Atmospheric Tomography with the ATA

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1 Introduction

High resolution imaging with arrays at radio wavelengths suffers from blurring of the images due to fluctuations in the delays of signals arriving at the different antennas after passing through the air. The effect is more familiar in the visual, where stars viewed through even a large astronomical telescope appear as fuzzy spots never much smaller than about one arc second. Analogous effects in the radio become increasingly problematic as the frequency increases. At a wavelength of one millimeter, for example, the average point source image size is about 1/2 arc second. Although it is somewhat smaller at longer wavelengths, it is still limited by atmospheric effects. Very high resolution can be achieved in the radio, but only when there is a bright point source in the field which can serve as a beacon to sharpen the image. This technique is known as "$selfcalibration''$ in the radio and is also the basis for the "$adaptiveoptics''$ improvement of visual images. Sharp resolution of faint objects remains a problem both for passive radio imaging and for radar imaging. Radar imaging at the short millimeter wavelengths will be an important development for the future. (Millimeter wave Radar systems are already coming into use on cars.) The effectiveness of millimeter radar systems to produce accurate, high resolution images depends on the development of techniques for circumventing the blurring effects of the atmosphere.

The delay fluctuations at radio wavelengths are due to turbulent motions of atmospheric water vapor. This turbulence is is a problem for both astronomical and radar imaging. It is also a problem in other fields. It affects weather. It interferes with the accurate measurement of delays in the signals returned from space craft. A number of groups are engaged in research into how to characterize this turbulence and correct for its effects.

High angular resolution radio telescopes consist of arrays of many separate radio antennas distributed over the ground with their outputs combined to form an image. The device that combines the signals is usually a correlator which actually multiplies the separate signals from every pair of antennas to produce an overall spatial correlation function of the object in the sky to be imaged. The last step in this rather technical process to create an image is to calculate the Fourier Transform of the correlation function. Whereas a typical optical telescope consists of a single large mirror which focuses the light from the distant star on to a photographic plate or electronic detector, one can think of the radio telescope as if we had separated the single mirror into many separate facets and the process of focusing the light to form an image involves the correlation process discussed above. The radio arrays are sometimes referred to as interferometers because of the way we combine the outputs of the separate antennas. When the radio array is spread out over a long range, we refer to it as a Very Long Baseline Interferometer (VLBI).

One scheme for correcting delay fluctuations that is getting a lot of attention is to use observations of the fluctuation in the radio noise emission from the same turbulent water vapor to determine the fluctuation in the delay of signals passing through the atmosphere. The physical basis of the scheme is simple. The dielectric constant of the water vapor is complex, with the real part providing the normal index of refraction and the imaginary part producing absorption, which at radio wavelengths is associated with rotational absorption transitions, largely in the far infrared. The real part of the index of refraction is approximately constant down to wavelengths of about 0.5 mm, and its effect in the atmosphere is to produce a nearly wavelength independent delay of radio waves longer than that wavelength. The imaginary part, the absorption, is associated with rotational transitions at particular wavelengths. The longest wavelength lines are at 13 and 1.6 millimeters, and there are many more lines in the far infrared which render the atmosphere opaque over the wavelength range 0.1 to .01 millimeter. Although the lines are at specific wavelengths, they are broadened by the pressure effects of the oxygen and nitrogen in the atmosphere, so that their absorptions are considerably spread out in wavelength. As a result, significant atmospheric absorption is present at all wavelengths shorter than 10 millimeters but very little above about 30 millimeters. Figure 1 shows the spectrum of atmospheric water vapor emission near the 13 and 1.6mm lines.

The following describes the effect of the atmosphere on a radio wave traversing it when there are turbulent density fluctuations present. A density increase at any point will cause an increase in the delay of the wave that is the same for all wavelengths longer than a few millimeters. At the same time, there will be an increase in the absorption of the wave that will depend on the precise wavelength. Because of the temperature of the atmosphere, there will also be an increase in the noise emission of the atmosphere associated with the absorption. Knowing the wavelength and the air temperature and pressure, one can expect to be able to calculate either the delay fluctuation or the emission fluctuation from a measurement of the other. Because of the wavelength dependence of the absorption (and emission) of the water vapor, one has to measure the emission near the 13 and 1.6 mm lines to correct the delay at either the longer or shorter wavelengths. Thus at each antenna in the array the fluctuations in the short wavelength noise emission from the water vapor in the direction viewed by the antenna should be a measure of the fluctuations in the delay along the same path. Measuring the former, we can calculate and correct for the latter. It is a simple idea that must be approximately correct. However, only modest success has been achieved with this idea to date, and the principal difficulties appear to be our limited understanding of the distribution of the atmospheric turbulence, the precise strength of the emission from the water vapor, and how to measure the emission with sufficient accuracy.

The Allen Telescope Array(ATA), with its large number of antennas distributed over the ground, offers a unique opportunity to study the character of atmospheric turbulence in sufficient detail to sort out the imaging problem. The ATA consists of 350 6m diameter antennas distributed in an irregular pattern over an area of about 800 meters diameter. The total collecting area of this array is 10,000 square meters, equivalent to a single 113m diameter circular reflector antenna. It's receivers pick up the full range of frequencies from 500MHz(600mm) to 12GHz(25mm). Figure 1 is a conceptual view of the array.

Our plan for Tomography (three dimensional imaging) of the atmosphere is to study the varying delays at cm wavelengths of a strong signal from a satellite, or bright radio source, as it arrives at the different antennas through the atmosphere. With the imaging correlator comparing the signals, it will be possible to study the detailed development of turbulence at different positions over the ground and at different heights above the ground, to observe it moving across the ground at wind speeds, and to measure how it correlates not only with winds but also with the temperature and pressure distributions. For example, is the turbulence strong only in boundary layers, or is it uniformly distributed? In addition to the detailed measurements of the distribution of atmospheric delay, there will be radiometric measurement of the average temperature and water vapor distributions above the ground and measurements of the fluctuating millimeter wave line emission. The goal is to understand the character of the turbulence and to improve our models of its correlation with the emission.

2 Technical Background

Since the development of high resolution radio interferometry, it has been clear that fluctuating irregularities in the atmosphere limit the possible resolution of radio telescopes, very much like the familiar atmospheric blurring of optical images (*Hinder* & *Ryle*, *1971*; *Hamaker*, *1978*; *Armstrong* & *Sramek*, *1982*; *Bieging et al*, *1984*; *Olmi* & *Downes*, 1992). Whereas the optical image blur, "seeing", is the result of small scale fluctuations in the principal atmospheric constituents O_2 and N_2, with an outer scale of turbulence of the order of 5m (*Roddier*, *1981*; *Coulman*, *1989*), it is large scale fluctuations of the polar molecule water vapor, with turbulent scales up to a few kilometers in extent, that dominate the radio image blur (*Tatarski*, *1961*; *Truehaft* & *Lanyi*, 1987).

Although the physical mechanism is different in the two wavelength regimes, it is striking that the typical limit on resolution imposed by the atmosphere is similar for both, about $0.5''$. The water vapor, including the fluctuating part, lies largely in a layer of 2-3 km thickness next to the surface of the earth.

Tatarski (1961) modeled propagation in the atmosphere assuming that the structure function for the index of refraction, the mean squared difference in N($\vec{x}$) at two points $\vec{r}$ apart, results from isotropic Kolmogorov turbulence.

$$D_N(\vec{r}) = \langle [N(\vec{x}+\vec{r}) - N(\vec{x})]^2 \rangle = C_N^2(r)^{2/3} \tag{1}$$

This structure function is the appropriate quantity for interferometric arrays because it describes the phase difference of signals arriving at separated pairs of antennas that are affected by the atmosphere. With the additional assumption that the atmospheric turbulent structure changes slowly and drifts past the observer at wind speeds, the spatial random structure is converted to a fluctuating time series. The transformation from space to time is made through the wind velocity. Tatarski was able to explain the scattering of centimeter wave radiation in the troposphere during trans-horizon propagation experiments. For the case of radio interferometric observations, Treuhaft and Lanyi (*1987*) used the same approximation, Equation (1), and, from numerical integrations, worked out the dependence of the interferometer visibility phase fluctuations on the separation of a pair of antennas. They included the finite thickness of the turbulent layer and considered all antenna separations including both large and small spacings with respect to the thickness of the layer. From the smooth dependence of the fluctuation on r, the antenna separation, which they calculated, they derived the following limiting cases, in agreement with Tatarski. For separations, r, small compared to the layer thickness, the mean squared fluctuations are proportional to $r^{5/3}$, and for large separations the dependence is $r^{2/3}$. Armstrong and Sramek (1982) and Sramek (1989) reported the results of a number of observations of the dependence of the interferometer phase fluctuations on antenna separation made with the VLA at 6 cm wavelength. They found that a power law dependence could be fit to each days' observations and, although there was a considerable scatter of the power law, the average was consistent with the predicted 2/3 power law for large separations. Because there is negligible dispersion in the water vapor refractivity at radio wavelengths, the phase at any frequency is simply proportional to the product of the delay and the frequency, allowing a simple scaling between operating frequencies. Similar agreement has been found with the theoretical predictions for the shorter spacings (Kasuga, 1986; Wright & Welch,1989; Olmi & Downes, 1992). Because of the increase in the phase fluctuations with antenna separation, there will be a maximum usable antenna separation at any wavelength during any given weather period, which sets the angular resolution limit for that period.

The phase fluctuations and the corresponding limitations on angular resolution are understood on the average, both observationally and theoretically. The difficulty is in understanding details of the turbulence on individual days. Current efforts are concentrated on ways to correct the problem, the equivalent of "*adaptiveoptics*" in the visible. Westwater (1967) and Schaper et al (1970) noted that because water vapor has a characteristic absorption at 22 GHz (13mm) a measurement of its emission in this line could be used to infer the corresponding propagation delay through the atmosphere. The implication is that a fluctuation in the delay due to a density fluctuation in the water vapor associated with turbulence would have a corresponding fluctuation in the radio emission, as discussed in the Introduction. They estimated that with then available technology one could expect an accuracy of about 1 cm in delay to result from an emission observation. A correction of interferometer phase with this level of accuracy would significantly improve interferometry at centimeter wavelengths, and some experiments were begun to explore the possibilities at the National Radio Astronomy Observatory.

In an early experiment, Waters (1971) mounted water line radiometers on the Greenbank interferometer and studied the correlation between the interferometer phase fluctuations at 3cm and 11cm with the atmospheric emission at 22 GHz. He detected correlations, but the coefficient varied, and it was suggested that the different atmospheric sampling due to the larger beams of the water vapor radiometers relative to the interferometer antennas may have been the problem.

In a later experiment, Resch et al (1984) mounted water vapor radiometers on antennas of the VLA and studied the correlation between water line emission and interferometer phase at 6cm wavelength. For this experiment, they mounted the water vapor radiometers at the foci of the VLA antennas, so that the radiometer beams were more similar to the interferometer beams. In addition, the radiometers operated at both 20.7 GHz and 31.4 GHz which would allow the separation of water vapor emission from liquid water cloud emission because of the different frequency dependences of their emission. They found some good correlations, allowing meaningful correction of the interferometer data, when the phase fluctuations exceeded about 2.5 mm in delay. They concluded from their limited success that better gain stability in the water vapor radiometers would be needed for regular reliable phase correction.

For Very Long Baseline Interferometry, the wide separation of the antennas means that the atmospheric fluctuations are uncorrelated at the separate antennas and therefore have the maximum effect. As a result, there has been a considerable effort to develop waver vapor radiometers to correct the VLBI phases. Current systems are able to measure water vapor columns with an uncertainty of about 1-2 mm (Elgered et al, 1993; Teitelbaum et al, 1996). These groups found that corrections from the radiometers do help some of the time with average delay errors but not always. In these applications, the radiometers typically use beams that are broad compared with the interferometer antennas, and that may be one reason why the corrections are not always significant. Note that a correction at the level of 1-2mm of delay path is useful for cm wavelengths but is not adequate for millimeter wavelengths.

With the development of high resolution interferometry at millimeter wavelengths, there has been a renewed interest in the possibility of phase correction with water vapor radiometry. There are several reasons for this. First, being able to carry out VLBI observations at millimeter wavelengths is very interesting scientifically, but the compact sources are relatively faint, and only a few are bright enough to be imaged with some form of self-calibration. Second, because the RMS delay fluctuation increases with antenna separation as $(separation)^{\alpha}$, where $\alpha \leq 1$ on the average, whereas the phase scales directly with the frequency, the achievable angular resolution in the presence of a particular delay fluctuation is poorer at shorter wavelengths. Finally, there are good practical reasons to push to resolutions as high as $.01''$ with connected interferometers for both passive and radar applications. Large, high resolution millimeter arrays are being designed to do just that at the present time. However, the brightness of thermal processes being observed is too small for self-calibration, and some other calibration scheme must be implemented to achieve the science goals.

Welch (1994) and Bremer et al (1995) described limited experiments showing good correlation between interferometer phase and receiver total power at millimeter wavelengths. Because of water vapor absorption in the millimeter continuum due to pressure broadening, the receiver total power fluctuations should be partly the result of atmospheric emission fluctuations due to water vapor emission. A number of groups have begun further experiments along these lines but with different strategies, all of which are aimed at developing a reliable system to correct for phase fluctuations using water vapor emission fluctuations. This is frequently described as Water Vapor Radiometry. In the following, we give some details about the basic issues and then describe recent results.

3 Basic issues

A recent paper that discusses the connection between the absorption and the dielectric properties of water vapor, relevant to the phase correction problem, is Sutton and Huchstaedt (1996). See also Serabyn et al (1998). They make the usual assumption that there is no significant contribution due to the absorption by multimers of water. Overall, the absorption properties of diatomic water vapor are understood, except at frequencies away from the dipole absorption lines. Here a significant excess absorption term, usually taken to be proportional to ν^2, must be added to the theoretical model to account for measured absorption. This defect is thought to be due to inadequacies in collision broadening theory. In principle this difficulty can be circumvented by calibration through direct observation of the correlation between absorption and delay fluctuations by water vapor in the atmosphere. A general description of the current theoretical understanding of problems of phase calibration by means of water vapor radiometry is given by Lay (1997).

The novel aspect of the proposals by Welch (1994) and Bremer et al (1995) is to observe emission at the same frequency as the astronomical interferometric observations. Thus, with the same receiver used for the astronomical observations, one obtains the data needed for correcting the phase. This is possible only at millimeter wavelengths, and the practical advantage of needing only one receiver is obvious. Not only is the use of the same receiver an advantage, but there are also common antenna beams. The same antenna that is receiving signals from the astronomical source through the fluctuating atmosphere is receiving the corresponding emission from the turbulent water vapor in its near zone quasi-cylindrical beam. There is an effect due to maxima and minima in the near zone beam which varies the weighting of the emission. However, it may average out over the beam. Having a common beam is an advantage over using a separate water vapor radiometer. The form of the correction is given in the following simple relations.

$$\Delta\phi_{atmos} = k_\nu \Delta T_{bw} \tag{2}$$

k_ν, the ratio of index of refraction to emission coefficient for water vapor, can be calculated from standard formulas (Thompson, Moran, and Swenson, chpt. 13, 2001; hereafter TMS). It's basically the ratio of the real to the imaginary part of the index of refraction of water vapor. $\Delta\phi_{atmos}$ is the atmospheric phase fluctuation, the ratio k_ν is frequency dependent, and ΔT_{bw} is the fluctuation of brightness due to water vapor. The system temperature, T_{sys}, has several components.

$$T_{sys} = T_{rcvr} + T_{sp} + \eta[T_{bw} + T_{bo}] + T_{2.7} \tag{3}$$

T_{rcvr} is the receiver temperature, T_{sp} is the pick-up from spillover, T_{bw} and T_{bo} are the sky brightness due to water vapor and oxygen respectively. η is the coupling efficiency, and $T_{2.7}$ is the cosmic background radiation. The time variable phase fluctuation must be corrected by

$$d\phi_{atmos}/dt = (k_\nu/\eta) dT_{sys}/dt = k_\nu dT_{bw}/dt \tag{4}$$

One could imagine making a real time correction of the phase by modulating the local oscillator phase.

$$\nu_{lo}(t) = -[k_\nu/(2\pi\eta)] dT_{sys}/dt \tag{5}$$

We note that this scheme can only work in clear sky. Clouds are strong emitters, especially at the shorter wavelengths, and it requires at least two frequencies to separate the cloud from the vapor contributions(TMS).

Apart from the possible presence of clouds to confuse this scheme, there are a number of other issues that are important. At 100 GHz, for example, a column of water vapor which produces a 1 K brightness produces a phase delay of about 200^o. That is, a 200^o visibility phase fluctuation would have an associated brightness fluctuation in front of one of the antennas of an interferometer pair of 1 K. A sensible goal for the phase correction would be to an RMS level of $\lambda/20$. At 100GHz, this corresponds to a phase fluctuation of 18^o or a delay error of 150μ, corresponding to an RMS brightness sensitivity of 0.09K. Using this example as a guide, we note the following problem areas.

1. Making a precise correction based on a measured brightness change requires an accurate knowledge of the water vapor delay and absorption coefficients and an accurate atmospheric model, since the coefficients are dependent on the local temperature and pressure in the atmosphere and therefore the location of the density fluctuation. If there is no other meteorological data beyond the brightness measurement, all of these factors cannot be easily sorted out. However, measuring phase fluctuations toward a bright calibration radio source along with brightness measurements should essentially give an overall calibration of the phase-brightness connection. This connection should then vary only slowly in time.

2. Gain variations can mimic the brightness fluctuations. For a typical system temperature of, say, 200K, a fractional gain fluctuation of .0005 will produce an apparent brightness change corresponding to the above 18^o phase shift. A gain stability of about 10^{-4} is required if gain drifts are not to contribute significantly.

3. The total power scales of the receivers on the different antennas must be nearly the same. During the typical run of observing with an array, it is necessary to observe a point source as a phase calibrator frequently in order to correct for thermal phase drifts in the electronics and baseline errors. If the power scales are close enough so that the change in atmospheric path resulting from a slew to a calibrator does not introduce an erroneous phase correction, then the phase-brightness correction (including thermal phase drifts and baseline errors) can be used successfully. A 10^o elevation change with a zenith optical depth of, say, 0.2 will produce a mean brightness change of about 10K. For this to be the same for two antennas within substantially less than the .09K above requires a relative system gain approaching 0.1%. This accuracy can be achieved, but not by the usual chopper wheel method of calibration of millimeter wave radiometers. If it is not practical to

achieve the necessary relative antenna gain calibration accuracy, one may still apply the phase correction during the separate source observations between the normal phase calibration. This remains a valuable step, because it may enable self-calibration on the source as a result of permitting longer coherent integration times on the source.

4. Apart from the very uniform gain scales discussed above, it is also necessary that there be no other detector drifts associated with slewing to the phase calibrator.

5. During tracking and slewing, there may be changes in antenna temperature due to changing ground pick-up that would erroneously be interpreted as atmospheric brightness (hence phase) changes. .09K is a small change in the pick-up. If all the antennas are built the same, such signals will tend to cancel.

The presence of clouds completely defeats the scheme described above. Even at the peak of the 22 GHz line, the same mass of liquid cloud attenuates (and therefore radiates) ten times more than the same amount of vapor. Yet its contribution to the delay is small. Thus total power fluctuations observed at just one frequency in the presence of clouds will not correctly predict delay corrections. The absorption of the water droplets is proportional to the square of frequency, at least at the longer wavelengths, and droplets are five to six times more emissive at 90 GHz than at 22 GHz.

Radiometer systems designed to measure both the vapor and the cloud contributions for meteorological purposes typically operate at two frequencies, such as 20.6 and 31.7 GHz (Westwater, 1993), and these systems recover vapor delays with accuracies of about 1mm. However, a much higher accuracy is needed to correct phase errors for millimeter wavelength interferometry. For example, the 1/20 wavelength level of correction noted above corresponds to 50μ at a wavelength of one millimeter. For sub-millimeter wavelengths, an even higher accuracy is required.

To separate the vapor from the cloud signatures requires radiometry near one of the dipole line transitions, either 22 GHz or 183 GHz. Higher frequency lines could be used, but only with difficulty because of their greater saturation. Because of the necessary precision, as well as the need to eliminate accurately the cloud contribution, a multi-frequency radiometer must be used, and it should be centered on the dipole line. Operation at the 22 GHz line offers some advantages. A relatively stable and inexpensive HEMT amplifier can be used, and the line will be optically thin at all the chosen wavelengths. The advantage of using the 183 GHz line is its greater strength, so that the emission is greater relative to the delay, and the gain stability requirement is an order of magnitude smaller. However, the greater line strength is also a disadvantage, because some part of the line is optically thick even at the driest sites. This requires that the observing frequencies be adjustable for the amount of water vapor on a particular day. The 183 GHz receiver is also more expensive and not as easily stabilized.

One important advantage of using a multichannel receiver operating at an emission line compared to a single channel system operating in the wings of the lines is that one measures differences between different channel outputs. That greatly reduces the gain stability requirements. It also reduces somewhat the accuracy with which the radiometer gain scales on the different antennas must be kept equal. Since the water vapor radiometer will be operating at a different frequency from the interferometer, some care must be taken to locate its feed to insure that the two beams closely overlap.

4 What Has Actually Been Achieved?

Experiments have been carried out at a number of observatories, including the Very Large Array of the NRAO, the Hat Creek Array of BIMA, the Plateau de Bure array of IRAM, the Compact Array of the ATNF, the Owens Valley Array of Caltech, the CSO/JCMT interferometer, and at the Deep Space Network of the Jet Propulsion Laboratory. All have had some successes, but very few phase corrected maps have been published. A review of results prior to 1999 may be found in Welch(1999) where the discussion is fairly optimistic about future success. An approximate summary of all the efforts both at millimeter wavelengths with connected interferometers and at centimeter wavelengths with VLBI systems is that the phase correction based on water vapor radiometry works about half the time and the correction gives not more than a factor of two or three in the reduction of phase fluctuations. While this is sometimes helpful, a better result is needed. For example, the ALMA system is planning baselines up to 12km for possible operation up to 900 GHz. The 12km spacings essentially amount to Very Long Baseline Interferometry.

We briefly discuss, as a typical example, experiments at Hat Creek. The scheme investigated at BIMA was single-frequency radiometry using the total power of the interferometer receivers to measure brightness fluctuations from which delay changes could be derived and applied. The λ3mm (75 - 115 GHz)receivers of the array were modified so that the total powers could be used for this correction. It required stabilizing the gains and also adjusting the total power scales of the different receivers to be close to the same values. Overall the gain was stabilized to 1×10^{-4}, including both the IF stages and the SIS mixers.

It was a challenge to get the power scales to be the same from one antenna to the next. We adopted the following strategy which worked reasonably well. We made rapid sequences of observations of the source under investigation and two phase calibrators. This gave total powers at three slightly different elevations many times over. From these, it was possible to construct a local tipping curve for each antenna, that is, a gradient of total power with elevation and an offset, many times in succession. Adjusting the power scales of all the antennas to make the gradients be the same for each antenna brought the power scales within about 0.2% overall. With the three elevations, offset differences as well as scale differences could be computed to accommodate the elevation effect noted above. This scaling was repeated throughout the observation to allow for the slowly changing offsets.

Figure 2 shows a short observation of the quasar 3C273 on a single baseline pair with a separation of 43m between the 6m antennas at 90 GHz. The three plots are, respectively, total power difference, raw interferometer phase, and corrected interferometer phase. Note that the sign of the total power difference is opposite that of the phase. Note also the strong correlation of the top two graphs. The final phase RMS after correction is about 20^o, corresponding to a delay error of 170 μ. This correction produces a decrease of about a factor of 2.5 in the phase fluctuation.

Figure 3 shows maps of M87 at low resolution ($6''$) made with the rapid scan of the BIMA array at 90 GHZ including the two QSO's 3C273 and 3C279 as discussed above. The first map (a) is a normally reduced (cleaned) map of M87 with the phase referred to 3C273 on the five minute time scale of the individual scans. The typical raw phase RMS on the various baselines is 75^o. At λ3mm with $6''$ resolution, M87 should be largely a point source, but the image is very noisy, showing many random error features. After the phase correction based on the brightness measurements, the typical phase RMS was reduced to 35^o, and the resulting map, (b), is substantially improved. The peak measured flux increased. The residual phase RMS may be due to imperfection in the relative scalings of the total powers.

Figure 3 shows encouraging results, but they are not entirely typical. Again, an overall summary is that this method works about one half of the time and the phase correction that can be achieved is not better than a factor of two to three. This is typical of the results of all the groups. The BIMA observations were done in the water-vapor continuum, which can work when the weather is completely clear. However, when there are clouds, they spoil the corrections. In this case a spectral line observation of either the 22GHz or the 183 GHz line permits the separation of the cloud emission from that of the water vapor, and the correction can be applied. This, of course, requires a separate receiver for the correction. But if that can be made to work, it is worth the trouble. The OVRO system is based on a spectral line observation of the 22GHz line, which permits correction in the presence of clouds. Even so, it has not been made to work more than half the time.

There continues to be a hope among the various experimental groups that if the radiometry can be done with more accuracy and stability the method will be reliable. However, there are a number of facts that suggest that a better physical understanding of the correction method wil also be required to achieve consistent and accurate corrections.

The basic assumption is that a fluctuation in the brightness in a direction in the atmosphere will accompany a proportional fluctuation in the phase of a wave along that direction. This does show a correlation some of the time as discussed above. However, there remain problems and questions.

- The BIMA system was stabilized to a level that should have been adequate for the scheme to work reliably in terms of the simple model described above, but sometimes there was little correlation between phase and total power fluctuations.
- The long term average of the emission along a line of sight through

the atmosphere, say, at the zenith does not really correlate with the long term average delay fluctuation. For example, it is familiar that whereas the average water vapor extinction at the zenith is less on a mountain top by a factor of 10 relative to sea level, the amount of delay fluctuation is typically less by only a factor of two.

- A similar lack of correlation between the average water vapor extinction and the average RMS fluctuation is generally observed at individual sites. Figures 4 and 5 show the run of average water vapor optical depth at 230GHz, observed at Hat Creek, CA, over several hours and the corresponding RMS phase fluctuation of a 100m baseline interferometer while observing a satellite at 12 GHz over the same time interval for two different days. In a worse case, Figure 5, they are actually anticorrelated.

- The correlation coefficient between brightness and phase fluctuations is not a constant number. It has been observed to be different by as much as a factor of two at BIMA on different days based on a calibration observation toward a QSO. A range of a factor of two has also been observed in the results of the OVRO multiline studies (Woody, private communication).

The first two points argue that the fluctuations are probably contained within distinct layers of varying thickness and that there may be at least two fluctuating components; one which is the rapid and nearly correlates with the rapid emission fluctuations and one that is associated with the slowly changing component. The latter component may be more uniformly distributed throughout the layer then the former. The significance of the third point may be related, since the basic simple model supposes that both emission and phase fluctuations arise from the same physical structures within the atmosphere.

As discussed in the introduction, the basic description of the atmospheric turbulence is based on Kolmogorov turbulence. Sramek's(1989) results from the VLA fit the Kolmogorov spectrum only on the long term average. The deviation on individual days is substantial. The points above suggest considerable inhomogeneity in the turbulence. The fact that a good correlation is observed only some of the time argues that if we had a better detailed understanding of the varying structure of the atmosphere we might be able to use that correlation with better accuracy and more of the time. To put it more strongly, the possibility of being able to make this phase correction by water vapor radiometry is so important that it is paramount that we try to understand it and make it work. More accurate radiometry cannot be the only answer, and more accurate integrated atmospheric models in the interpretation of the radiometry cannot be the only answer. A better understanding of the atmospheric structure is crucial.

5 A Plan for Investigation of the Atmosphere

The ATA with its 350 small antennas in a sparce array will provide a unique opportunity for the detailed investigation of the structure of the atmosphere. Current instruments, even the VLA, allow an investigation of the atmosphere only along a limited number of lines of sight. The model that is used to represent observed delay fluctuations assumes density fluctuations that are frozen in and moving at wind speeds. This is the commonly used Taylor approximation. This is clearly an oversimplification at least some of the time. There are times when there are no winds either on the surface or at altitude, and yet the fluctuations persist. There are times when there are up and down drafts comparable to the surface wind speeds. What is the frozen in turbulent pattern in these cases? With the ATA, we can measure the fluctuating atmospheric structure in detail. Several experiments are planned.

- An overhead point source can be studied with over 60,000 antenna separations well distributed in length and direction on the ground over an extent of nearly one kilometer. This will provide a detailed two dimensional image and show the horizontal drifting pattern whatever it is.

- The array can be subdivided into many large sub-arrays. Thus, several radio sources at different elevations can be observed at once. A correlation of fluctuations observed at different angles will give a picture of the altitude distribution. For example, sources could be the eight GPS satellites that are always visible, or it could be a distribution of bright radio sources spread out at, say, 10^o angular separations in different directions along the sky. The correlation of fluctuations observed at a sequence of angles can be studied. A careful sequence of such images should reveal the altitude of the fluctuations, their extents in width and height, and their motions.

- Along with these array observations we will make measurements using a radiometric sounder observing the zenith brightness in the edge of the 5mm oxygen band to measure the local average distribution of temperature and water vapor with height(e.g. Miner et al, 1972; Westwater, 1993). Absolute accuracies of 1-2K in the temperature and .5 gm/m^3 in the mean water vapor density could be achievable, which will allow more accurate modeling of the water vapor emission coefficients to aid in the study of the correlation.

- In addition, we will use a 6m millimeter wave antenna operating at 3mm wavelength to observe the fluctuating emission from selected parts of the atmosphere. This will allow the study of the correlation between emission and phase fluctuation. The latter will be observed in detail with the ATA which will show which are the interesting parts of the atmosphere to study.

- For the phase fluctuation measurements at centimetert wavelengths, we will use observations at two wavelengths at least in order to be able to remove small background ionospheric fluctuations.

The goal is (a) to get an understanding of the distribution of the water vapor fluctuations, day to night and in different weather conditions, (b) to understand what is required to effect the close correlation with the mm wave emission fluctuation, and (c) to develop a strategy for successful use of water vapor radiometry to correct the radio image blur.

6 References

1. J. W. Armstrong, and R. A. Sramek,“ Observations of tropospheric phase scintillation at 5 GHz on vertical paths″, *Radio Science*, 17, pp 1579-1586, 1982.

2. J. E. Baldwin and Wang Shougan (eds) "*Radio Astronomical Seeing*", IAP, Beijing, 1989.

3. J. H. Bieging, J. Morgan, W. J. Welch, S. N. Vogel, and M. C. Wright, "Interferometric measurements of atmospheric phase noise at 89 GHz", *Radio Science*, 19, pp 1505, 1984.

4. M. Bremer, S. Guilloteau, and R. Lucas, *IRAM Newsletter*, 24, Nov., pp 6-8, 1995.

5. Michael Bremer, Stephane Guilloteau, and Robert Lucas, "Atmospheric phase correction based on sky emission in the 210-248 GHz band", in *Science with Large Millimeter Arrays*, P. A. Shaver (ed), Springer-Verlag Berlin, pp 371-374, 1996.

6. C. E. Coulman," Atmospheric structure, Turbulence and radio astronomical 'seeing'", in URSI/IAU Symp. on *Radio Astronomical Seeing* J. E. Baldwin and Wang Shougan (eds), IAP, Beijing, pp 11-20, 1989.

7. Gunnar Elgered, " Tropospheric radio-path delay from ground-based microwave radiometry", in *Atmospheric remote sensing by Microwave Radiometry*, Michael A. Janssen(ed), Wiley, New York, pp 215-150, 1993.

8. B. Frye, R. Forster, J. Lugten, R. Plambeck, D. Thornton, and J. Welch, "Gain and phase stabilities of some components used in the BIMA array", BIMA memo 43, 1996.

9. Peter J. Hall, "Phase correction strategies for the Australia Telescope Compact Array at short wavelengths", in *Science with Large Millimeter Arrays*, P. A. Shaver (ed), Springer-Verlag Berlin, pp 375-378, 1996.

10. J. P. Hamaker, "Atmospheric delay fluctuations with scale sizes greater than one kilometer, observed with a radio interferometer array", *Radio Science*, 13, pp 873-891, 1978.

11. R. Hinder and M. Ryle, " Atmospheric limitations to the angular resolution of aperture synthesis radio telescopes", *Mon. Not. Roy. Astron. Soc.*, 154, pp 229-253, 1971.

12. A. Ishimaru, " *Wave Propagation and Scattering in Random Media*″, Vol. 2, Academic Press, New York, 1978.

13. Michael A. Janssen(ed),"*Atmospheric Remote Sensing by Microwave Radiometry*″, Wiley, New York, 1993.

14. G. Miner, Wm. J. Welch, and D. D Thornton, " The inference of atmospheric temperature profiles from ground-based measurements of microwave emission from atmospheric oxygen″, *J. Geophys. Res.*, 77, pp 975, 1972.

15. T. Kasuga, M. Ishiguro, and R. Kawabe, *IEEE Trans on Ant and Prop.*, Ap-34, pp 797, 1986.

16. O. P. Lay, R. E. Hills, and J. Carlstrom, "If fiber optics and digital correlating spectrometer on the JCMT-CSO interferometer″, in *Astronomy with Millimeter and Submillimeter Interferometry*, M. Ishiguro and Wm. J. Welch (eds), ASP Conference Series, 59, pp 117-118, 1994.

17. O. P. Lay, "Phase calibration and water vapor radiometry for millimeter arrays″, *Astron. & Astrophys. Supp. Ser.*, 122, pp 547-557, 1997.

18. O. P. Lay, M.C. Wiedner, J.E. Carlstrom, and R.E. Hills, "The CSO-JCMT interferometer and 183 GHz radiometric phase correction″, 1998, preprint.

19. K. B. Marvel and D. P. Woody, "Phase correction at millimeter wavelengths using observations of water vapor at 22 GHz″, in *Advanced Technology MMW, Radio, and Teraherz Telescopes*, T. G. Phillips, ed., *Proc. of SPIE*, pp 33357, 1998.

20. L. Olmi, and D. Downes, "Interferometric measurement of tropospheric phase fluctuations at 86 GHz on antenna spacings of 24m to 288m″, *Astron. & Astrophysics*, 262, pp 634-643, 1992.

21. A. A. Penzias, and C. A. Burrus, "Millimeter wavelength radio-astronomy techniques″, *Annual Review of Astronomy and Astrophysics*, 11, pp 51-72, 1973.

22. R. L. Plambeck, “Long term performance of 4 K Gifford-McMahon refrigerators on the BIMA array″, in *Advances in Cryogenic Engineering*, P. Kittel (ed), vol 43, New York, Plenum Press, 1997.

23. G. M. Resch, D. E. Hogg, and P. J. Napier, “Radiometric correction of atmospheric path length fluctuations in interferometric experiments″, *Radio Science*, 19, pp 411-422, 1984.

24. F. Roddier, “The effects of atmospheric turbulence in optical astronomy″, *Prog. Opt.*, 19, pp 283-368, 1981.

25. L. W. Schaper, D.H. Staelin, and J.W. Waters, “The estimation of tropospheric electrical path length by microwave radiometry″, *Proc IEEE*, 58, pp 272-273, 1970.

26. E. Serabyn, E. W. Weisstein, D. C. Lis, and J. R. Pardo, “Submillimeter FTS measurements of atmospheric opacity above Mauna Kea″, Applied Optics, 1998.

27. R. A. Sramek, “Atmospheric phase stability at the VLA″, in URSI/IAU Symp. on *Radio Astronomical Seeing*, J. E. Baldwin and Wang Shougan (eds), IAP, Beijing, pp 21-30, 1989.

28. D. H. Staelin, “Measurements and interpretation of the microwave spectrum of the terrestrial atmosphere near 1-cm wavelength″, *J. Geophys. Res*, 71, pp 2875-2881, 1966.

29. E. C. Sutton and R.M. Hueckstaedt, “Radiometric monitoring of atmospheric water vapor as it pertains to phase correction in millimeter interferometry″, *Astron. & Atrophys. Suppl Ser*, 119, pp 559-567, 1996.

30. V. I. Tatarski, *Wave Propagation in a Turbulent Medium*, Dover, New York, 1961.

31. A. Richard Thompson, James M. Moran, and George W. Swenson, Jr., *Interferometry and Synthesis in Radio Astronomy*, Wiley, new York, 1986.

32. R. N. Treuhaft and G. E. Lanyi, “The effect of the dynamic wet troposphere on radio interferometric measurements″, *Radio Science*, 19, pp 251-265, 1987.

33. J. W. Waters, "Analysis of water vapor data from the Greenbank interferometer", *Prog. Rep.* 2, Nat. Radio Astronomy Observatory, Charlottesville, VA, 1971.

34. Wm. J. Welch, "The Berkeley-Illinois-Maryland-Association millimeter array", in *Astronomy with Millimeter and Submillimeter Interferometry*, M Ishiguro and Wm J Welch (eds), ASP Conference Series, 59, pp 1-9, 1994.

35. E. R. Westwater, "An analysis of the correction of range errors due to atmospheric refraction by microwave radiometric techniques", ESSA Tech. Rpt. IER 30-ITSA 30, Institute for Telecommunication Sciences, Boulder, Colorado, 1967.

36. E. R. Westwater, "Ground-based microwave remote sensing of meteorological variables", in *Atmospheric Remote Sensing by Microwave Radiometry*, Michael A. Janssen(ed), Wiley, New York, pp 145-207, 1993.

37. M. C. Wright and Wm. J. Welch, "Interferometer measurements of atmospheric phase noise at 3 mm", in URSI/IAU Symp. on *Radio Astronomical Seeing* J. E. Baldwin and Wang Shougan (eds), IAP, Beijing, pp 71-74, 1989.

38. S. Zivanovic, W. J. Welch, and J. R. Forster, "A new method for improving the interferometric resolution by compensating for the atmospheric induced phase shift", *Radio Science*, 30, 4, pp877, 1995.

39. Wm. J. Welch "Correcting Atmospheric Phase Fluctuations by Means of Water-Vapor Radiometry" in Review of Radio Science, 1996-1999, W. R. Stone, Ed., Oxford Univ. Press, Oxford, 1999. pp. 787-808.

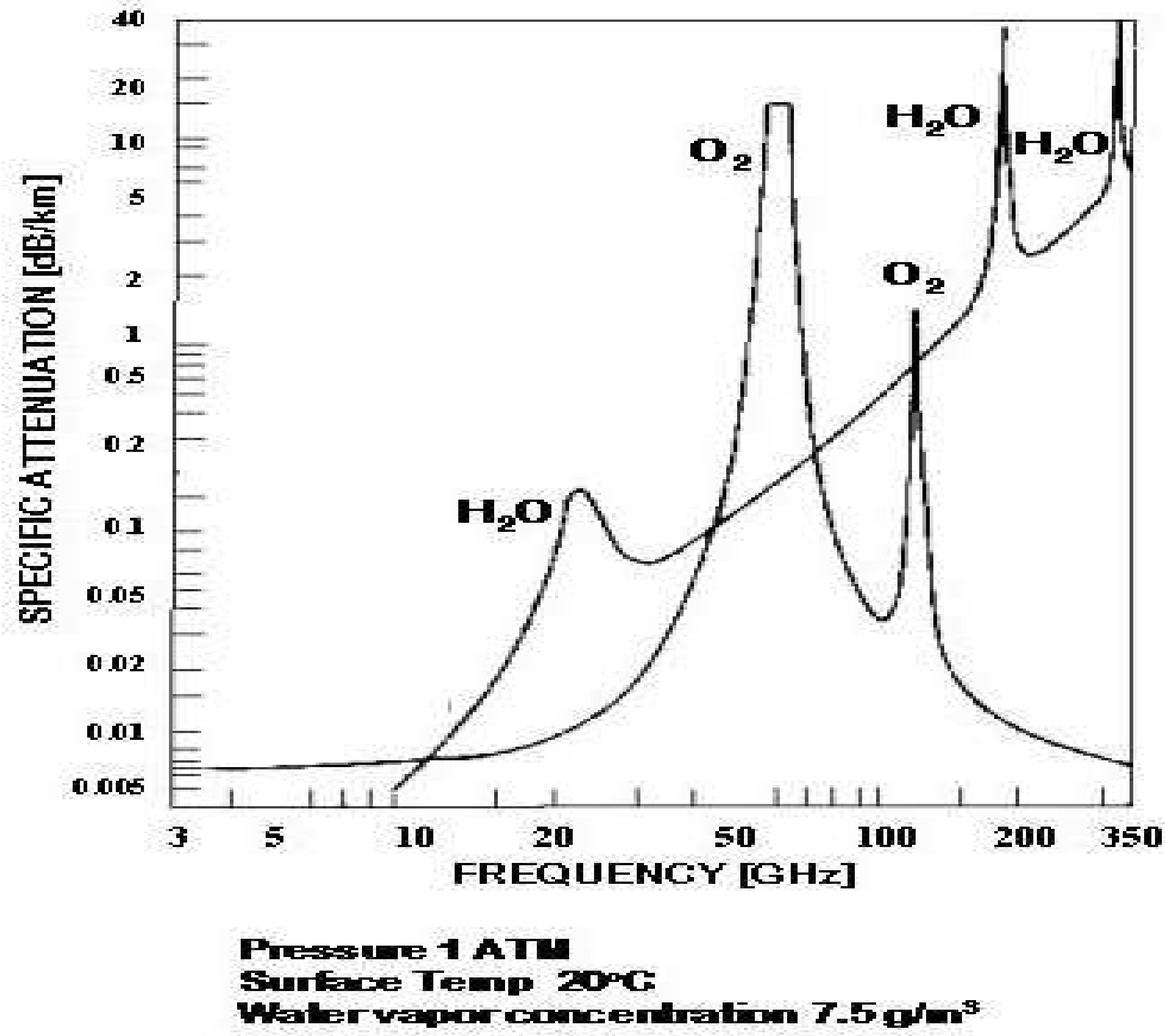

Figure 1: Atmospheric water vapor absorption at frequencies near the 13mm(22 GHz) and 1.6mm(186 GHz) resonance lines. Both the effects of the pressure broadening of the individual lines and the presence of the infra-red line wings are evident. The absorption of atmospheric molecular oxygen is also shown.

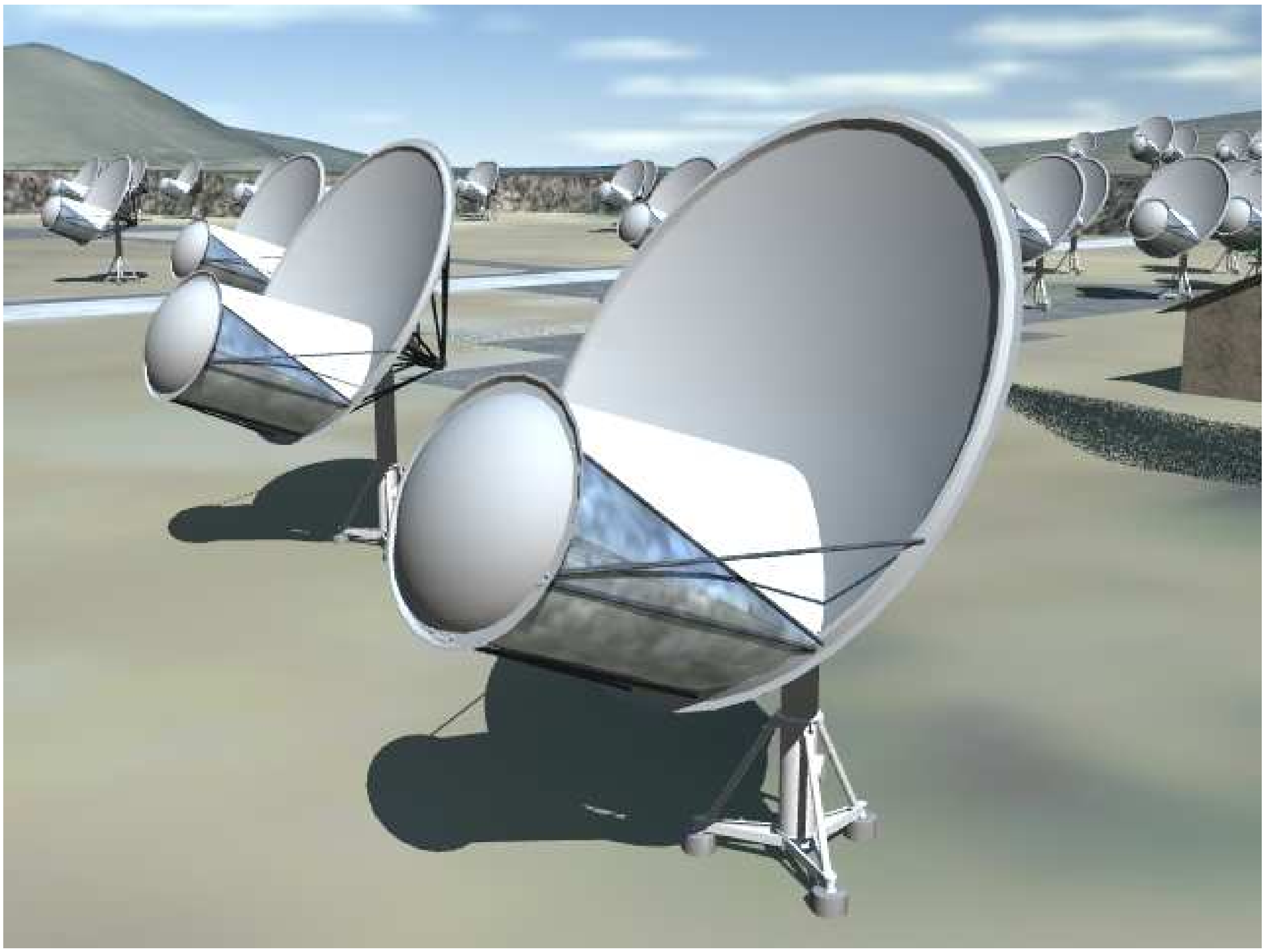

Figure 2: An artists conception of a number of antennas in the Allen Telescope Array

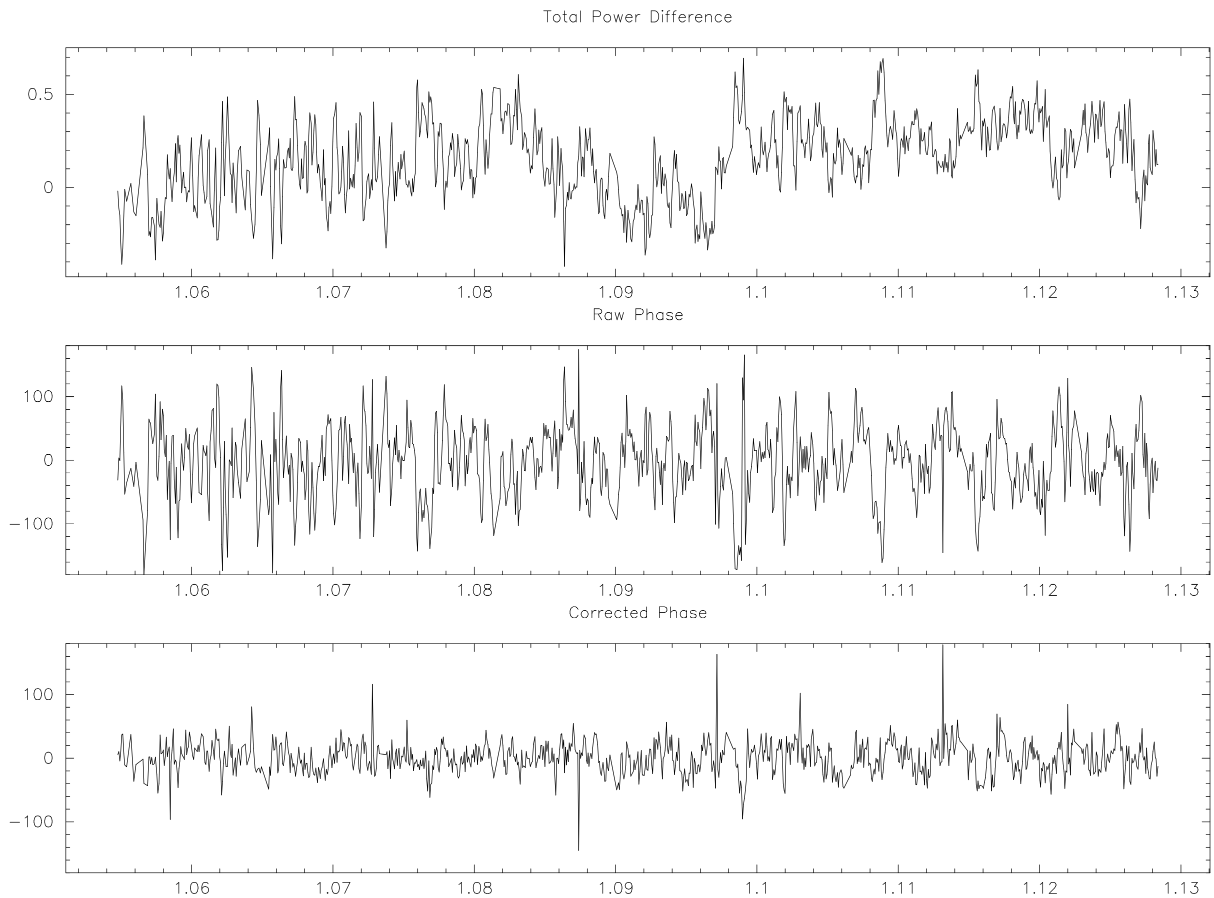

Figure 3: This is for a single interferometer pair at Hat Creek at 90 GHz. Total power difference is at the top, raw phase is in the middle, and corrected phase at the bottom. The top two curves have the opposite sign. The final RMS phase after correction is about 20^o.

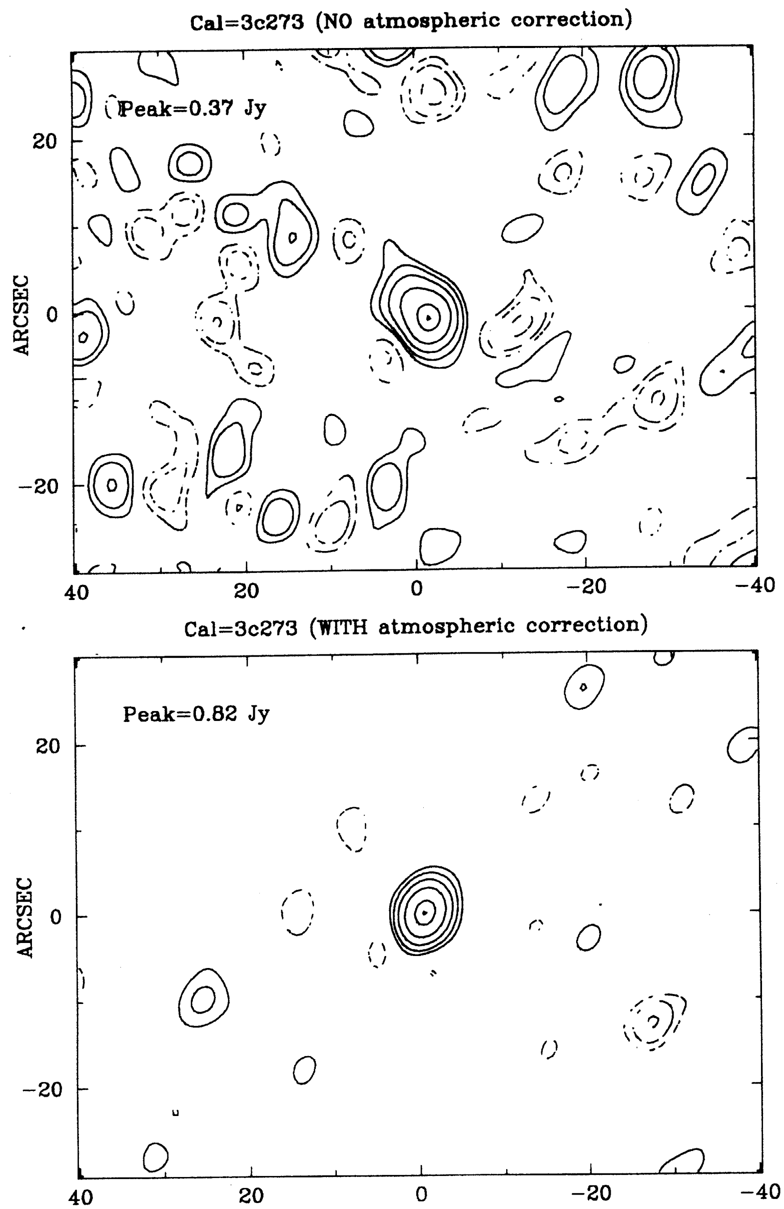

Figure 4: Two maps of M87 at 90 GHz made with the 5 most widely separated antennas (5,6,7,8,and 9) of the C array. It is a three and a half hour track. 3C273, 3C279, and M87 were observed in rapid succession in a five minute cycle. In the top picture, M87 is phase referenced to 3C273, inverted and cleaned. In the bottom picture, the atmospheric phase correction is applied as discussed in the text, including 3C273 as the phase calibrator. The correction uses system gains determined from the three elevations of each scan. Percentage contours are 5,10,20,40,80,99 in both. The improvement is notable.

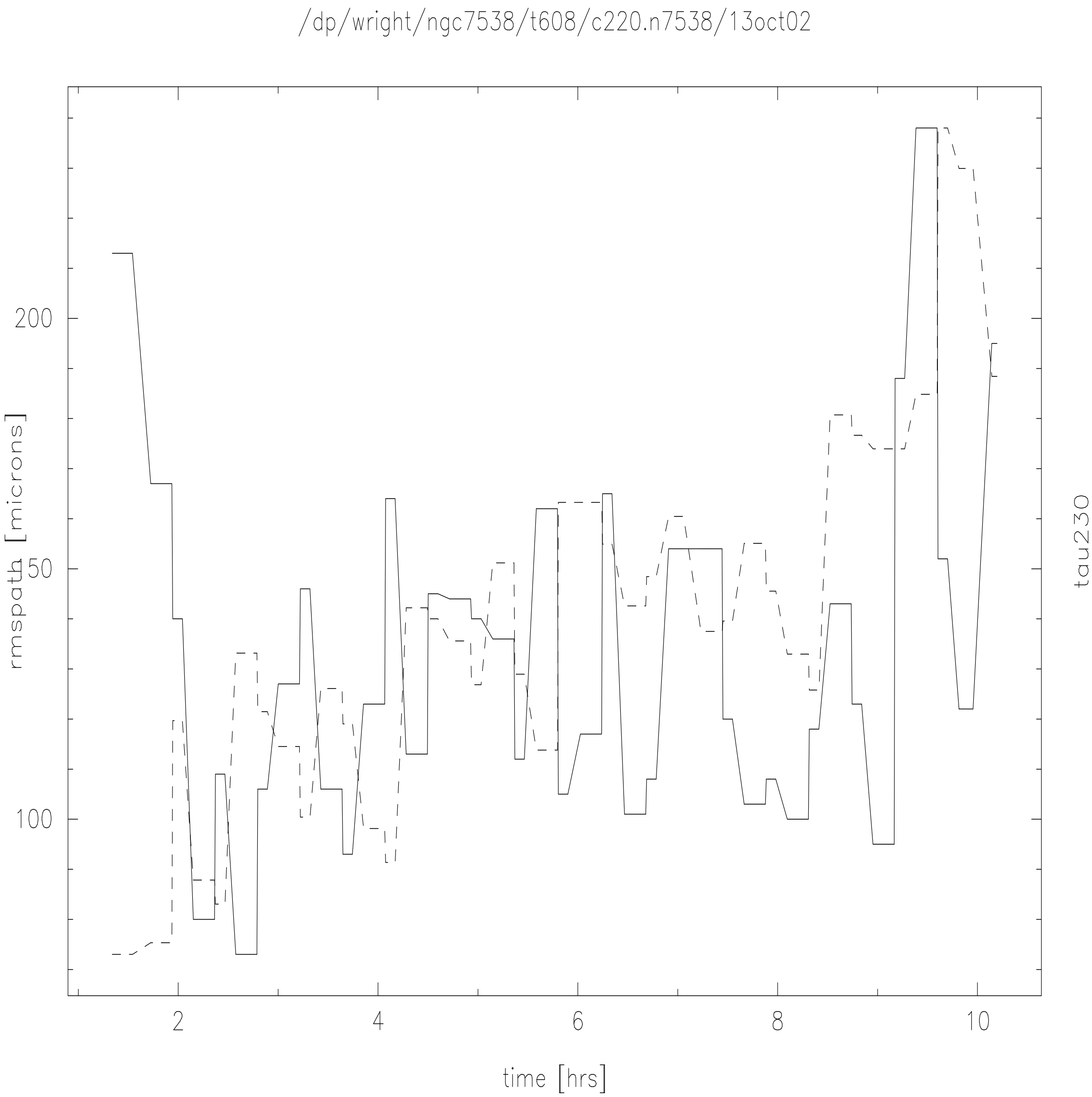

Figure 5: Measurement of RMS path fluctuations on the 100m baseline satellite interferometer and the 230GHz optical depth at Hat Creek, CA. The solid line is the RMS path, and the dashed line is the τ230 ranging from 0.28 to 0.34 for 13Oct03. The correlation is weak.

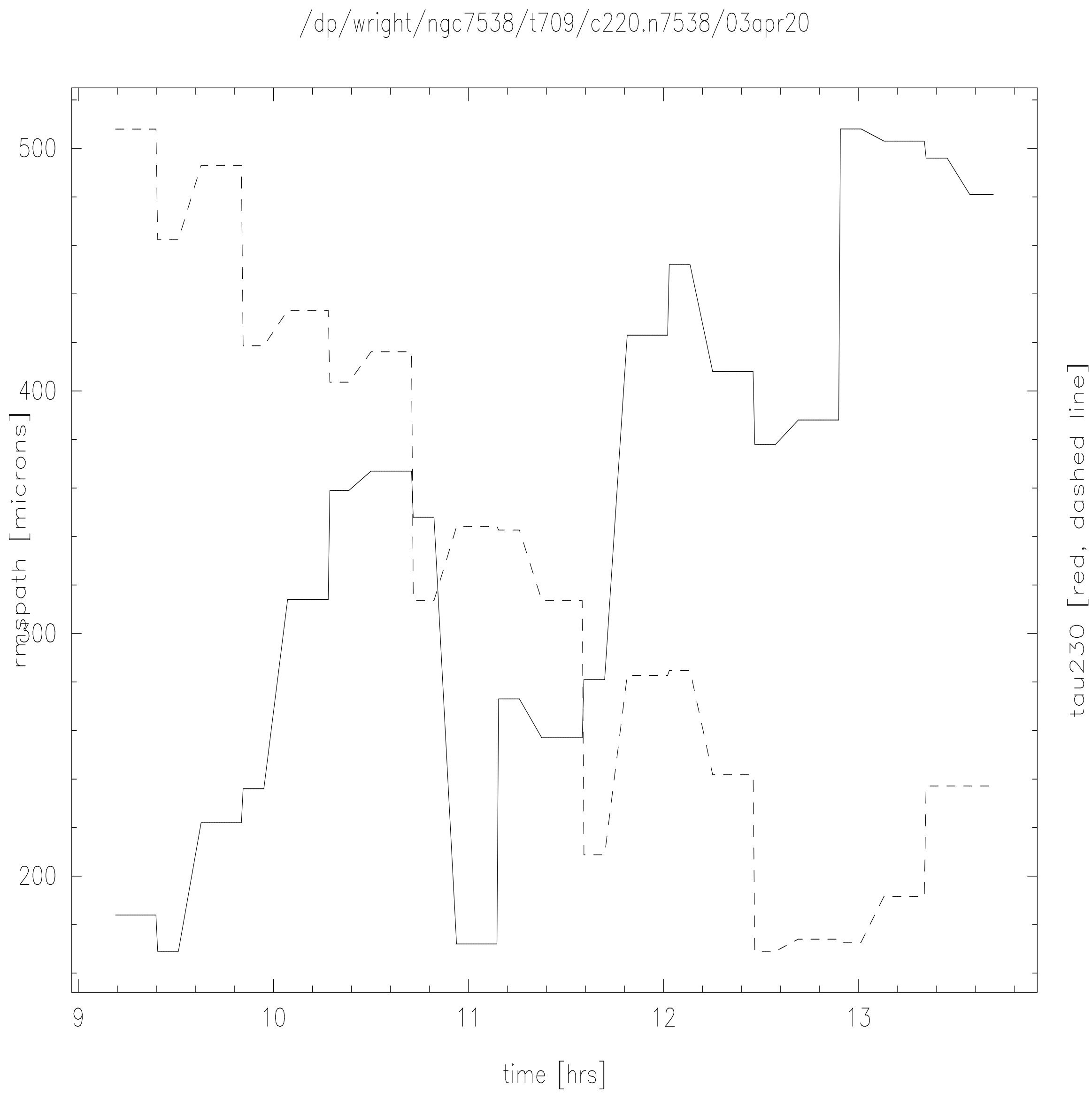

Figure 6: The same as the previous figure, but for 20April03. RMS path increases from about 200 to 500 μ while $\tau 230$ decreases from 0.59 to 0.55. RMSpath and $\tau 230$ are nearly anticorrelated here.