

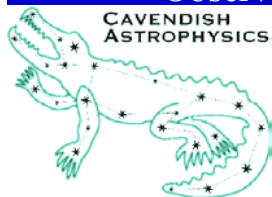
Testing the ALMA WVR's on the Submillimeter Array

Richard Hills on behalf of
the AWVR testing collaboration:

P.G.Anathasubramanian¹, R.E.Hills, K.G.Isaak², M.Owen, J.S.Richer,
H.Smith, A.J.Stirling³, R.Williamson⁴, Cavendish Lab, Cambridge, UK,
V.Belitsky, R.Booth, M.Hagström, L.Helldner, M.Pantaleev, L.E.Pettersson,
Onsala Space Observatory, Sweden, and
T.R.Hunter, S.Paine, A.Peck, M.A.Reid, A.Schinckel, K.Young,
Harvard-Smithsonian Center for Astrophysics, Submillimeter Array Project.

¹ Raman Research Institute, India, ² University of Cardiff, UK, ³ Meteorological Office, UK,

⁴ Columbia University, NY, USA. The SMA is a joint project of the Smithsonian Astrophysical
Observatory, Cambridge, Mass, USA, and ASIAA, Taipei, Taiwan

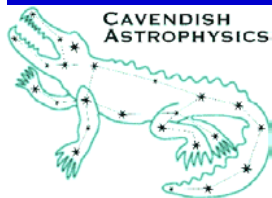
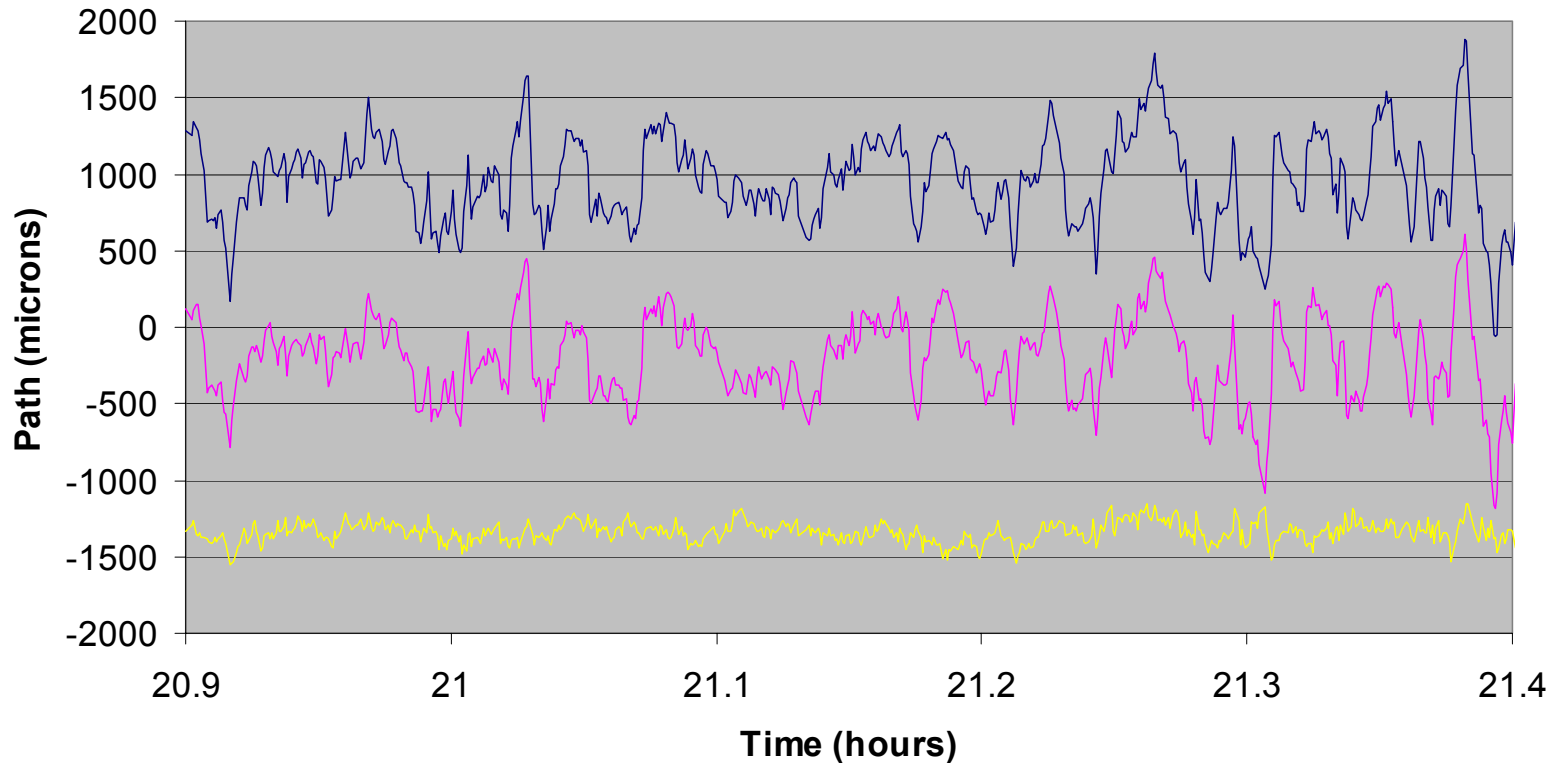


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ALMA radiometers on SMA – it works!

Interferometer (blue), Radiometer (pink) and Difference (yellow)

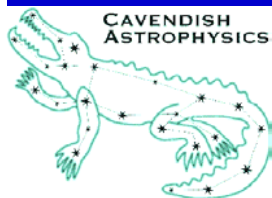


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Why is this hard?

- Goal is to measure path fluctuations to ~ 15 to 50 microns (50 to 160 fs!) for total water vapour of 0.5 to 4 mm (~ 3 to 25 mm of total path), so $\ll 1\%$ of total.
- Essentially making two absolute measurements and then taking the difference.
- So radiometers have to be very sensitive (~ 60 mK with 1 second integration) and stable, but also match each other very well in calibration, channel frequencies, coupling to sky...
- Saving grace is that we only need short term fluctuations and values over a small region of sky.

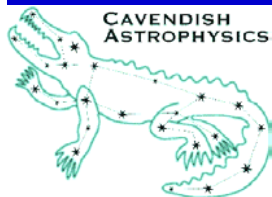


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Steps along the way:

- Lab testing: stability, beams, frequency response...
- Side by side tests on Mauna Kea
- Sky dips
- Interferometry:
 - Deglitch
 - Unwrap
 - Sidebands
- Radiometers:
 - Convert brightness temperatures to path
 - Timing, “Tune-up”, de-spike.



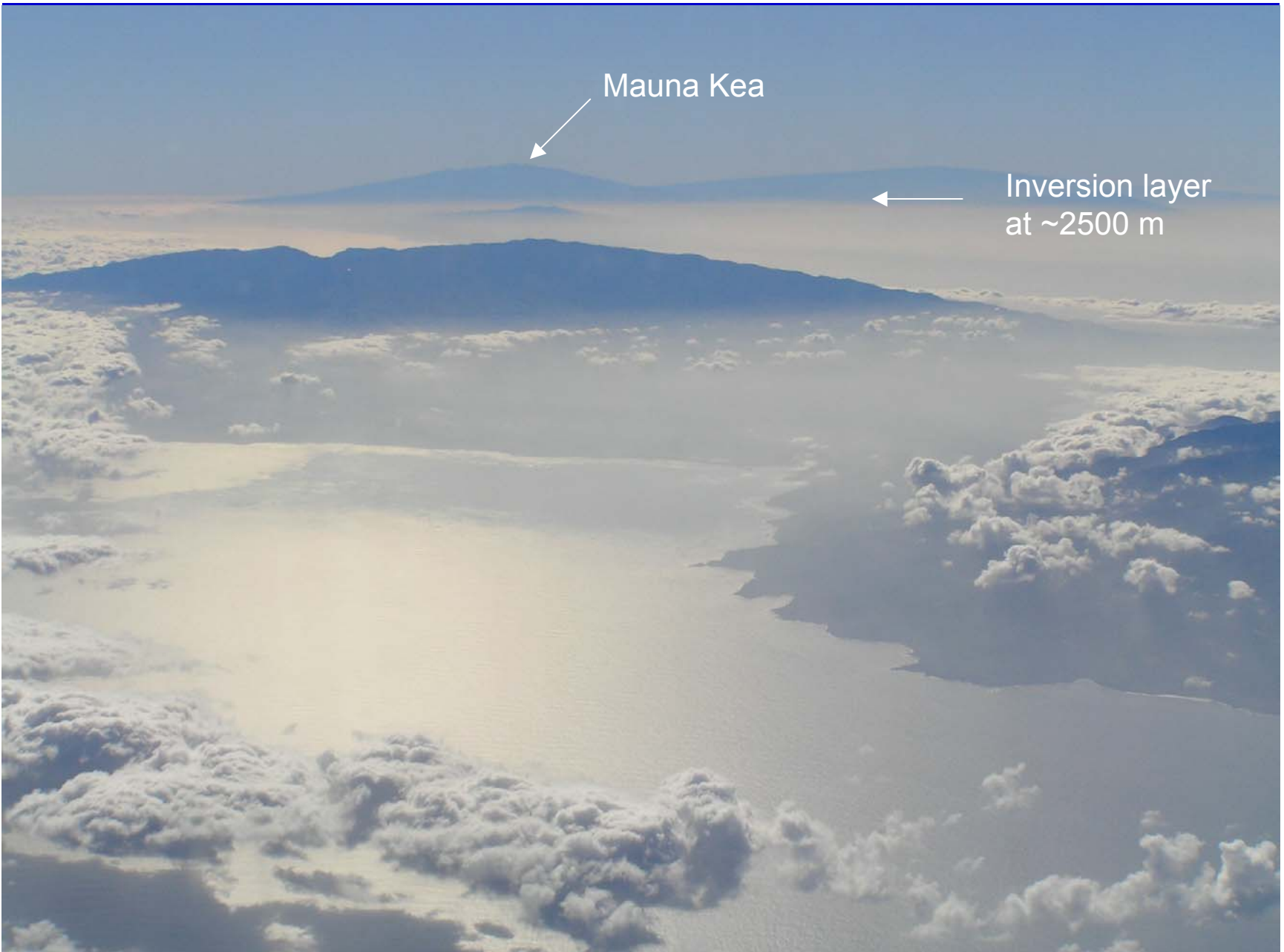
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Mauna Kea



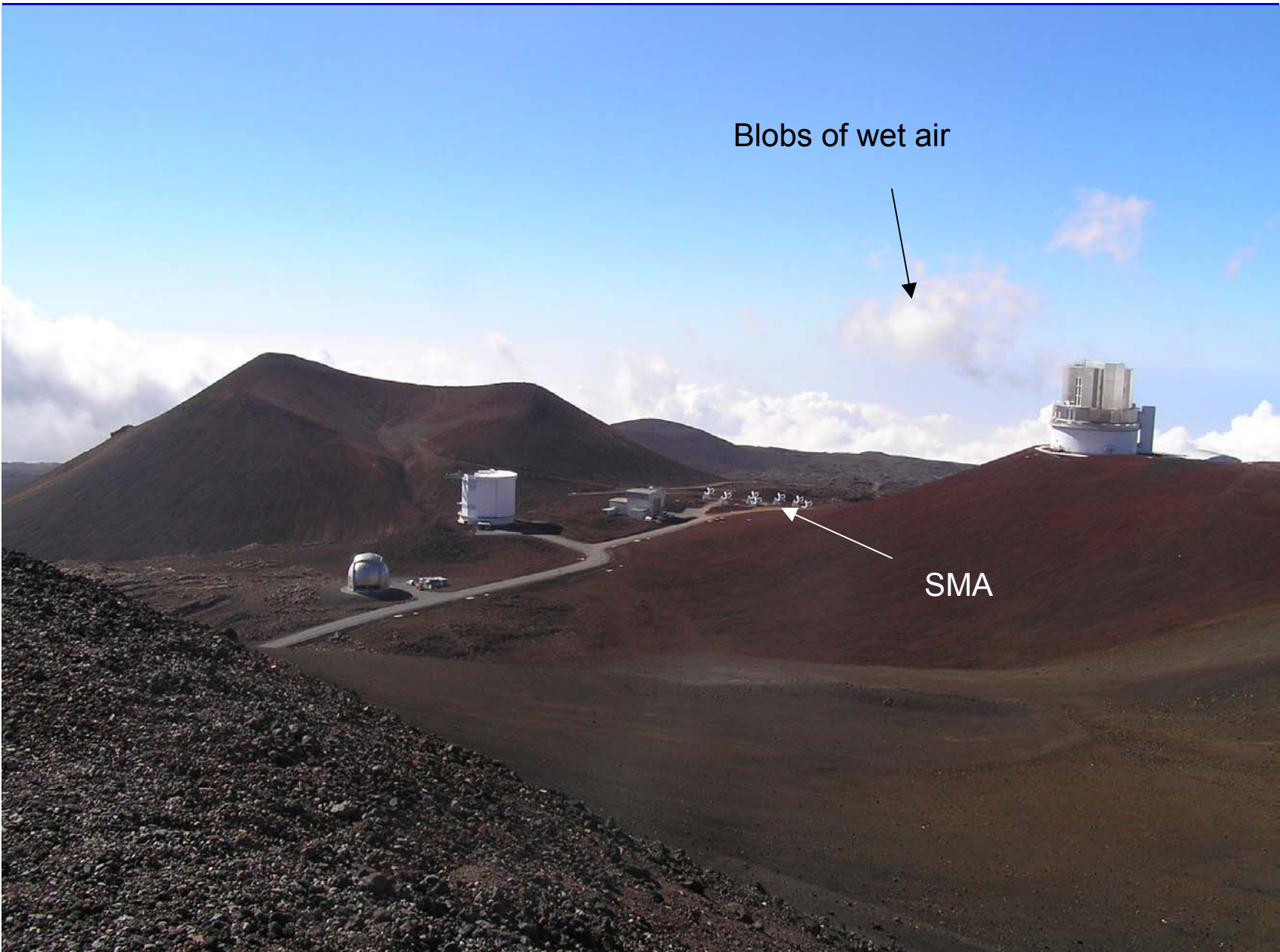
Inversion layer
at ~2500 m



Blobs of wet air

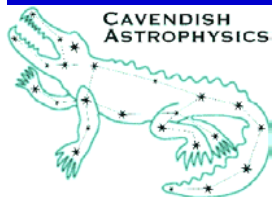
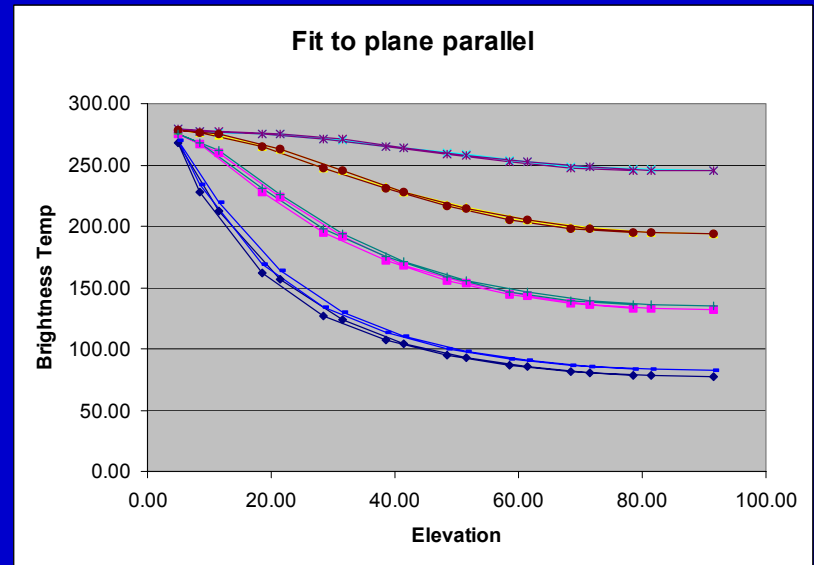
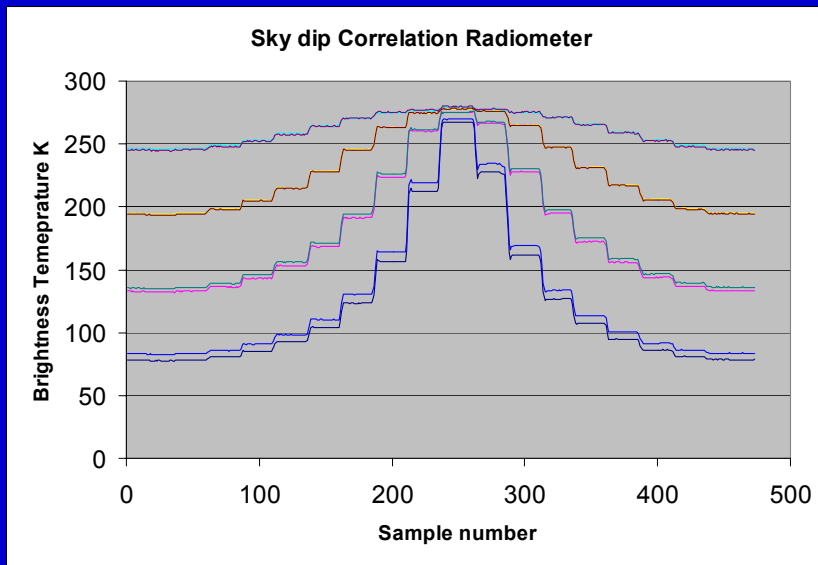


SMA

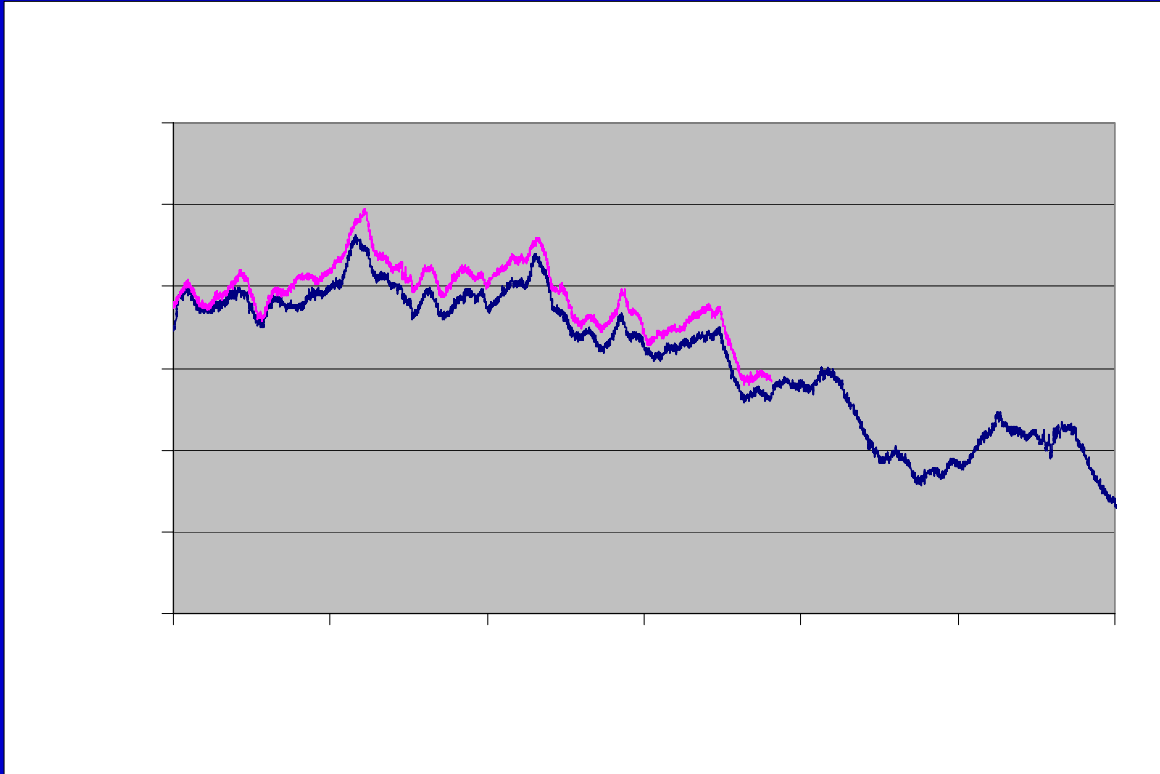


First test Radiometers OFF the antennas

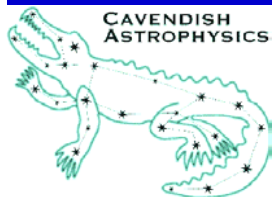
- IF atmosphere is stable can do sky dips to check the calibration, etc. Looked fine.



Compare Radiometers looking at same sky



- Good – not perfect due to different beams?

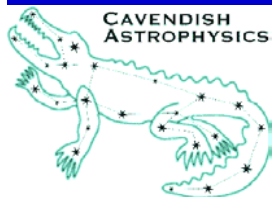


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Then install on telescopes

- Radiometers pick off the beam from the sky by using a polarizing grid plus (lots of) optics – see Ross Williamson’s talk at this meeting.
- Need to check losses and spill-over. Use sky dips – find some elevation dependence – see Scott Paine’s talk at this meeting.
- Also had to cut out LO leakage into astronomical receivers – additional grid. Some offsets from reflections.

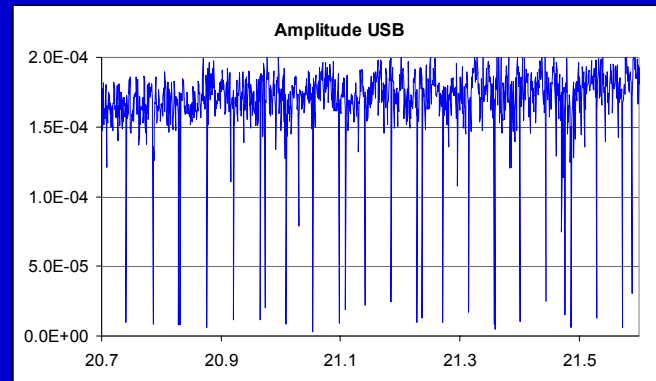
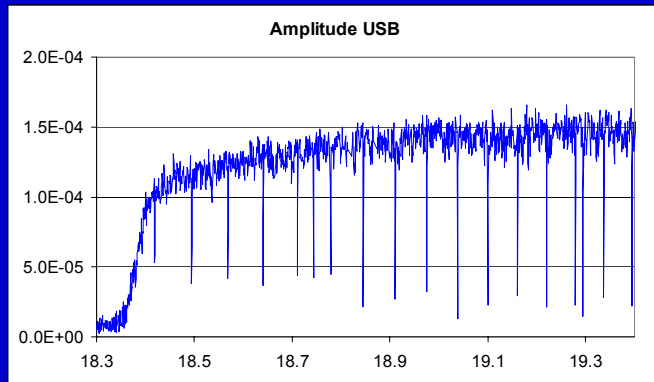


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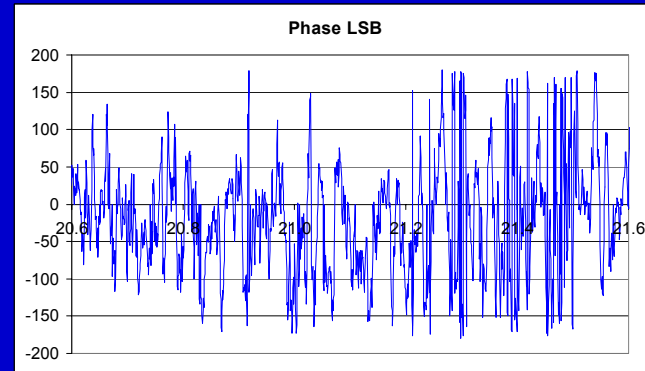
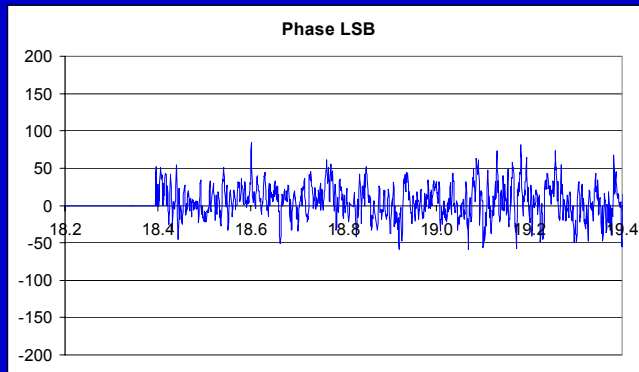




Interferometer Data

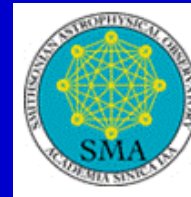
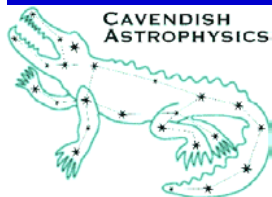


Dropouts seen. These are caused by reading out every 2.6 secs which is faster than software designed to do. Edit these out.



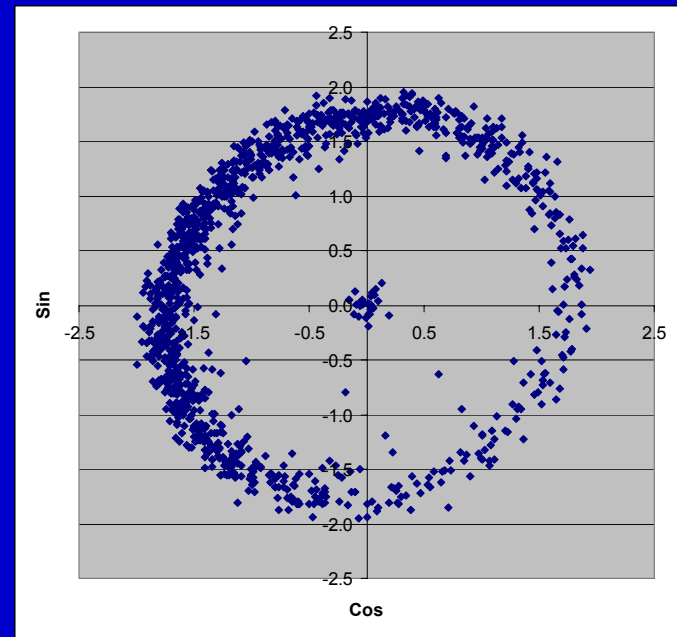
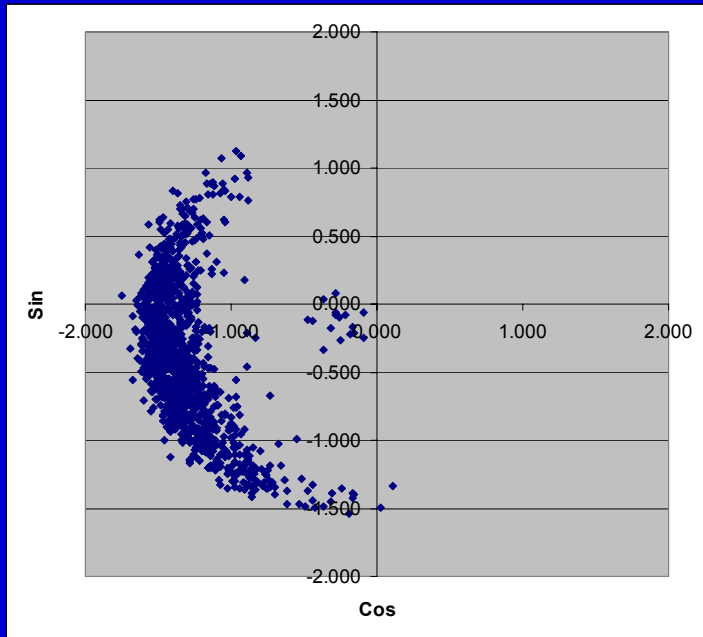
Phase fluctuation > 180 degrees at end

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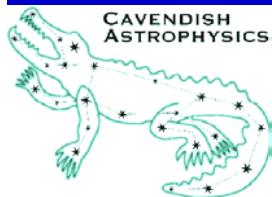


Phase Unwrapping

- Plot Phase and Amplitude as complex quantity



- Join up the dots! Only an issue when phase very bad

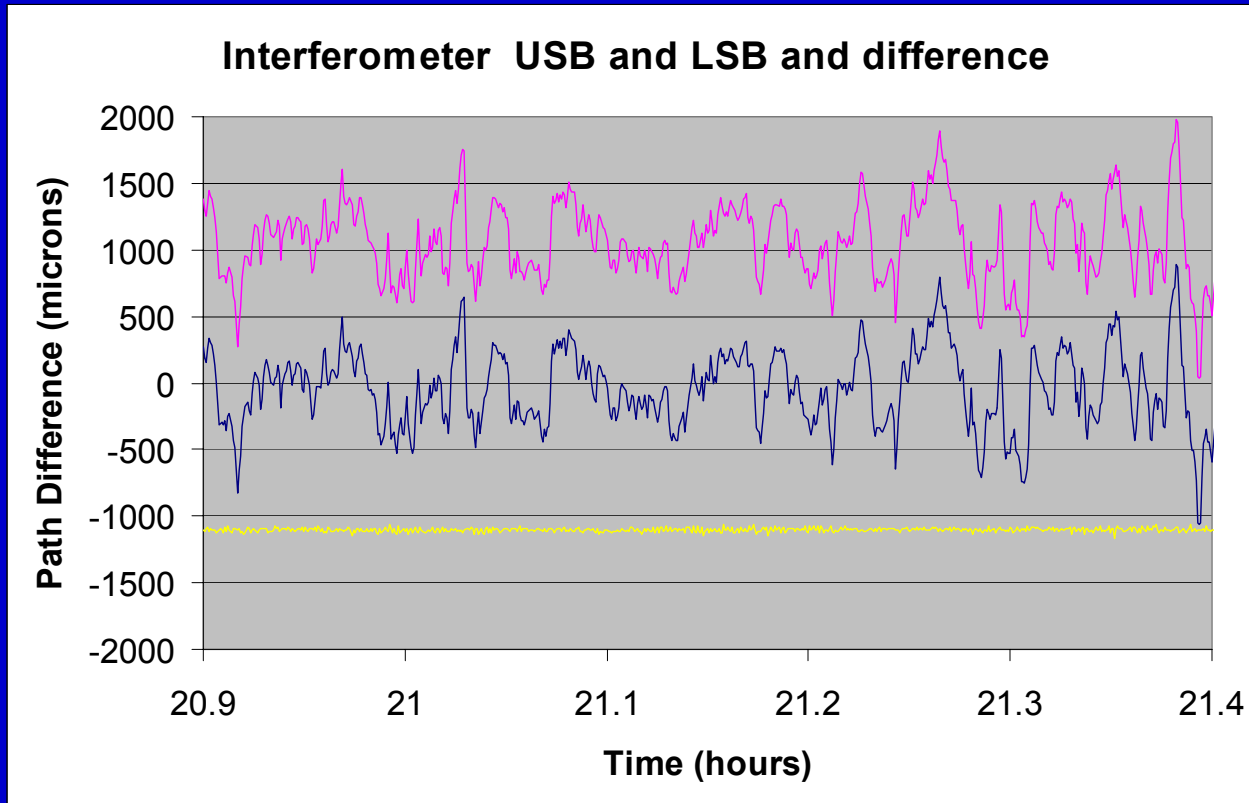


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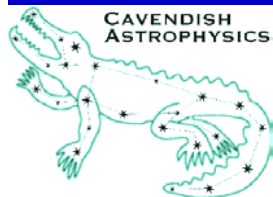


Interferometer has 2 independent sidebands

- Convert these to path. Differences indicate noise.



rms 295 microns: difference 15 !

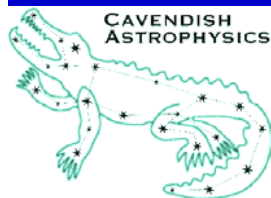
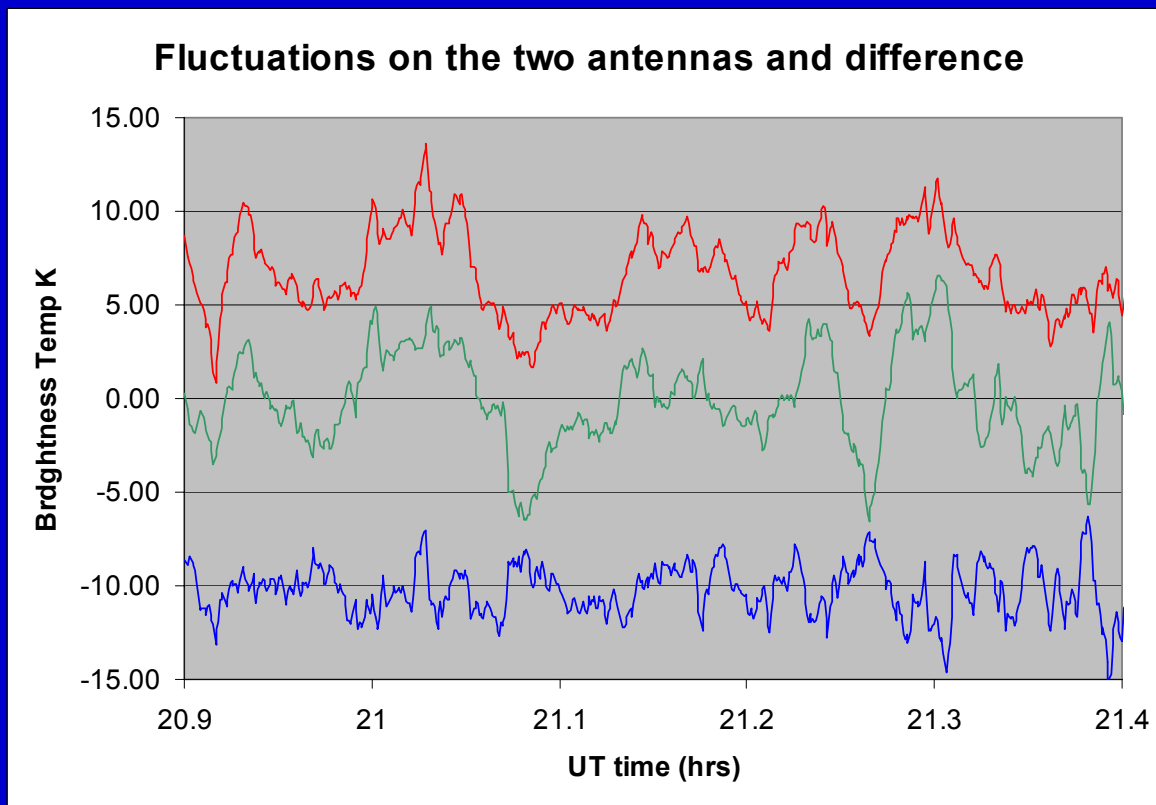


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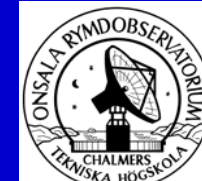


Radiometer Data

- We want the differences between the two radiometers:

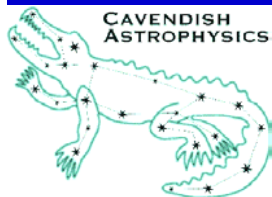


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Conversion from Brightness Temp to Path

- First option is to fit a simple model to the outputs of the 4 (or 8) temperatures seen in the 4 filters. Possibilities:
 - fit only total water
 - water plus temperature, or
 - 2 layers with some water in each and different temperatures
- Then find path for that model (remember that water-to-path conversion depends on temperature).
- Find that you have to be careful in fitting too many parameters to each individual set of data.



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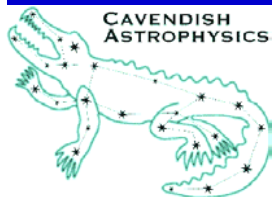
Conversion from Brightness Temp to Path 2

- Simplified approach:

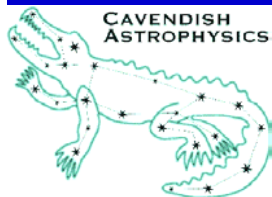
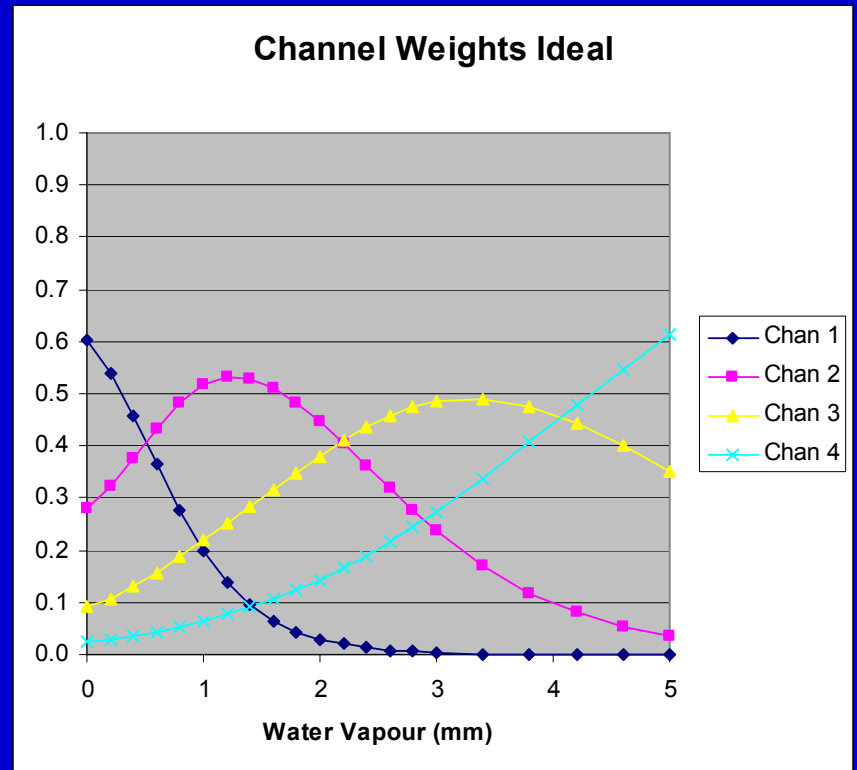
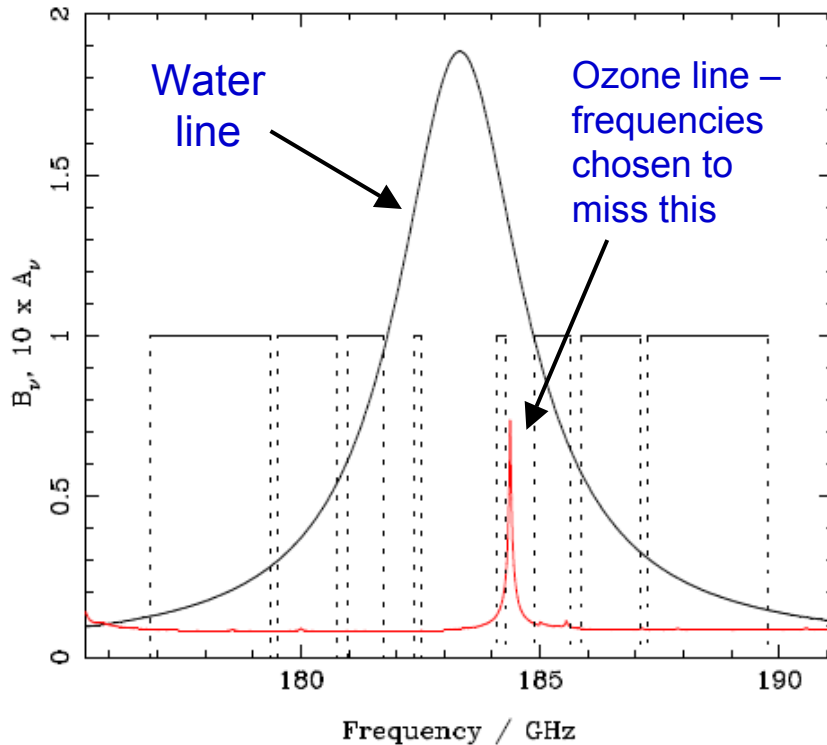
$$T_b = T_{\text{atm}} (1 - e^{-\tau}), \quad \tau \sim E w \quad \text{and} \quad p \sim R w$$

where w is the amount of water and p the path, E is the emissivity and R is the refractivity

- For fluctuations this leads to $\Delta T_b = E (T_{\text{atm}} - T_b) \Delta w$
and so $\Delta p = R \Delta T_b / E (T_{\text{atm}} - T_b)$
- Do this for each channel individually to give 4 estimates of the path fluctuation. Take weighted mean taking account of sensitivity and noise.



Weights for the channels

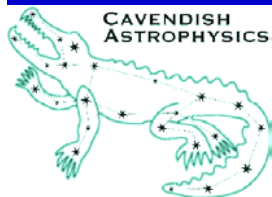
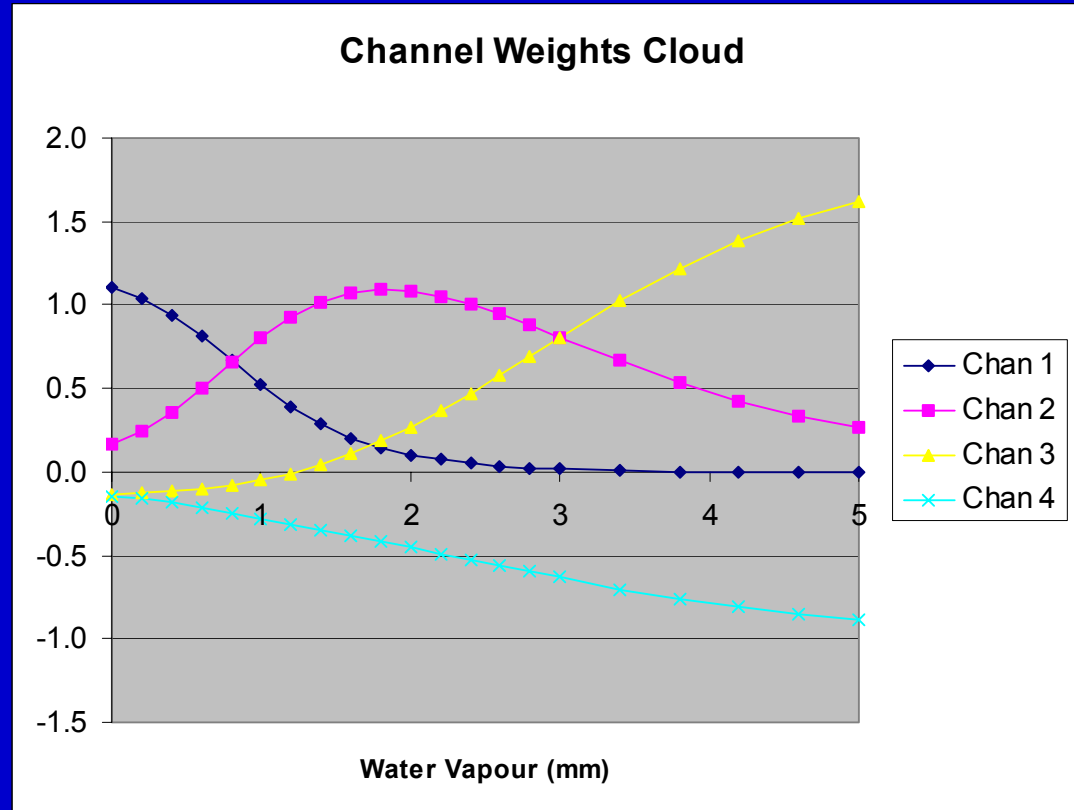


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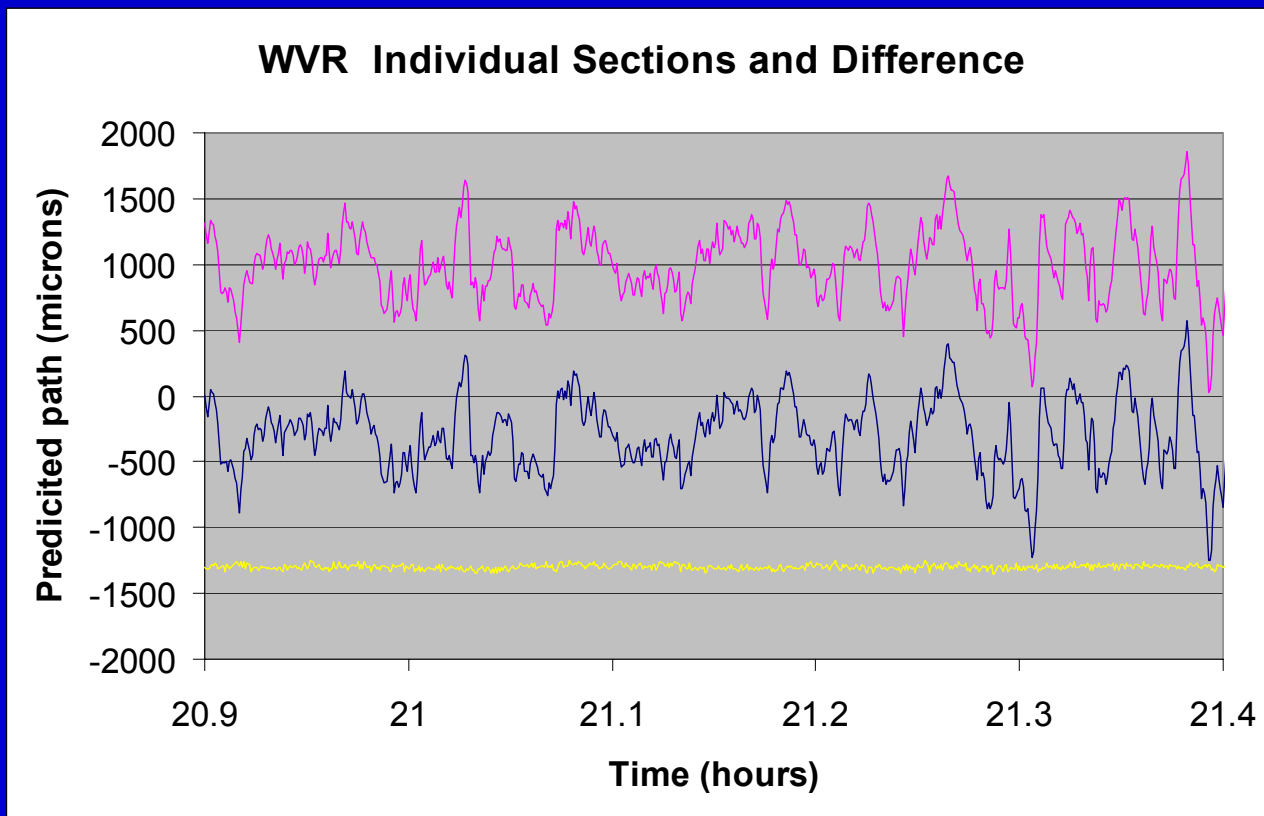
Can discriminate against thin cloud

- Effectively taking difference on and off the line
- Some sacrifice of sensitivity in doing this

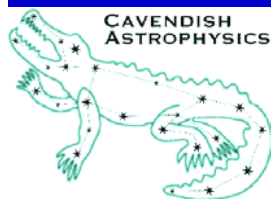


Noise level of Radiometers

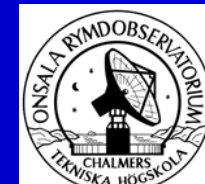
- Each radiometer has 2 sets of 4 channels – reduce independently:



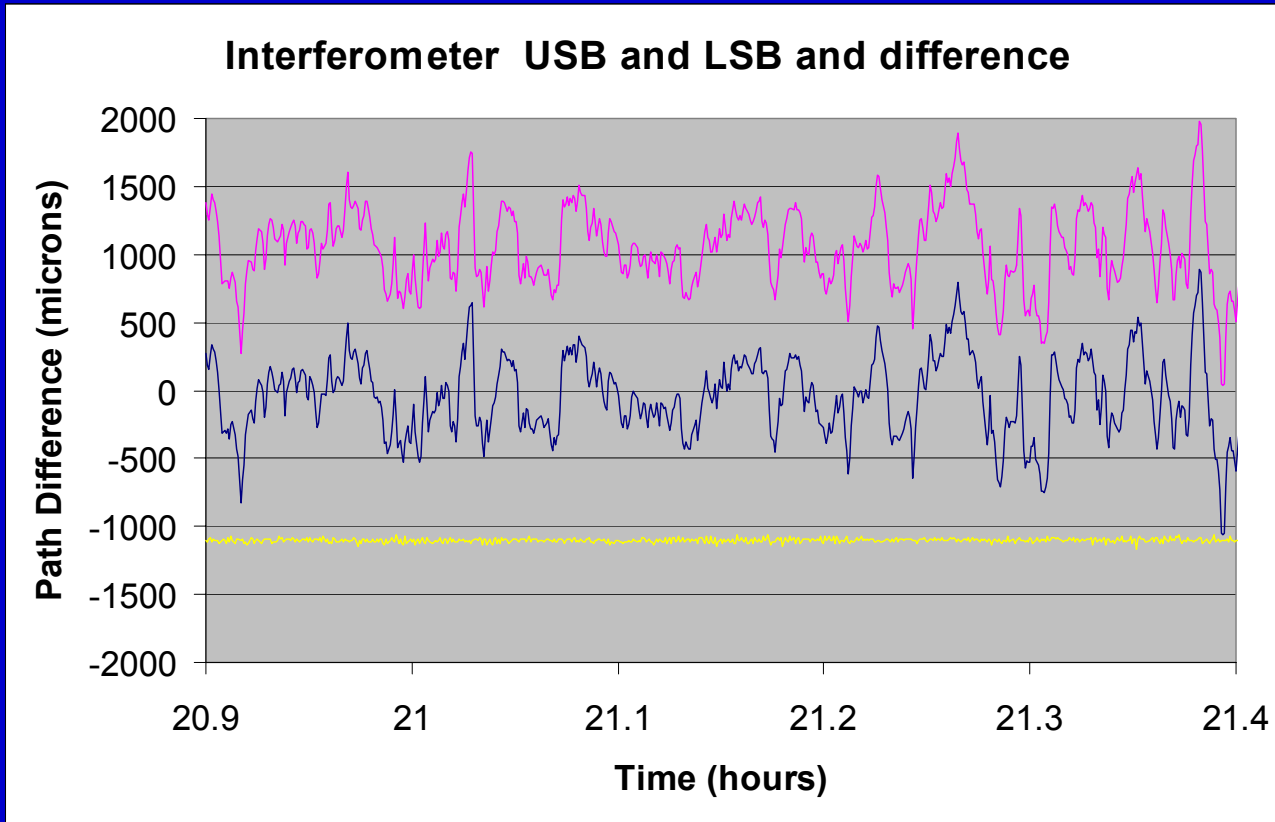
rms 283 microns: difference 19!



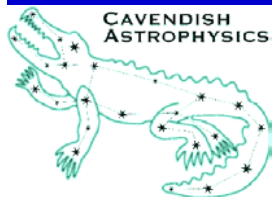
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Remember what we had from the Interferometer



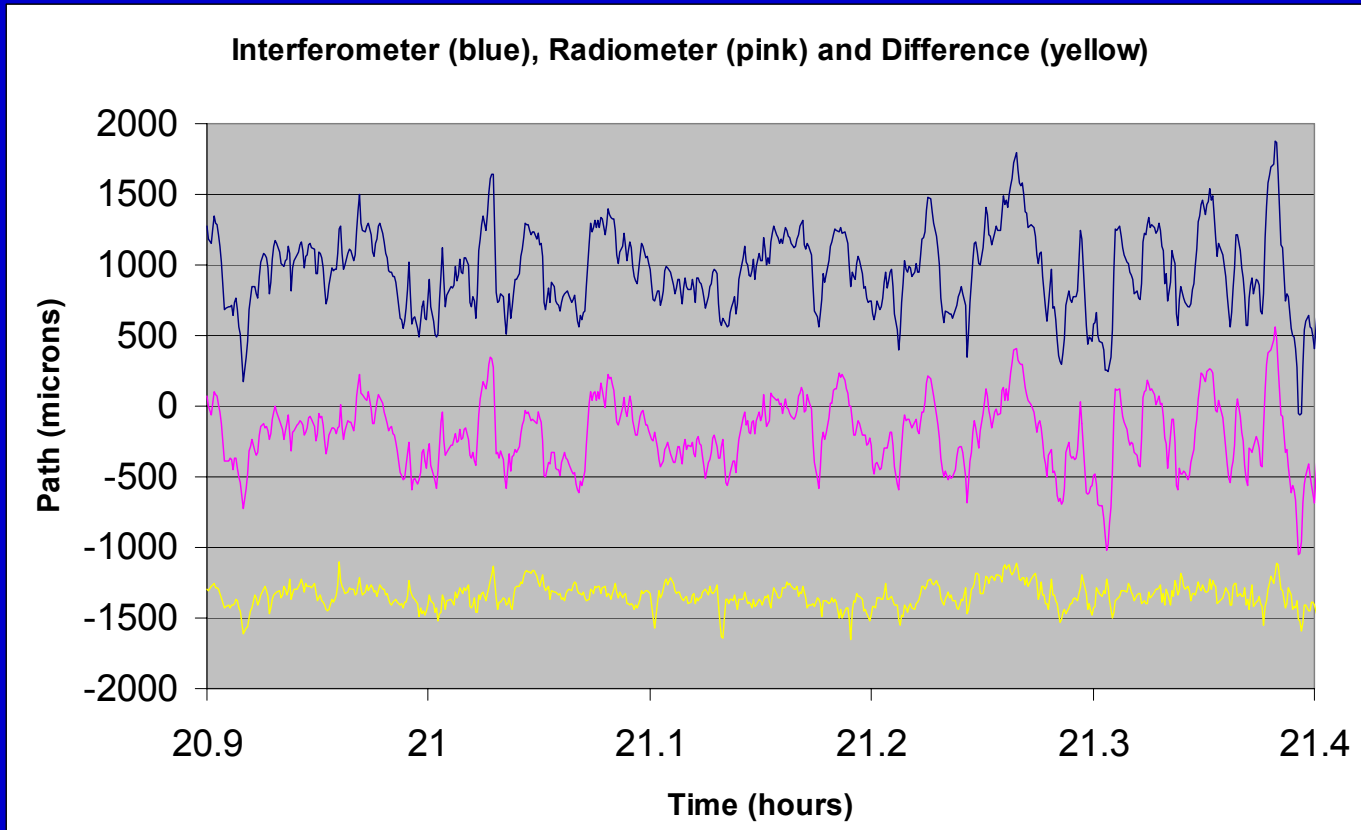
rms 295 microns: difference 15 !



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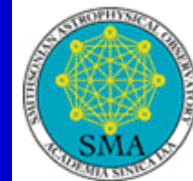
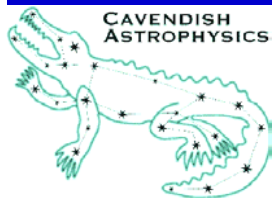


So now put these together

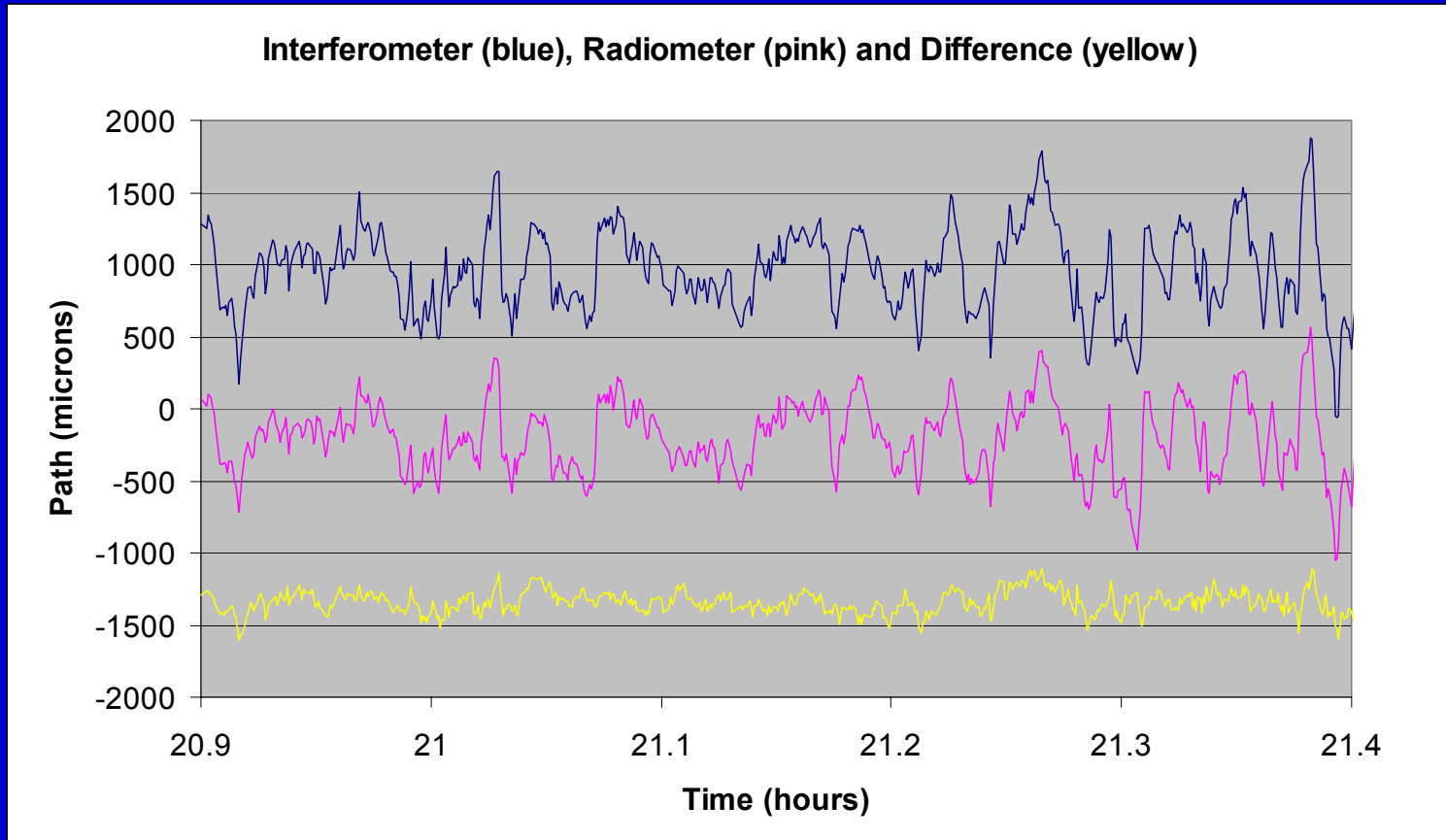


rms of residual 82 microns

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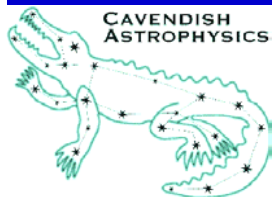


Remove samples taken during Calibrations



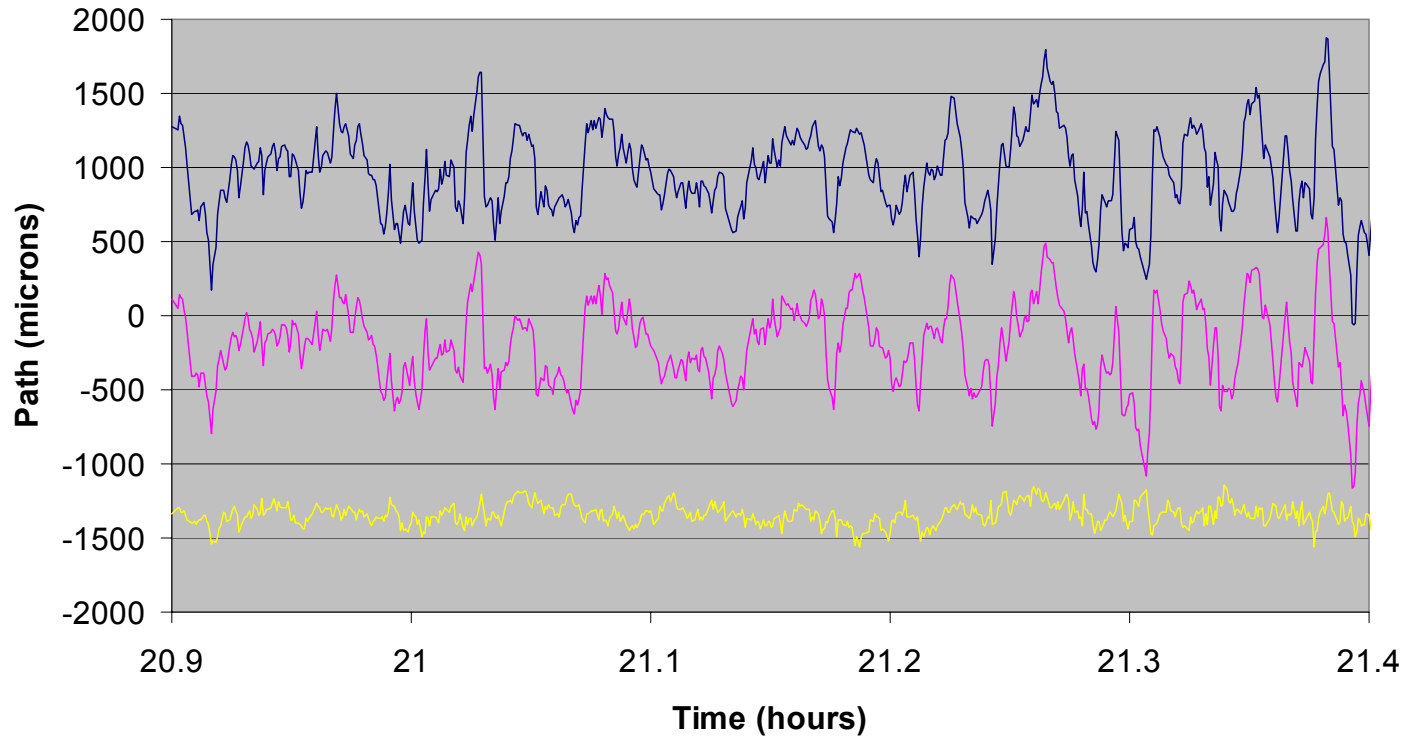
rms of residual 78 microns

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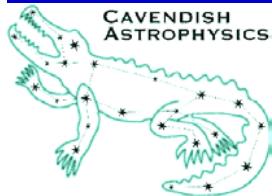
Adjust Scale Factor to optimum – 1.13

Interferometer (blue), Radiometer (pink) and Difference (yellow)



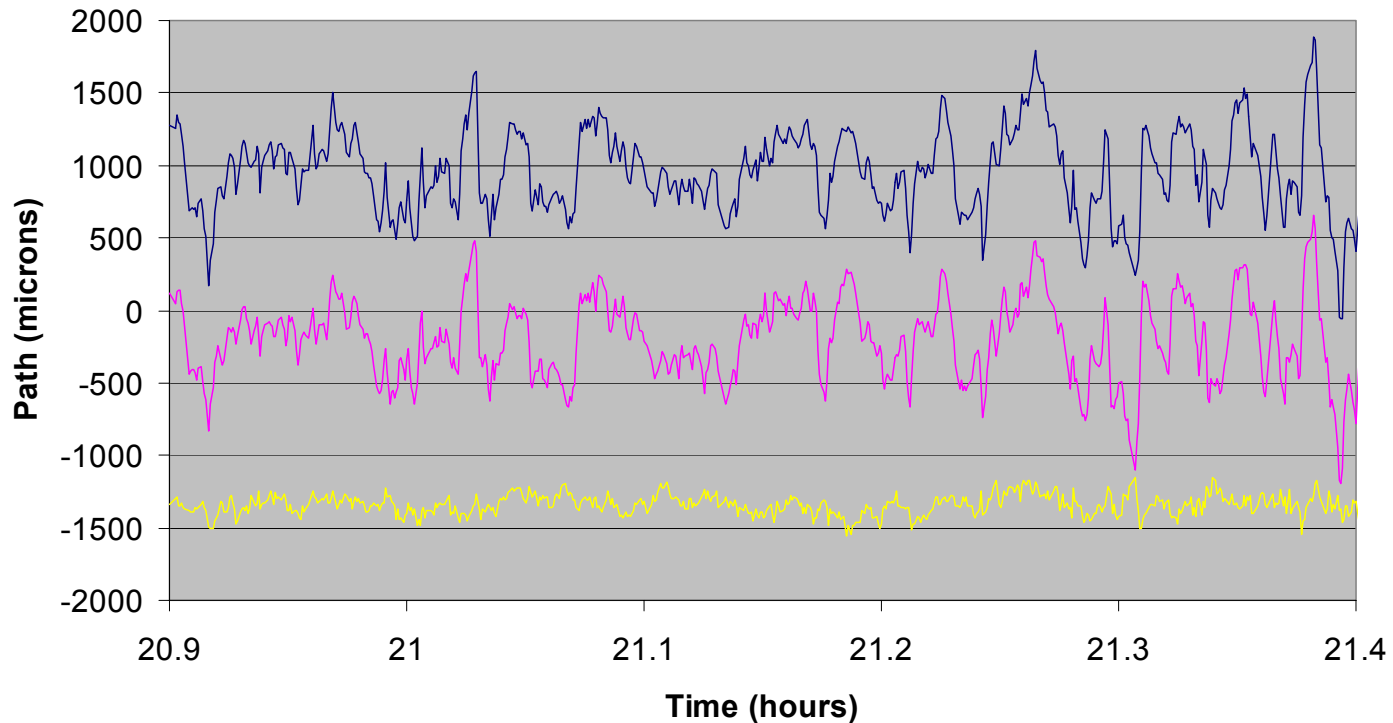
rms of residual 70 microns

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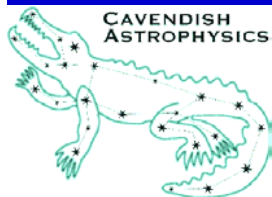
Optimum weights instead of model

Interferometer (blue), Radiometer (pink) and Difference (yellow)



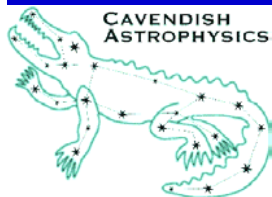
rms of residual 69 microns

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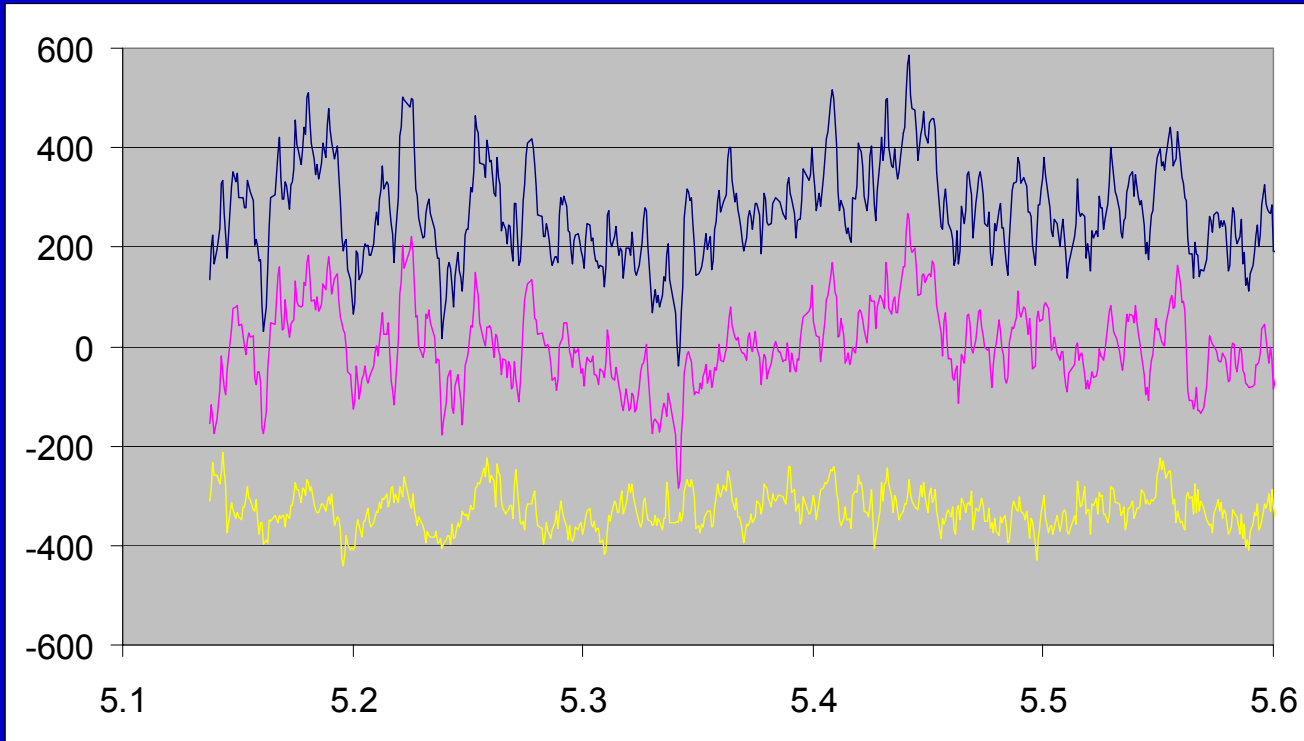
So why don't we do better?

- NOT noise
- Instrumental effects in Interferometer – not at this level
- Instrumental effects in Radiometer – can't think what
- Single temperature assumption – need to check
- Mismatch of WVR and Interferometer beams – perhaps
- Uncorrelated dry component – seems most plausible
- But still doing pretty well. Coherence in this data at 1.3mm observing wavelength goes from $\sim 14\%$ to $\sim 90\%$!



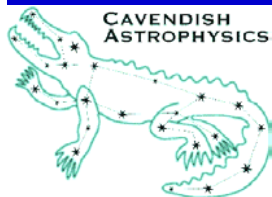
Another Example – Evening

- Here total rms = 83 microns residual = 27 microns



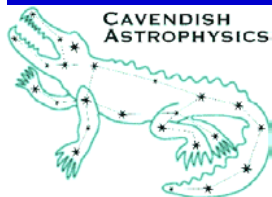
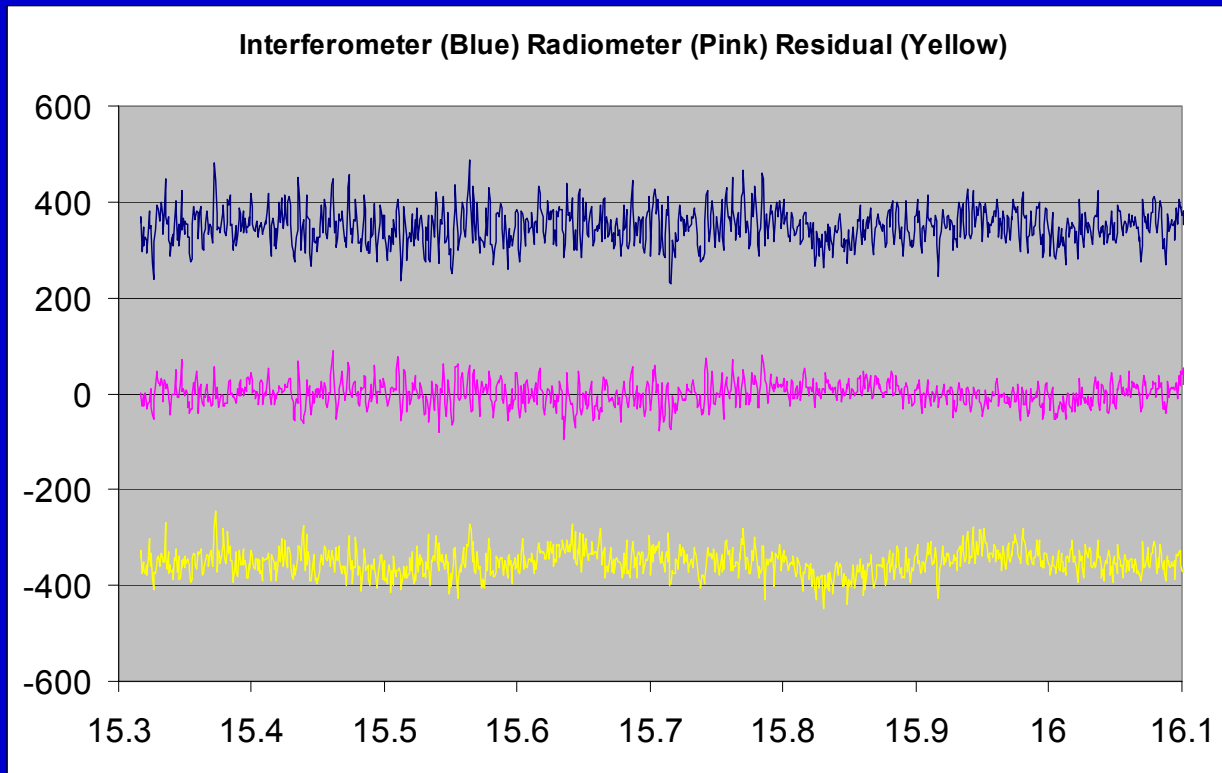
noise contribution \sim 12 microns

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Very stable conditions – Night-time

- Total path rms 37 microns, residual 27, noise ~ 15



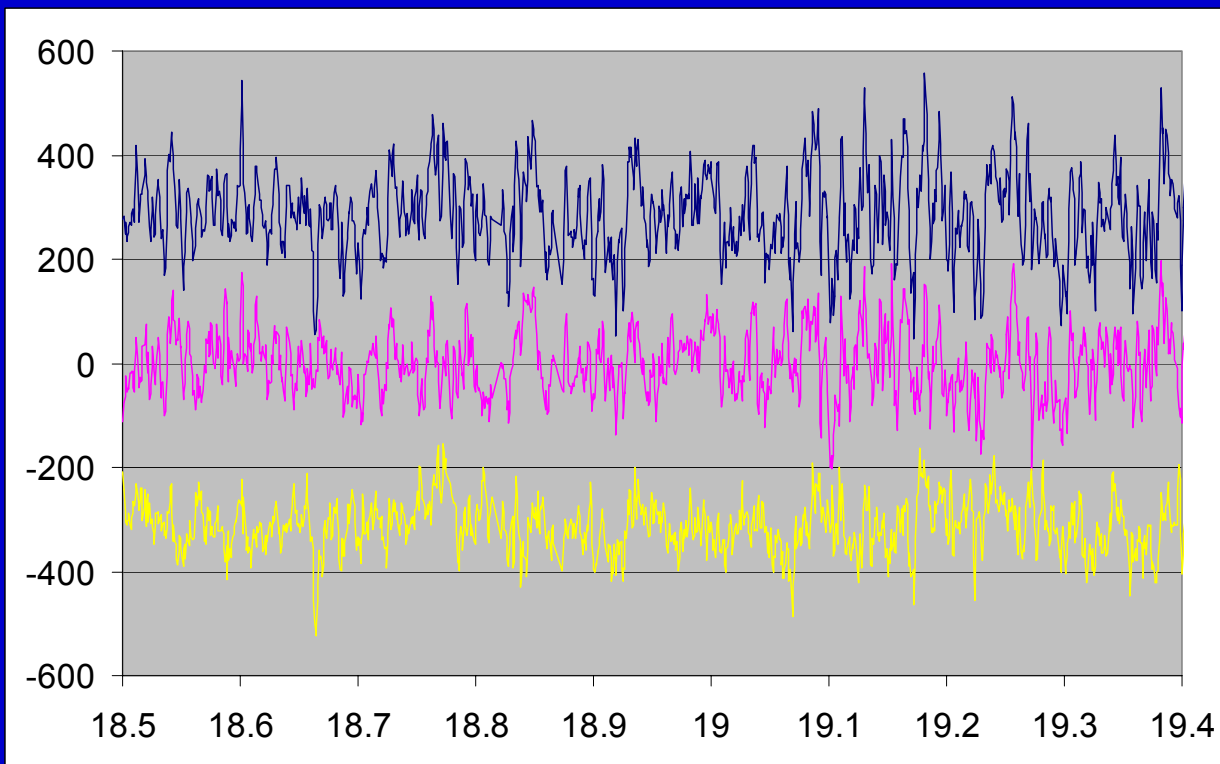
Clear excess noise on Interferometer

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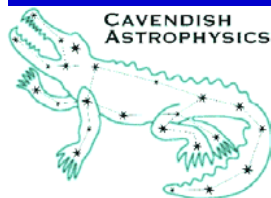


Thin Cloud Passing Over

- Total path fluct 80 microns, residual 49, noise ~ 14



Some question whether this is all sky

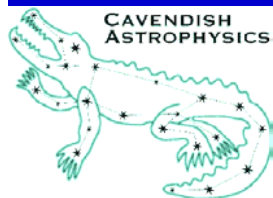


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Conclusions

- Correction is meeting the ALMA specifications under good conditions. It should do better when various interferometer problems have been fixed.
- Factor of ~ 4 reduction in phase variations seems to be about the best we can do so far. (But this is a factor ~ 16 reduction in the amount of de-correlation loss).
- When wet clouds are present we definitely do less well.
- Hope (!) that ice clouds are less of a problem.
- Key question outstanding is whether we can “carry” the wvr correction from a source to a nearby reference.



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