Quantitative characterisation of sky conditions on Paranal with the microwave radiometer LHATPRO – five years and learning

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ESO 2017 Calibration Workshop

Subjects & Questions

- Homogeneity of precipitable water vapour (PWV) across the sky
  - Q1: Is a measurement at zenith representative of my line of sight?
- Photometric sky quality classification
  - Q2: Can we help the weather officer with an automated process giving a quantitative and reliable result?
- Future: atmospheric characterisation
  - Q3: What does it take to characterise the relevant properties of the atmosphere and make precise, local, short-term forecasts?

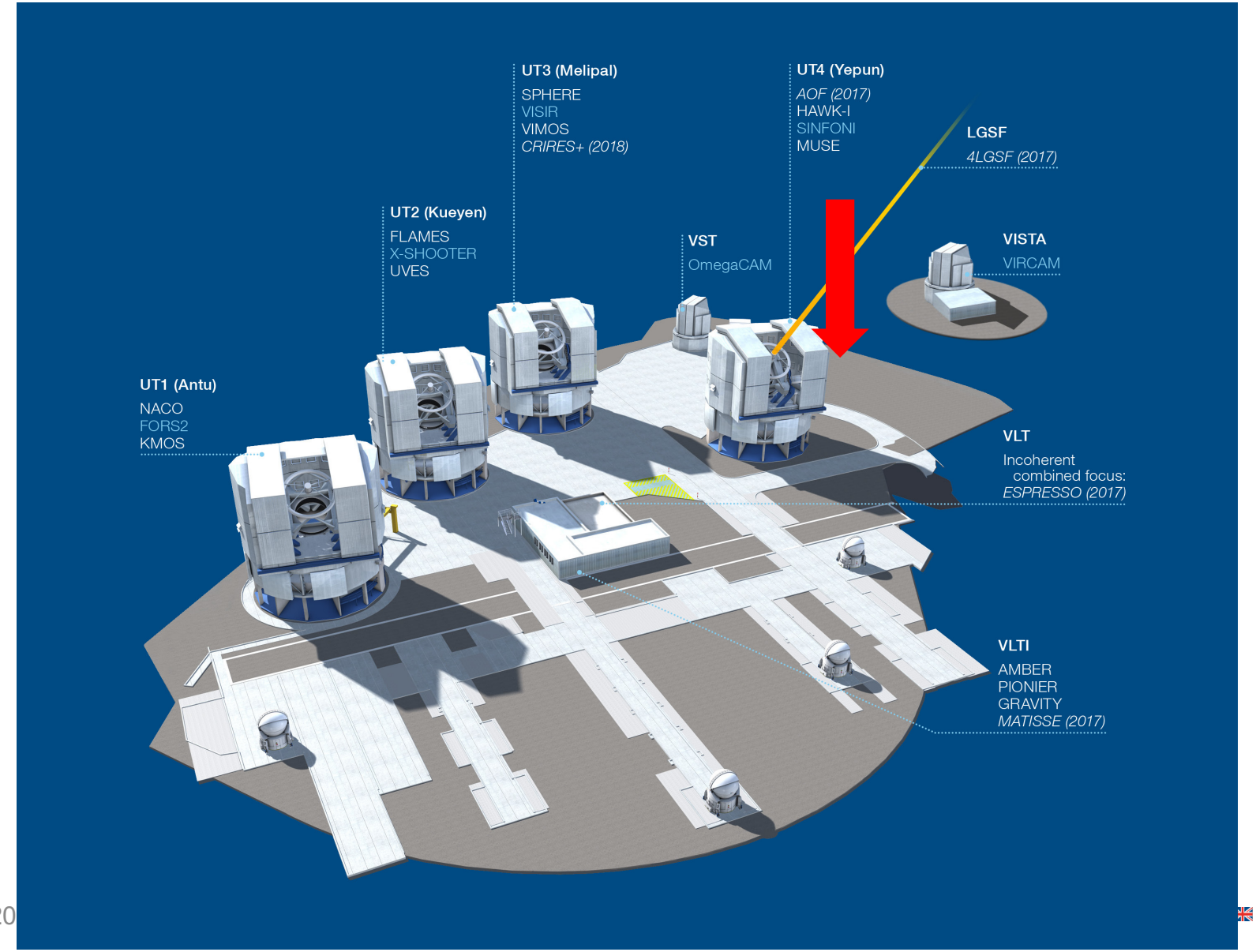
Water vapour monitor

- Median PWV on Paranal: 2.4 mm
- Low Humidity and Temperature Profiling Radiometer (LHATPRO); Kerber et al. SPIE 2012
  - Built by Radiometer Physics GmbH (RPG)
  - Operational since Nov 2011
  - Precipitable water vapour (PWV): 183 GHz line
  - Temperature: O_2 band 51-58 GHz
  - range 0.1-25 mm, saturation setting in at 20 mm
  - PWV accuracy: ca 0.1 mm, precision: ca 30 μm
  - All-sky pointing, sidereal tracking

LHATPRO – IR channel

- IR camera
  - Observes in lock step with PWV
  - Sky brightness temperature at 10.5 μm
  - Range: down to -120°C
  - Capability to detect cold, high altitude, thin clouds
- Clouds on Paranal
  - Cirrus most frequent kind of clouds on Paranal
  - Difficult to detect otherwise (moonless nights)

LHATPRO on Paranal



LHATPRO – IR channel

LHATPRO - Operational scheme

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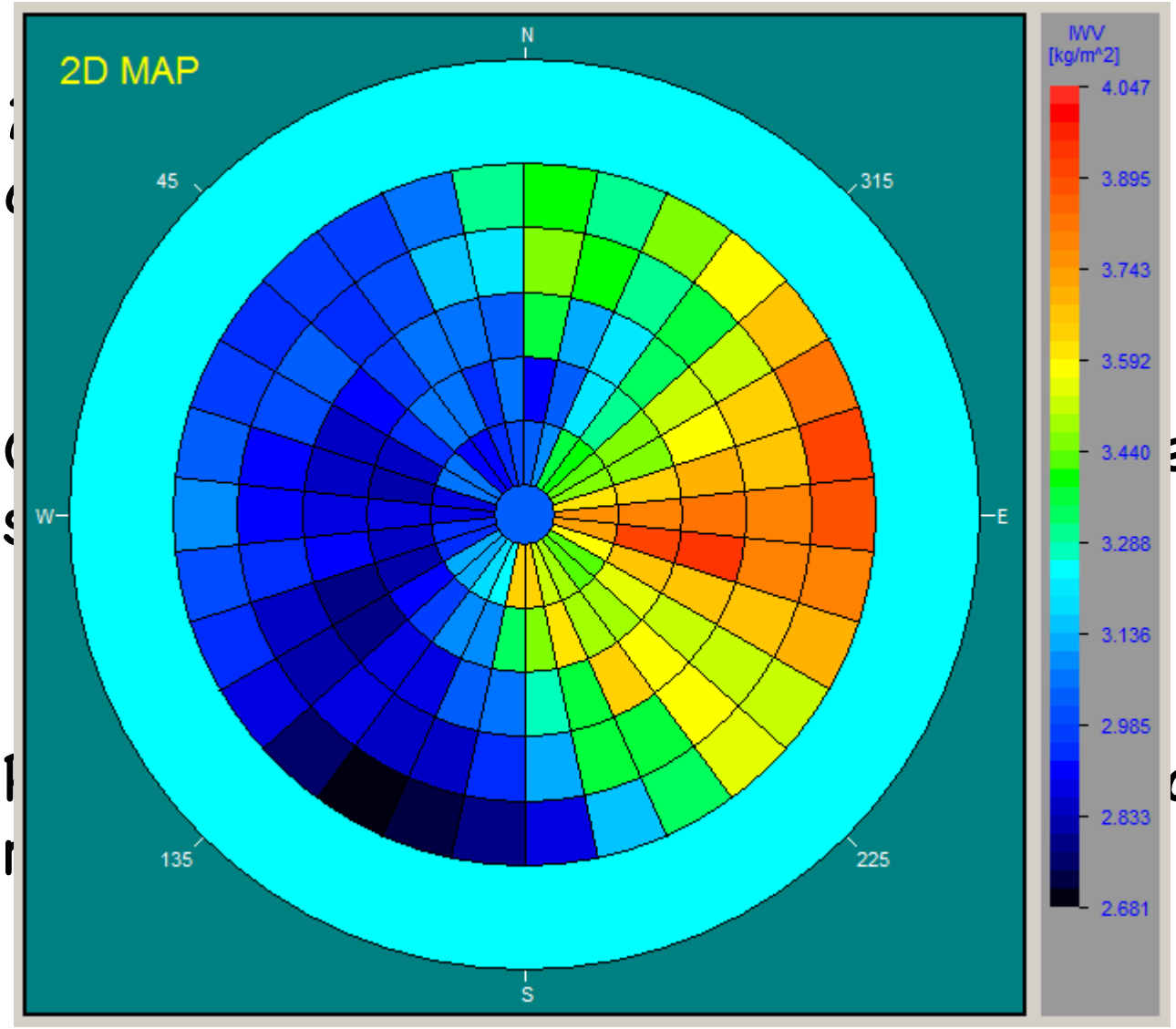
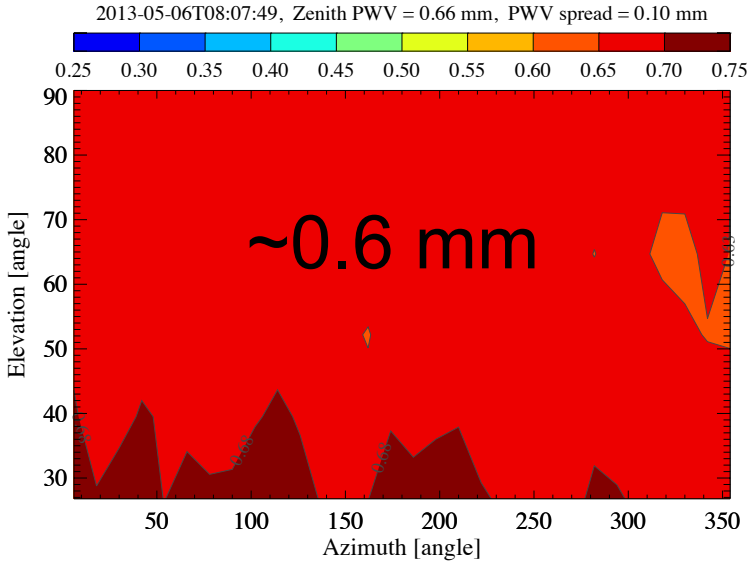
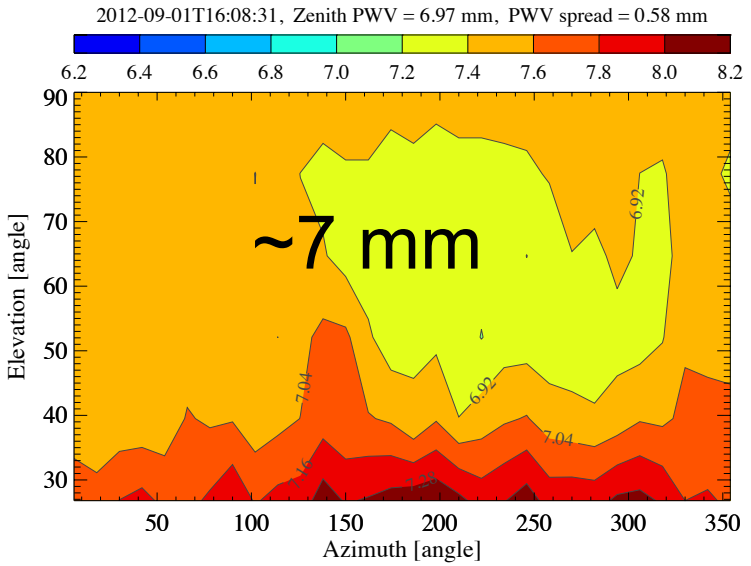
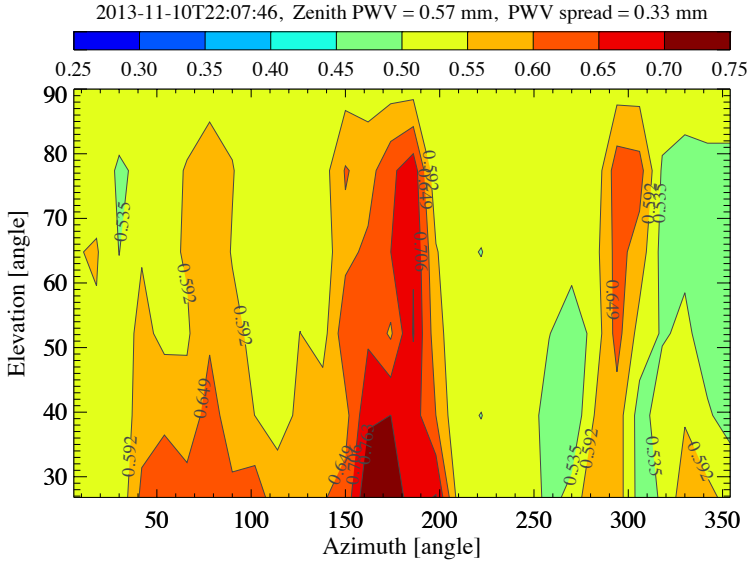
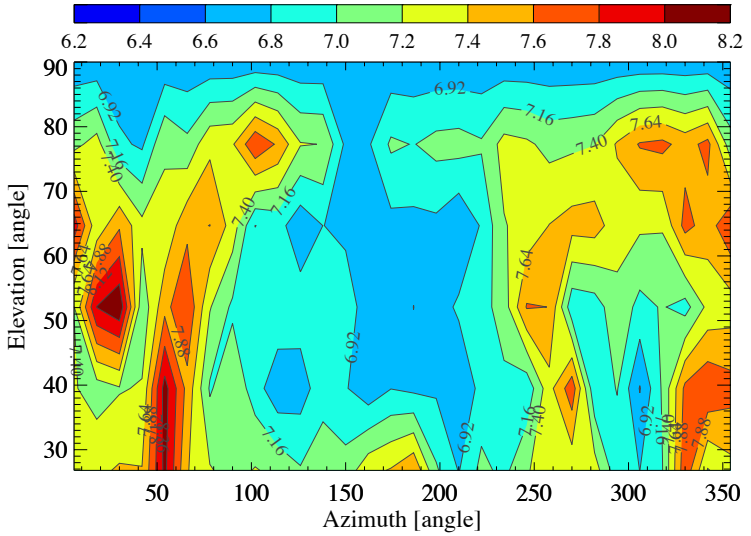


PWV homogeneity









PWV homogeneity

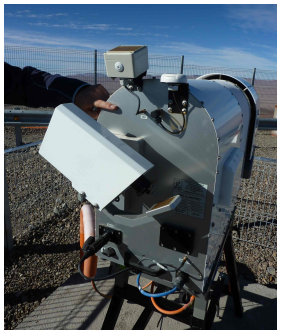
- From ca 2900 all-sky scans

Percentiles	PWV variation SDev [mm]	PWV variation SDev [%]	PWV variation PtV [mm]	PWV variation Ptv [%]
10	0.03	1.4	0.15	7
25	0.04	1.9	0.19	9
50	**0.05**	**2.8**	**0.28**	**13**
75	0.11	4.2	0.54	19
90	0.20	5.9	0.90	26

PWV homogeneity

- PWV is homogeneous to a few % across the sky
- User provided PWV constraint in place
- Measurement at zenith is adequate for Science Operations
- Line of sight support is an interesting option for high precision work
  - Implement as "on demand" capability

ESO Sky quality classification



- Weather officer
  - Empirical, qualitative
  - experience
- LHATPRO IR
  - Automated, quantitative
  - Diagnostic tool

ESO Sky quality classification

- **Photometric (PHOT)**
  - No visible clouds; transpar… under 2%.
- **Clear (CLR)**
  - Less than 1… covered by cl… 0%.
- **Variabl…**
  - Transpa… 10% and 20%.
- **Variable, …(THK)**
  - Large tran…icy variations possible, equivalent to no constraint on the transparency conditions.

Challenge:
Quantitative definition
vs
Empirical evaluation

Time series analysis

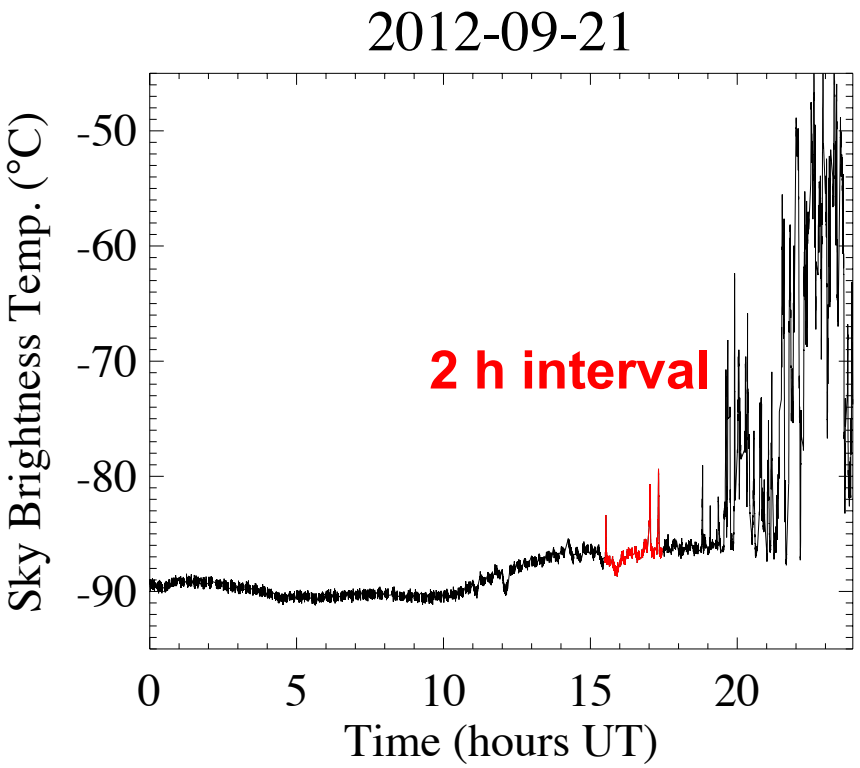
- 24 months of zenith-staring data
  - July 2012 to June 2014
- Detrended Fluctuation Analysis (DFA)
  - Tool for analysis of variation in time series
  - DNA sequencing, financial systems, atmosphere
  - Time series, sliced of equal length τ
  - Each segment detrended, DFA function is power law with exponent alpha

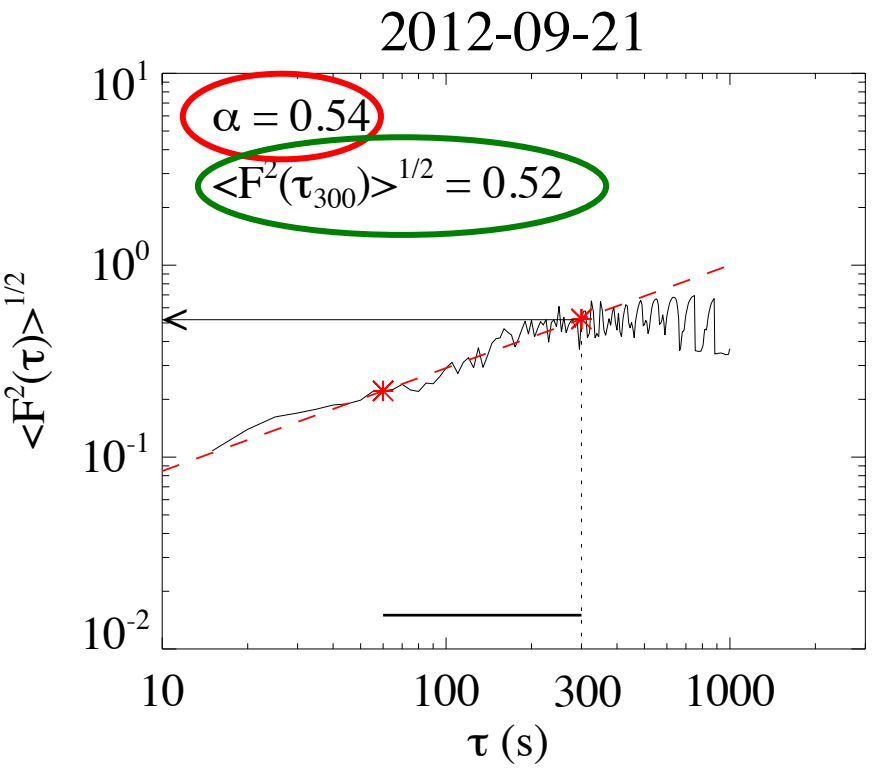
$$F^2(\tau) = \frac{1}{\tau} \sum_{t=k\tau+1}^{(k+1)\tau} \{y(t) - z(t)\}^2$$

$$k = 0,1,2,\ldots,\left(\frac{N}{\tau} - 1\right)$$

$$\langle F^2(\tau) \rangle^{1/2} \sim \tau^{\alpha}$$

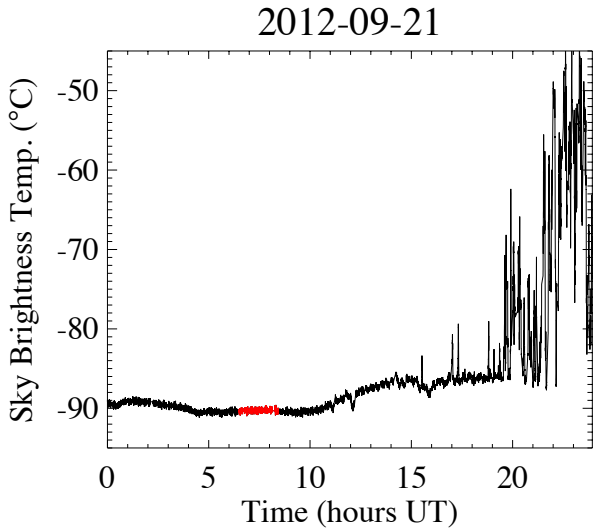
Time series analysis

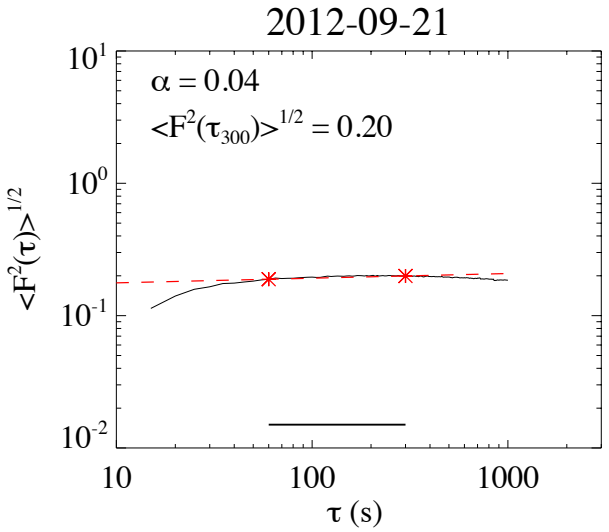


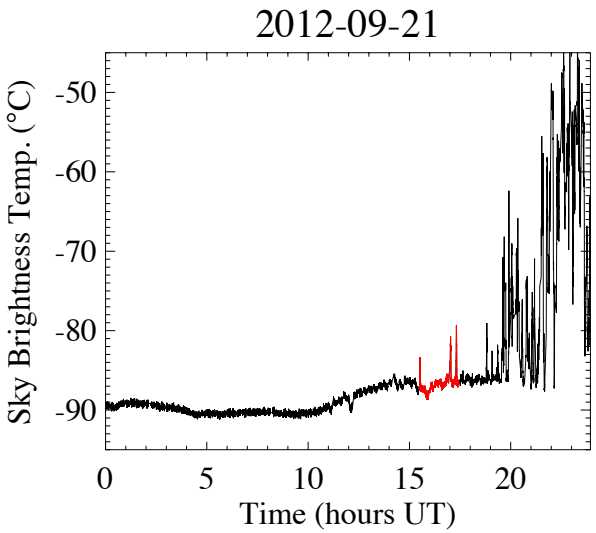


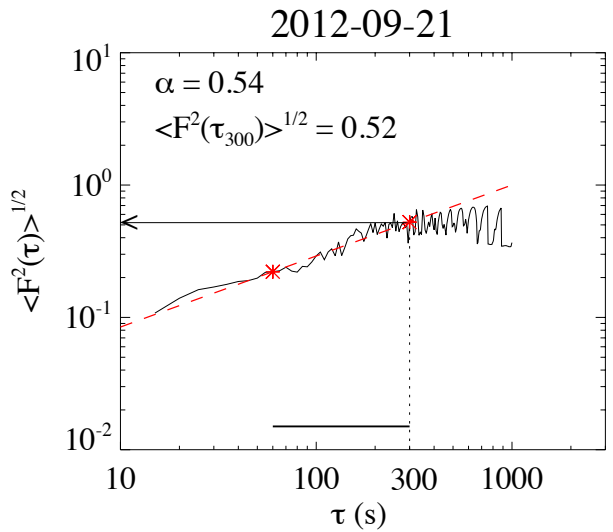
DFA

Time series analysis

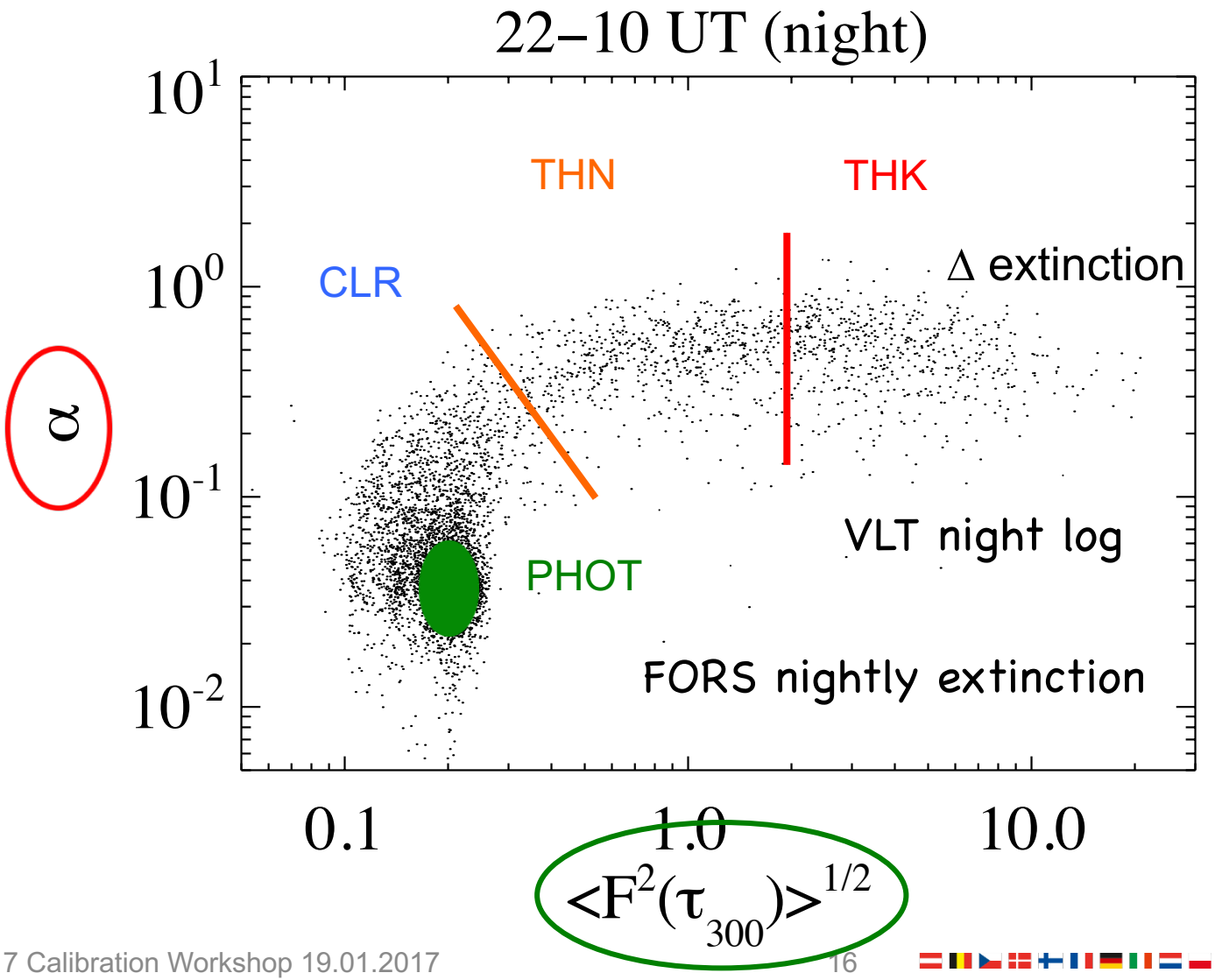




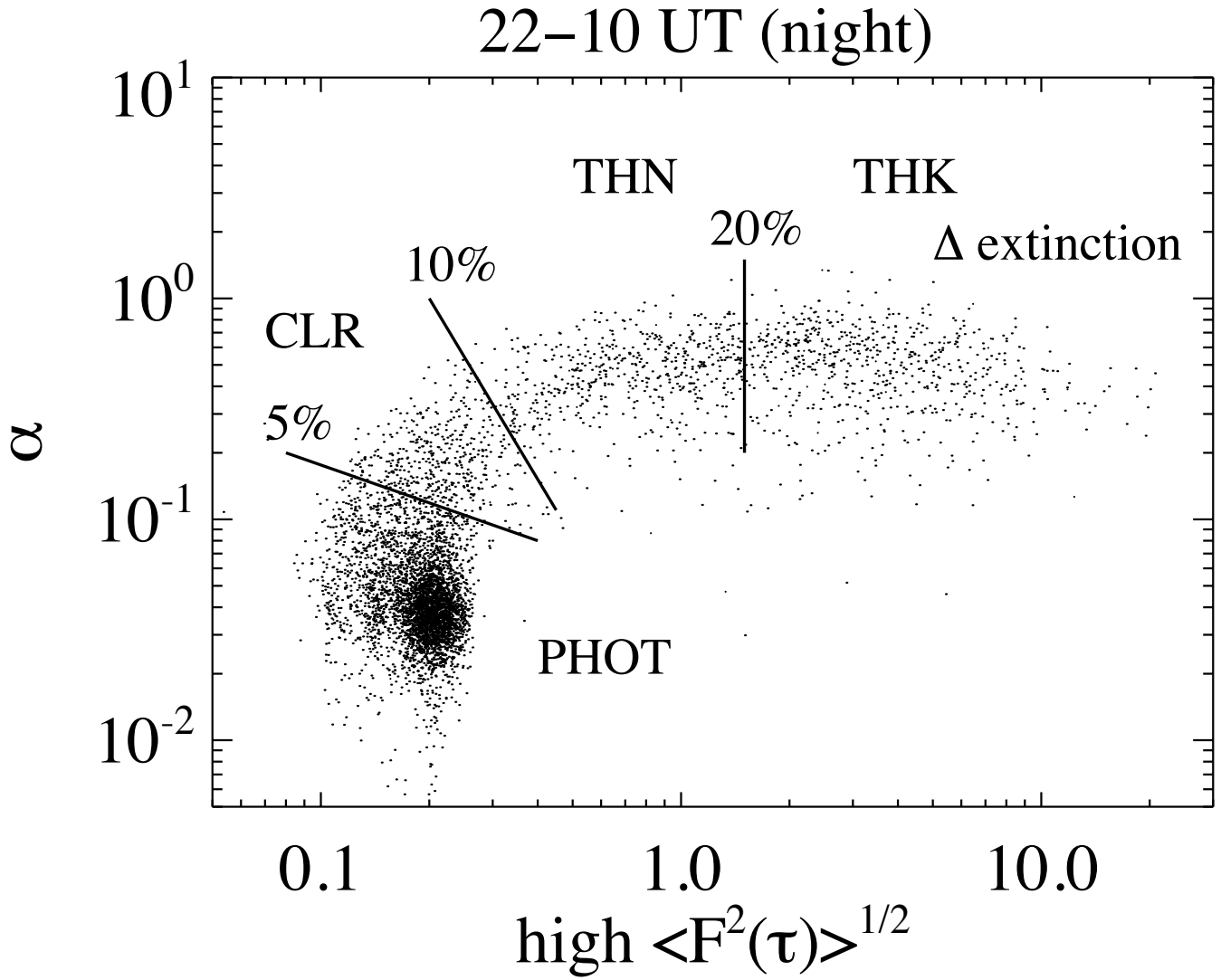




DFA Diagnostic Diagram



DFA Diagnostic Diagram



ESO Sky quality classification

- **Probability of detection**

	Night log		
LHATPRO	**CLR+PHOT**	**THN**	**THK**
CLR+PHOT	**72.0**	1.3	0.5
THN	4.0	**7.7**	0.1
THK	0.8	0.8	**13.0**

- Good matches (diagonal): 92.5%
- Validated with:
  - Night log and FORS 2 extinction measurements

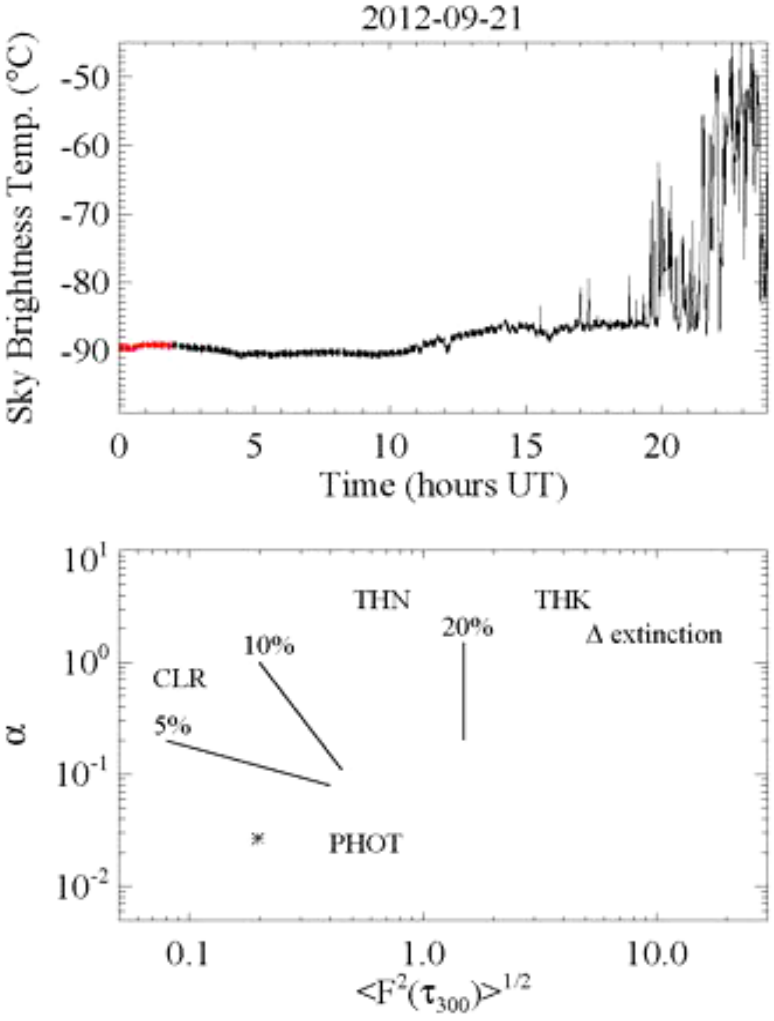
Results & Limitations

- Sky quality mapped onto DFA diagnostic diagram
  - Automated and quantitative description
  - Kerber et al. 2016
- Answer to 15 year old challenge
  - Quantitative definition vs empirical evaluation
- Current limitations:
  - Pencil beam (1.4 degrees) - h/w not the method
  - DFA requires minimal number of data points
    - 2 h interval can be advanced every 15 or 30 min
  - Transition - sky quality classes: slightly fuzzy
    - limited statistics in these regions
    - dedicated photometry in cloudy conditions (Calibration Proposal)

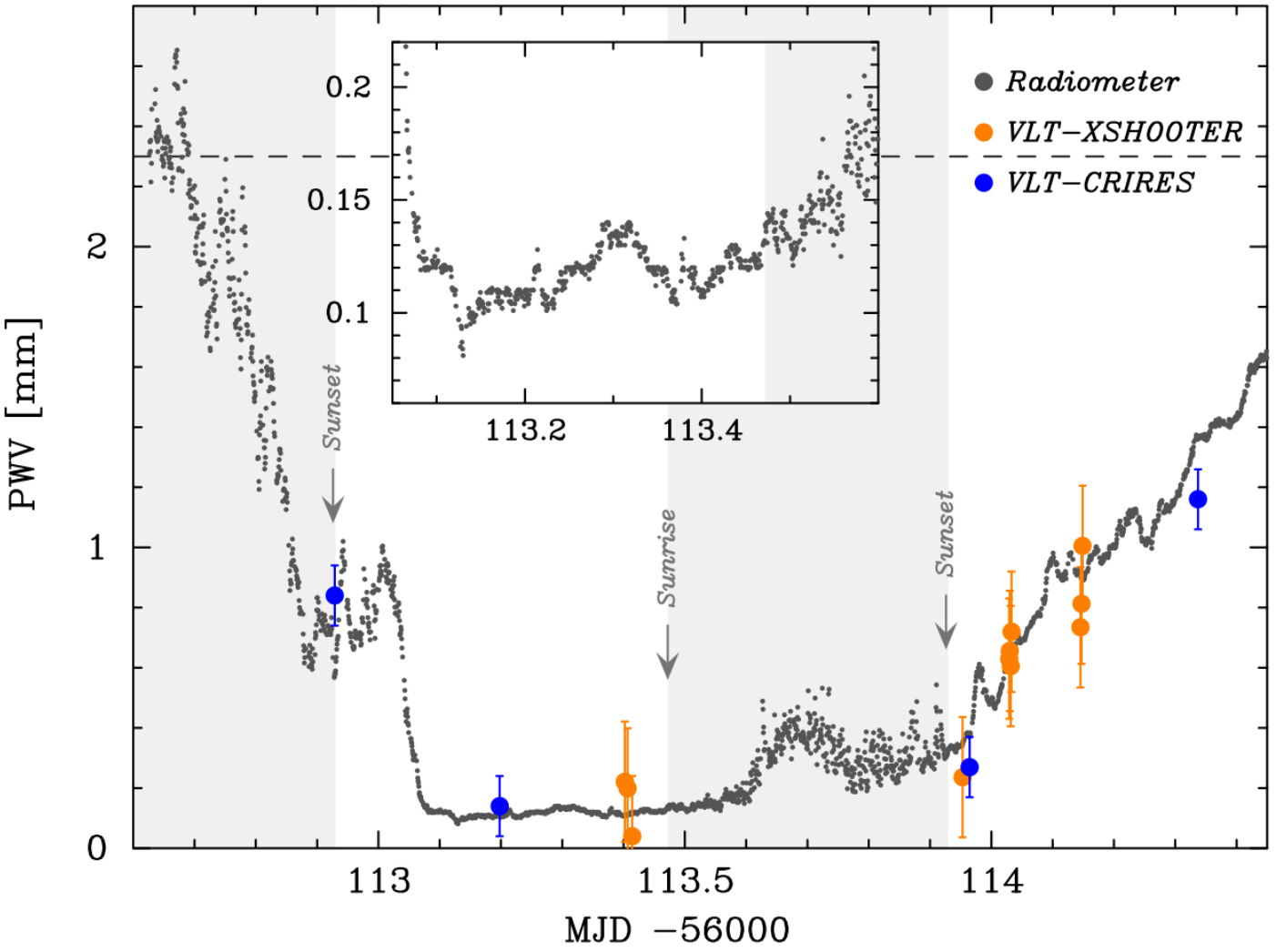
Next steps

- Implement as dynamic tool for SciOps
  - Update every ~15 min possible
  - Support work of weather officer
- Paradigm: PHOT is defined all-sky, "all night"
- Astronomers need to know variation of extinction
  - along line of sight
  - during a given observation

Future: 24 h on Paranal



Future: low PWV Science



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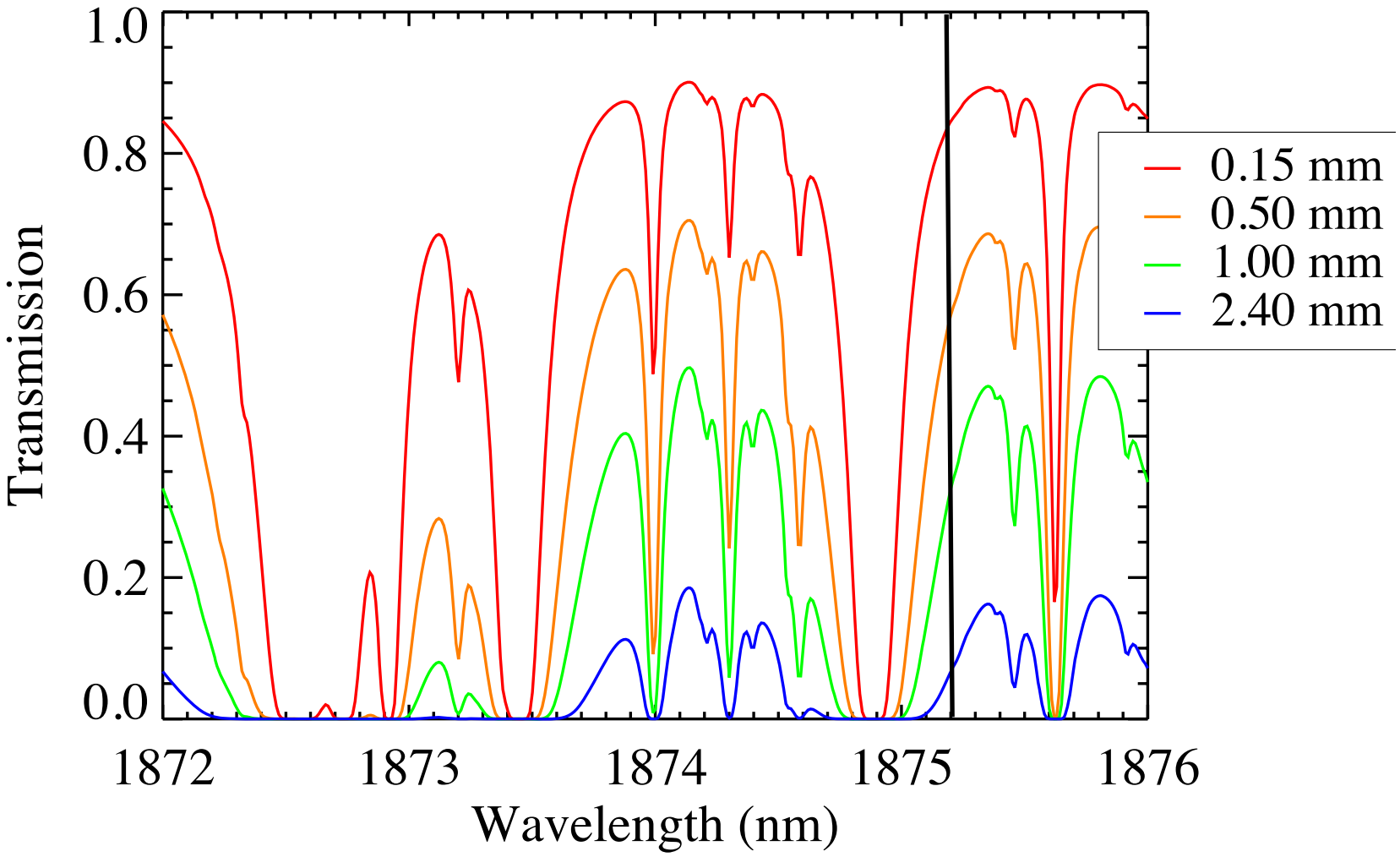
Future: low PWV Science



Future Atmospheric Characterisation

- Tools:
  - ASM: Temperature, relative humidity, wind
  - LHATPRO: profiles (10 km) Temp, RH, PWV
    - RPG is developing improved IR (2 filters) channel
  - Stereo-SCIDAR: C_n^2 profiles (J. Osborn et al. 2016)
  - AOF: telemetry of WFS, properties of Na layer
  - Sophisticated atmospheric models (E. Masciadri et a;. 2013. 2016), etc
- High fidelity local short-term forecast: 1 h

Questions & Answers

- Homogeneity of precipitable water vapour (PWV) across the sky
  - Q1: Is a measurement at zenith representative of my line of sight? **YES,** PWV constraint in place
- Photometric sky quality classification
  - Q2: Can we help the weather officer with an automated process giving a quantitative and reliable result? **YES,** ready for implementation
- Future atmospheric characterisation
  - Q3: What does it take to characterise the relevant properties of the atmosphere and make precise localised short-term forecasts? Unique instrument suite on Paranal to find out

Future Steps

- Line of sight support with LHATPRO
  - PWV for optimum telluric correction
  - IR sky brightness temperature - precision photometry
- Sky Quality: Dynamic Diagnostic Tool
- Evaluate paradigm "PHOT" for future operations
- Enable low PWV Science as "observations of opportunity"
- Combine measurement and modeling to learn how to get the high-fidelity 1 h forecast
- And keep learning …