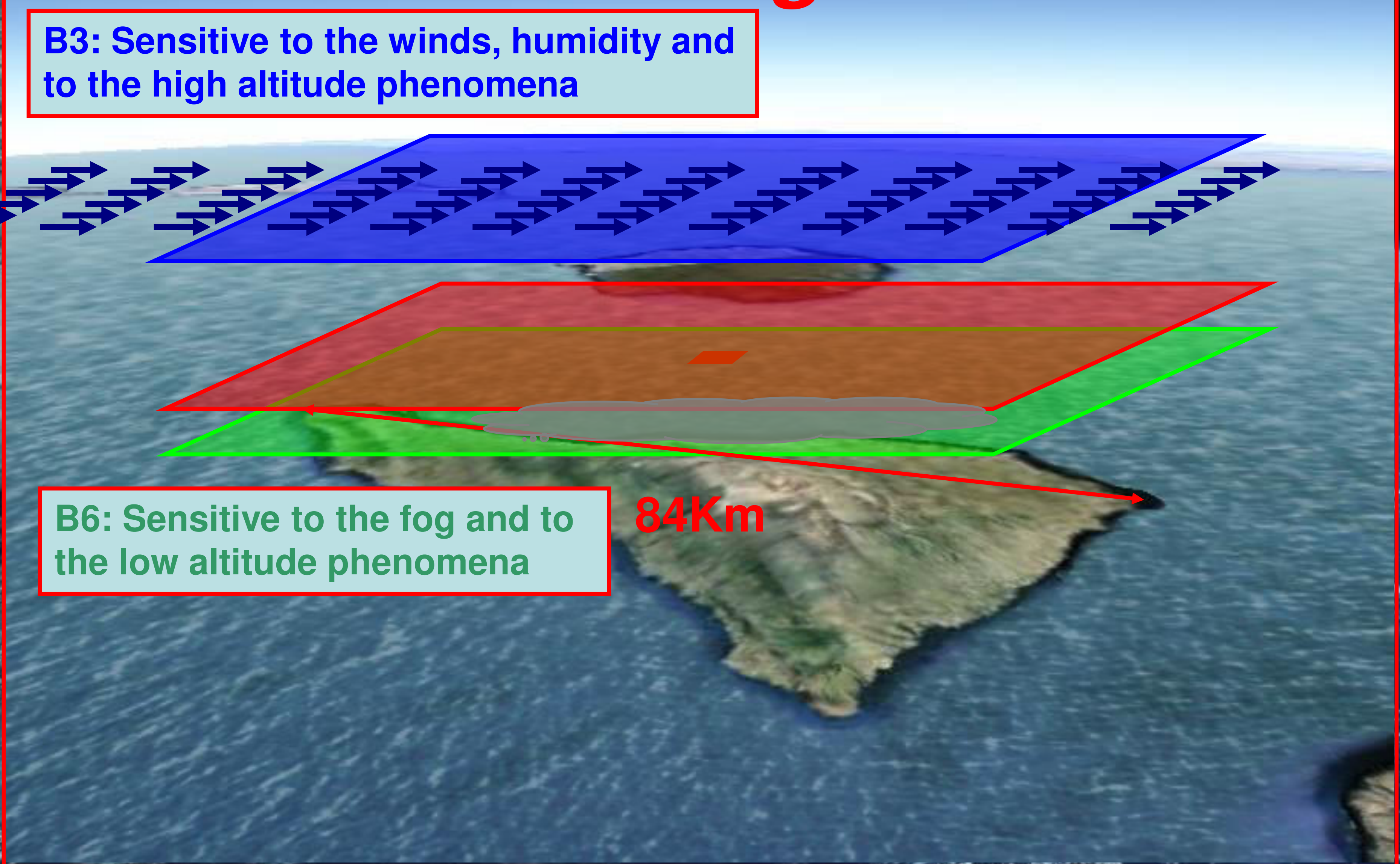
$$\frac{d\tau_\lambda(z)}{dz}$$




Nov2007 Paranal
Brightness Temperature
21000
18000
15000
12000
9000
6000
3000
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
Days
B3
B4
B6

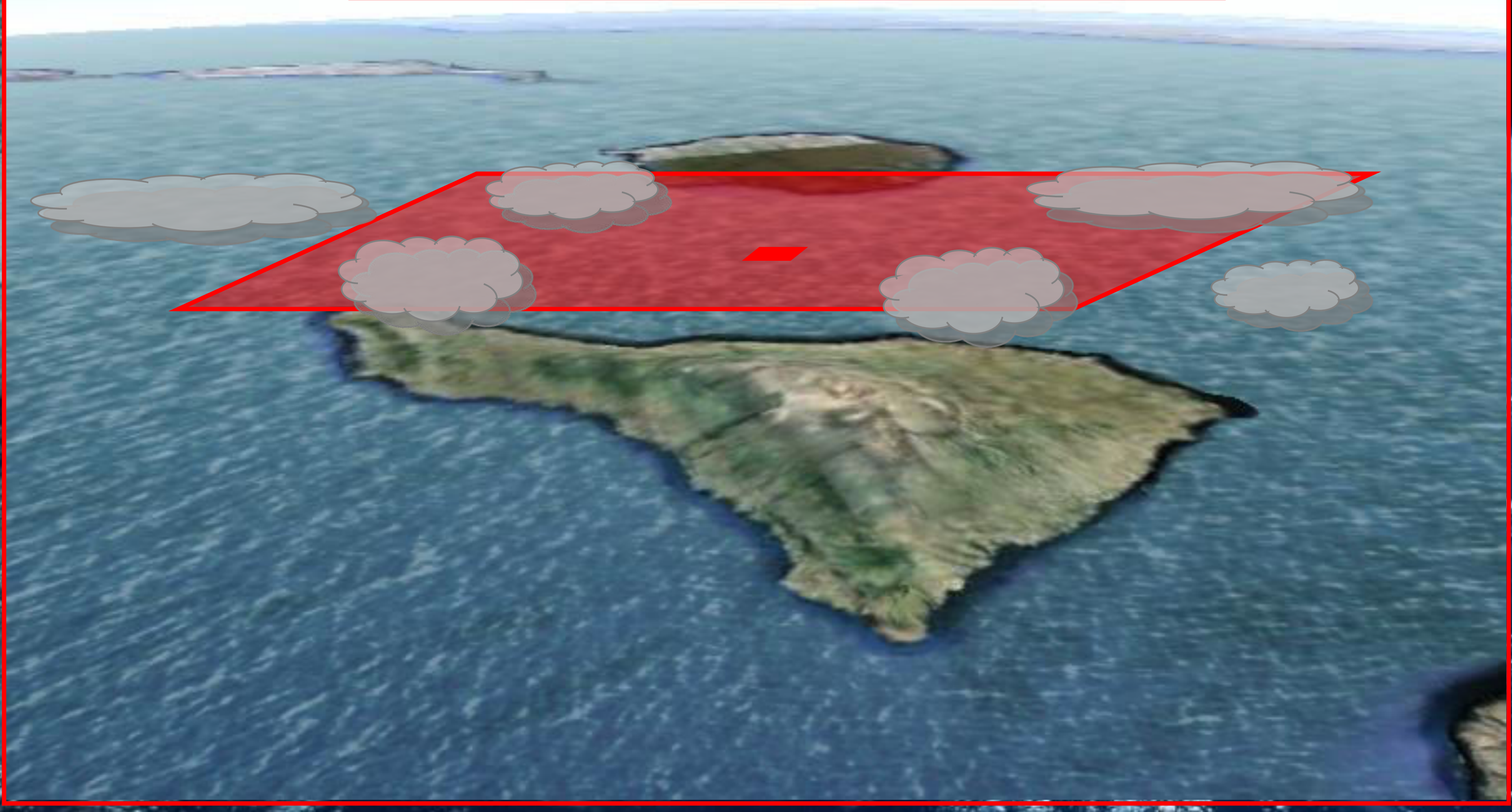

GOES Weighting Functions
Nov2007 Paranal
Example Paranal Nov2007
3 Points for Every Night
Time 2.45/5.45/8.45
Altitude (m)
12000
9000
6000
3000
0
≈8000m
≈4000m
≈3000m
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
Days
B3
B4
B6

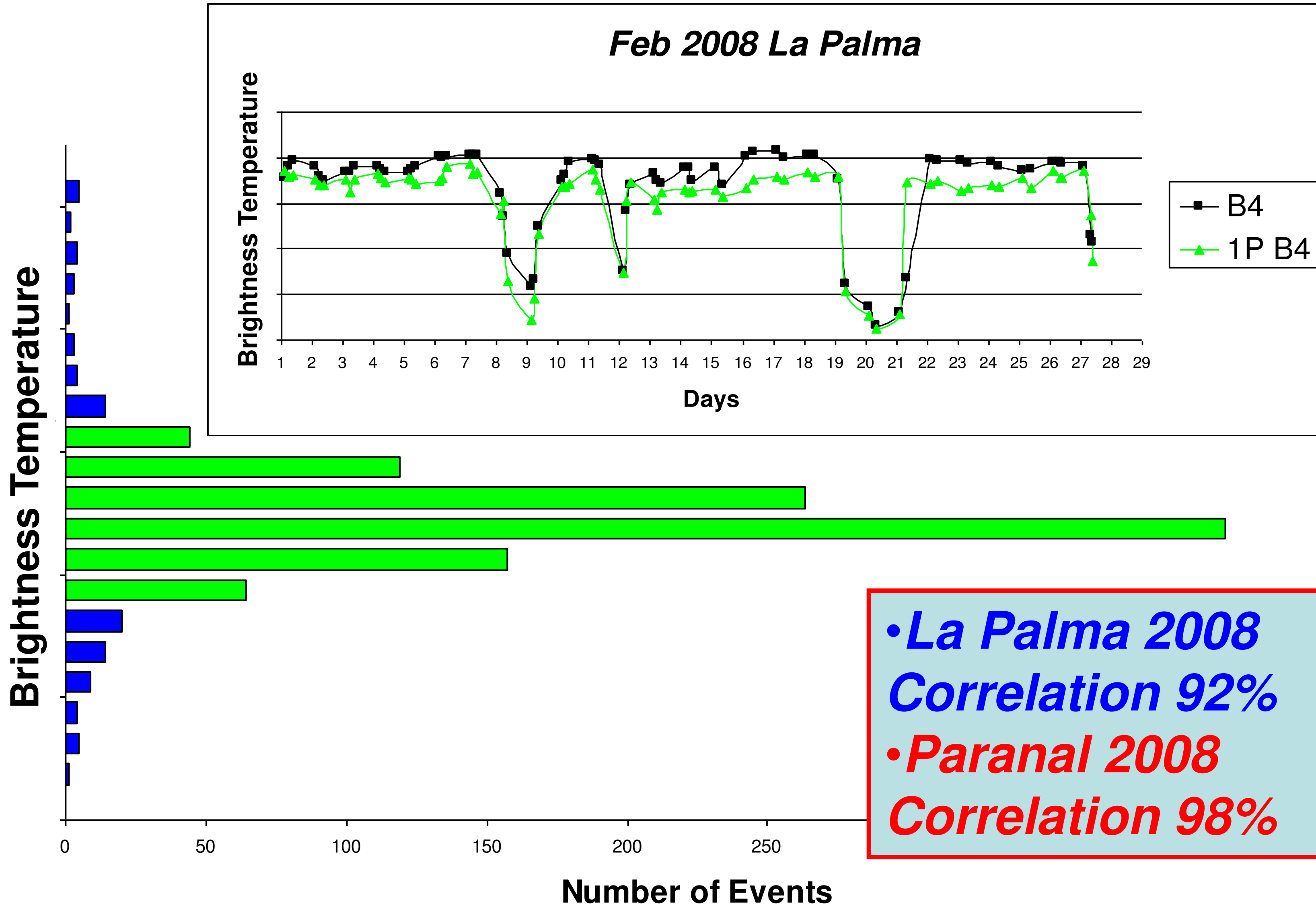
Matrix vs Single Pixel



Matrix vs Single Pixel

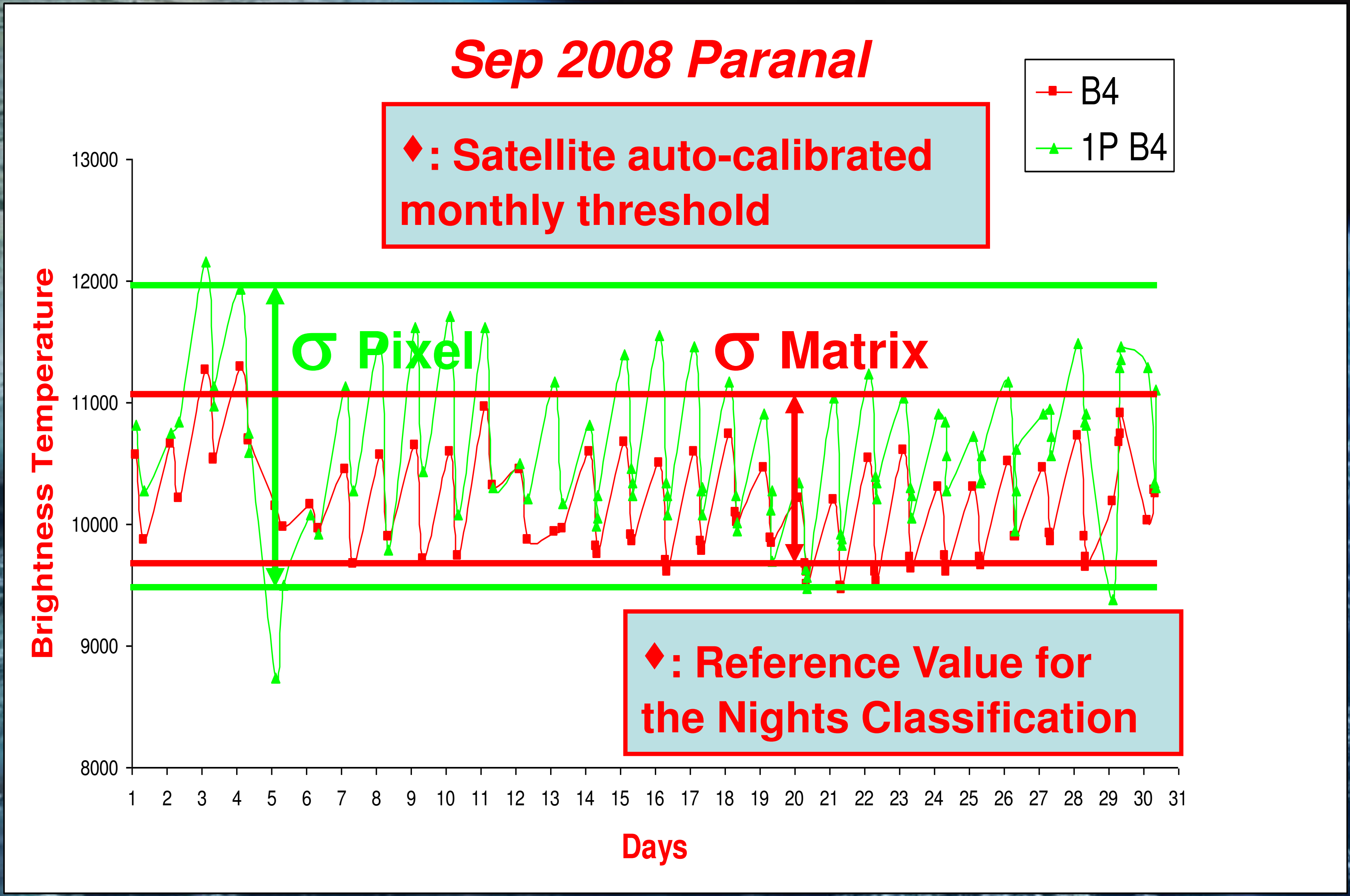
B4 Matrix high standard deviation



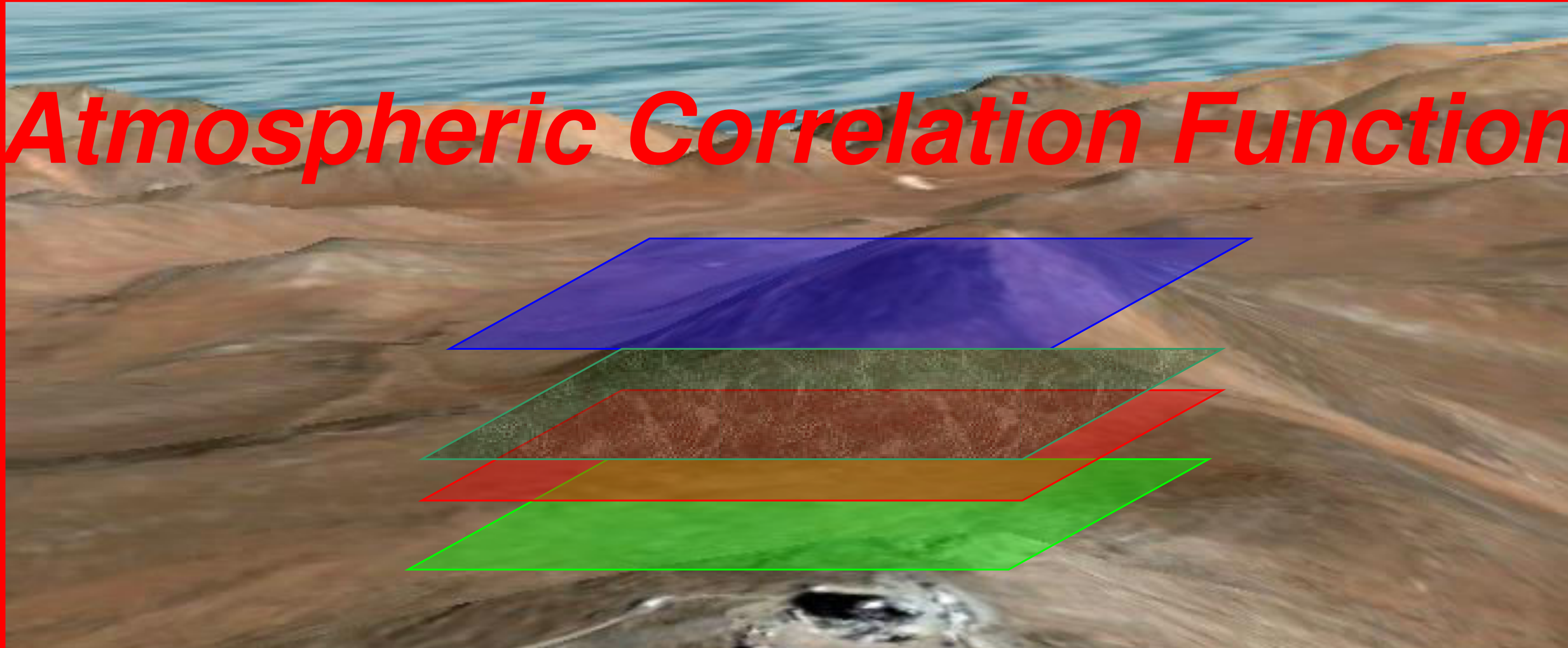


- *La Palma 2008 Correlation 92%*
- *Paranal 2008 Correlation 98%*

Matrix vs. Single Pixel

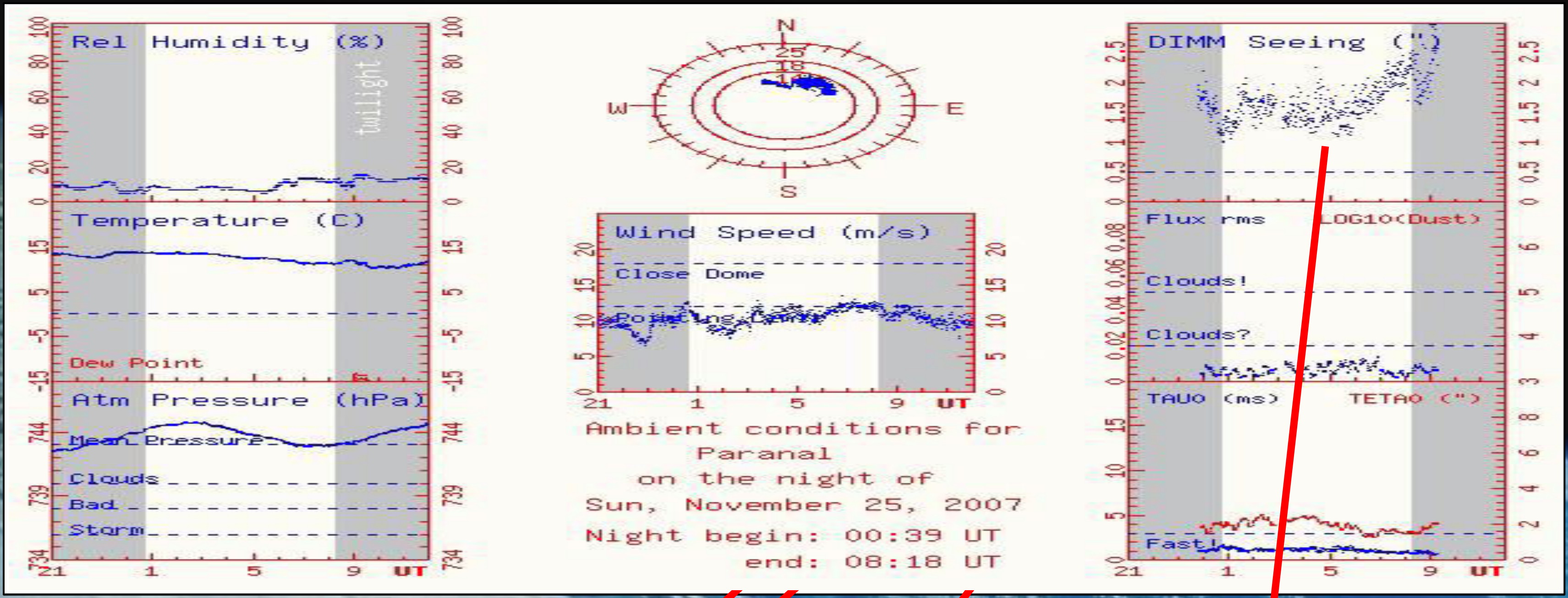


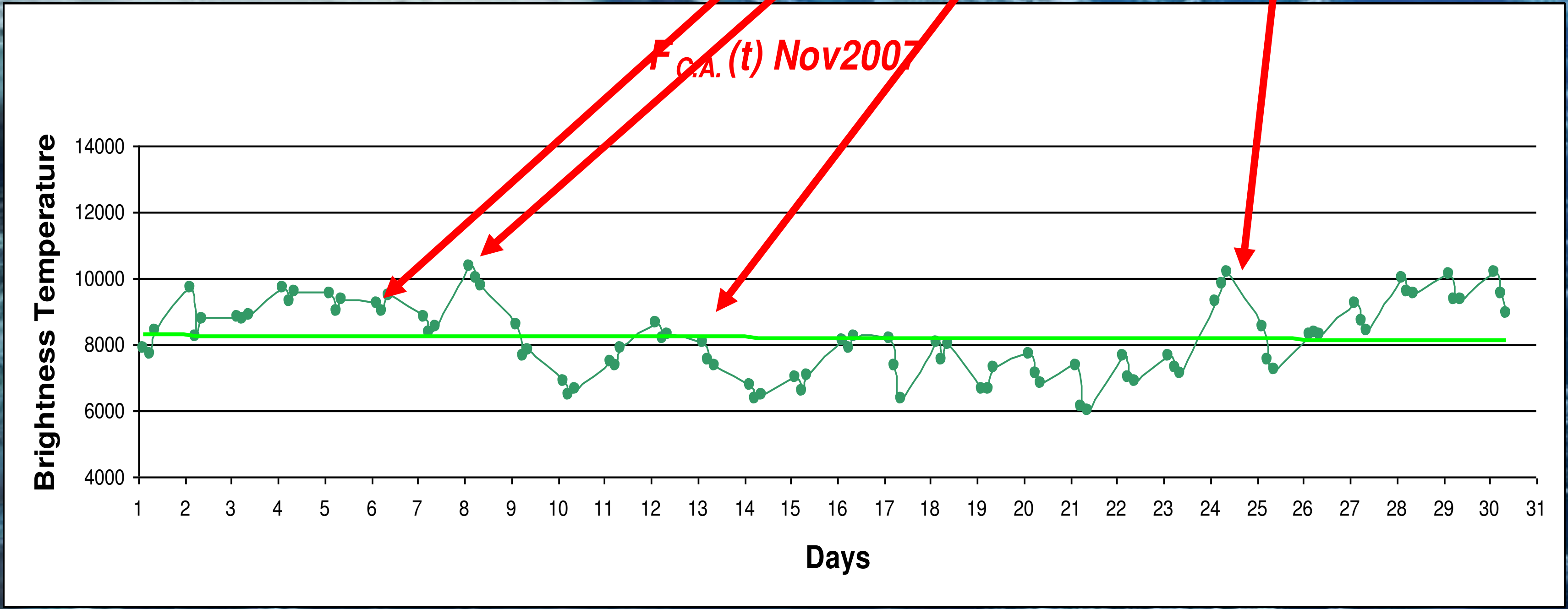
Atmospheric Correlation Function



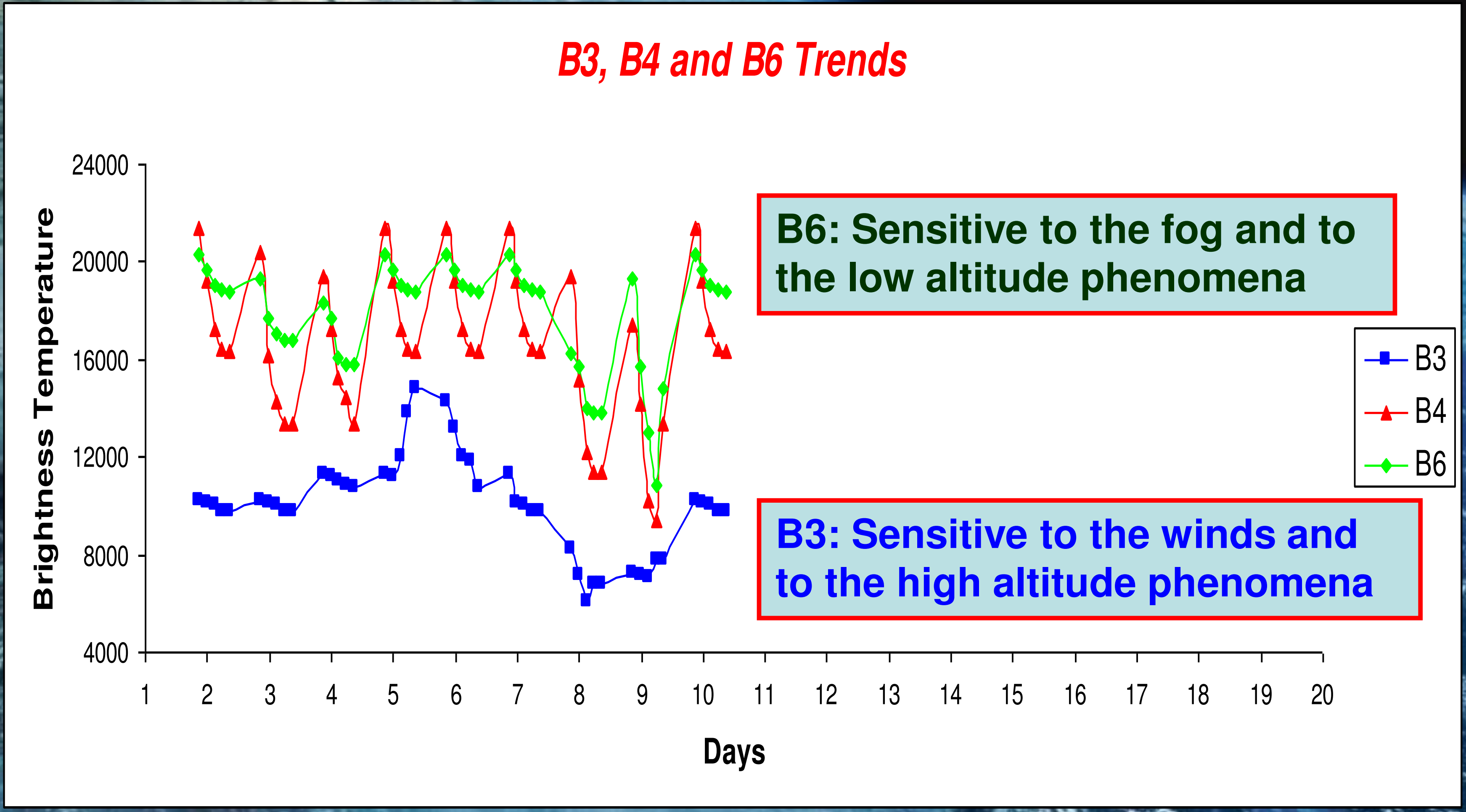
$$I_{C.A.} = \frac{R_{\lambda_3} + R_{\lambda_4} - R_{\lambda_6}}{\tau(z_0)} +$$

$$- \frac{\int_{z_0}^{\infty} B_{\lambda_3}[T(z)]K_{\lambda_3} + B_{\lambda_4}[T(z)]K_{\lambda_4} - B_{\lambda_6}[T(z)]K_{\lambda_6} dz}{\tau(z_0)}$$

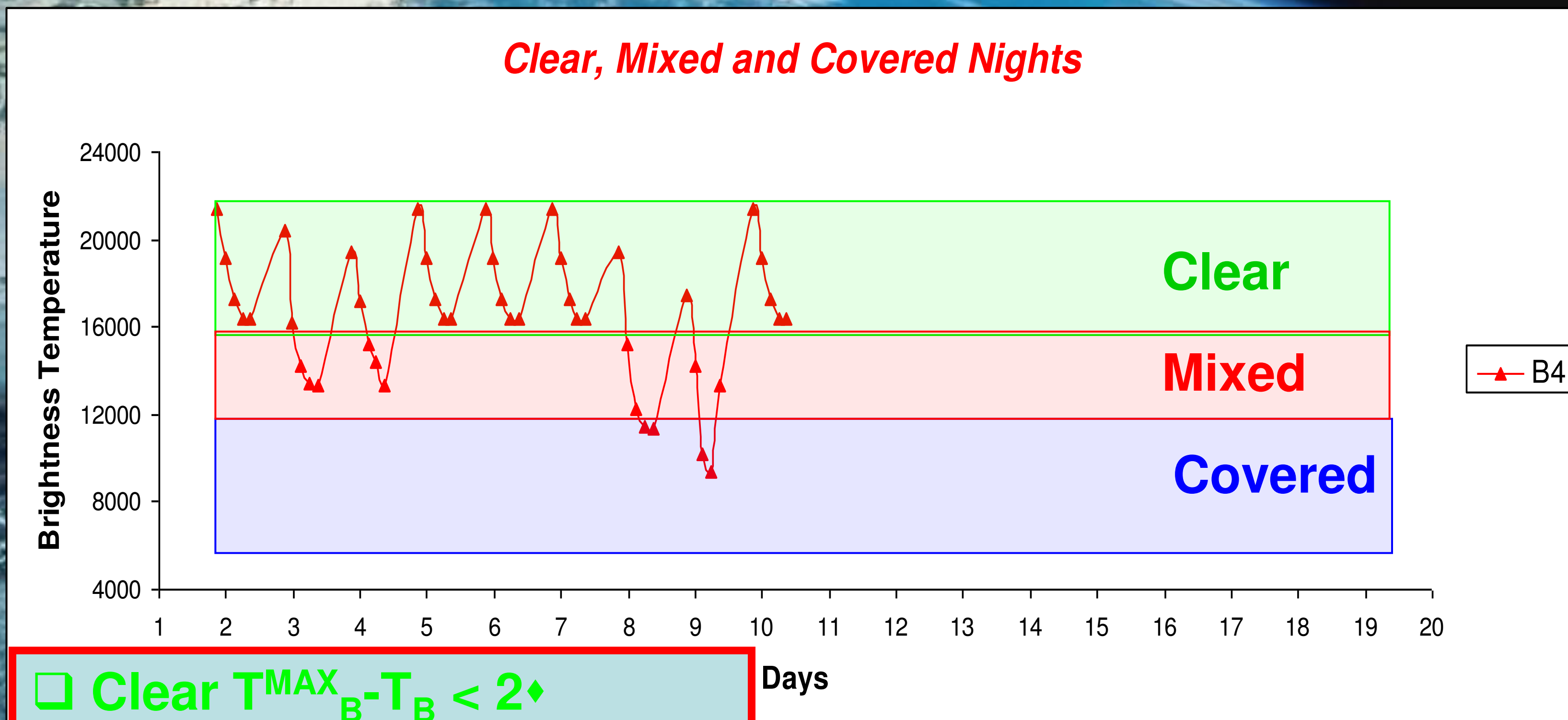

Rel Humidity (%)
twilight
Temperature (C)
Dew Point
Atm Pressure (hPa)
Mean Pressure
Clouds
Bad
Storm
N
W
E
S
Wind Speed (m/s)
Close Dome
Pointing Limit
Ambient conditions for
Paranal
on the night of
Sun, November 25, 2007
Night begin: 00:39 UT
end: 08:18 UT
DIMM Seeing (")
Flux rms
LOG10(Dust)
Clouds!
Clouds?
TAU0 (ms)
TETA0 (")
Fast!
UT


F C.A. (t) Nov2007
Brightness Temperature
14000
12000
10000
8000
6000
4000
Days
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31

Simulation of the model

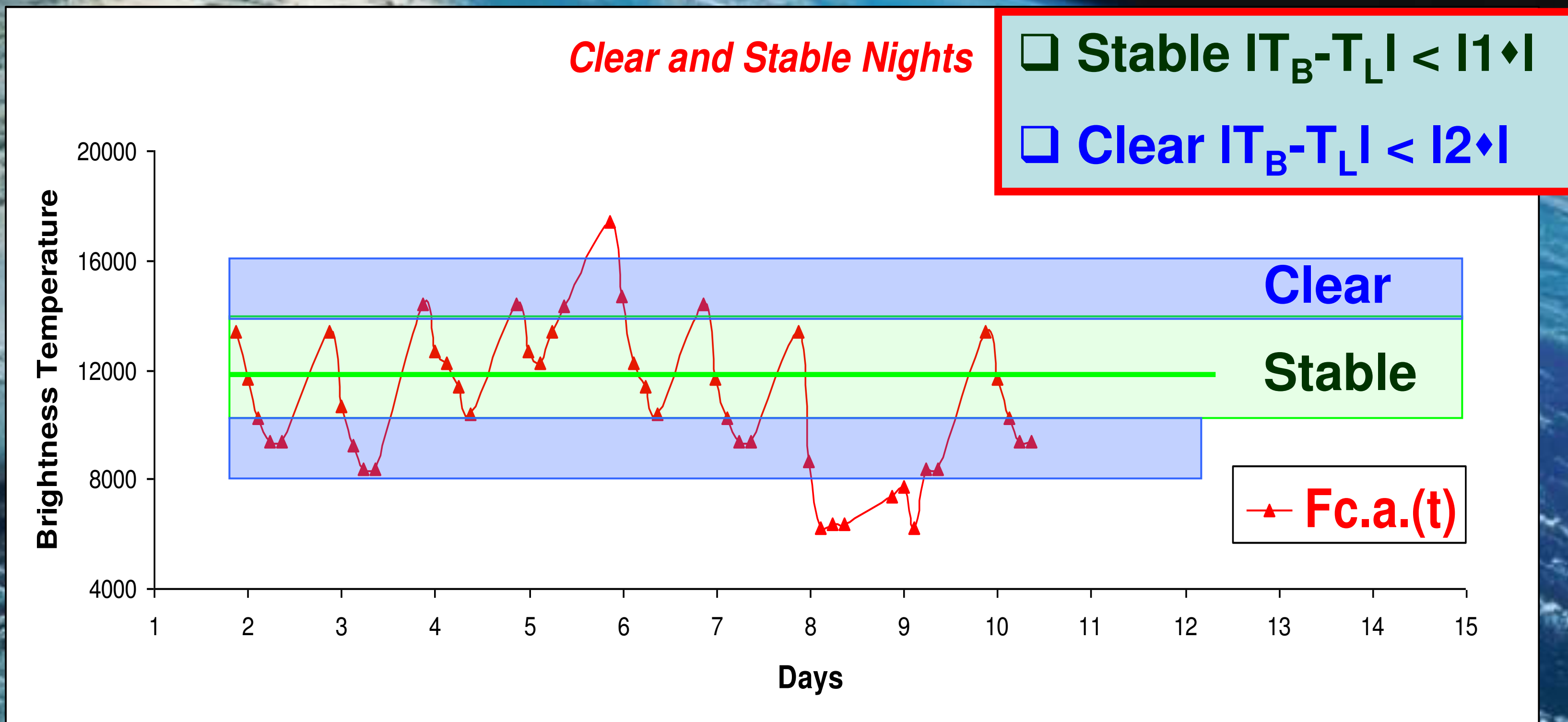


Clear, Mixed, and Covered Classification



- Clear $T^{MAX}_{B}-T_{B} < 2$♦
- Mixed 2♦ $< T^{MAX}_{B}-T_{B} < 3$♦
- Covered $T^{MAX}_{B}-T_{B} > 3$♦

Stable and Clear Classification



The Selected Sites for the Model Validation

Description of LOGBooks

January 2009

Observing: 156.7 hours
Weather Loss: 156.0 hours
Technical Loss: 18.7 hours
Scheduled Maintenance: 0 hours

Liverpool Log

Date	Hours Used			Comment
	Observing	Weather	Technical	
31 Jan	0.0	10.5	0.0	Ice.
30 Jan	0.0	10.5	0.0	Ice.
29 Jan	6.0	4.5	0.0	High humidity second half of night.
28 Jan	10.6	0.0	0.0	Non-photometric
27 Jan	10.6	0.0	0.0	Photometric
26 Jan	10.6	0.0	0.0	Non-photometric
25 Jan	3.6	7.0	0.0	Non-photometric. High humidity at start and end of night.
24 Jan	8.6	0.0	2.0	Non-photometric. Cass rotator jammed at start of night.
23 Jan	9.6	0.0	1.0	Non-photometric. Cass torque errors leading to node reboot & unrelated altitude node reboot.
22 Jan	0.0	3.0	7.6	High humidity at times. Cass rotator jammed.
21 Jan	9.5	0.0	1.1	Photometric. Cass torque errors leading to node reboot. Also unrelated AZM node reboot.
20 Jan	10.2	0.0	0.5	Photometric. Cass node reboot.

CAMC Log January 2009

090120 RM Obs toda la noche. Buena noche. 15 tiras. Rebuteo en la 12. 9.54 horas buenas. Fluctuaciones.

090121 RM Obs toda la noche (buena). 15 tiras. 10.96 horas buenas.

090122 RM Obs media noche. Tiras 1-11, 2 NotObs. Parada por humedad en 1 y 7. 1 hora buena. Problema con Seals al abrir en la 8, observa con Domo cerrado.

090123 RM Obs casi toda la noche. tiras 1-14, la 8 NotObs. Rebuteo en 3 y 6. Humedad en 10 y 13. 3.85 horas buenas. Error en single_find_act: archivo que no puede borrar.

090124 RM Obs toda la noche. 11 tiras. 6.21 horas buenas.

090125 MS Cortes por lluvia y alta humedad. 5 tiras, 1 hora buena. En la apertura del domo despues del cierre por lluvia fallan los seals y observa las tiras 4 y 5 con el domo cerrado.

JM Modificado automati.pas (linea 1007) para que intente abrir varias veces si fallan los seals.

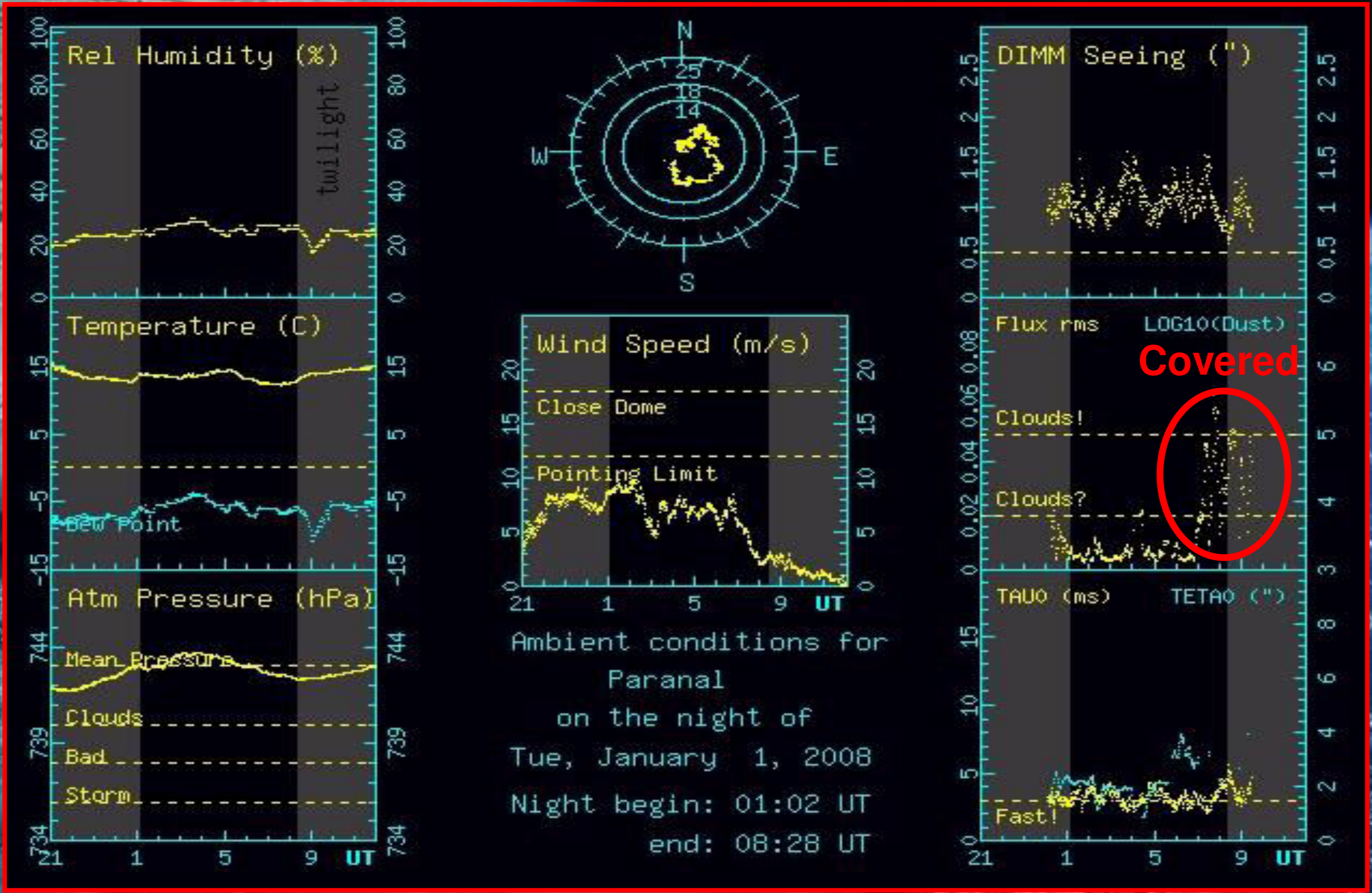
090126 MS Obs 2/3 de la noche. Empieza tarde por continuos fallos en los seals. 7 tiras, 6.5 horas buenas.

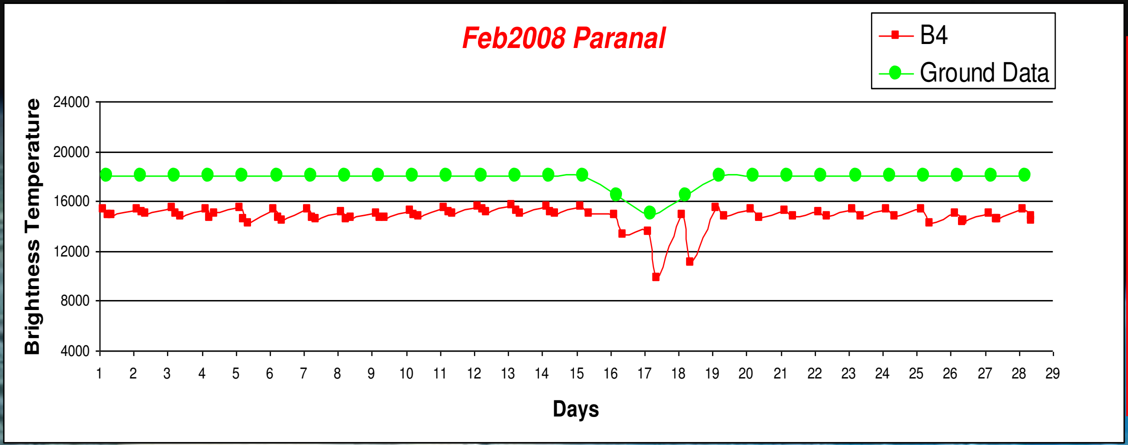
090127 MS Obs toda la noche. 11 tiras, fluctuaciones.

090128 MS Obs toda la noche. 18 tiras, fallan todas las pares hasta la 12 por camera not idle y despues de un rebuteo en la 11 no vuelve a fallar. Errores continuos de checksum en el mic 3. Aun asi la punteria fue buena y todas las tiras estaban bien reducidas, 6 horas buenas y el resto fluctuaciones.

Analysis of clear nights was based on visual inspection of the sky: an empirical method subject to personal judgment biases

Paranal Web Pages



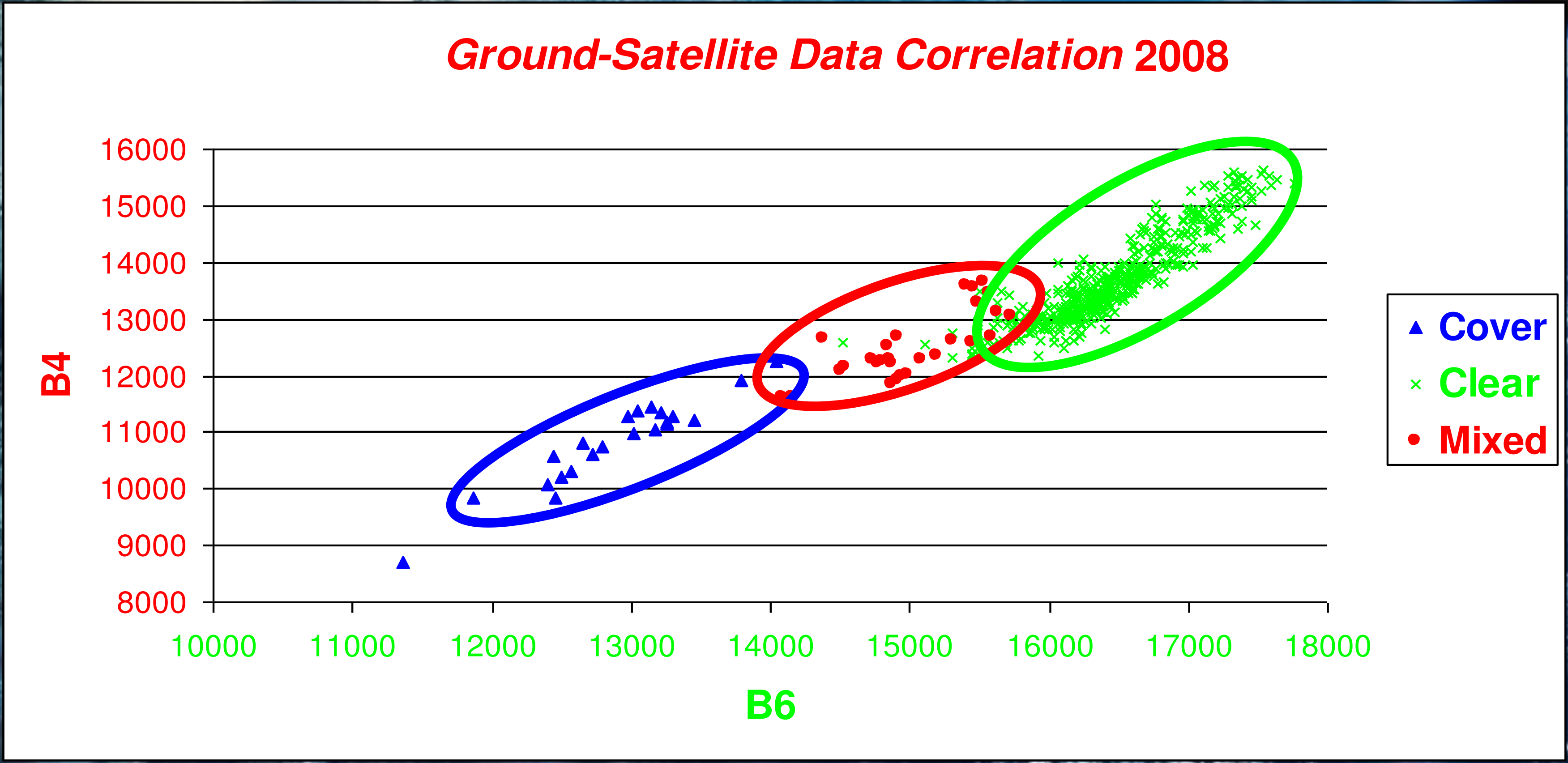


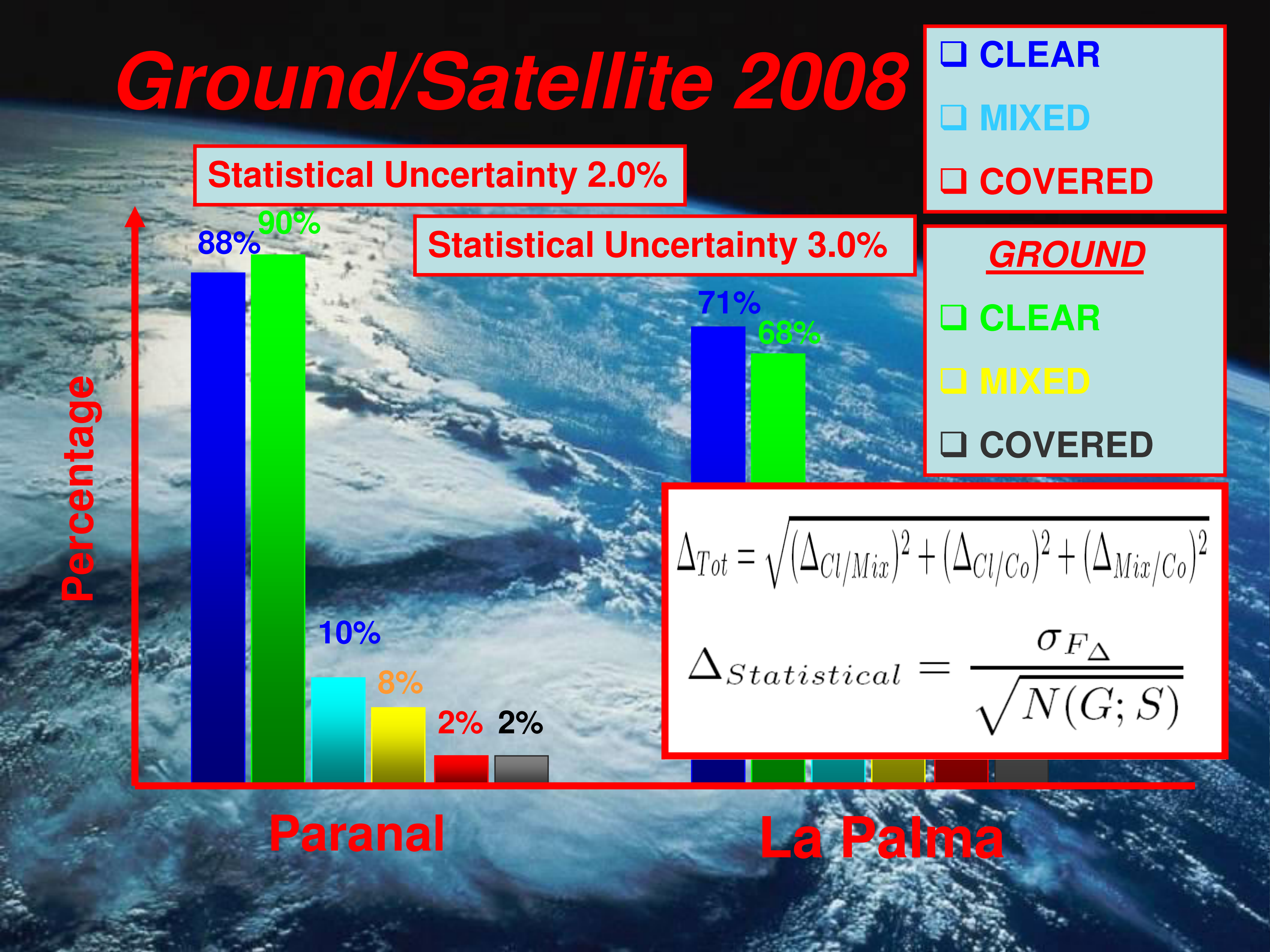
Punctual Uncertainty

5%

Statistical Uncertainty

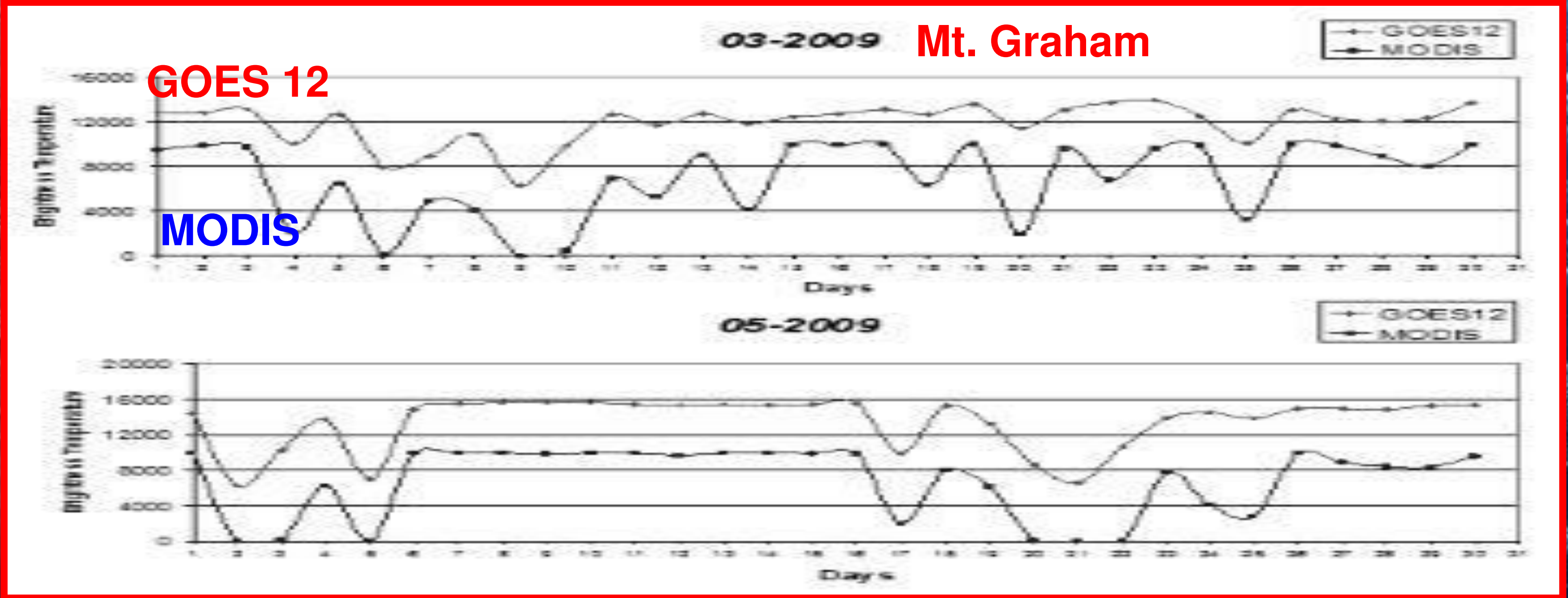
2%




Ground/Satellite 2008
Statistical Uncertainty 2.0%
Statistical Uncertainty 3.0%
❑ CLEAR
❑ MIXED
❑ COVERED
GROUND
❑ CLEAR
❑ MIXED
❑ COVERED
Percentage
88%
90%
10%
8%
2%
2%
71%
68%
Paranal
La Palma
$\Delta_{Tot} = \sqrt{(\Delta_{Cl/Mix})^2 + (\Delta_{Cl/Co})^2 + (\Delta_{Mix/Co})^2}$
$\Delta_{Statistical} = \frac{\sigma_{F_\Delta}}{\sqrt{N(G;S)}}$

MODIS-GOES 12 Comparison

The comparison with the two groups of data allows us to overcome the limitations of the individual satellite. At the same time it helps us to understand important features of the two satellites.



MODIS-GOES 12 Comparison

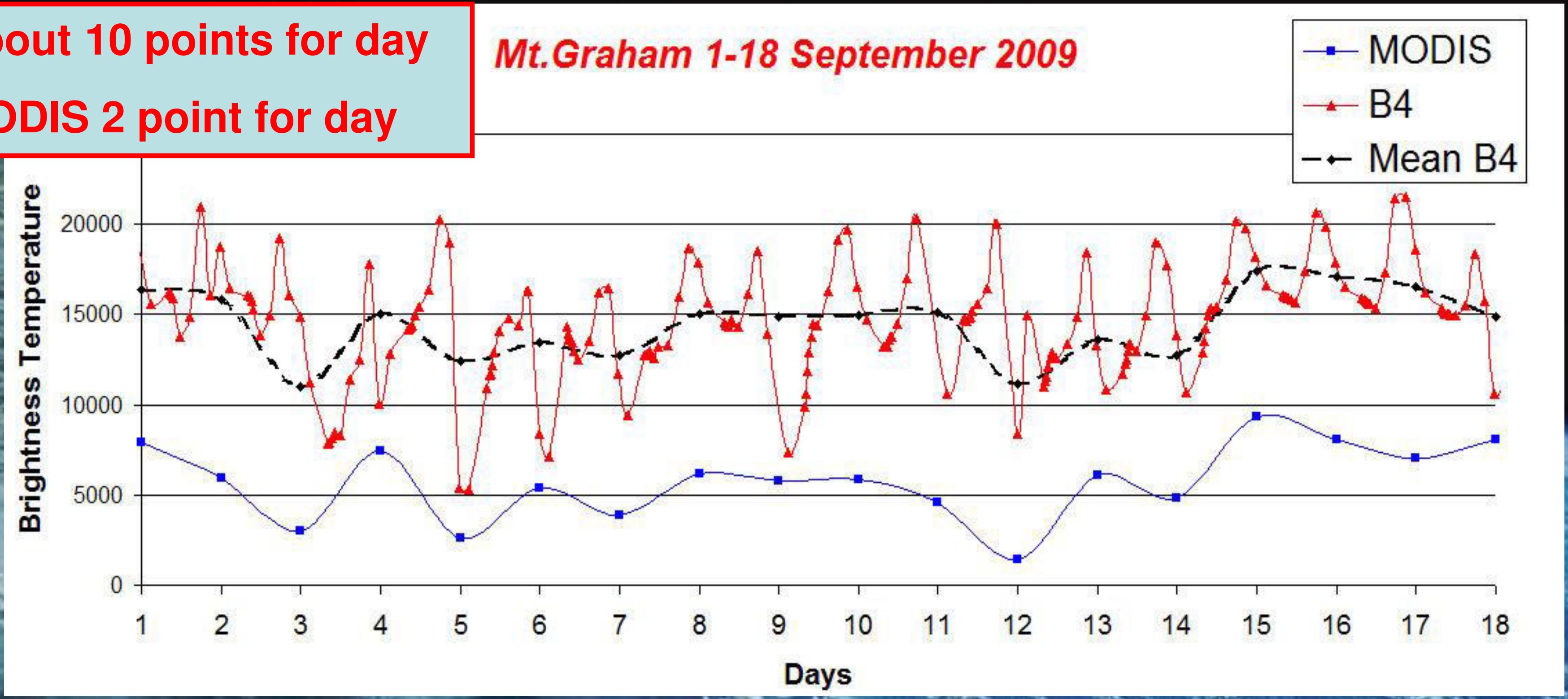
Table 5. Table shows the comparison between the GOES results and the MODIS results at Mt. Graham in 2009. In the first column we have the month, in the second column the coverage detected by GOES, in the third column the percentage of clear nights detected by GOES, in the fourth column the coverage detected by MODIS and in the fifth column the percentage of clear nights detected by MODIS. The GOES results correspond to the analysis of a single night point (2:45 local time).

2009	GOES Mt.Graham		MODIS Mt.Graham	
Month	Covered	Clear	Covered	Clear
1	33	67	35	65
2	36	64	37	63
3	30	70	31	69
4	27	73	30	70
5	33	67	33	67
6	57	43	55	45
7	47	53	49	51
8	34	66	38	62
9	37	63	36	64
10	34	66	36	64
11	23	77	23	77
12	52	48	48	52
Average	37	63	38	62

Table 6. Table shows the monthly correlation coefficient at Mt. Graham in 2009.

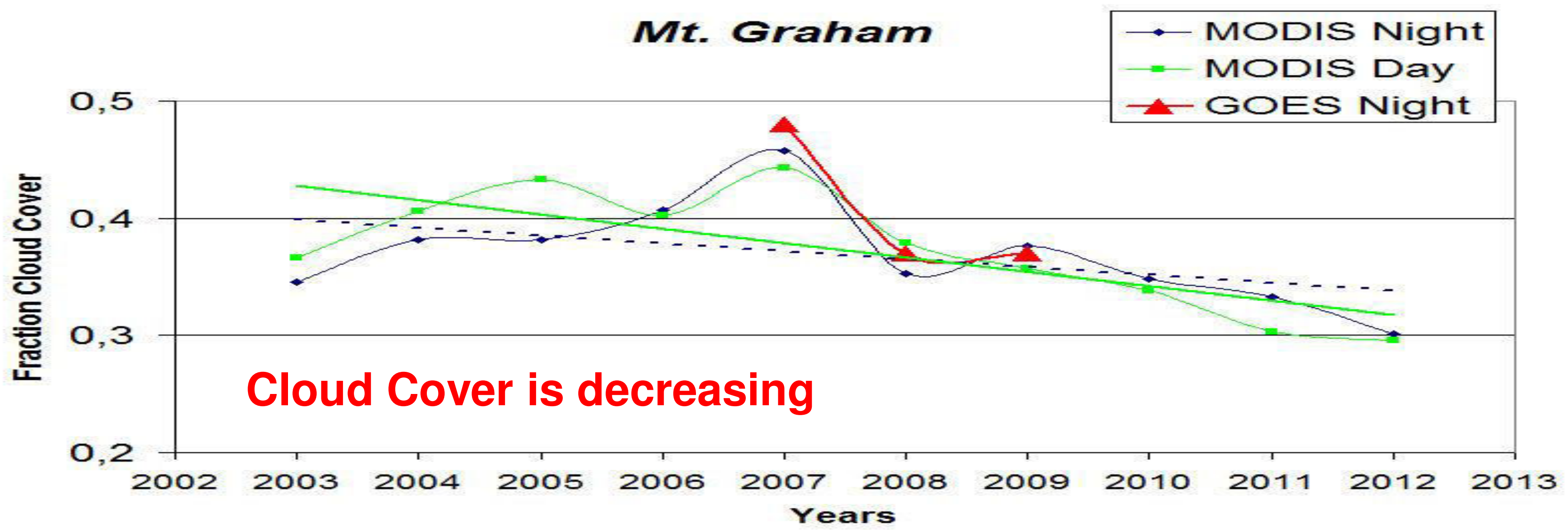
Month	Punctual Correlation [%]	ϵ_{Max} [%]
1	93	3
2	93	4
3	97	3
4	97	3
5	97	3
6	97	3
7	100	3
8	97	3
9	93	3
10	93	3
11	97	3
12	93	3
Average	96	3

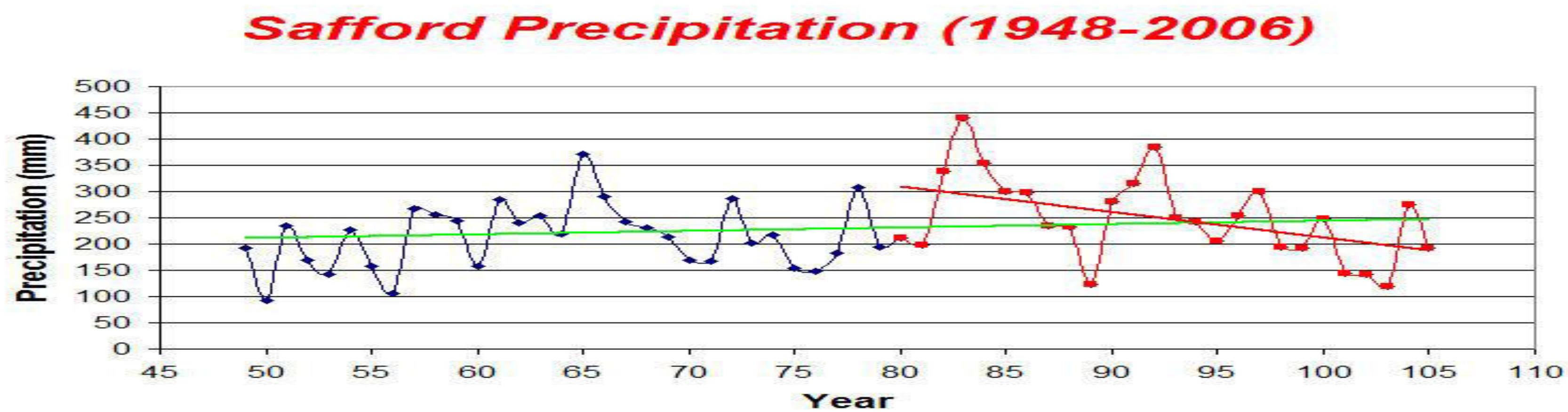
- •About 10 points for day
- •MODIS 2 point for day



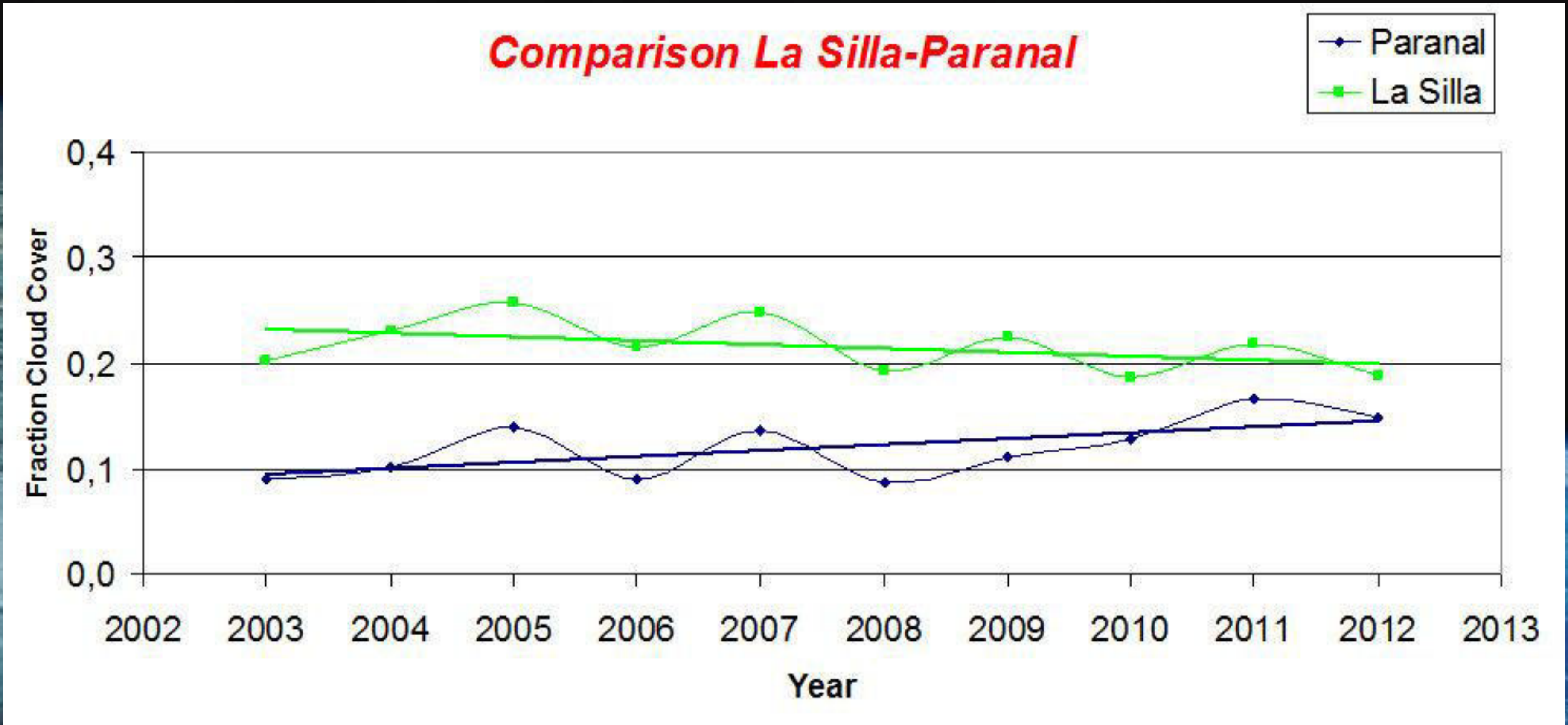
- •GOES main advantage is the great temporal resolution
- •GOES data access is free
- •MODIS data comes already elaborated (Black Box)
- •MODIS data processing is very fast

Long term analysis

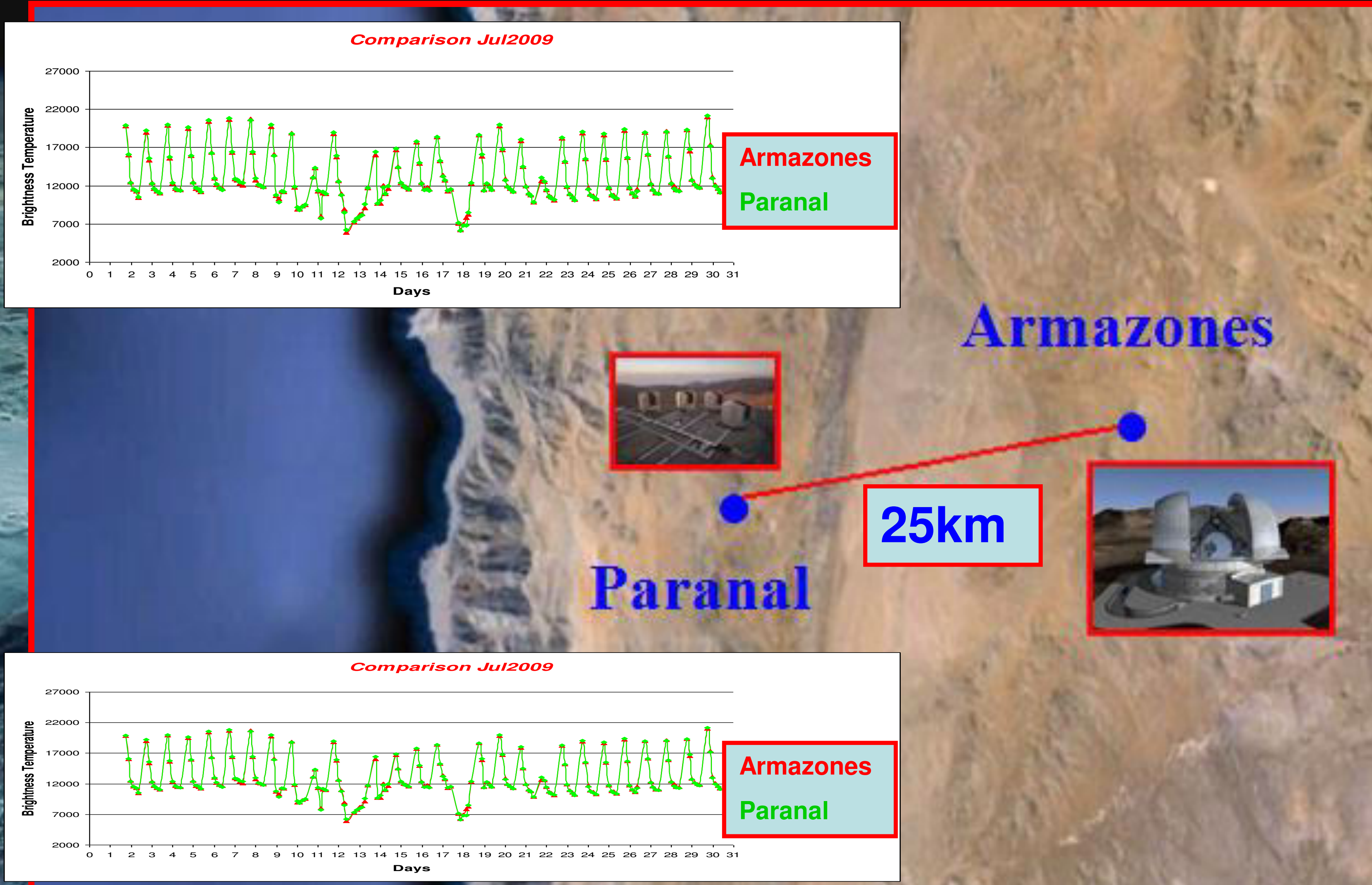




Rainfall recorded at the meteorological station of Safford



- **Analysis of about 4000 points (annual averages)**
- **The cloud cover is increasing at Paranal**
- **The cloud cover is decreasing at La Silla**



- Correlation Coefficient (2007) Paranal-Armazones 0.97
- Correlation Coefficient (2009) Paranal-Armazones 0.98

Forecasting of weather conditions

1) Mathematical approach with the Fourier transform for the analysis of cloud cover
2) Correlation between the points of the afternoon and the points of the night for cloud cover
3) Correlation between the atmospheric correlation function and the seeing measured from the ground
4) Algorithm for predicting short terms night conditions

Discrete Fourier Transform (DFT)

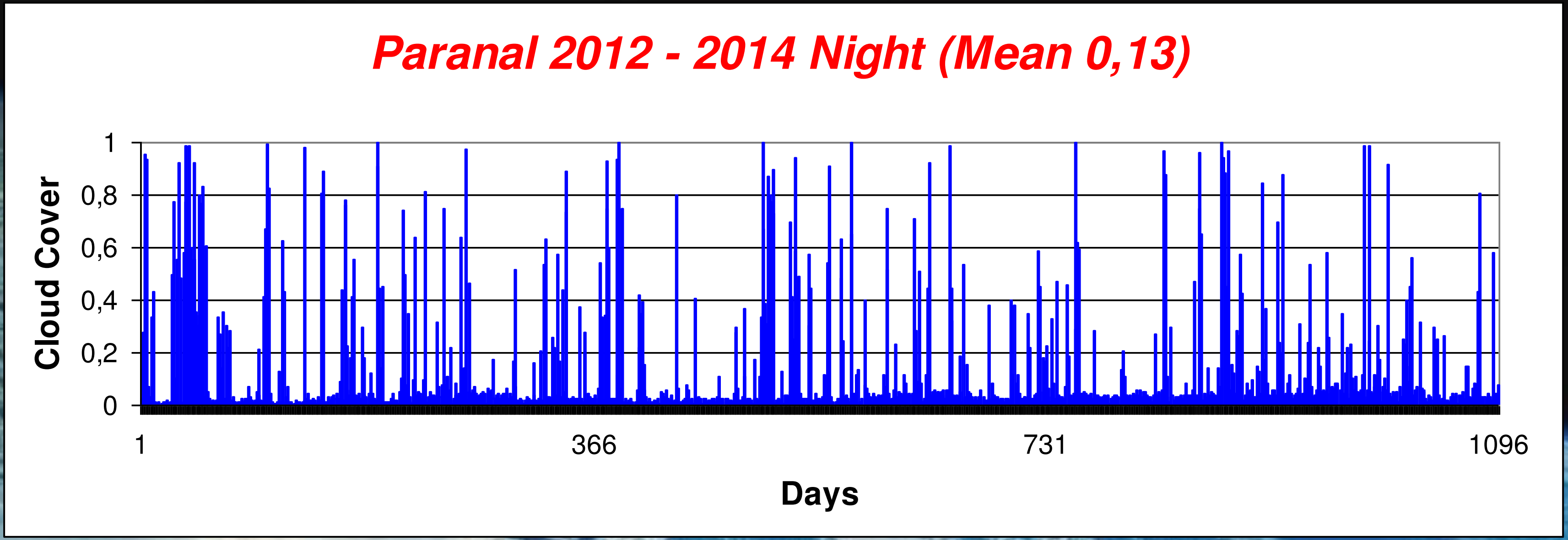
- **The Discrete Fourier Transform (DFT) is the equivalent of the continuous Fourier Transform for signals known only at instants separated by sample times (i.e. a finite sequence of data)**

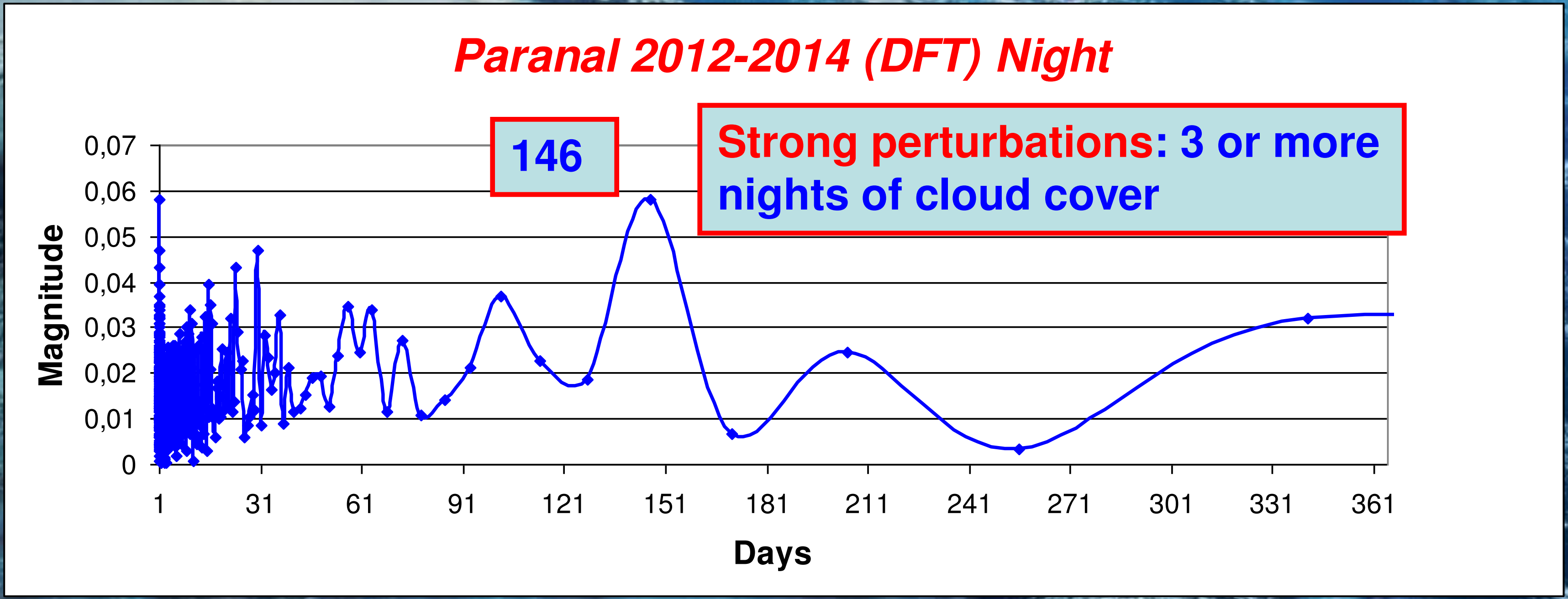
$$F(j\omega) = \int_{-\infty}^{\infty} f(t) e^{-j\omega t} dt$$

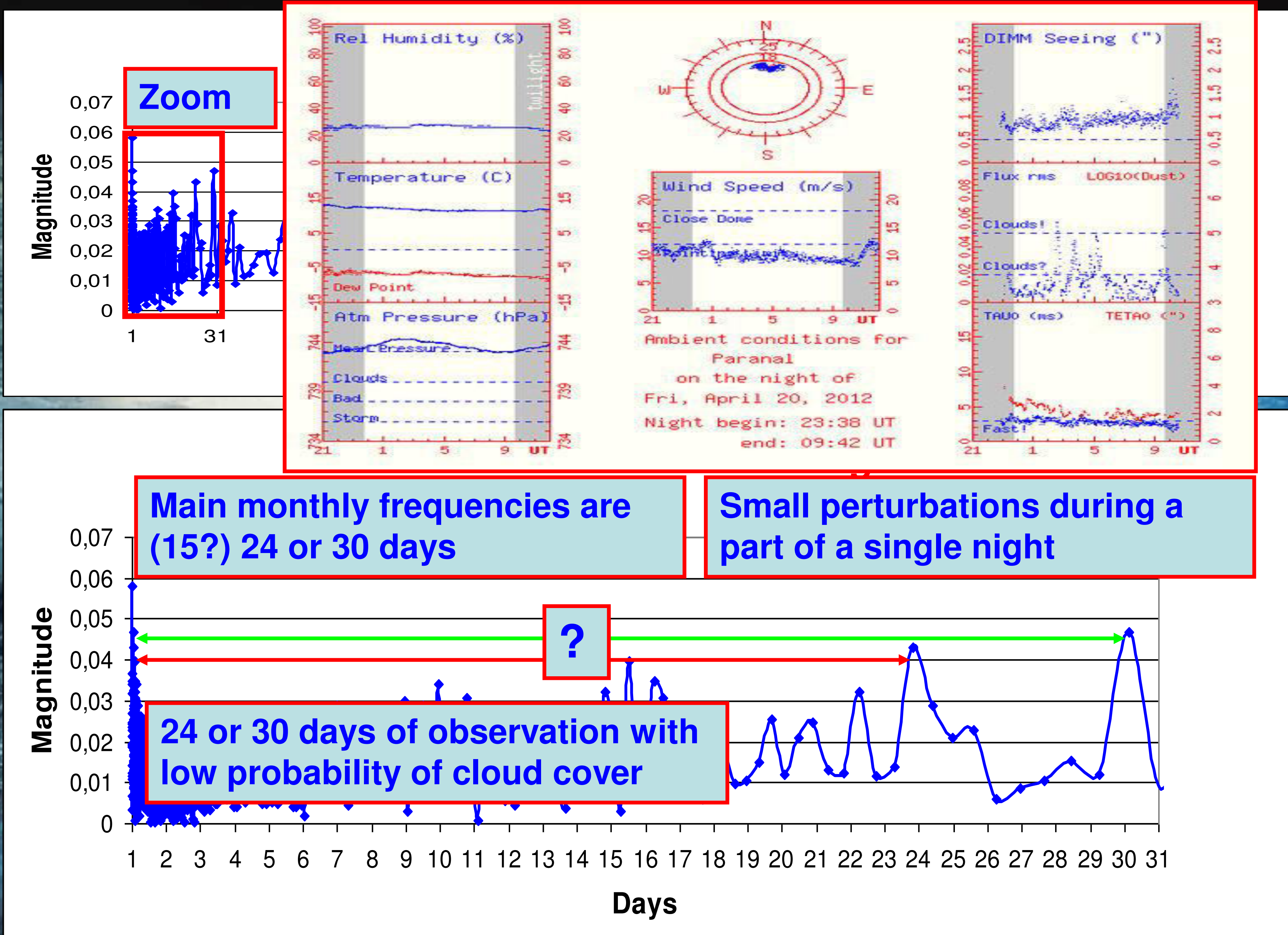
$$\Rightarrow$$

$$F(j\omega) = \sum_{k=0}^{N-1} f[k] e^{-j\omega kT}$$

- **The Cooley–Tukey algorithm: the most common Fast Fourier Transform (FFT) algorithm to calculate DFT**
- **We analyze three years at Paranal with MODIS (2012-2014)**


Paranal 2012 - 2014 Night (Mean 0,13)
Cloud Cover
1
0,8
0,6
0,4
0,2
0
1
366
731
1096
Days


Paranal 2012-2014 (DFT) Night
146
Strong perturbations: 3 or more nights of cloud cover
Magnitude
0,07
0,06
0,05
0,04
0,03
0,02
0,01
0
1
31
61
91
121
151
181
211
241
271
301
331
361
Days



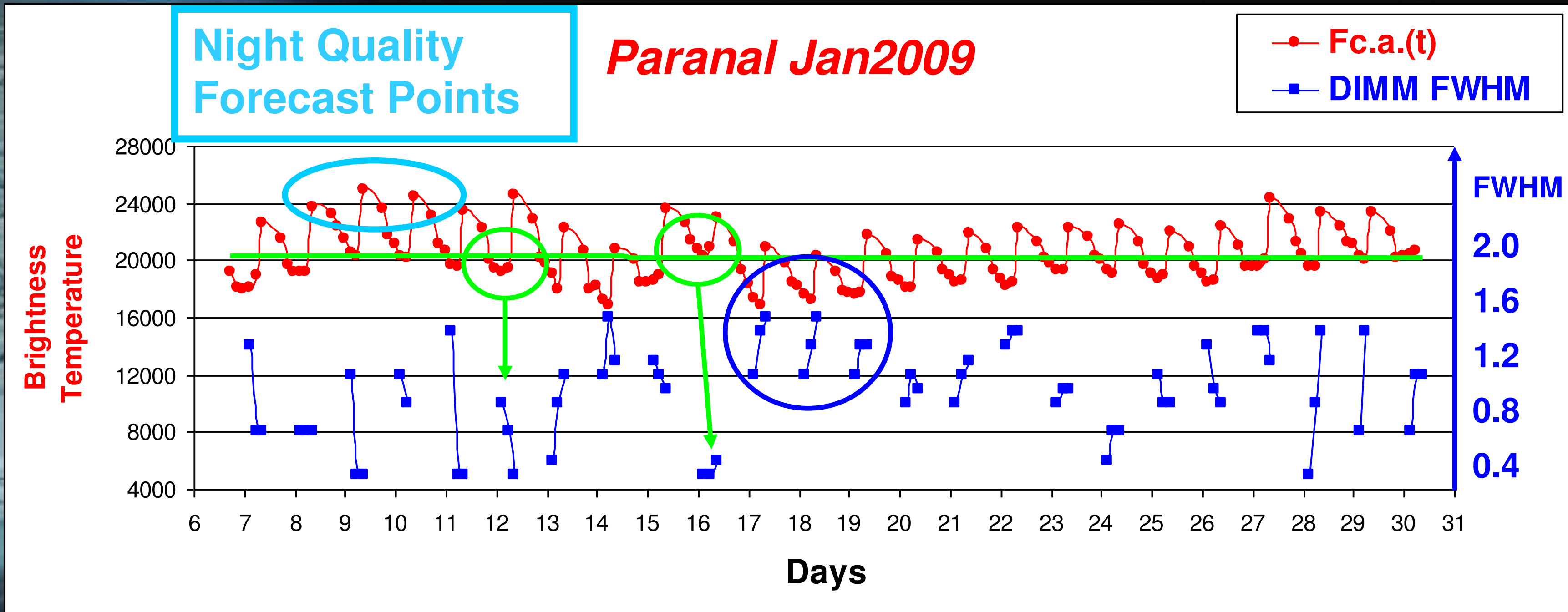
Zoom
Magnitude
0,07
0,06
0,05
0,04
0,03
0,02
0,01
0
1
31
Rel Humidity (%)
Twilight
Temperature (C)
Dew Point
Atm Pressure (hPa)
Clouds
Bad
Storm
N
E
S
W
Wind Speed (m/s)
Close Dome
Ambient conditions for
Paranal
on the night of
Fri, April 20, 2012
Night begin: 23:38 UT
end: 09:42 UT
DIMM Seeing (")
Flux rms
LOG10(Dust)
Clouds!
Clouds?
TAU0 (ms)
TETA0 (")
Fast!
UT
Main monthly frequencies are (15?) 24 or 30 days
Small perturbations during a part of a single night
?
24 or 30 days of observation with low probability of cloud cover
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
Days

Forecast at Paranal and La Palma for the year 2009

Table 9. Forecast at Paranal and at La Palma for the year 2009. $A \to N$ is the correlation between the afternoon and the next night and $N \to M$ is the correlation between the morning and the night before.

		Paranal		La Palma	
Months	Days	$A \to N$ Correlation	$N \to M$ Correlation	$A \to N$ Correlation	$N \to M$ Correlation
January	31	100.0	100.0	93.5	96.8
February	28	96.4	100.0	85.7	92.9
March	31	96.8	100.0	90.3	93.5
April	30	96.7	100.0	90.0	96.7
May	31	100.0	96.8	100.0	96.8
June	30	100.0	93.3	90.0	90.0
July	31	93.5	93.5	96.8	96.8
August	31	96.8	96.8	96.8	100.0
September	30	100.0	100.0	96.7	100.0
October	31	100.0	100.0	96.8	96.8
November	30	100.0	100.0	100.0	100.0
December	31	96.8	96.8	96.8	96.8

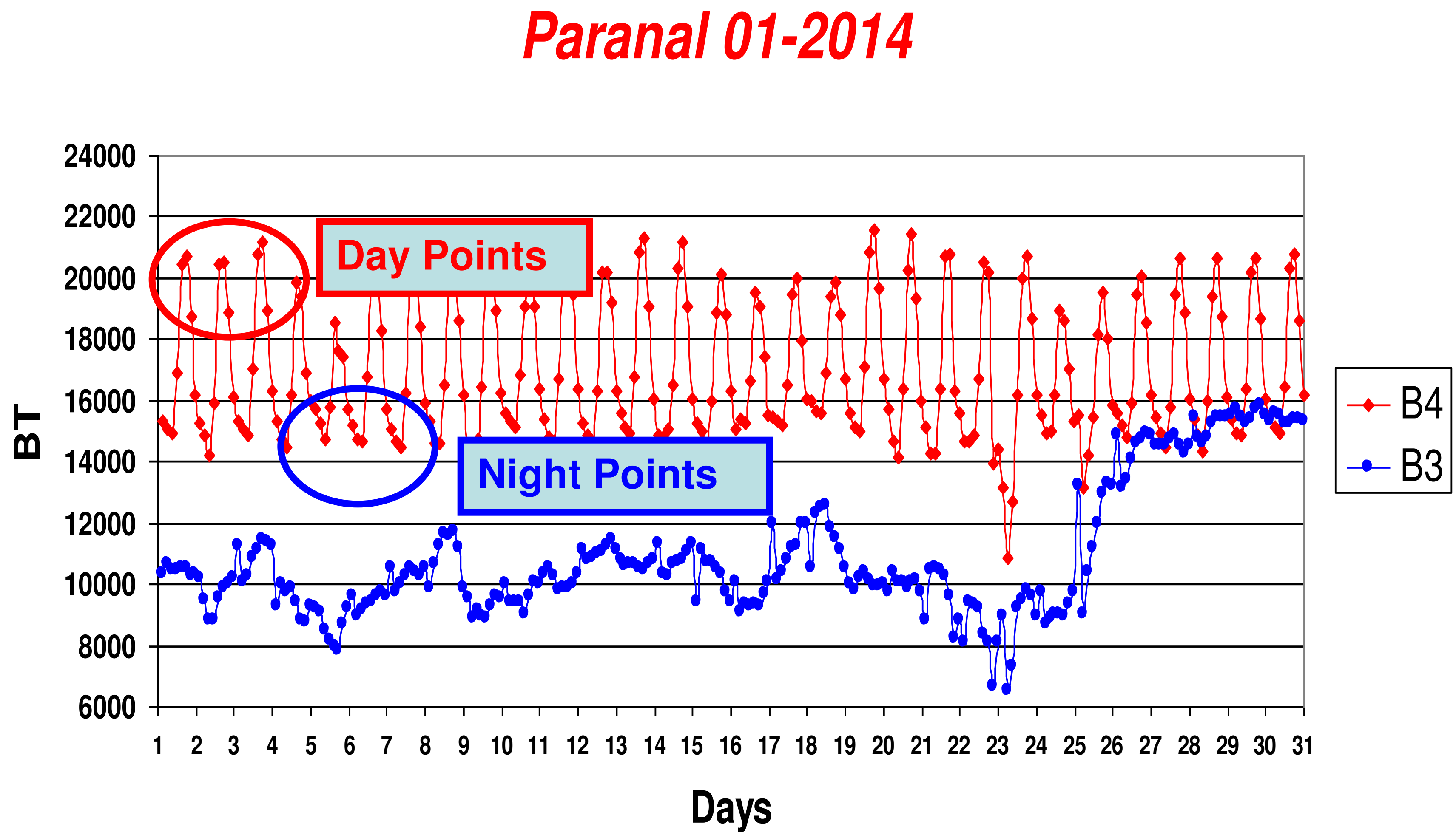
Night Quality Forecast



- ❑ Stable $|T_B - T_L| < |1♦|$
- ❑ Clear $1♦ < |T_B - T_L| < 2♦$
- ❑ Covered $|T_B - T_L| > |2♦|$

Stable: Clear nights thermally stable, thermal inhomogeneity can cause winds, high humidity and a variable seeing

We can make a short-term forecasting of the night quality through the study of day data of this function

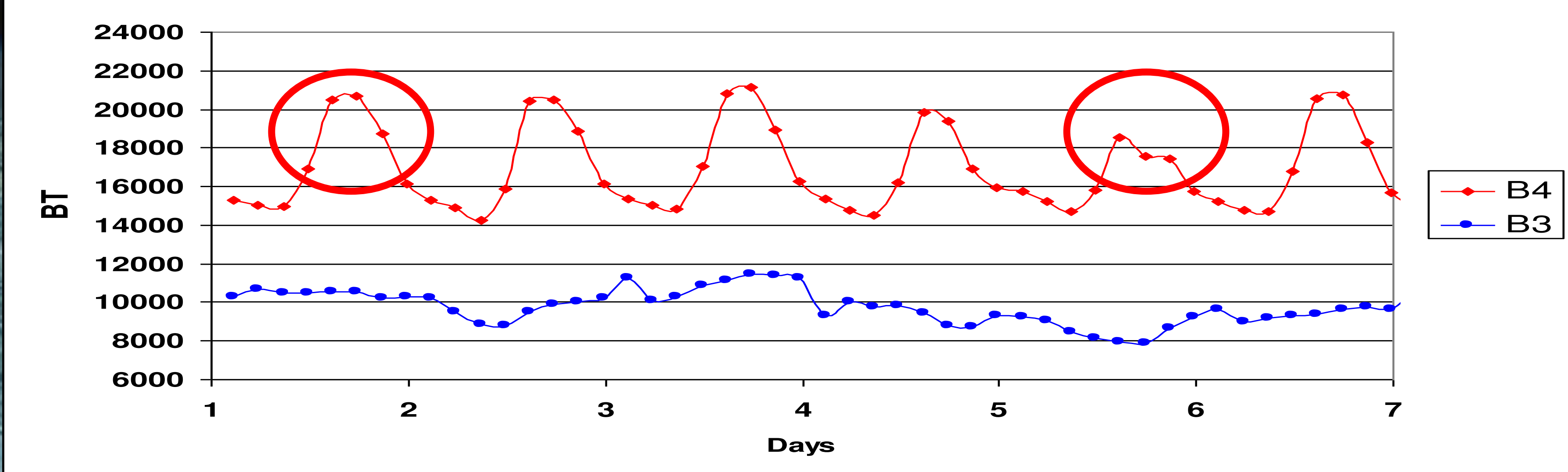


Example Paranal Jan2014

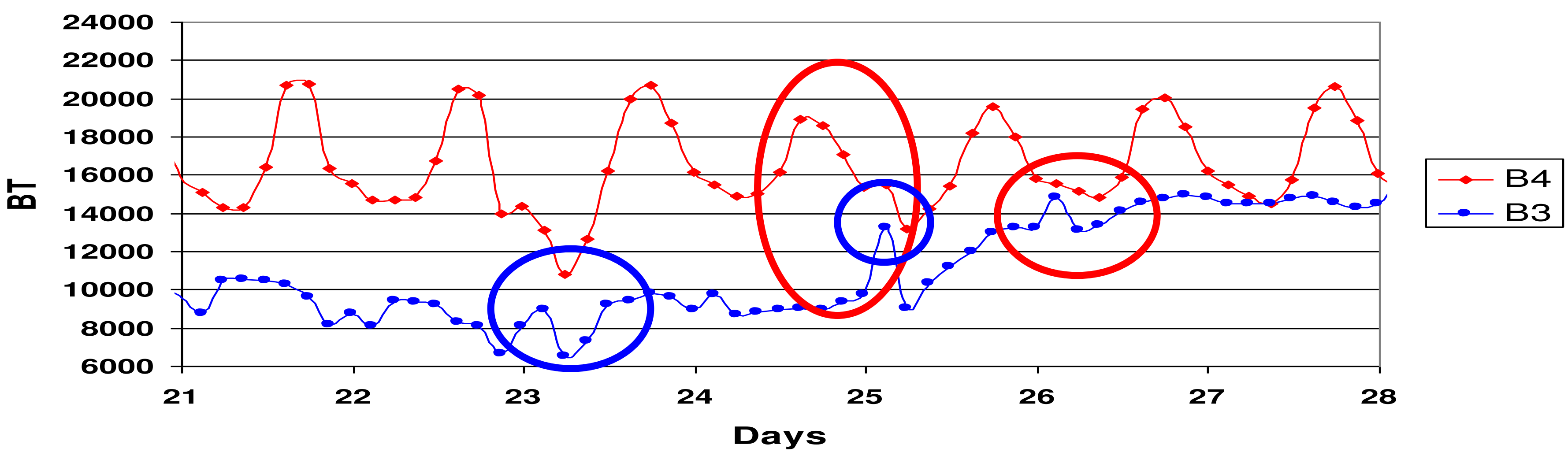
8 Points for day:

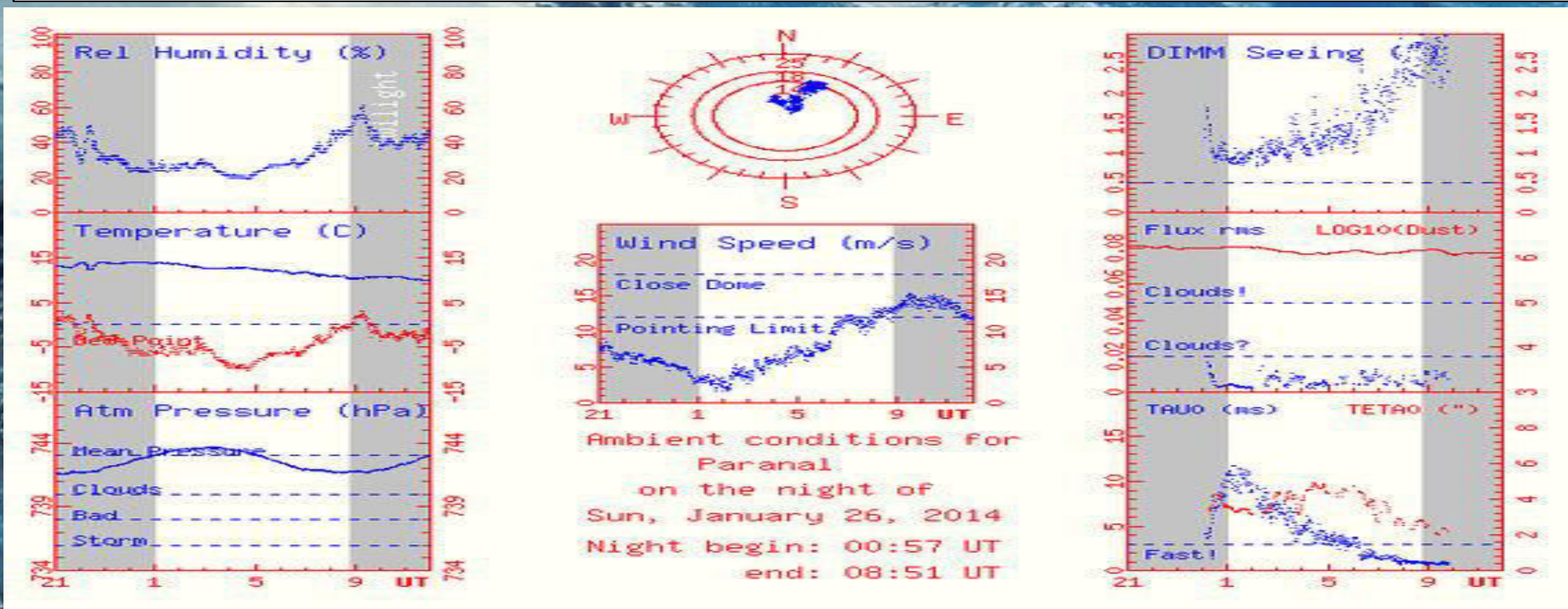
Time 2.45/5.45/8.45/11:45/14:45/17:45/20:45/23:45

Paranal 01-2014



Paranal 01-2014





Conclusion and Future Work

- New model for the study of cloud cover (Matrix and Remote Sounding)
- Long term analysis
- Empirical satellite study of the SEEING
- Correlation between MODIS and GOES
- Physical study of the model
- Implementation of the model for short-term forecast of the night quality
- Study of possible climate change in the long term

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
Mon. Not. R. Astron. Soc. (2010) doi:10.1111/j.1365-2966.2010.17766.x

Fraction of clear skies above astronomical sites: a new analysis from the *GOES12* satellite

S. Cavazzani
[1]Department of Astronc
[2]INAF-Osservatorio As
[3]Department of Physics

Accepted 2010 Septeml

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
Mon. Not. R. Astron. Soc. (2011) doi:10.1111/j.1365-2966.2011.19949.x

Site testing at astronomical sites: evaluation of seeing using satellite-based data

S. Cavazzani,[1★
[1]Department of Astronomy,
[2]INAF–Osservatorio Astroı

Accepted 2011 October 4. I

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **429,** 1849–1857 (2013) doi:10.1093/mnras/sts311

Satellite characterization of four interesting sites for astronomical instrumentation

S. Cavazza
[1]Department of Ast
[2]INAF–Osservatori

Accepted 2012 Octo

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS (2015) doi:10.1093/mnras/stv1319

Long-term analysis of clear sky at astronomical sites: a comparison between polar and geostationary satellites

S. Cavazzani,[1,2]★ V. Zitelli[3] and S. Ortolani[1,2]
[1]*Department of Astronomy, University of Padova, Vicolo dell'Osservatorio 3, I-35122, Padua, Italy*
[2]*INAF-Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122, Padua, Italy*
[3]*INAF-Osservatorio Astronomico di Bologna, Via Ranzani 1, I-40127, Bologna, Italy*

Accepted 2015 June 10. Received 2015 May 25; in original form 2015 March 17


GOES-R


Thanks!