Appendix A

Pointing Equations for the 12m Telescope

A.1 Primary Pointing Equations

The basic pointing model in use at the 12m is much the same as that described by Stumpff (1972, Kleinheubacher Berichte, 15, 431) and Ulich (1981, Int. J. Infrared & Millimeter Waves, 2, 293). The azimuth and elevation terms used to correct the nominal encoder positions are given by the equations

\[
\Delta A = IA + CA \sec(E) + NPAE \tan(E) + AN \tan(E) \sin(A) \\
- AW \tan(E) \cos(A) + A_{obs} \sec(E) \\
\Delta E = IE + ECEC \cos(E) + AN \cos(A) + AW \sin(A) + E_{obs} + R_0 f(E)
\]  

(A.1)  

(A.2)

where \( A \) and \( E \) are the azimuth and elevation of the source and

\( AI \) is the azimuth encoder zero offset,

\( CA \) is the collimation error of the electromagnetic axis,

\( NPAE \) Non-perpendicularity between the mount azimuth and elevation axes,

\( AN \) is the azimuth axis offset/misalignment north-south,

\( AW \) is the azimuth axis offset/misalignment east-west,

\( A_{obs} \) is the observer-applied azimuth correction,

\( \Delta E \) is the total elevation encoder correction,

\( IE \) is the elevation encoder zero offset,

\( ECEC \) is the gravitational flexure correction at the horizon,

\( E_{obs} \) is the observer-applied elevation correction,

\( R_0 \) is the weather dependent term to the atmospheric refraction correction,

\( f(E) \) is the elevation dependence of the atmospheric refraction correction.

The weather-dependent refraction coefficient, which is practically independent of wavelength, is given by Liebe & Hopponen (1977, IEEE Trans. Antennas Propagation, AP-25, 336, equation 9) as

\[
N_0 = (n - 1) \times 10^6 \\
= R_0 (\text{radians}) \times 10^6 \\
= 103.56 \frac{P_d}{T_s} + 95.5 \frac{P_w}{T_s} + 499500 \frac{P_w}{T_s^2} \text{ ppm}
\]  

(A.3)
and is given similarly by Crane (in *Methods of Experimental Physics*, volume 12, part B, page 186, equation 2.5.1) as

\[ N_0 = 103.43 \frac{P_d}{T_s} + 96.0 \frac{P_w}{T_s} + 499835 \frac{P_w}{T_s^2} \text{ ppm} \]  

(A.4)

where I have ignored the partial pressure contribution due to carbon dioxide (only \(\sim 0.03\%\) of the total pressure), \(n\) is the complex index of refraction, and the pressures and temperatures are as defined below. A similar expression to the two given above can also be found in Allen (1963, “Astrophysical Quantities”, page 120). Taking the Liebe & Hopponen relation (Equation A.3) for \(N_0\) and solving for \(R_0\) in arcseconds yields

\[ R_0 = 21.36 \frac{P_d}{T_s} - 1.66 \frac{P_w}{T_s} + 103029.27 \frac{P_w}{T_s^2}, \]  

(A.5)

where

- \(P_d\) is the partial pressure of dry gases in the atmosphere (in Torr),
- \(P_w\) is the partial pressure of water vapor at the surface (in Torr),
- \(P_s\) is the total surface barometric pressure (in Torr), which is equal to \(P_d + P_w\), and
- \(T_s\) is the surface ambient air temperature (in Kelvin).

\(P_s\) must be measured by a barometer at the telescope site. \(P_w\) may be calculated from the expression

\[ P_w = RH \frac{e_{sat}}{100}, \]  

(A.6)

where \(RH\) is the surface relative humidity (in percent) and \(e_{sat}\) is the surface saturated water vapor pressure (in Torr) and is given by Crane (in *Methods of Experimental Physics*, volume 12, part B, page 187, equation 2.5.3) as

\[ \log(e_{sat}) = 24.67 - \frac{2990.14}{T_s} - 5.31 \log(T_s) \]  

(A.7)

Note that Ulich (1981) quotes a similar expression for \(\log(e_{sat})\), but does not give a reference.

The weather-dependent term \(R_0\) is calculated using the on-site weather station, and is recalculated every time the surface temperature changes by more than 1.5\(^\circ\), the surface relative humidity changes by more than 5\%, or the surface barometric pressure changes by more than 1 Torr. \(R_0\) usually remains in the range 48" to 60". A plot of \(R_0\) as a function of \(T_s\) and relative humidity for a constant total surface barometric pressure is shown in Figure A.1. The elevation dependence of the refraction correction is given by

\[ f(E) = \frac{\cos(E)}{\sin(E) + 0.00175 \tan(87.5 - E)}. \]  

(A.8)

This term is recomputed for each elevation of observation.
The 12m staff determines the pointing coefficients regularly. To derive a new pointing model a campaign of optical and radio pointing sources measurements are made. Both the optical and radio pointing sources are observed at as many azimuth and elevation positions as possible and the corrections necessary to receive peak flux from the sources are measured. The corrections are then input to a fitting program and the coefficients are determined. The total rms of the fit is typically 3" – 5".

A.1.1 Secondary Pointing Corrections

In addition to the primary pointing corrections, a set of secondary pointing corrections are used at the 12m. In azimuth, these corrections are given by the equation

$$\Delta A_1 \cos(E) = IA_1 \cos(E) + CA_1,$$  \hspace{1cm} (A.9)

where the left-hand side of the equation corresponds to the “cross-elevation” azimuth correction on the sky, given at a particular elevation by the observer-applied azimuth correction. In elevation, the secondary correction is

$$\Delta E_1 = ECEC_1 \cos(E) + IE_1,$$  \hspace{1cm} (A.10)

These terms correspond to the linear (in $\cos(E)$) terms in the principal pointing equations given above: $A_1$ is the supplemental azimuth encoder offset, $C_1$ is the supplemental electromagnetic collimation error correction, $B_1$ is the supplemental gravitational bend error, and $E_1$ is the supplemental elevation encoder offset.

Each of the four receiver bays has their own set of these secondary coefficients to compensate for slight differences between feed and mirror alignments in each bay. The intent of these pointing coefficients is to keep the required pointing offsets as close to zero as possible. The determination of these coefficients requires much less data than the main pointing equations and can thus be adjusted on a more frequent basis.
Figure A.1: $R_0$ as a function of $T_s$ and relative humidity for a constant total barometric pressure of 610 Torr.