CCAT Pointing: Requirements and Source Densities
draft 1.0, 21 Nov 2005
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1 Abstract

We calculate the sensitivity degradation of the CCAT telescope due to pointing error and tracking jitter, in order to derive requirements for the telescope design. We find that for efficient spectrograph operation at 350 \( \mu m \), CCAT should provide a total boresight pointing error of less than 0.61 arcsec in each dimension. We also estimate the slew angles from pointing sources to spectroscopy sources, and find that the bright extragalactic sources discovered in imaging surveys will provide suitable pointing targets with a density of more than 1 per square degree, requiring typical slew angles of less than 1 degree.

2 Introduction, Approach

The Cornell-Caltech Atacama Telescope (CCAT) will be the largest submillimeter telescope ever built. The 25-meter aperture size, combined with the desire to operate in the 200 \( \mu m \) window, means that the diffraction-limited beam sizes of CCAT will be as small as 2 arcseconds. This will drive the telescope pointing and tracking requirements, and thus contribute to its cost and feasibility. The imagers are CCAT are envisioned as large-format (\( 10^4 \) – \( 10^6 \) pixel) bolometer arrays with high filling factor and good uniformity. In light of the successful experience of the latest generation of submm-mm imagers, it seems very likely that observing modes for imagers will be scan mapping – rastering the array such that any given position on the sky is sampled with many detectors on a few second–few minute timescale. Thus the absolute pointing of the telescope will not be critical for these observations. It is spectroscopy which will drive the telescope pointing, as the observations will typically be oriented toward long integrations on point sources using long-slit or single-mode inputs. For this analysis we assume that the telescope is a perfect cassegrain system, and include only the effect of the secondary obscuration. Obscuration from a 3-meter secondary is included, but no imperfections in reflector figure or surface quality, and no obscuration from secondary supports. The performance degradation we calculate is thus an upper limit to that of the true system, since all of the imperfections will tend to increase the beamsize, and reduce the effects of pointing errors.

3 Analysis

We adopt two simple cases for the analysis: a long slit spectrometer with rectangular pixels, similar to the ZEUS instrument, and a single-mode Gaussian feed system such as the Z-Spec instrument. Our approach is to calculate the loss in signal due to a misalignment of the telescope boresight with the desired position on the sky corresponding to a point source.

3.1 Coupling to a slit spectrometer

For the slit spectrometer, the coupling between the point source and the spectrometer is given by the overlap integral of the point spread function (PSF) produced by the point source, with the slit. We take the PSF given by Fresnel-Kirchhoff diffraction from the primary and secondary, neglecting at present the aberrations in the telescope and the effects of support legs. The point spread function in intensity units can then be taken
Figure 1: Spectrograph slit width optimization assuming an aligned point source on a perfect Cassegrain telescope with secondary obscuration ratio of 0.12, corresponding to CCAT with a 3 meter secondary. The light curve is the point source coupling, the heavy curve is a sensitivity metric assuming background noise from sky and telescope.

directly from Schroeder, Equation 10.2.8

\[
i(P) = \frac{1}{(1 - \epsilon^2)^2} \left[ \frac{2J_1(v)}{v} - \epsilon^2 \frac{2J_1(\epsilon v)}{\epsilon v} \right]
\]

where \( J_1 \) is the Bessel function, \( \epsilon \) is the secondary obscuration ratio and \( v \) is the normalized coordinate:

\[
v = \frac{2\pi}{\lambda} fr,
\]

with \( f \) is the system f-ratio, and \( r \) the distance from boresight in the focal plane. This function is numerically integrated against the slit — a one-dimensional boxcar function of width \( w \) and center coordinate \( \delta \) — and normalized by the total energy in the source:

\[
C(w, \delta) = \frac{\int i(P) [H(x - w/2 - \delta) - H(x + w/2 - \delta)] \, dx \, dy}{\int i(P) \, dx \, dy}.
\]

The coupling for the case of the slit aligned (\( \delta = 0 \)) is shown in Figure 1. For submillimeter observations, the photon noise in the measurement arises from the sky and telescope background, and scales as the square root of the slit width. Assuming that the pixel pitch is well-matched to the slit size, then the ratio of signal coupling to square root of slit provides the scaling for the SNR. This is also plotted in Figure 1; it is seen that optimal slit width under these ideal conditions is the familiar \( d_{opt} = 1.2f\lambda \).
3.2 Affect of misalignment in a slit spectrometer.

In the ideal photon-noise-limited scenario, the noise is independent of the source position, so the SNR depends only on the source coupling. We allow a probability distribution for the misalignment \( \delta \), and calculate the time average coupling with:

\[
C_{\text{ave}}(w, \delta) = \frac{\int C(w, \delta)P(\delta)d\delta}{\int P(\delta)d\delta},
\]

where \( P(\delta) \) describes the time probability misalignment \( \delta \). For calculation purposes, we define \( P(\delta) \) as a simple normal distribution with mean value \( \delta_0 \) and RMS error \( \sigma \). \( \delta_0 \) is the average offset in the boresight position, potentially caused by an error in a slew from a pointing source, or an incorrect guider offset. \( \sigma \) might be due to jitter in the tracking mechanisms, or drift in the pointing system for long integrations. The calculations is performed for several slit widths, values of \( \delta_0 \), and \( \sigma \) – a synopsis of the results is plotted in Figure 2.

3.3 Gaussian Coupling

For a feedhorn-coupled instrument, we use the Gaussian beam formalism presented in Goldsmith Chapter 6. The beam waist at the focal plane is set by the telescope geometry and the chosen edge taper \( T_e \):

\[
w_0 = 0.216 \left[ T_e(dB) \right]^{0.5} \frac{F}{D_p} \lambda,
\]

where \( F \) and \( D_p \) are the telescope effective focal length and primary diameter. If perfectly pointed, the point source coupling, or aperture efficiency is limited by the edge taper and the secondary blockage as given by Goldsmith 6.8. A telescope pointing error of \( \theta \) manifests as a waist offset of \( F \theta = \delta \) at the focal plane, and the loss due to this can be calculated as per Goldsmith 4.30a:

\[
C = \exp \left[ -2 \left( \frac{\delta}{\sqrt{2w_0}} \right)^2 \right].
\]

The time averaging is then as in Equation 4—the results for 10 dB and 20 dB edge tapers are plotted in Figure 2.

3.4 Telescope pointing requirements

Pointing and tracking requirements can be obtained for a given observational requirement with Figure 2. It is clear that the effect of a given mean pointing error \( \delta \) is comparable to the effect of the same value of RMS jitter \( \sigma \), and that both degrade the performance more rapidly for the Gaussian-illuminated telescope than for the slit spectrometer. To generate a requirement, we require that at the shortest wavelength for routine operation, 350 \( \mu \)m, the coupling (thus observing efficiency) due to pointing error in 1-D be greater than 90% over long integrations, and consider the Gaussian system with 10dB edge taper. For this case, the aperture efficiency is 0.775 when perfectly pointed. Permitting this to degrade by only 10% to 0.70 (light line plotted in Figure) requires, for example, either zero mean offset and 0.66 arcsec of RMS jitter, or zero jitter and the 0.61 arcsec mean offset. Allowing these two errors to contribute equally, we see that a mean offset and RMS jitter of 0.45 arcsec (each) degrade the 350 \( \mu \)m performance by our 90% threshold. We thus adopt these as requirements.
Figure 2: Sensitivity degradation due to pointing error for both slit spectrometers (solid curves) and single-mode Gaussian feed instruments (dashed curves) for the 25-meter CCAT telescope. The ordinate is in units of arcseconds, and is the RMS pointing jitter for $\lambda=1$ mm – for shorter wavelengths, the axis must be scaled with $\lambda$ relative to 1 mm. The heaviest curves correspond to zero mean offset, the lighter curves correspond to (in order of decreasing line weight) 1.32, 1.98, and 2.97 arcsecond (for $\lambda=1$ mm) mean misalignment throughout the observation. The intercepts (zero pointing jitter) provides the aperture efficiency of these ideal systems.

4 Pointing slew angles

An important question is the availability of pointing sources – the density of suitable sources determines the distance through which the telescope must slew from a pointing source to the science target. A simple approach for this is to consider using the brightest of the extragalactic sources discovered in the imaging
### Table 1: Pointing Requirements, Source Densities for CCAT

<table>
<thead>
<tr>
<th>λ [µm]</th>
<th>Pt. Rq. (as)</th>
<th>w/jitter</th>
<th>broadband pointing density 5σ, 30s</th>
<th>spacing 20σ, 30s</th>
<th>bin 200 density 20σ, 30s</th>
<th>bin 200 density 20σ, 30s</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>0.35</td>
<td>0.26</td>
<td>2490</td>
<td>&lt;0.1</td>
<td>&gt;200</td>
<td>10600</td>
</tr>
<tr>
<td>350</td>
<td>0.61</td>
<td>0.46</td>
<td>131</td>
<td>13</td>
<td>17</td>
<td>923</td>
</tr>
<tr>
<td>450</td>
<td>0.78</td>
<td>0.59</td>
<td>104</td>
<td>13</td>
<td>17</td>
<td>710</td>
</tr>
<tr>
<td>610</td>
<td>1.06</td>
<td>0.80</td>
<td>117</td>
<td>0.5</td>
<td>85</td>
<td>790</td>
</tr>
<tr>
<td>850</td>
<td>1.48</td>
<td>1.12</td>
<td>34</td>
<td>7</td>
<td>23</td>
<td>231</td>
</tr>
<tr>
<td>1100</td>
<td>1.92</td>
<td>1.45</td>
<td>11.8</td>
<td>2</td>
<td>42</td>
<td>179</td>
</tr>
</tbody>
</table>

NOTES: The pointing requirement (column 2) is a measure of the overall error budget in one dimension, the value in column 3 is the permissible error in both RMS jitter and mean misalignment if they contribute equally. Columns 4–6 refer to using a broadband pointing camera which has the same sensitivity as the CCAT facility cameras. Columns 7–11 refer to using the spectrograph itself to point, and assuming that 200 points are binned together. Sensitivities are based on the CCAT sensitivity spreadsheet (Herter 2004), assuming 0.4 mm PWV. The cameras have larger sensitivity margin because they will be inexpensive pointing cameras, thus may not achieve the full sensitivity appropriate available in a given band. Flux densities in columns 4, 7, 8 are in mJy, source densities in columns 5, 9 are in deg$^{-2}$ estimated from the submillimeter source counts (Blain et al. 2002), and the spacings in columns 6, 10 are in arcminutes. The spacing represent the typical distance through which the telescope must slew from a pointing object to a science object.

Surveys with the facility cameras. The bright galaxies in these fields will be measured with high SNR, thus with good positional accuracy, and will be well-tied into the astrometric grid of primary calibrators. For follow-up spectroscopy, the spectrograph can be pointed with a small offset pointing camera coupling a broad band, or with the spectrograph itself, by binning many spectral channels.

To estimate the density of useful sources, we require $20\sigma$ detections in very modest integration times $\sim 100$ seconds. We then use the CCAT facility sensitivities (Herter 2004) to convert this into flux densities – for the case of a broadband pointing camera, we allow a sensitivity margin relative to the optimized facility cameras by requiring $50\sigma$ detection. We then compare these flux densities to the submillimeter source count models (e.g. Blain et al. 2002) to determine the density of sources. Values are presented in Table 4, with the caveat that the source densities often are based on extrapolation to the bright end of the number counts. Even with the sensitivity margins included, the typical pointing source is found with a density greater than 1 per square degree for all bands except for the 200 µm. The slew angles should thus be less than or of order 1 degree.

## References


