Practical implementation of the atmospheric phase correction for the Plateau de Bure Interferometer

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1 Introduction

As soon as the new dual frequency receivers have been installed on the Plateau de Bure, it has been clear that the atmospheric phase correction method investigated by Michael Bremer at IRAM could be implemented in the interferometer, thanks to the good stability of the receivers: see the May 1995 Newsletter, the Nov. 1995 Newsletter, and the technical reports prepared by M. Bremer.

The purpose of the present document is to describe how the correction method has been implemented in CLIC, for the continuum data, and how the real time acquisition system will be modified to apply the correction in real time to the spectroscopic data.

2 Background

The principle of the method is the following: the atmospheric phase fluctuations are due to different, time-varying water vapor content in the line of sight of each antenna across the atmosphere; these differences in water vapor content are measurable by monitoring their emission at radio frequencies. We thus use the differences in emission, measured by using the 1mm channel of the receivers as an atmospheric monitor, to correct for phase fluctuations in both the 1mm and 3mm windows.

2.1 Monitoring the atmospheric emission

The radiation temperature [1] of the atmosphere $T_{\rm EM}$ is determined by using the usual "chopper wheel" calibration technique: one compares the emission of the atmosphere, to both an ambient load of radiation temperature $T_{\rm CHOP}$ (the absorbing table that is switched in to the beam), and a cold load of radiation temperature $T_{\rm COLD}$ (an absorber in the receiver dewars towards which the beam is redirected by switching in a corner mirror).

The three measurements give ($T_{\rm AMB}$ is the temperature in the receiver cabin and $\eta_{\rm F}$ the forward efficiency):

$$C_{\rm SKY} = K(T_{\rm R} + (1-\eta_{\rm F})T_{\rm AMB} + \eta_{\rm F}T_{\rm EM})$$

$$C_{\rm CHOP} = K(T_{\rm R} + T_{\rm CHOP})$$

$$C_{\rm COLD} = K(T_{\rm R} + T_{\rm COLD})$$

[1] "radiation temperature" here actually stands for "Rayleigh-Jeans equivalent brightness temperature"

These measurements are combined to give $T_{\rm R}$ and $T_{\rm EM}$. Actually $T_{\rm R}$ is quite stable and we can avoid too frequent cold load measurements by assuming $T_{\rm R}$ constant.

The system noise of the atmospheric monitor is given by:

$$T_{\rm SYS} = \frac{T_{\rm R} + (1-\eta_{\rm F})T_{\rm AMB}}{\eta_{\rm F}} + T_{\rm EM} = T_{\rm LOSS} + tem$$

Note that this is different from the usual formula for the system temperature, since our reference plane is *below* the atmosphere, not above.

Thus a variation $\Delta T_{\rm EM}$ of atmospheric emission leads to a variation ΔP of the total power P, given by:

$$\Delta P/P = (\Delta T_{\rm EM} + \Delta T_{\rm LOSS})/T_{\rm SYS}$$

where we allowed for a change in $T_{\rm LOSS}$ due to a variety of possible causes: variations in receiver noise, ambient temperature, forward efficiency (or ground noise).

2.2 Atmosphere model

The atmosphere model in use at Bure has been extended to compute the atmospheric excess pathlength by integrating the refractive index of wet air along the line of sight across the atmosphere.

The total precipitable water vapor content is computed, using an iterative procedure, to verify the condition:

$$T_{\rm EM}(observed) = (T_{\rm EM,S}(w_{\rm H_2O}) + GT_{\rm EM,I}(w_{\rm H_2O}))/(1+G)$$

where G is the image side band gain ratio, and $T_{\rm EM,S}$ and $T_{\rm EM,I}$ are the radiation temperatures of the atmosphere computed from the atmosphere model in the signal and image side bands of the monitoring receiver. The model depends also on the ambient pressure, the ambient temperature, and the source elevation, which are known or directly measured.

The atmospheric excess pathlength l at the observing frequency is then computed by integration when $w_{\rm H_2O}$ is known. One also computes the derivative $\frac{\partial l}{\partial T_{\rm EM}}$.

2.3 The phase correction

The atmospheric phase affecting the observations is given by:

$$\phi(t) = \frac{2\pi}{\lambda} l(t)$$

Ideally one would like use $T_{\rm EM}$ measured every second for each antenna, to compute the corresponding $\phi(t)$, and to correct the measured baseline phases.

Practically this is not feasible, since $\phi(t)$ amounts to many turns, and instrumental effects affect the measured $T_{\rm EM}$. The receiver gains, the forward efficiencies vary with the source elevation. So when the antennas are moved in elevation by more that a few degrees, like when switching between observed sources, these effects spoil the measured $T_{\rm EM}$ and prevent the use of the derived pathlength values.

Instead we use a differential procedure: once the antennas track a given source, one calibrates the atmosphere to calculate $T_{\rm EM}(t_0)$, $l(t_0)$, and $\partial l/\partial T_{\rm EM}(t_0)$.

The relative change in total power is:

$$\Delta T_{\rm EM}(t) = T_{\rm SYS}\frac{\Delta P(t)}{P} + \Delta T_{\rm LOSS}(t)$$

The phase correction applied is then:

$$\Delta\phi(t) = \frac{2\pi}{\lambda}\frac{\partial l}{\partial T_{\rm EM}}\left(T_{\rm SYS}\frac{\Delta P(t)}{P} + \Delta T_{\rm LOSS}(t)\right)$$

which we may rewrite as

$$\Delta\phi(t) = \frac{2\pi}{\lambda}\frac{\partial l}{\partial T_{\rm EM}}\frac{T_{\rm SYS}(t_0)}{P(t_0)}\left(P(t) - P_{\rm REF}(t)\right)$$

The choice of $P_{\rm REF}(t)$ will be made in order to include as much as possible all the slow effects that contribute to $\Delta T_{\rm LOSS}(t)$. It is not a problem if long term atmospheric effects are also included in $P_{\rm REF}(t)$; these effects will not be removed by the radiometric phase correction, but by the traditional phase referencing on a nearby calibrator.

Several choices of $P_{\rm REF}(t)$ may be used:

1. Use for a given time interval (e.g. a scan of $1-4$ min. duration) the average of $P(t)$ in the same interval. This "minimal" choice has the advantage of correcting the amplitude of the decorrelation effect as much as possible (of course decorrelation effects occurring inside an elementary sampling interval, one second, will not be corrected; but this may usually be neglected). The average phase should not be affected. This is the scheme we plan to apply in quasi-real time in the correlators, to the spectral line data.

2. Use, for a longer time scale (e.g. the on-source time between two observations of the phase calibrator), a linear fit to the $P(t)$ data as the $P_{\rm REF}(t)$ reference. This is basically the same choice, but additionnaly allows for a linear drift of $\Delta T_{\rm LOSS}$ during the observation. This choice is currently implemented in CLIC (see below).

3. Use a smooth curve approximation to $P(t)$ on a longer time scale (one or several hours). This approximation should be different for the source data and the phase calibrator data. This has not been really tried yet.

4. Use a realistic model of the system noise as a function of azimut and elevation, and other parameters: although some effects should be easily calibrated out (e.g. by monitoring the temperature of the receiver cabin), such a detailed knowledge of the ground noise properties of the PdB antennas is difficult to reach, and not yet available.

3 Implementation in the acquisition - data reduction system:

3.1 In quasi-real time:

- Task `RDI` solves the atmospheric calibration observations (with or without cold load measurement), to obtain the correction factors F in $\Delta\phi(t) = F\left(P(t) - P_{\rm REF}(t)\right)$. There is one such coefficient for each side band of each receiver in each antenna. The standard atmospheric model is used, but the data is interpolated out of a pre-computed table to save computing time (the table name is the logical name `GAG_ATMOSPHERE` which should translate to `COMP$DISK:[CONTROL.OBS]ATM-BURE-VAX.BIN`). The new parameters are stored in

the data files in the new header section named "Atmospheric monitor". *This is currently implemented.*

At the same time a default is set for the quantity $P_{\rm REF}(t)$ discussed above: it is the measured atmosphere emission at the time of the last calibration. This will have to be refined by the command `MONITOR`.

- The correlators will soon do the correction on the spectral line data, using the scan-averaged atmospheric emission as a reference. For safety reasons, spectral data will have to be averaged both with and without phase correction. More powerful CPU's will be needed for the correlators (which are being installed and tested).

- The CLIC data format had to be extended to allow storing both phase-corrected and uncorrected data. So far the data section of each observation in a CLIC file would contain one record of continuum data for each second (or longer time records after data compression by `COMPRESS`), and a single average record containing scan-averaged continuum and spectral line data. In the new format there will potentially be two such average records, one with uncorrected, the other with phase-corrected data.

  In fact three observing modes are possible, selected by a new OBS command:

  - `SET PHASE ON`, to record only phase-corrected data.
  - `SET PHASE OFF`, to record only uncorrected data.
  - `SET PHASE BOTH`, to record both uncorrected and phase-corrected data.

3.2 In the calibration program (CLIC):

- *Filling in the data parameters of receiver 2:* Receiver 1 (3mm) data recorded before Nov. 11 1995 did not contain information on receiver 2 parameters, on which the phase correction is based. The current CLIC version automatically fills in these parameters when the data is read. Of course this only works if at least one correlator unit was connected to receiver 2. An informational message is given when this operation is done. This has been effective for some time already (2 months).

- *Solving the atmospheric calibrations* for the atmospheric monitor parameters. For the newest data (since Nov 11, 1995) this is done in real time. For older data this must be done manually, using either command `ATMOSPHERE`, which does exactly what is currently done by RDI at Bure, or command `MONITOR`. To execute these commands, the currect index of CLIC should include all data to be processed, including the atmospheric calibrations scans (procedure `CALI`).

- *Setting a reasonable value for* $P_{\rm REF}(t)$. This is done using command `MONITOR` which applies the second option described above: a linear fit to $P(t)$. The description of the command is:

  `MONITOR delta_time`

  The scans in the current index are grouped in intervals of maximum duration 'delta_time' (in seconds); source changes will also be used to separate intervals. In each interval a straight line is fitted in the variation of atmospheric emission as a function of time; this line will be the reference value $P_{\rm REF}(t)$ for the atmospheric correction.

  The default for 'delta_time' is 3600 s, which usually results in using the on-source time between two phase calibrator observations as intervals for evaluation of $P_{\rm REF}(t)$.

One may also try and extend 'delta_time' and use this command to process the source observations and the phase calibrator observations separately (but beware that using very long times will produce long term phase drifts into the phase correction, which will have to be removed by the usual phase calibrations anyway).

After using this command, one may plot $P_{\rm REF}(t)$ using `SET Y ATM_REF` and `SET X TIME`, in antenna mode; $P(t)$ itself is available with `SET Y ATM_EM`.

- *Finally, applying (or not) the correction* is done via `SET PHASE ATMOSPHERE` (or `SET PHASE NOATMOSPHERE`). This should work for all plots and *uv* table construction, focus solving, flux solving, ... When the corrected spectral line data is available, it will switch to the phase-corrected average records.

  After a plot, one may check the F coefficients used by typing `SHOW CORR`. The coefficients are given in radians per unit of $P(t)$.

References

[1] Bremer, M., IRAM working report, April 1994

[2] Bremer, M., IRAM working report n. 238, Nov. 1995