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Atmospheric Noise in Single Dish Observations

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Abstract

Atmospheric noise and pointing fluctuations will severely impact the signal-to-noise and image fidelity of ALMA observations. Single dish observations are required for extended sources. For wideband total power observations, the maximum integration time ~ 0.1 s in order to keep atmospheric fluctuations less than the thermal noise. A gain stability $\sim 10^{-4}$ in 0.1 s is required. For OTF mapping, the noise is limited by the atmospheric fluctuations between the ON and OFF positions. For sources which are only a few beamwidths across, OTF mapping is inefficient. The single dish capability of ALMA could be improved by instrumenting a few antennas to scan the beam pattern, either with x-y nutating subreflectors, or better, with array receivers. A number of experiments are possible to check the conclusions of atmospheric modeling. These could be done on existing submillimeter telescopes such as the JCMT, and might impact the ALMA design.

1 Preamble

The ALMA telescope will be the largest telescope at sub-millimeter wavelengths, both for single dish and interferometer observations. Whilst interferometer measurements are better suited for observations of compact sources, single dish observations, and single dish techniques, are needed for extended objects. This is especially true at the highest frequencies where the primary beam width is so small. Single dish observations are required to image the large scale structure of many astronomical sources. Single dish observations provide low spatial frequency data for mosaiced images, and may limit the overall image fidelity (Holdaway & Woody 1998). In this memo we discuss the errors in a wideband total power measurement. Noise contributions come from thermal noise in the radiometer and the atmosphere, from gain variations through the radiometer and atmosphere, and from atmospheric fluctuations both in position and in time. Ideally we would like to maximize the signal-to-noise for both interferometer and single dish observations using all the antennas efficiently. Spectral line observations are easier than total power observations because one may remove a spectral baseline caused by total power fluctuations from the instrument and atmosphere, and because the thermal noise is higher in the narrower bandwidth channels. Spectral line observations may be limited by bandpass variations rather than total power fluctuations. Since the atmospheric noise varies at different sites, we need to consider whether experience and tests done at existing sites are relevant to Chajnantor.

2 Error analysis

We consider total power measurements with a single dish radiometer. The measured total power, $p[K] = g \times T[K]$, where $T[K]$ includes noise power from the radiometer and atmosphere, and g is the normalized gain though the system so that both p and T are expressed in units of temperature. There are error terms, δp, given by $g \times \delta T$ and $\delta g \times T$.

Thermal noise from the radiometer and the atmosphere contributes an RMS noise, $\delta T = T_{sys}/\sqrt{(}2B \times t)$, where T_{sys} is the system temperature, B is the bandwidth, and t is the integration time. The zenith emission from water vapor is $\sim$ 30 K at 100 GHz with 10 mm of precipitable water. A similar value is obtained for observations at 300 GHz with 1 mm of precipitable water, so we will adopt a total system temperature of 100 K in a 1 GHz bandwidth as a reference.

$\delta T = 2mK \times T_{sys}/[100K]/\sqrt{(}B[GHz] \times t[secs])$ —— (1)

Gain variations give an error $\delta g/g\times$ the total noise power. A gain stability of 10^{-4} in 0.1s with a $1/freq$ spectrum gives:

$\delta T = 1mK \times T_{sys}/[100K] \times \delta g/g[10^{-5}] \times t[sec]$ —— (2)

An additional source of noise comes from atmospheric fluctuations as discussed by Holdaway, Owen & Emerson (1995). We can estimate the fluctuations in the atmospheric emission from the path length variations measured with millimeter wavelength interferometers and from satellite phase monitors. At millimeter wavelengths, refractive index fluctuations are expected to be dominated by water vapor variations. We can calculate the atmospheric emission from atmospheric profiles. For Hat Creek at 100 GHz a calculated value of 0.44 mK per micron of path length is in good agreement with measured values 0.4 to 0.5 mK per micron. For the VLA site and Chajnantor at 230 GHz we expect $\sim$ 1.7 mK per micron of path length.

Consider the atmospheric path length variations for observations over an angle θ, and a time interval δt. At a height, h, an offset, θ, between two positions in the sky gives an displacement $d = h \times airmass \times \theta$. There is considerable evidence for fluctuations in atmospheric boundary layers, e.g. cross correlation of water vapor radiometer fluctuations at Hat Creek yields heights of 2 - 3 km. An offset, $\theta = 1'$, gives a displacement $d = 1$ m over a path of 3.4 km. The fluctuations over a distance d are given by the structure function; the RMS scales as $\sim d^{\beta/2}$, where $\beta/2 \sim 0.6$ over distances of less than $\sim$ 100 m. The median RMS path length fluctuation, σ, measured on a 100 m baseline at Hat Creek in good weather is $\sim$ 290 microns. Scaling this using $\beta/2 = 0.6$, the path length fluctuations over 1 m are $\sim$ 18 microns giving $\delta T \sim 8$ mK over 1 arcmin.

For Chajnantor at 230 GHz we expect

$\delta T = 1.7mK \times \sigma[\mu] \times (\theta[arcmin] \times h[km] \times airmass/340)^{\beta/2}$ —— (3)

where σ is the RMS path length measured on a 100 m baseline.

The time interval, δt, between observations also contributes atmospheric noise corresponding to a displacement $v \times \delta t$, where the velocity of atmospheric water vapor fluctuations, $v \sim 10$ m/s. Over a time interval ~ 0.1 s, this contributes a similar fluctuation in brightness temperature as a $1'$ angular offset.

$\delta T = 1.7mK \times \sigma[\mu] \times (v[m/s] \times \delta t[sec]/100)^{\beta/2}$ —— (4)

For the ALMA site, the median seeing is 254 micron measured at 36 degree elevation on a 300 m baseline. Scaling this to zenith on a 100 m baseline using $\beta/2 = 0.6$, we obtain a median $\sigma \sim 80$ micron. There are seasonal and diurnal variations in both σ and β (Sramek 1990, Olmi & Downes 1992, Wright 1996). For example, Sramek measured a median seeing for the VLA which scales to 150 microns for winter nights and 400 micron for summer days, on a 100 m baseline with $\beta/2 = 0.6$. The median seeing at the ALMA site is about a factor of two better than the VLA site in winter. On spatial scales smaller than the thickness of the turbulent region, β should tend towards the the value 5/3 expected for three dimensional, Kolmogorov turbulence. This is observed on short baselines at Hat creek on turbulent summer afternoons. If β is steeper, then the extrapolations to short baselines are reduced.

3 Possible calibration schemes

Assuming that the above error terms add in quadrature, evidently we must calibrate the atmospheric fluctuations on time scales ~ 0.1 sec in order that atmospheric temporal fluctuations be less than the thermal noise. This is usually done by beam switching (using focal plane choppers or nutating subreflectors), or by slewing the antenna across the source using on-the-fly (OTF) observing. In either case we must have a gain stability of $\sim 10^{-4}$ in 0.1 sec in order to be limited by thermal noise. Any calibration must also be stable to better than 10^{-4} in 0.1 second.

3.1 On-the-fly observing

Sources larger than several beam widths are usually observed by scanning the antenna across the source, establishing a reference at either ends of the scan. Beam switching during the scan limits the errors from spatial and temporal atmospheric fluctuations, but the errors are propagated as $\sqrt{(}N_{throws})$ (see Holdaway, Owen & Emerson 1995). If the sample rate is faster than ~ 10 Hz, then atmospheric fluctuations are smaller than thermal noise. In this case the gain and atmospheric spatial fluctuations over the length of the scan may become the limiting errors. The OFF positions at the ends of each scan across the source also suffer from atmospheric noise fluctuations since they are observed at different times and displacements from the ON positions. The shortest time for a scan across the source is determined by the antenna acceleration. In practice this is likely to be 1-2 seconds resulting in significant atmospheric noise in the OFF positions. For a raster scan across an extended source, there will also be atmospheric fluctuations between the OFF positions for each scan.

3.2 Beam switching

Sources which are smaller than a few beamwidths across are not efficiently observed using on-the-fly techniques. These sources need single dish observations, but the antenna switching time is about 10x longer than the maximum time on source before the noise is dominated by either atmospheric or gain fluctuations. In this case, one might do better with beam switching. The usual beam throws of a few arcmin at ~ 5 Hz suffice to keep atmospheric fluctuations smaller than the thermal noise in a 10 GHz bandwidth. Larger throws or slower switching may increase the noise.

4 Taylor hypothesis

Under the Taylor hypothesis, the bulk velocity of the turbulent pattern is larger than the internal velocities, and the temporal and spatial fluctuations are simply related through the bulk velocity. For sufficiently high scanning speeds the turbulence may be considered to be frozen. An antenna scan at 1 degree/sec, or a beam scan of $6'$ at 10 Hz, corresponds to 17 m/s at a height of 1 km, so the Taylor criteria is approximately satisfied for water vapor fluctuations less than ~ 10 m/s.

If the atmospheric turbulence is considered to be a spatially frozen pattern which moves across the telescope then there is a preferred direction in which beam switching or telescope scans will cancel out noise from atmospheric fluctuations. In practice, the atmospheric turbulence may be rearranging itself with similar velocities to any drift velocity. At Hat Creek, cross correlations of interferometer phase, total power, or WVR fluctuations on different antennas, have multiple peaks; i.e. there is not usually a unique velocity which dominates the temporal fluctuations. Taylor's hypothesis may be more valid on large open sites such as for the VLA or ALMA. If a frozen turbulence screen is drifting past the antenna then we should be able to obtain better sky subtraction by scanning the antenna or subreflector in the direction of the drift velocity. This is an experiment which should be tried.

5 Atmospheric refraction

Anomalous refraction can change the antenna pointing by more than the beamwidth at submillimeter wavelengths. We could simply say that we should not schedule single dish observing under poor conditions, but this might be too restrictive. Atmospheric pointing errors will severely limit the fidelity of mosaic images (Holdaway 1997), and radiometric correction of anomalous refraction (Lamb & Woody 1998) has been proposed. One can devise experiments to measure and correct for antenna pointing errors induced by atmospheric refraction. For example, Church & Hills (1990) measured atmospheric pointing errors at the JCMT by scanning the subreflector in a small circle. Atmospheric pointing errors which persist over larger times and distances can be measured by observing a nearby calibrator with the same or adjacent antennas (analogs of rapid switching and paired antenna phase correction). Pointing self-calibration may be possible for mosaic observations (Holdaway 1997). Similarly, by scanning the beam whilst scanning the antenna in a larger basket weave, one could correct for pointing errors and knit together the rows and columns of a mosaic. A subreflector which allows nutation in both Az and El provides great flexibility for optimizing single dish observing techniques. An orthogonal sinusoidal nutation in both Az and El gives a circular motion. A sinusoidal nutation has more gentle accelerations than a beam switch, and so can be driven faster. A nutation in the direction of a frozen turbulence drift could be used to deconvolve the sky brightness from the atmospheric emission.

6 How many antennas are used for single dish observing?

For mosaic observations, the single dish data fill a similar area of the u-v plane as the shortest interferometer baselines. If there is no special equipment for single dish observations, then we can use all the antennas. If we assume that the atmosphere is uncorrelated over each antenna, we can average the data, and need only a fraction of the time for single dish observations to complement interferometer mosaics. However systematic atmospheric pointing errors may limit the image fidelity (Holdaway 1997).

Alternatively we could instrument some antennas to do single dish observations in an optimum way whilst the rest of the array is used for interferometer observations. This would be particularly useful for imaging transient phenomena, such as comets. With the usual signal-to-noise penalty for single dish observations, this implies that a few antennas are needed for single dish observations.

In addition to providing the missing spatial frequencies for interferometric mosaics, the ALMA array will provide the largest submillimeter wavelength telescope on a superb site. To exploit this potential it is desirable that a significant collecting area be instrumented for the best possible single dish observations. The use of heterodyne or bolometer array receivers should be considered. As well as speeding up the observations, both on-the-fly and beam switched observations are improved using array receivers. A heterodyne receiver array can be electrically phased to steer the beam pattern much faster than a nutating subreflector. Bolometer arrays installed on existing telescopes should provide some valuable tests of atmospheric modeling and single dish techniques which are relevant to the ALMA design.

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