ALMA Memo #300
Reducing Atmospheric Noise in Single Dish observations with ALMA

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Abstract

We propose a method that takes advantage of the large variation of atmospheric transmission across the 8 GHz receiver bandpass of ALMA, at some sky frequencies, to cancel the time variations of atmospheric water emission that otherwise limit single dish continuum emission mapping of extended sources. This technique could be useful for on-the-fly maps of extended sources for which the use of a focal plane chopper or a nutating subreflector is not practical due to limited beam throw.

1 Introduction

ALMA receivers are specified to be high bandwidth (8 GHz) in order to provide high sensitivity for continuum observations. However since many sources are more extended than the primary beam, especially at short wavelengths, it will be necessary to complement interferometric observations with single dish measurements to recover the zero and short spacing fluxes that cannot be measured in interferometric mode. In a recent memo, Wright (2000) studies the system requirements imposed by these needs. In this memo I propose an alternate method to subtract the atmospheric emission in single dish continuum mapping.

2 Atmospheric noise in single-dish observations

The single dish continuum measurements are limited by three sources of noise:

- **Receiver statistical noise**: for bandwidth B, assuming switching with total integration time τ (ON+OFF):

$$\sigma_N = 2\frac{T_{\rm SYS}}{\sqrt{B\tau}}$$

Assuming $T_{\rm SYS} = 170$ K, $B = 8$ GHz, $\tau = 0.1$ s:

$$\sigma_N = 2\frac{170}{\sqrt{810^9 \times 0.1}} = 12 \text{ mK}$$

- **Gain fluctuations**: for the above parameters and an assumed gain stability of 10^{-4}:

$$\sigma_G = 10^{-4} T_{\rm SYS} = 17 \text{ mK}$$

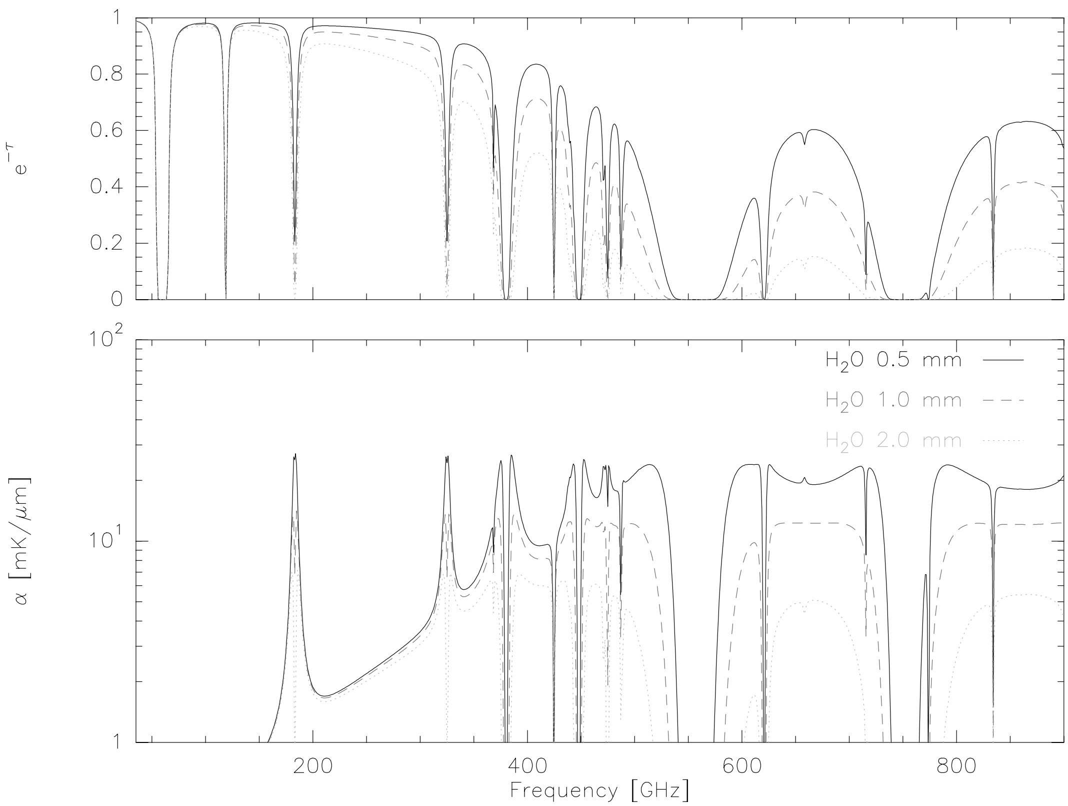

Figure 1: top: atmospheric transmission at Chajnantor (0.5/1.0/2.0 mm water content); bottom:variation of $\alpha(\nu)$ (mK/μm) as a function of ν (GHz) in the same conditions.

– **Atmospheric fluctuations**: Following Holdaway et al. (1995), Wright (2000),we use for the atmospheric power fluctuations:

$$\sigma_A = \alpha(\nu)\sigma_w(\frac{\Delta l}{300})^{0.6}\frac{1}{\sqrt{1+(D/\Delta l)^2}} \text{ mK}$$

here

- σ_w stands the atmospheric path rms fluctuation on a 300 m baseline (150 μm, scaled at zenith for median conditions at Chajnantor) ;
- $\alpha(\nu)$ is the ratio of water emission to path length in mK/μm at the observing frequency (1.7 at 230 GHz, 6 at 350 GHz, for typical Chajnantor conditions; see figure 1) ;
- Δl is the effective length over which the emission fluctuations occur during the referencing process: $\Delta l = \sqrt{(\theta h)^2 + (v\Delta t)^2}$, where in the first term θ is the offset angle of the OFF position, h the height of the fluctuating layer ($\sim$ 2000m), in the second term v the wind speed at that height ($\sim$ 10 m/s), and Δt the time elapsed between ON and OFF measurements.
- The last term is introduced here (after discussions with S. Guilloteau) to approximately take into account the averaging effect of the antenna aperture when it is much larger than Δl. In that case $(D/\Delta l)^2$ is an estimate of the number of independent cells in the antenna aperture that are to be averaged.

Let us assume we observe at 350 GHz. For on the fly $\theta \sim 1'$, $\Delta t \sim 2$s, $\Delta l \sim 20$ m.

$$\sigma_A = 6 \times 150 \times (20/300)^{0.6} = 177 \text{ mK}$$

For beam switching at 5 Hz, $\theta \sim 32''$ (2 beams), $\Delta t \sim 0.2$s, $\Delta l \sim 2$ m.

$$\sigma_A = 6 \times 150 \times (2/300)^{0.6} \times 2/12 = 7.5 \text{ mK}$$

That is, atmospheric fluctuations are the limiting factor to sensitivity at submillimeter wavelengths, unless beam switching at ~ 5 Hz is used.

3 Proposed method

We propose to choose the frequency of continuum observations in order to get a significant variation of atmospheric transmission across the 8 GHz bandwidth, between different 2 GHz subbands.

The emission power, expressed in temperature units, is:

$$T_{\rm EM}(\nu, t) = \alpha(\nu) w(t) + T_{\rm A}(\nu)$$

where $\alpha(\nu)$ is the emission coefficient expressed in mK/μm, $w(t)$ the time variable path length due to water, $T_{\rm A}(\nu)$ the source antenna temperature.

Using two frequencies with significantly different values of α provides a solution for canceling out $w(t)$:

$$T_{\rm EM}(\nu_1, t) = \alpha(\nu_1) w(t) + T_{\rm A}(\nu_1)$$
$$T_{\rm EM}(\nu_2, t) = \alpha(\nu_2) w(t) + T_{\rm A}(\nu_2)$$

If we assume $T_{\rm A}(\nu_1) \sim T_{\rm A}(\nu_2) = T_{\rm A}(\nu)$:

$$T_{\rm A}(\nu) = \frac{\alpha(\nu_1) T_{\rm EM}(\nu_2, t) - \alpha(\nu_2) T_{\rm EM}(\nu_1, t)}{\alpha(\nu_1) - \alpha(\nu_2)}$$

Sensitivity:

$$\Delta T_{\rm A} = \frac{\sqrt{\alpha(\nu_1)^2 + \alpha(\nu_2)^2}}{|\alpha(\nu_1) - \alpha(\nu_2)|} \Delta T_{\rm EM}$$

Obviously we need $\alpha(\nu_1) - \alpha(\nu_2)$ to be as high as possible and comparable to $\alpha(\nu_2)$ in order not to degrade the sensitivity too much.

Let us consider an observation at 330 GHz. From Figure 2 we can build Table 1 in which one sees readily that subband 1 is very sensitive to water fluctuations below 1mm of precipitable water. For 2mm, the line saturates and the fluctuations are not well measured any more.

With 0.5 mm of water, using subbands 1 and 4:

$$T_{\rm A}(\nu) = \frac{\alpha(\nu_1) T_{\rm EM}(\nu_4, t) - \alpha(\nu_4) T_{\rm EM}(\nu_1, t)}{\alpha(\nu_1) - \alpha(\nu_4)}$$

$$T_{\rm A}(\nu) = 1.46 T_{\rm EM}(\nu_4, t) - 0.46 T_{\rm EM}(\nu_1, t)$$

With 1.0 mm of water this becomes:

$$T_{\rm A}(\nu) = 1.84 T_{\rm EM}(\nu_4, t) - 0.84 T_{\rm EM}(\nu_1, t)$$

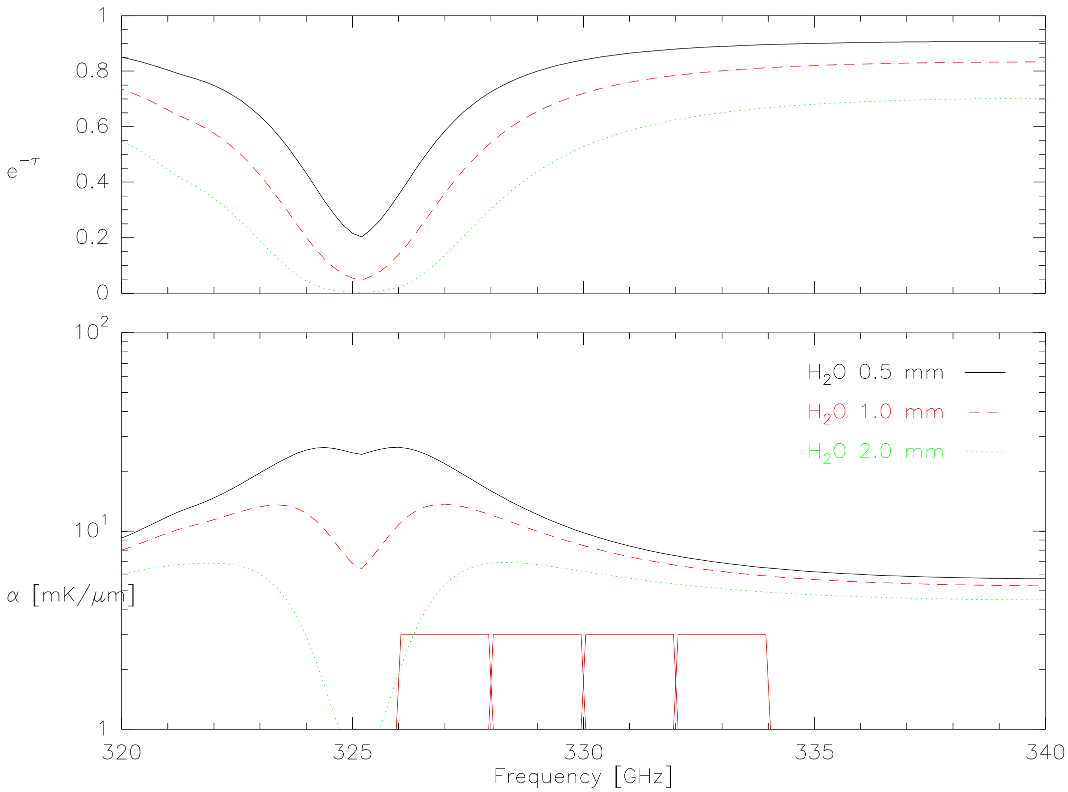

Figure 2: One example setup - top: atmospheric transmission at Chajnantor (0.3mm water content); bottom:variation of $\alpha(\nu)$ (mK/μm) as a function of ν (GHz) across the 326 to 336 GHz band, showing the four 2 GHz wide subbands.

Table 1: Data corresponding to the example in Figure 2. $\alpha(\nu)$ is the coefficient relating emission to path length variations (in mK/μm) and x_i are the weights to be used to cancel water vapor emission fluctuations (see text)

2 GHz subband		1	2	3	4	
ν[GHz]		327	329	331	333	
$\alpha(\nu)$ [mK/μm]	0.5 mm H2O	21.86	12.11	8.40	6.91	
	1.0 mm H2O	13.65	9.98	7.41	6.25	
	2.0 mm H2O	5.37	6.77	5.78	5.12	
x_i	0.5 mm H2O	-0.62	0.27	0.61	0.74	1.17
	1.0 mm H2O	-1.00	0.06	0.80	1.14	1.72
	2.0 mm H2O	1.66	-3.42	0.19	2.57	4.60

In our example the sensitivity is degraded by a factor $\sqrt{1.46^2+0.46^2}=1.5$ over the radiometric sensitivity in a 2GHz bandwidth in the first case; in the second case this factor increases to 2.0. We can apply the same method to subbands 2 and 3, with subband 1 as a reference, to improve signal-to-noise ; In fact an optimal solution exists that takes into account all subband to subband differences:

$$T_{\rm A}(\nu) = \Sigma x_i T_{{\rm EM}i}$$

where

$$\Sigma x_i = 1$$

$$\Sigma x_i \alpha(\nu_i) = 0$$

$$\Sigma x_i^2 \quad minimum.$$

Thus the optimal weighting solution can be worked out exactly in each case. For the above example the optimal coefficients are listed in Table 1, as well as the degradation factor (compared to a 2 GHz bandwidth) in the last column of the table, in each case. For beam switching using the full 8 GHz band, that factor would be 0.71 (the bandwidth is 8 GHz but there is a $\sqrt{2}$ loss due to referencing).

In an Appendix I listed some frequencies where this method can be applied.

4 Discussion

- The method depends on the actual value of $\alpha(\nu)$ which may be computed from an atmospheric model, on which we have to rely to determine the optimum frequencies. The relative coefficients used to determine the antenna temperature may however be determined experimentally by observing blank sky and taking the ratios of the signals observed in the various subbands. Using this empirical method will also take into account effects like imperfections in the side band rejection factors.
- We have so far neglected the variation of $T_{\rm A}(\nu)$ with frequency. In fact one may easily correct for the source spectral index if it is known from observations made at widely different frequencies. One should naturally be cautious about the presence of lines in the various subbands. This can naturally be checked by using the correlator in low resolution mode to analyze all subbands.
- One should consider second order effects such as the loss of sensitivity due to the increased noise temperature in the subband(s) used to get the atmospheric signal, due to atmospheric emission; this is compensated by the fact that the atmospheric signal itself is increased in the same proportion in that subband. Also the source signal in those subband(s) is slightly reduced by atmospheric absorption. The need to have at least a subband to measure atmospheric emission fluctuations leads to choose observing frequencies near the edge of atmospheric windows, where a relative loss in sensitivity is expected. This is somewhat compensated since the most transparent part of the atmospheric windows tends to be near their low frequency edge (at least for the 1.3mm and 0.8mm windows).
- I have so far only considered only subbands in the same receiver side band. Naturally subbands in opposite side bands may be used if a side band separating receiver is available. This is a more favorable situation since the larger frequency difference (up to 24 GHz) increases the probability to have strongly different values $\alpha(\nu)$. Some setups in the Appendix correspond to this situation.

At the highest frequencies (above about 500 GHz) the method present here fails due to the saturation effects, since the optical depth is of order unity: one would need precipitable water contents below 0.5mm.

- One could envisage using the 183 GHz water monitor as providing the measurements for the water emission fluctuations, since it will always be available. For this method to work, the ratio $\alpha(183)/\alpha(\nu)$ must be high enough to compensate the lower sensitivity of the 183 GHz radiometer, and only the unsaturated wings of the 183 GHz line may be used. For instance to observe at $\nu = 350$ GHz for 1mm water content ($\alpha(\nu) = 5$), one needs $\alpha(\nu) > 7$ in the 183 GHz line where a single polarization is observed, assuming 8 GHz bandwidth and the same receiver temperature than at 350 GHz. But this is reached only in two bands ~ 3 GHz wide on each side of the line, while the center is saturated. So this method would be limited to the 1.3mm band where $\alpha(\nu)$ is lower, unless the 183 GHz radiometer is cooled.

  Another drawback would be that the 183 GHz monitor is to be directed to a *different point in the sky* where astronomical emission may be present, and not negligible: one would need to map the whole region at 183 GHz to be able correct for this effect.

- One should investigate the dependence on receiver gain fluctuations. The atmospheric power fluctuations will only be efficiently subtracted if the **relative** gains of the subbands are stable enough. The relative gains should be stable enough not to degrade in a significant way the radiometric sensitivity, that is (assuming 0.1s integration time):

$$\frac{\Delta g_i}{g_i} < \frac{1}{\sqrt{B\Delta t}} = 7 \times 10^{-5}$$

  The common mode gain fluctuations are not subtracted and should be below the same level.

  One possible solution to improve the stability of the system would be to turn the dual polarization receiver in a correlation receiver, using a 45° grid in front of the lens to select linear polarization from the sky at $PA = 45°$, while redirecting $PA = 135°$ linear polarization to a stable cold load. Then by correlating mixer outputs H and V, one gets the difference of powers in the sky and the load, and receiver gains fluctuations are canceled (they originate in two different receivers and are not correlated). Such a simple device could be installed in the band where the most sensitive continuum measurements are desired. Care should of course be taken to stabilize the reference load in temperature to ~ 0.01K.

In conclusion: this method could be useful for on-the-fly maps of extended sources for which the use of a focal plane chopper or a nutating subreflector is not practical due to limited beam throw.

References

Holdaway, M.A., Owen, F.N., Emerson, D.T., 1995, MMA Memo 137
Wright, M.C.H., 2000, ALMA Memo 289

A A few possible setups

A.1 Single side band setups

These setups do not take into account the possibility of using side-band separating receivers to recover the water emission from the image sideband.

2 GHz subband		1	2	3	4	
ν[GHz]		185.0	187.0	189.0	191.0	
$\alpha(\nu)$ [mK/μm]	0.5 mm H2O	22.12	9.73	5.35	3.62	
$\alpha(\nu)$ [mK/μm]	1.0 mm H2O	14.13	8.45	4.99	3.46	
$\alpha(\nu)$ [mK/μm]	2.0 mm H2O	5.81	6.38	4.33	3.16	
x_i	0.5 mm H2O	-0.33	0.27	0.49	0.57	0.87
x_i	1.0 mm H2O	-0.49	0.17	0.57	0.75	1.07
x_i	2.0 mm H2O	-0.44	-0.87	0.70	1.61	2.01

2 GHz subband		1	2	3	4	
ν[GHz]		318.0	320.0	322.0	324.0	
$\alpha(\nu)$ [mK/μm]	0.5 mm H2O	6.67	9.21	14.69	25.60	
$\alpha(\nu)$ [mK/μm]	1.0 mm H2O	6.06	8.01	11.41	12.31	
$\alpha(\nu)$ [mK/μm]	2.0 mm H2O	5.00	6.05	6.88	2.94	
x_i	0.5 mm H2O	0.74	0.57	0.21	-0.52	1.09
x_i	1.0 mm H2O	1.50	0.78	-0.48	-0.81	1.93
x_i	2.0 mm H2O	0.38	-0.25	-0.75	1.62	1.84

2 GHz subband		1	2	3	4	
ν[GHz]		327.0	329.0	331.0	333.0	
$\alpha(\nu)$ [mK/μm]	0.5 mm H2O	21.86	12.11	8.40	6.91	
$\alpha(\nu)$ [mK/μm]	1.0 mm H2O	13.65	9.98	7.41	6.25	
$\alpha(\nu)$ [mK/μm]	2.0 mm H2O	5.37	6.77	5.78	5.12	
x_i	0.5 mm H2O	-0.62	0.27	0.61	0.74	1.17
x_i	1.0 mm H2O	-1.00	0.06	0.80	1.14	1.72
x_i	2.0 mm H2O	1.66	-3.42	0.19	2.57	4.60

A.2 Dual side band setups

These setups take into account the possibility of using side-band separating receivers to recover the water emission from the image sideband.

2 GHz subband		1	2	3	4	
ν[GHz]		186.0	202.0	204.0	206.0	
$\alpha(\nu)$ [mK/μm]	0.5 mm H2O	14.48	1.80	1.75	1.72	
$\alpha(\nu)$ [mK/μm]	1.0 mm H2O	11.50	1.76	1.71	1.68	
$\alpha(\nu)$ [mK/μm]	2.0 mm H2O	7.23	1.69	1.64	1.61	
x_i	0.5 mm H2O	-0.14	0.38	0.38	0.38	0.67
x_i	1.0 mm H2O	-0.18	0.39	0.39	0.39	0.70
x_i	2.0 mm H2O	-0.30	0.43	0.43	0.44	0.80

2 GHz subband		1	2	3	4	
ν[GHz]		303.0	305.0	307.0	323.0	
$\alpha(\nu)$ [mK/μm]	0.5 mm H2O	3.70	3.83	3.97	19.67	
$\alpha(\nu)$ [mK/μm]	1.0 mm H2O	3.52	3.63	3.76	13.27	
$\alpha(\nu)$ [mK/μm]	2.0 mm H2O	3.19	3.28	3.38	6.06	
x_i	0.5 mm H2O	0.42	0.41	0.41	-0.24	0.76
x_i	1.0 mm H2O	0.47	0.46	0.45	-0.38	0.88
x_i	2.0 mm H2O	0.79	0.73	0.66	-1.17	1.72

2 GHz subband		1	2	3	4	
ν[GHz]		323.0	339.0	341.0	343.0	
$\alpha(\nu)$ [mK/μm]	0.5 mm H2O	19.67	5.77	5.74	5.77	
$\alpha(\nu)$ [mK/μm]	1.0 mm H2O	13.27	5.32	5.28	5.32	
$\alpha(\nu)$ [mK/μm]	2.0 mm H2O	6.06	4.51	4.49	4.51	
x_i	0.5 mm H2O	-0.41	0.47	0.47	0.47	0.92
x_i	1.0 mm H2O	-0.67	0.55	0.56	0.55	1.17
x_i	2.0 mm H2O	-2.88	1.27	1.33	1.28	3.65

2 GHz subband		1	2	3	4	
ν[GHz]		352.0	354.0	356.0	372.0	
$\alpha(\nu)$ [mK/μm]	0.5 mm H2O	6.52	6.82	7.18	19.02	
$\alpha(\nu)$ [mK/μm]	1.0 mm H2O	5.92	6.16	6.46	12.75	
$\alpha(\nu)$ [mK/μm]	2.0 mm H2O	4.89	5.04	5.21	5.73	
x_i	0.5 mm H2O	0.55	0.52	0.49	-0.56	1.06
x_i	1.0 mm H2O	0.71	0.65	0.58	-0.94	1.46
x_i	2.0 mm H2O	4.47	2.60	0.35	-6.42	8.25

2 GHz subband		1	2	3	4	
ν[GHz]		388.0	404.0	406.0	408.0	
$\alpha(\nu)$ [mK/μm]	0.5 mm H2O	21.59	9.84	9.65	9.54	
$\alpha(\nu)$ [mK/μm]	1.0 mm H2O	13.61	8.42	8.27	8.19	
$\alpha(\nu)$ [mK/μm]	2.0 mm H2O	5.43	6.15	6.09	6.04	
x_i	0.5 mm H2O	-0.81	0.58	0.61	0.62	1.32
x_i	1.0 mm H2O	-1.56	0.80	0.86	0.90	2.15
x_i	2.0 mm H2O	9.06	-3.73	-2.53	-1.80	10.28

2 GHz subband		1	2	3	4	
ν[GHz]		443.5	459.5	461.5	463.5	
$\alpha(\nu)$ [mK/μm]	0.5 mm H2O	23.88	17.74	16.88	16.48	
$\alpha(\nu)$ [mK/μm]	1.0 mm H2O	7.90	12.30	12.00	11.83	
$\alpha(\nu)$ [mK/μm]	2.0 mm H2O	0.95	5.94	6.08	6.11	
x_i	0.5 mm H2O	-2.42	0.77	1.22	1.43	3.16
x_i	1.0 mm H2O	2.88	-0.85	-0.59	-0.45	3.10
x_i	2.0 mm H2O	1.19	-0.04	-0.07	-0.08	1.19