Finding Atmospheric attenuation parameters for GBT Observations

Glen Langston

December 14, 2006

Abstract

This note is a users guide for the `findTau` program (version 1.0) for estimating the atmospheric attenuation parameter, τ, required for accurate calibration of high frequency GBT observations. Version 1.0 of this program can estimate τ, the receiver temperature, T_{rx}, and atmospheric temperature, T_{sky}, based on a set of input system temperature measurements, T_{sys}, as a function of antenna elevation. The test modes of `findTau` and an example execution are presented.

1 Introduction

For typical astronomical observations, astronomers desire absolute intensity calibration to 1 % accuracy, but are usually willing to live with 5 % accuracy. To achieve this level of accuracy, atmospheric attenuation of astronomical signals must be computed.

Atmospheric attenuation of radio frequency signals is primarily due to oxygen and water in the atmosphere. The atmospheric opacity is regularly estimates (based on local weather data) by an automated system written by Ron Maddalena. The purpose of `findTau` is to allow comparison between weather based estimates and direct GBT observations.

The program has an number of features, including the capability of generating test data and plots of the input data and the fit. The appendix describes the use of the program. Figure 1 show the model data and a fit to the model.

2 Model

The `findTau` atmospheric model is simple:

$$T_{sys}(el) = T_{sky}[1 - e^{-\tau/\sin el}] + T_{rx}$$

where el is the elevation of the telescope during the observation.

The optimum parameters are found by performing calculations of the least squares difference between data model for all reasonable τ, T_{rx}, and T_{sky}. The program reports values fit values which yield the minimum least squares difference for the model and input data.

The search ranges are $0.009 < \tau < 1.0$, $8. < T_{rx} < 120.$ K and $250 < T_{sky} < 270$ K. To facilitate fitting of limited input data (ie. only small elevation range coverage), `findTau` allows constraining any of these parameters.

The program takes as input an ASCII input file. An example input file can be generated using the following command:

`findTau -M`

3 Plotting

It is valuable to confirm the fit results by comparison with the observed data. The `findTau -P` option allows generation of ASCII input files to `gnuplot`, and a plotting task is spawned to show all fits to the system temperature.

4 Accuracy

There are a number of alternatives to the model in the first equation, and here we make a rough estimate of the uncertainty in the intensity calibration scale associated with an uncertainty in the τ estimate. We assume that intensities of measured spectral lines will be increased by the factor in the equation below.

$$T_A^* = T_A' e^{\tau / \sin el}$$

In the following analysis, we take $el = 30$ degrees as a representative elevation value, and since $\sin el = 30 = 0.5$, a typical correction factor is $F = e^{2*\tau}$. A typical "large" τ value is .1, so for a required accuracy of $\Delta\tau$ for 5% calibration accuracy, the estimated τ accuracy is given by the following equation.

$$\frac{\Delta F}{F} = e^{2\tau} 2 \frac{\Delta \tau}{\tau} < 0.05$$

or

$$\Delta\tau_{\tau=0.1} < 0.05 * 2\tau e^{2\tau}$$

$$\Delta\tau_{\tau=0.1} < 0.01 \times 1.22 \sim 0.012,$$

which implies achieving 5 % intensity accuracy requires knowing τ to ± 0.012, if τ is near 0.1.

We next address the question of how sensitive the τ estimate is based on an assumed value of T_{sky}. Table 1 shows 12 fits to four sets of data obtained as a part of the Turner and Langston Q-band survey of TMC-1. The fits assuming T_{sky}=260K are shown if figures 2 and 3.

We have no independent estimate of the actual attenuation at the time of these observations, so only check the dependence on the fit values as a function of assumed T_{sky} value. It is expected that the LCP and RCP values should yield the same τ value, so we take the average of these values as the best estimate for each frequency. Further note that the increase in assumed T_{sky} and resulting τ values are anti-correlated. This is because if there is a stronger

Frequency (MHz)	Polarization	T_{sky} (K)	Fit τ	Fit T_{rx} (K)
45100	LCP	250.	0.092	71.5
45100	LCP	260.	0.087	71.5
45100	LCP	270.	0.080	74.1
45100	RCP	250.	0.101	48.6
45100	RCP	260.	0.094	50.1
45100	RCP	270.	0.087	51.9
45290	LCP	250.	0.108	72.6
45290	LCP	260.	0.103	72.6
45290	LCP	270.	0.099	72.6
45290	RCP	250.	0.113	52.7
45290	RCP	260.	0.108	52.7
45290	RCP	270.	0.103	52.7

Table 1: Tests of variation of fit τ and T_{rx} as a function of reasonable variations in T_{sky}

atmospheric effect, less opacity is needed for that to contribute to the total system temperature, T_{sys}.

The spread in τ values in Table 1 is $0.080 < \tau < 0.113$. At $el = 30$ degrees, the correction factor range is $1.17 < F < 1.25$, or $\Delta F/F = 7$ %. If $T_{sky} = 260.$ K is assumed then the difference between the estimate τ and for an actual T_{sky} = 260.±10. K results in less than a 5 % error in the intensity calibration.

Clearly assuming, $T_{sky} = 260.$ K, and applying τ factor to observations at similar frequencies should yield calibration accuracy of approximately 5 %, but if better accuracy is required, a better estimate of τ will be required.

5 Summary

The program `findTau` can estimate τ and T_{rx} for high frequency observations in good weather conditions to an accuracy of approximately 5 %. The program runs in the NRAO-GB Linux environment and is located at `/opt/local/bin/findTau`.

A number of improvements are being considered, including adding a table of receiver temperatures from laboratory measurements. It is possible to include an improved the atmospheric temperature model, but additional model parameters are required. An additional option is to compute the τ values based on estimates of the millimeters of water vapor in the atmosphere. This change will allow combining of different frequency ranges in a single fit.

6 References

1. Maddalena, R., (2006) "GB weather web page" `http://www.gb.nrao.edu/~rmaddale/Weather/`
2. Turner, B and Langston, G (2007), *Astrophysical Journal*, in preparation.

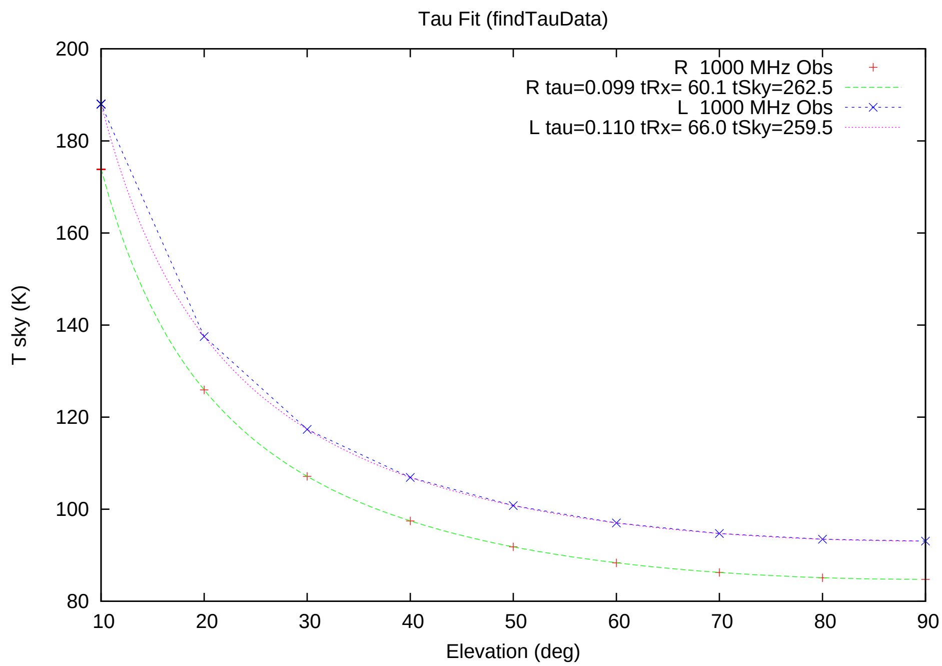

Figure 1: Model Atmosphere data and fits to the simulated atmosphere. The model atmosphere data were generated using the `findTau -M` option. The default model is $\tau = 0.1$, $T_{rx} = 60.K$, $T_{sky} = 260.$ K for RCP polarization and The default model is $\tau = 0.11$, $T_{rx} = 66.K$, $T_{sky} = 260.$ K for LCP polarization. The model data is placed in a file for 9 elevations between 10 and 90 degrees. The plot was produced using `findTau -P findTau.txt`
.

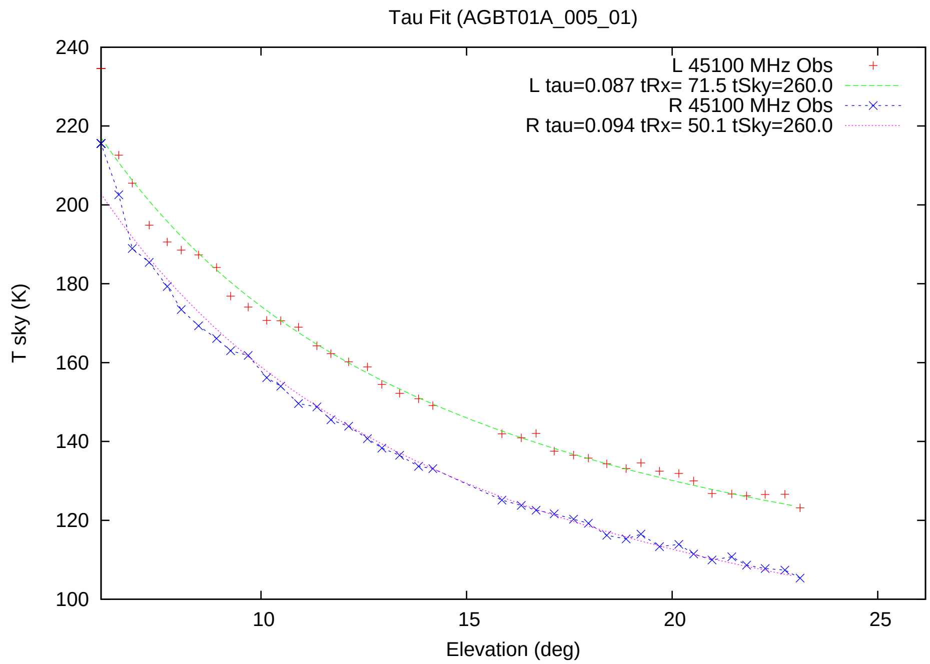

Figure 2: Model Atmosphere data and fits to Q band observations from Turner and Langston 2007. The program arguments were: `findTau -P -d 10 -s 260.  AGBT01A_005_01.tsy`

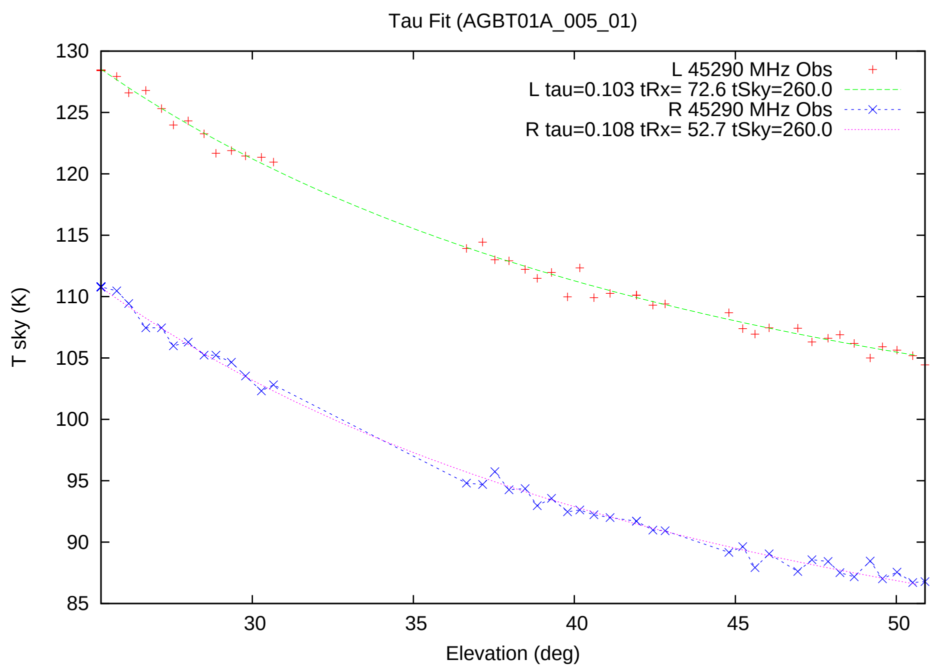

Figure 3: Model Atmosphere data and fits to Q band observations from Turner and Langston 2007.

A Example findTau executions

This appendix lists examples of execution of `findTau`.

A.1 Help

With no arguments, `findTau` prints a short help message:

```
radar{glangsto}113: findTau
findTau: Least Squares fit to tau, tRx and tSys to measured tSys versus elevation data
findTau: Version 1.0
usage: findTau [-p] [-m] [-d <deltaFreqMHz>] [-t <tau>] [-r <tRx>] [-s <tSky>] <fileName>
where <fileName>  log file with Tsys (K) versus elevation data (deg)
where -t <tau>    optionally include an assumed tau value (range 0 to ?)
where -s <tSky>   optionally include an assumed T Sky (K)
where -r <tRx>    optionally include an assumed T receiver (K)
where -d <dMHz>   optionally include an tolerance for frequency ranges (default 500 MHz)
where -p          optionally plot the tSys vs elevation obsevations
where -m          optionally write out a model data set for fit tests
The output model tau file name is findTau.txt
The input file has keyword=Values pairs all on a single line
Example input: AGBT01A_005_01.tsy
# Comments and blank lines are ignored in input file.
# GBT project  Source      date+time       Scan Pol Freq.(MHz) El(degree) System T (K)
AGBT01A_005_01 TMC-CP 2005-02-02T01:28:44.15  34 P=L F=  45775. El=  76.88 Tsys=  89.41
AGBT01A_005_01 TMC-CP 2005-02-02T01:30:58.15  35 P=L F=  45775. El=  76.77 Tsys=  90.38
```

A.2 Model

The `findTau` program can also produce a small model data set for testing. The example execution and model data are listed below:

```
radar{glangsto}117: findTau -M
Opened model file: findTau.txt
#Test Data for model P=R tau=  0.100 tRx= 60.000 tSky=260.000
#Test Data for model P=L tau=  0.110 tRx= 66.000 tSky=260.000
radar{glangsto}118: cat findTau.txt
#Test Data for model P=R tau=  0.100 tRx= 60.000 tSky=260.000
#Test Data for model P=L tau=  0.110 tRx= 66.000 tSky=260.000
findTauData F= 1000. El= 10.000 P=R Tsys= 173.825
findTauData F= 1000. El= 10.000 P=L Tsys= 188.005
findTauData F= 1000. El= 20.000 P=R Tsys= 125.914
findTauData F= 1000. El= 20.000 P=L Tsys= 137.507
findTauData F= 1000. El= 30.000 P=R Tsys= 107.130
findTauData F= 1000. El= 30.000 P=L Tsys= 117.345
findTauData F= 1000. El= 40.000 P=R Tsys=  97.459
findTauData F= 1000. El= 40.000 P=L Tsys= 106.895
findTauData F= 1000. El= 50.000 P=R Tsys=  91.819
findTauData F= 1000. El= 50.000 P=L Tsys= 100.778
findTauData F= 1000. El= 60.000 P=R Tsys=  88.354
findTauData F= 1000. El= 60.000 P=L Tsys=  97.013
findTauData F= 1000. El= 70.000 P=R Tsys=  86.247
findTauData F= 1000. El= 70.000 P=L Tsys=  94.722
findTauData F= 1000. El= 80.000 P=R Tsys=  85.105
findTauData F= 1000. El= 80.000 P=L Tsys=  93.478
findTauData F= 1000. El= 90.000 P=R Tsys=  84.742
findTauData F= 1000. El= 90.000 P=L Tsys=  93.083
```

A.3 Model Fit

After creating the model, the data can be fit and the result plotted. During execution, `findTau` prints a number of diagnostic messages and fit results. The final output is the median τ value for all input data.

```
radar{glangsto}119: findTau -P findTau.txt
  1   5:    1000 L:   50.00  100.78
Number of good points for fit = 9 (0)
Min and max T sys = 84.742, 173.825 K
Min and max Els   = 10.000, 90.000 d
Best fits: tau=  0.011 tRx= 92.620 tSky=262.500; lsq=      24.193
Best fits: tau=  0.014 tRx= 91.880 tSky=262.500; lsq=      23.304
Best fits: tau=  0.016 tRx= 92.250 tSky=262.000; lsq=      22.208
Best fits: tau=  0.018 tRx= 95.210 tSky=264.500; lsq=      20.955
Best fits: tau=  0.023 tRx= 92.250 tSky=264.000; lsq=      19.435
Best fits: tau=  0.030 tRx= 85.590 tSky=264.500; lsq=      17.642
Best fits: tau=  0.037 tRx= 82.630 tSky=263.500; lsq=      15.556
Best fits: tau=  0.044 tRx= 82.630 tSky=264.500; lsq=      13.005
Best fits: tau=  0.055 tRx= 75.600 tSky=264.500; lsq=      10.088
Best fits: tau=  0.069 tRx= 69.680 tSky=264.000; lsq=      6.7523
Best fits: tau=  0.087 tRx= 63.020 tSky=264.500; lsq=      2.4604
Best fits: tau=  0.099 tRx= 60.060 tSky=262.500
Freq  1000, Pol R N=9 El min=   90.0 El max=   10.0: Tau=0.098830 Trx=60.060000 Tsky=262.500000
Number of good points for fit = 9 (0)
Min and max T sys = 93.083, 188.005 K
Min and max Els   = 10.000, 90.000 d
Best fits: tau=  0.011 tRx=102.240 tSky=261.500; lsq=      26.039
Best fits: tau=  0.014 tRx=101.500 tSky=262.000; lsq=      25.145
Best fits: tau=  0.016 tRx=101.500 tSky=264.000; lsq=      24.064
Best fits: tau=  0.018 tRx=103.720 tSky=264.500; lsq=      22.833
Best fits: tau=  0.023 tRx=100.760 tSky=264.000; lsq=      21.359
Best fits: tau=  0.030 tRx= 94.840 tSky=263.000; lsq=      19.638
Best fits: tau=  0.034 tRx= 96.690 tSky=264.500; lsq=      17.583
Best fits: tau=  0.044 tRx= 89.660 tSky=264.500; lsq=      15.203
Best fits: tau=  0.053 tRx= 86.700 tSky=264.000; lsq=      12.484
Best fits: tau=  0.064 tRx= 82.630 tSky=264.500; lsq=       9.336
Best fits: tau=  0.080 tRx= 77.080 tSky=264.500; lsq=      5.4602
Best fits: tau=  0.110 tRx= 65.980 tSky=259.000; lsq=    0.092638
Best fits: tau=  0.110 tRx= 65.980 tSky=259.500
Freq  1000, Pol L N=9 El min=   90.0 El max=   10.0: Tau=0.110347 Trx=65.980000 Tsky=259.500000
Median Tau:   0.105
```

A.4 Q-band Example

The program has been successfully used to model GBT spectrometer observations of T_{sys} versus elevation. For most circumstances, the atmospheric temperature T_{sky} variation has a small impact on the estimated τ values. In this case $T_{sky} = 260.$ K is assumed.

The model data are from the first epoch observations of a Q-band survey of TMC-1. The data were collected using IDL.

```
findTau -P -d 10 -s 260. AGBT01A_005_01.tsy
Combining frequencies within 10 MHz
Assuming T Atmosphere =   260.00 K
  0  10:   45770 L:   75.70   89.55
  1   9:   45770 R:   76.30   82.07
  2   8:   45490 L:   69.93   97.89
...
```

```
Number of good points for fit = 11 (0)
11.36 Min and max T sys = 88.460, 90.380 K
Min and max Els   = 74.990, 76.880 d
Best fits: tau=  0.011 tRx= 86.700 tSky=260.000; lsq=     0.56223
Best fits: tau=  0.023 tRx= 83.740 tSky=260.000
Freq 45770, Pol L N=11 El min=   76.9 El max=   75.0: Tau=0.022820 Trx=83.740000 Tsky=260.000000
Number of good points for fit = 11 (0)
Min and max T sys = 80.950, 82.070 K
Min and max Els   = 74.990, 76.880 d
Best fits: tau=  0.016 tRx= 77.450 tSky=260.000; lsq=     0.35649
Best fits: tau=  0.078 tRx= 61.540 tSky=260.000
Freq 45770, Pol R N=11 El min=   76.9 El max=   75.0: Tau=0.078100 Trx=61.540000 Tsky=260.000000
Number of good points for fit = 30 (0)
Min and max T sys = 96.730, 99.040 K
Min and max Els   = 62.840, 73.610 d
Best fits: tau=  0.014 tRx= 94.100 tSky=260.000; lsq=     0.58113
Best fits: tau=  0.064 tRx= 80.410 tSky=260.000
Freq 45490, Pol L N=30 El min=   73.6 El max=   62.8: Tau=0.064280 Trx=80.410000 Tsky=260.000000
Number of good points for fit = 30 (0)
Min and max T sys = 80.340, 82.310 K
Min and max Els   = 62.840, 73.610 d
Best fits: tau=  0.011 tRx= 78.190 tSky=260.000; lsq=     0.42327
Best fits: tau=  0.069 tRx= 62.650 tSky=260.000
Freq 45490, Pol R N=30 El min=   73.6 El max=   62.8: Tau=0.068887 Trx=62.650000 Tsky=260.000000
```

A small amount of the input data are listed below:

```
radar{glangsto}138: head -20 AGBT01A_005_01.tsy
AGBT01A_005_01 TMC-CP 2005-02-02T01:28:44.15  34 P=L F=  45775. El=  76.88 Tsys=  89.41
AGBT01A_005_01 TMC-CP 2005-02-02T01:30:58.15  35 P=L F=  45775. El=  76.77 Tsys=  90.38
AGBT01A_005_01 TMC-CP 2005-02-02T01:35:30.15  37 P=L F=  45775. El=  76.44 Tsys=  90.28
AGBT01A_005_01 TMC-CP 2005-02-02T01:40:00.15  39 P=L F=  45775. El=  76.08 Tsys=  90.27
AGBT01A_005_01 TMC-CP 2005-02-02T01:42:15.15  40 P=L F=  45775. El=  75.88 Tsys=  88.46
AGBT01A_005_01 TMC-CP 2005-02-02T01:46:45.15  42 P=L F=  45775. El=  75.44 Tsys=  90.34
AGBT01A_005_01 TMC-CP 2005-02-02T01:49:00.15  43 P=L F=  45775. El=  75.20 Tsys=  89.50
AGBT01A_005_01 TMC-CP 2005-02-02T01:33:13.15  36 P=L F=  45775. El=  76.61 Tsys=  89.60
AGBT01A_005_01 TMC-CP 2005-02-02T01:37:44.15  38 P=L F=  45775. El=  76.30 Tsys=  90.15
AGBT01A_005_01 TMC-CP 2005-02-02T01:44:29.15  41 P=L F=  45775. El=  75.70 Tsys=  89.55
AGBT01A_005_01 TMC-CP 2005-02-02T01:51:13.15  44 P=L F=  45775. El=  74.99 Tsys=  89.50
AGBT01A_005_01 TMC-CP 2005-02-02T01:28:44.15  34 P=R F=  45775. El=  76.88 Tsys=  81.23
AGBT01A_005_01 TMC-CP 2005-02-02T01:30:58.15  35 P=R F=  45775. El=  76.77 Tsys=  81.89
AGBT01A_005_01 TMC-CP 2005-02-02T01:35:30.15  37 P=R F=  45775. El=  76.44 Tsys=  81.28
AGBT01A_005_01 TMC-CP 2005-02-02T01:40:00.15  39 P=R F=  45775. El=  76.08 Tsys=  81.80
AGBT01A_005_01 TMC-CP 2005-02-02T01:42:15.15  40 P=R F=  45775. El=  75.88 Tsys=  81.54
AGBT01A_005_01 TMC-CP 2005-02-02T01:46:45.15  42 P=R F=  45775. El=  75.44 Tsys=  81.85
AGBT01A_005_01 TMC-CP 2005-02-02T01:49:00.15  43 P=R F=  45775. El=  75.20 Tsys=  80.95
AGBT01A_005_01 TMC-CP 2005-02-02T01:33:13.15  36 P=R F=  45775. El=  76.61 Tsys=  81.53
AGBT01A_005_01 TMC-CP 2005-02-02T01:37:44.15  38 P=R F=  45775. El=  76.30 Tsys=  82.07
```