ALMA Water Vapour Radiometry: Tests at the SMA

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Grenoble, June 2007

Outline

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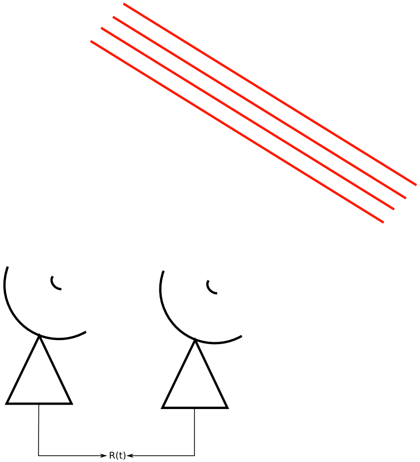
Atmospheric Phase Fluctuations



- Physical properties of atmosphere along line of sight of each telescope are different and vary with time
- Water most important
- Also ‘dry’ fluctuations (due to temperature)

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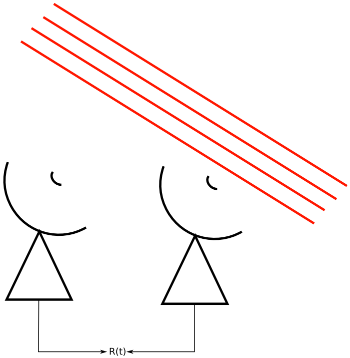

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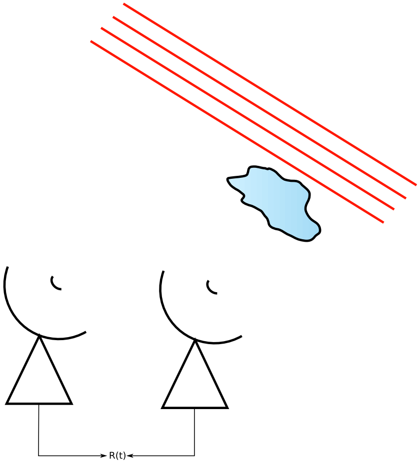

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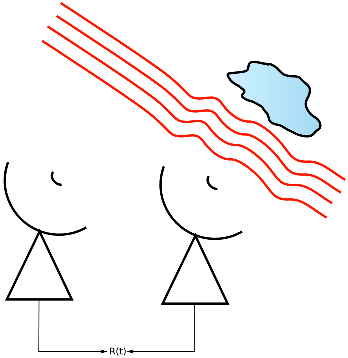

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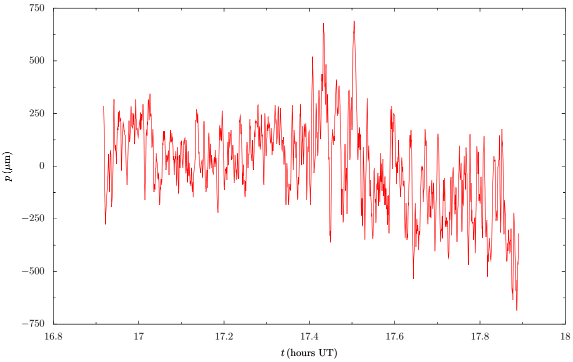
Atmospheric Phase Fluctuations (2)

- To first order, de-correlation is proportional to square of the root-mean-square of phase fluctuations, σ_ϕ^2. (More precisely $R(\nu) \propto e^{-\sigma_\phi^2/2}$).
- Magnitude of fluctuations depends baseline length (as well as the weather):

$$\sigma_\phi^2 = \left\langle (\phi(\mathbf{r}) - \phi(\mathbf{r}+\mathbf{L}))^2 \right\rangle = \left(\frac{L}{L_0}\right)^\alpha, \qquad (1)$$

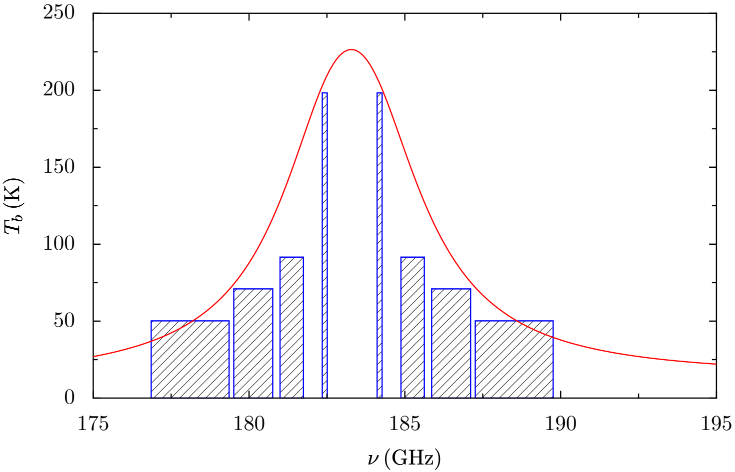
  where α most likely between $2/3$ and $5/3$
- Dominant timescales of fluctuation depend on wind speed.

Illustration of Phase Fluctuations

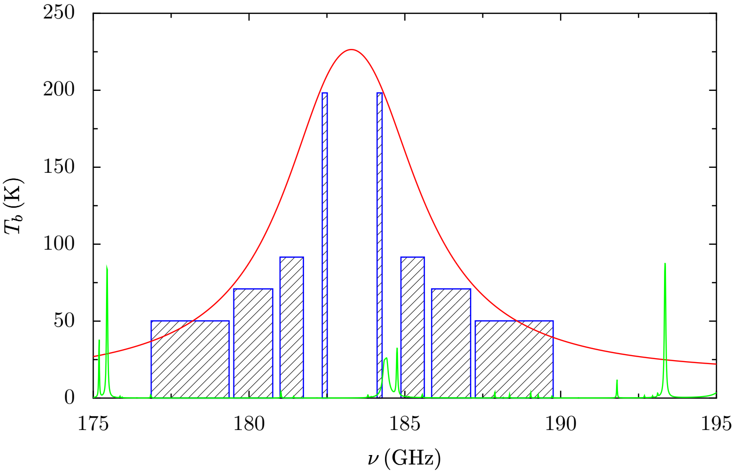


- Mauna Kea, Hawaii
- 200 m baseline
- About 3.5 mm line-of-sight water
- $\sigma_\phi = 207\,\mu$m.

The 183 GHz Water Vapour Line



The 183 GHz Water Vapour Line (+ Ozone)



Outline

The Sub-Millimetre Array (SMA)

The Radiometers

- Tests used the two ALMA prototype radiometers:
  - 1 Hz sampling
  - One baseline only
  - Two different designs (correlation and Dicke)
  - Production design to be based on the Dicke switching principle although further simplifications
- Correlation radiometer
  - Sideband separation, pseudo correlation design
- Dicke radiometer
  - Double sideband, chop-wheel at about 20 Hz
- Calibration: Both designs with integrated cold and ambient loads.

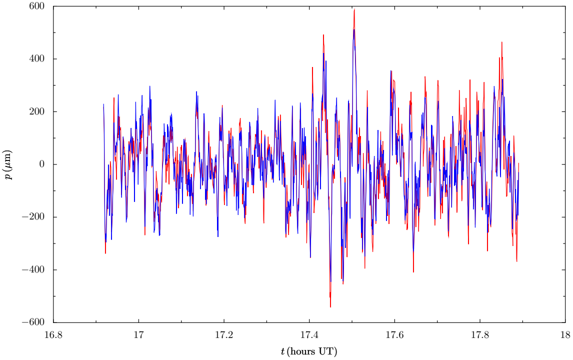
The Radiometers on the SMA

- People at the SMA: M. Reid, A. Peck, S. Paine, T. Hunter
- The SMA was an evolving facility during these tests
- Optical interface to the SMA
  - Design by R. Williamson
  - Polarising grid, so radiometer beam in the same direction as the astronomical beam
  - Significant amount of additional optics
- Software interface to the SMA
  - Not based on ALMA software
  - Some problems arose (more on this later)
- Most data on a ≈200 m baseline
- Interferometer sampled at 2.6 s (slower than the radiometers, ALMA)

Outline

Sample observation (Feb. 17, 200 m baseline)

Path as measured by the interferometer (red) and as predicted by radiometers (blue)



- Observed $\sigma_\phi = 207\,\mu$m.
- Fluctuation around 5-min average: $\sigma_\phi = 153\,\mu$m.
- Residual after correction: $\sigma_\phi = 62\,\mu$m .
- 1 hour observation

Sample observation (Feb. 17, 200 m baseline)

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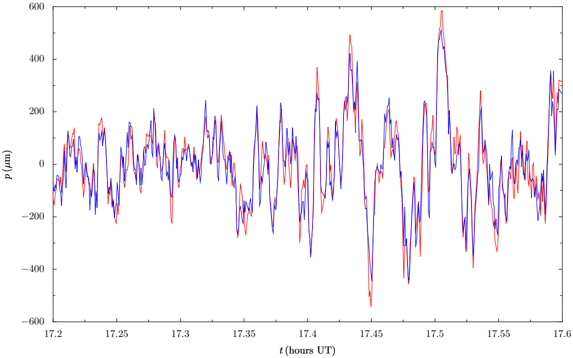

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- 25-minute section

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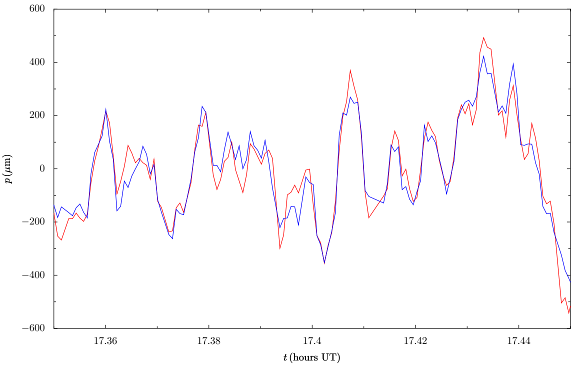
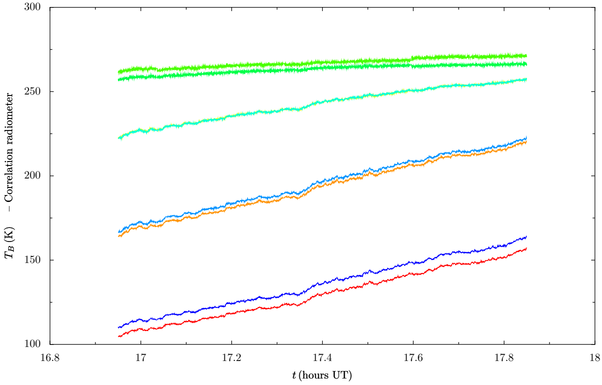


- Observed $\sigma_\phi = 207\,\mu$m.
- Fluctuation around 5-min average: $\sigma_\phi = 153\,\mu$m.
- Residual after correction: $\sigma_\phi = 62\,\mu$m .
- 5-minute section

Outline

Radiometer Outputs

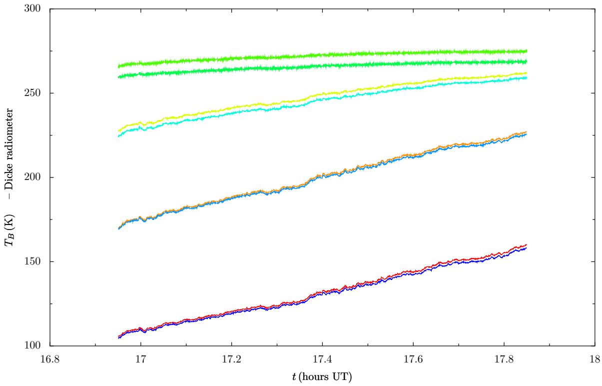
Correlation Radiometer



- Eight outputs
- Blue line highest, red line lowest frequency
- Pseudo-continuum can be seen in data from correlation radiometer

Radiometer Outputs

Dicke Radiometer



- Eight outputs
- Blue line highest, red line lowest frequency
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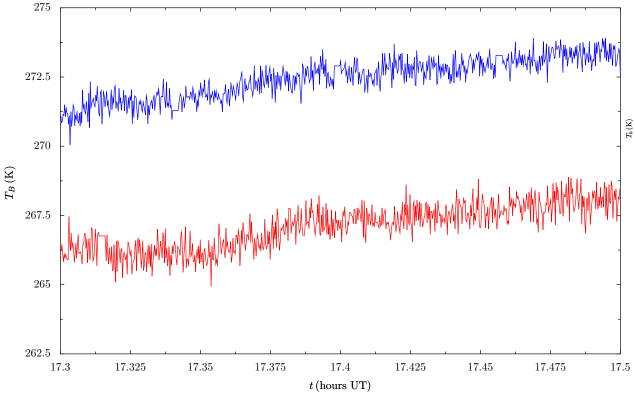
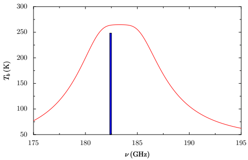
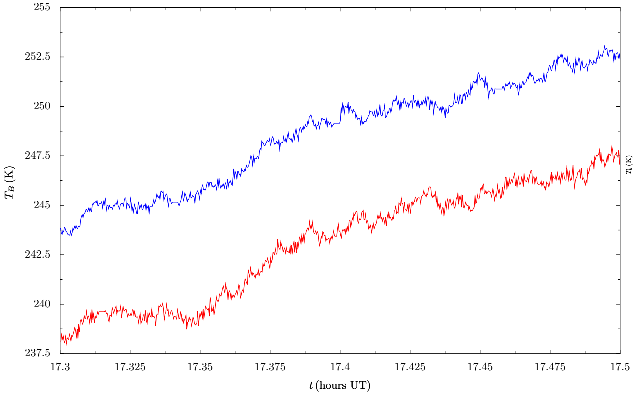
Centre channel outputs

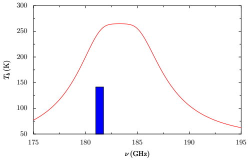




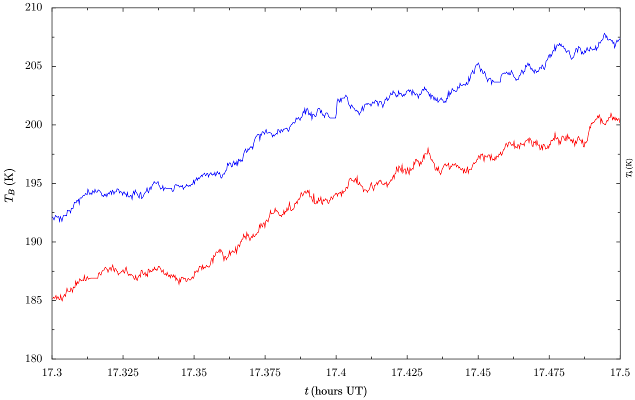
- Most sensitive in very dry conditions

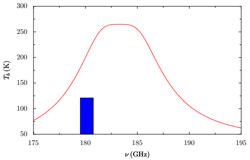
Centre channel outputs





Outside channel comparison





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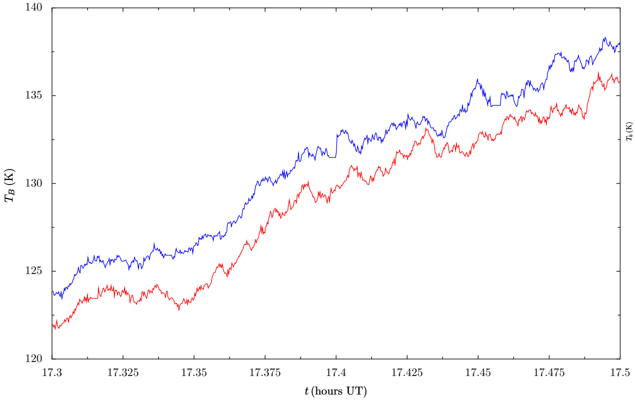
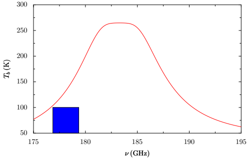


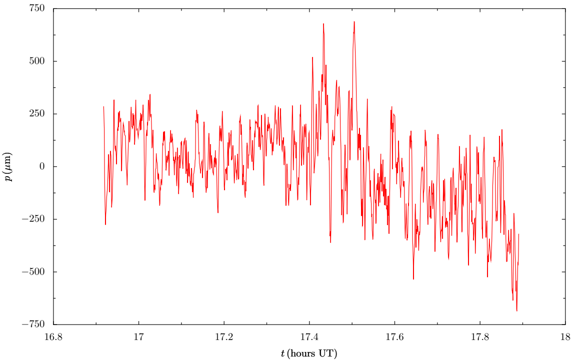


- Most sensitive in the wettest conditions

Outline

Interferometer Data

- Phase measurements by tracking bright quasars
  - Single baseline data
  - Significant phase wrapping in some conditions



Interferometer Data

- Phase measurements by tracking bright quasars
  - Single baseline data
  - Significant phase wrapping in some conditions
- Normal dump time 5 s so some drop-outs seen, easily excised.
- Contribution of interferometer phase stability to observed phase fluctuations not well quantified.
- Some concern over synchronisation of data. Data taken at 1 s sampling suffered badly from timing drifts (most likely in radiometer computers)

Outline

Conversion factors: the simplest model

- Simplest model where fluctuations occur in a single layer
- $\delta p \approx \frac{\partial p}{\partial c} \delta T_{\mathrm{B}} / \frac{\partial T_{\mathrm{B}}}{\partial c}$
  - δp is fluctuation in path, δT_{B} is fluctuation in radiometer brightness temp
  - c is water column
  - $\frac{\partial T_{\mathrm{B}}}{\partial c}$ depends on water column, temperature, etc. Trickiest to determine.
  - $\frac{\partial p}{\partial c}$ less uncertain to estimate but (relatively weak) function of observing frequency
- Assuming $\frac{\partial T_{\mathrm{B}}}{\partial c}$, $\frac{\partial p}{\partial c}$ constant can linearise as $\delta p \approx \sum_i a_i \delta T_{\mathrm{B},i}$

Conversion factors (2)

- Slightly more sophisticated: consider fluctuations in optical depth:

$$T_{\mathrm{B}} = T_{\mathrm{atm}}\left(1 - e^{-\tau}\right) \implies \delta\tau \approx \frac{\delta T_{\mathrm{B}}}{T_{\mathrm{atm}} - T_{\mathrm{B}}}, \qquad (2)$$

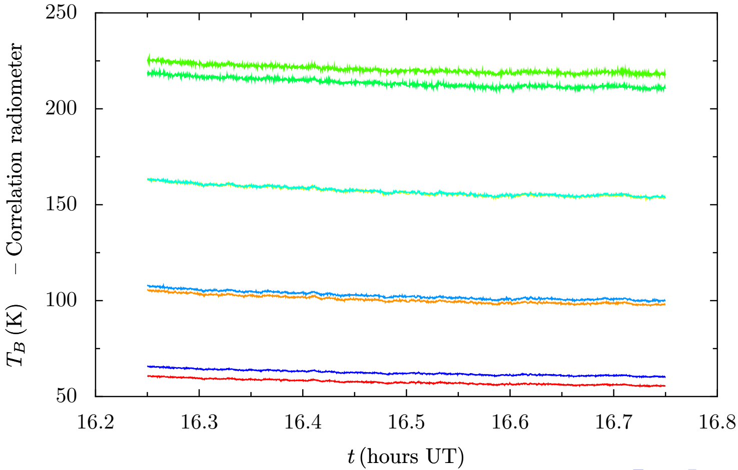
  and use $\delta p \approx \sum_i b_i \delta\tau_i$
- This adjustment significant in one observation with large airmass change – otherwise very small improvement.

Conversion factors (3)

- Determining a_i for a particular set of atmospheric conditions (also radiometer pair?) a key problem:
  - Physical modelling; compute $\frac{\partial p}{\partial c}$, $\frac{\partial T_\mathrm{B}}{\partial c}$
  - Machine learning, neural network
- In these tests we **measure** phase
- We are interested in the best obtainable performance of radiometers:
  - Best obtainable performance means optimal a_i set
  - Look for optimal set directly by least-squares comparison of measured phase and path predicted by $\sum_i a_i \delta T_{\mathrm{B},i}$

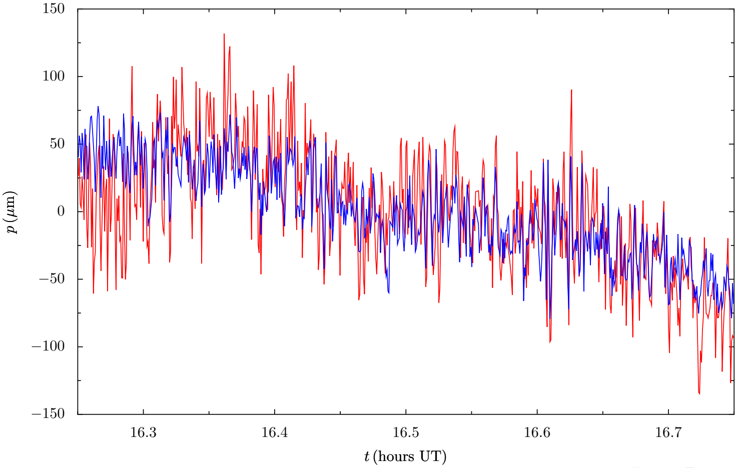
May 3: Good Conditions

About 1.4 mm line-of-sight water, short baseline



May 3: Good Conditions

σ_ϕ reduced from 46 to 29 μm



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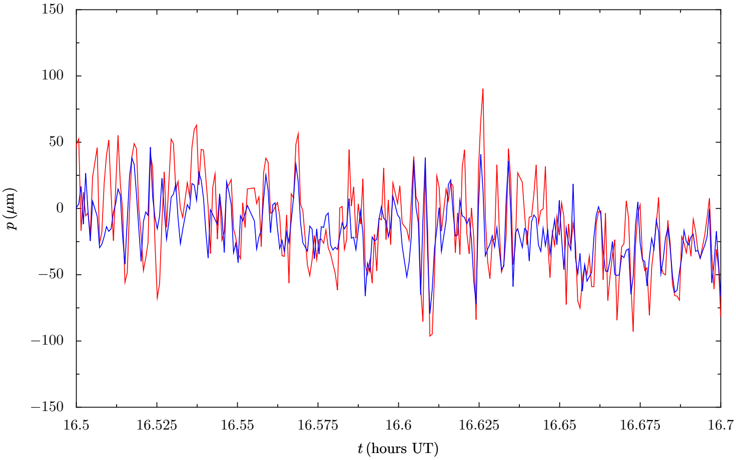
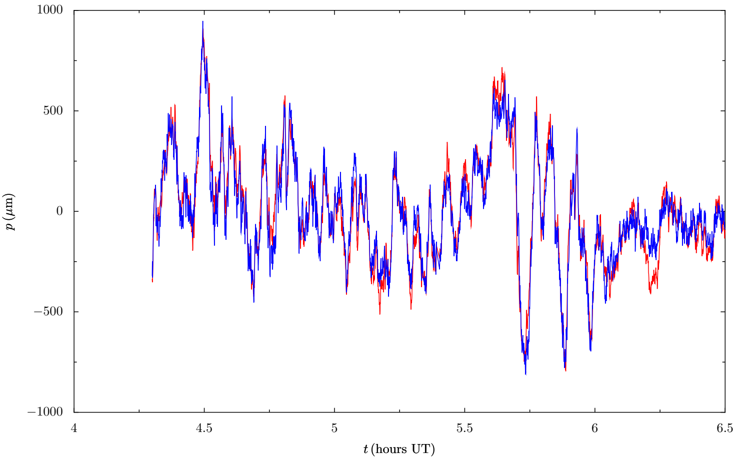


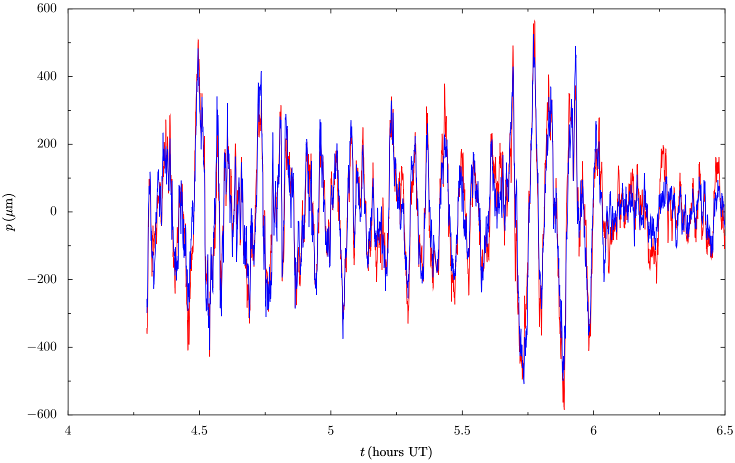
July 18: Can track long time-scale fluctuations

Total fluctuations (no running mean removed): σ_ϕ reduced from 271 to 75 μm



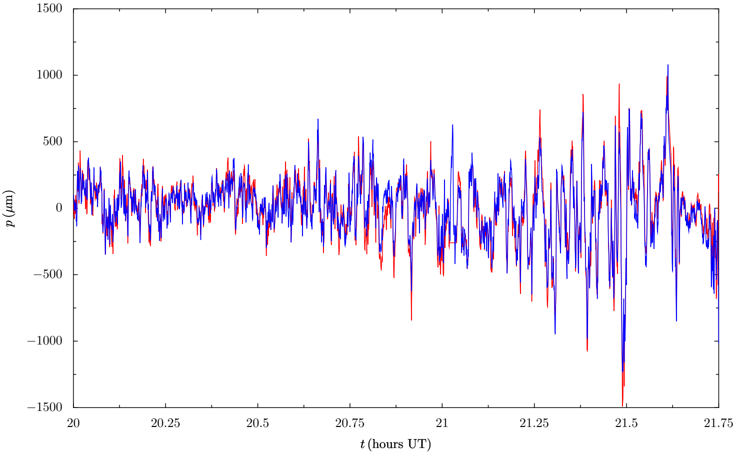
July 18: Can track long time-scale fluctuations

Fluctuations from five minute average: σ_ϕ reduced from 164 to 56 μm



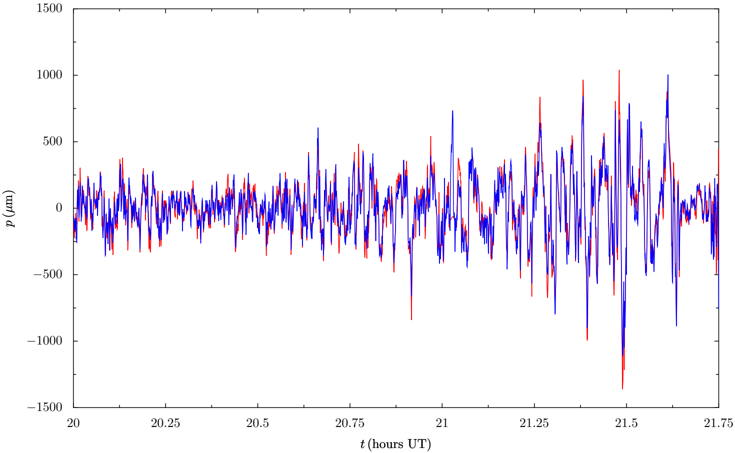
February 24: Short time scale fluctuations

Total fluctuations – observed $\sigma_\phi = 258\,\mu$m, residual $\sigma_\phi = 93\,\mu$m



February 24: Short time scale fluctuations

Fluctuations from five minute average – observed $\sigma_\phi = 241\,\mu\mathrm{m}$, residual $\sigma_\phi = 72\,\mu\mathrm{m}$



Outline

Table of observations

Date	Time (UT)	Elev (deg)	Baseline (m)	Raw σ_ϕ (μm)	5-minσ_ϕ (μm)	Res. (μm)	c (mm)	Spec (μm)	Sampling (s)	Comment
20060217	16.9–17.9	16–30	212	207	153	62	3.6	68	2.6	
—	19.8–20.2	38–44	212	238	239	73	2.0	47	2.6	
20060224	18.4–19.4	25–40	212?	81	79	47	2.5	51	2.6	
—	20.0–21.75	47–72	212?	258	241	72	2.4	52	2.6	
20060503	15.3–16.8	44-65	64	54	37	28	1.4	35	2.6	
20060524	5.1–5.7	50–55	212	103	87	34	2.6	53	2.6	
—	5.9–8.8	55–64	212	90	73	31	1.8	41	2.6	
20060601	5.3–6.7	57–64	212	62	40	31	2.4	48	2.6	
—	7.3–8.3	55 –63	212	154	72	56	2.4	50	2.6	
20060718	4.3–6.5	40–62	212	271	163	56	2.3	50	2.6	11 s offset, timing issues.
20060920	4.2-5.5	27–41	64	83	71	60	3.1	60	1.3	High intf. noise. Timing issues.
—	6-6.7	46–61	64	72	62	50	2.3	48	1.3	—
20061030	19.3-20.3	67–72	415	332	282	139	7.0	119	1.3	Very wet conditions. Quality of fit limited by time drift.

Outline

Status, future plans

- Prototype radiometers now back in Europe
  - Currently used for low level software integration work at ESO, Garching
- Contract for production radiometers signed
- First production radiometers to be completed by mid-summer 2008.
- In Cambridge:
  - Development of WVR algorithms
  - Possibly involvement in atmospheric profiling (most likely using O_2 sounding)

Final Remarks

- Results from SMA tests very encouraging – the radiometers clearly can meet the spec in the majority if not all of conditions.
- Few issues with radiometers identified. Majority of problems arose from interfacing to the SMA.
- Development of WVR algorithms most likely to proceed without further observational data until end of 2008.