Adaptive Optics for Radio Interferometers

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Abstract

Radio interferometry has the potential to achieve milliarcsecond resolution of important astrophysical processes, but a significant impediment, particularly at millimeter and submillimeter wavelengths, is the scintillation due to turbulence in the troposphere. Since this is largely due to water vapor, considerable effort has been put into measuring absolute humidity along the line of sight of observations to derive corrections for the delay fluctuations. Alternatively, measurement of atmospheric delay variations by observing a bright point-like calibrator close to the science target has been investigated as a more direct probe of refractive index changes. While great strides have been made in the instrumentation and application of the results, the goal of a robust, reliable seeing correction remains elusive. Full realization of the potentials of these techniques will require a concerted effort to understand the complex behavior of the atmosphere, including the wet and dry components. Over the next few years we expect close collaboration among the radio astronomy community, as well as the meteorological community, to achieve significant progress towards routine high-resolution interferometry.

Introduction

Many important astrophysical questions, such as identifying and understanding the formation of planetary systems, demand ever increasing spatial resolution. These investigations will require milliarcsecond resolution across the full electromagnetic spectrum. Adaptive optics for infrared and optical ground-based telescopes already routinely yield images with resolutions of tens of milliarcseconds. The dramatic advances in telescopes and technology throughout the microwave, millimeter and submillimeter now potentially make similar resolution available across this part of the spectrum. Many of the interesting objects have thermal emission from dust which increases steeply into the millimeter and submillimeter bands, making these bands the preferred frequency for these observations.

Subarcsecond imaging at millimeter wavelengths promises to yield fundamental discoveries on the origin of galaxies and the formation of planetary systems. Resolved images of the molecular gas reservoir in high-redshift galaxies will reveal the spatial dimensions of the first starbursts [1], and determine if massive galaxies form from the merger of gas-rich systems or from large, gravitationally bound disks [2]. Spatially and kinematically resolved images of the molecular gas surrounding active galactic nuclei will measure the mass of the central black hole to determine the origin of the correlation between black hole and stellar masses [3]. High resolution images of the gas and dust around nearby circumstellar disks will establish the initial conditions for planetary systems [4].

Figure 1 illustrates the exciting results enabled with high resolution imaging of protoplanetary disks, which are disks of gas and dust that surround young stars and are the progenitors of planetary systems. The images, obtained with CARMA at 0.35" resolution or better, demonstrate a diverse set of disk geometries, including cleared inner regions, asymmetries, and smooth emission profiles. These spatial variations may reflect the diversity of planets that form in these disks. These images probe the conditions for planet formation on spatial dimensions comparable to the orbit of Uranus. Improving the resolution to 0.1" or better will reveal the properties of circumstellar disks on spatial dimensions corresponding to the orbit of Jupiter, and ultimately for the terrestrial planet region.

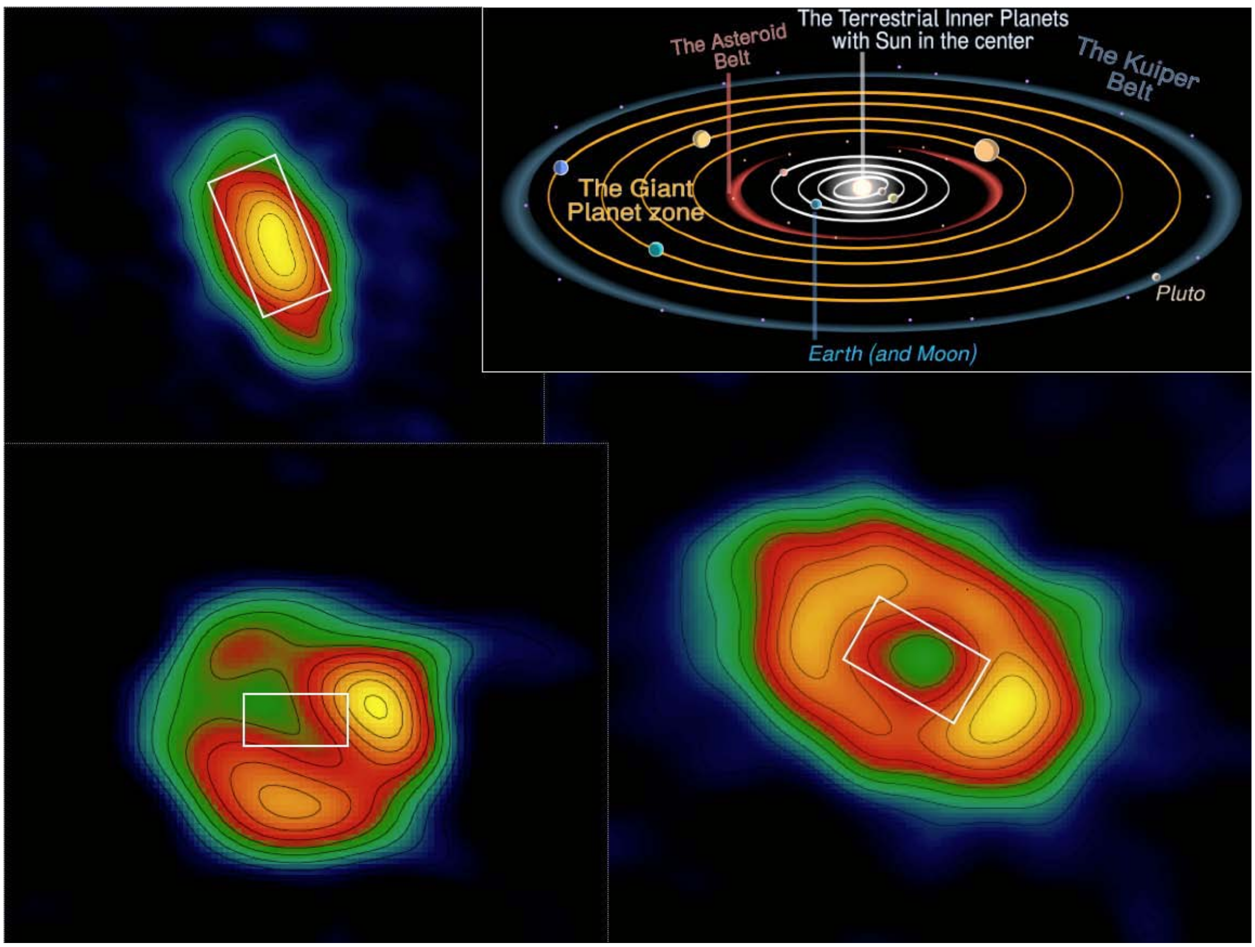

Fig. 1: CARMA λ1.3 mm continuum images of three circumstellar disks surrounding young (~ 1 Myr) stars in the Taurus-Auriga molecular cloud. The images, with angular resolution between 0.2" and 0.35", trace the dense circumstellar dust that may ultimately form planetary systems. The images emphasize the diversity of disk structures, and possibly planetary systems, that are present around young stars. The white rectangle corresponds to the size of the solar system shown in the insert in the upper right.

The major obstacle to achieving these long-baseline high-resolution images is the fluctuating atmospheric delays along the line of sight of each interferometer element. Radio seeing at typical millimeter and submillimeter sites varies considerably but is typically limited at a few hundred milliarcseconds. Frequently it is much worse than this, and since all sites show almost no correlation between atmospheric transparency and seeing, very low opacity can be accompanied by very poor atmospheric phase stability. Conditions that are excellent apart from the seeing limitations can be made eminently usable if a suitable correction scheme can be deployed.

Similar atmospheric fluctuations limited infrared and optical observations before the advent of adaptive optics techniques, such as artificial stars and fast deformable mirrors. Although the dry air temperature and density fluctuations that interfere with optical seeing also affect observations throughout the submillimeter to long radio wavelengths, these bands suffer from additional delay fluctuations caused by water vapor in the troposphere and, at the longer radio wavelengths, ionospheric turbulence effects. In these bands water vapor fluctuations are believed to be the dominant cause of atmospheric imaging errors since the refractivity of water vapor is 20 times higher for radio waves than for the optical. At the highest frequencies, the dry air effects may not be negligible since the water content at high, dry sites can become very low (<1 mm precipitable water vapor). The daytime dry air effects are not measured by the optical instruments and are likely to be much worse than the nighttime effects, further complicating the characterization of the best submillimeter sites.

An important distinction between radio and optical astronomy is that radio interferometers have to calibrate instrumental phases by observing a bright calibrator that is often outside, possibly many degrees away from, the science field of view. Any phase calibration scheme therefore has to be able to remove the atmospheric spatial phase difference between the source and calibrator to determine the slowly-varying instrumental phase. Rapid temporal delay fluctuations on the source lead to reduced coherence, and loss of recovered flux with corresponding sensitivity degradation. Slower time fluctuations on source, as well as spatial delay differences between the calibrator and source, blur the final image with the attendant degradation in resolution and fidelity. Fluctuations occur on a continuum of time scales generally described by a Kolmogorov spectrum, with the important ranges being a couple of seconds to a few minutes for coherence, and a few minutes to tens of minutes for image quality.

Phase Correction Methods

There are two general approaches to adaptive optics in the radio (these techniques are described more thoroughly in [5])—either one measures the column of water vapor above each antenna in the direction of the source, then converts water column to delay; or one monitors the atmospheric phase fluctuations on a calibrator up to a few degrees from the source, under the assumption that those wavefront distortions are similar to the ones along the line of sight to the source itself. Each of these has advantages and disadvantages and it may require some combination of both methods to achieve the ultimate image fidelity.

Precipitable Water Vapor Measurement

This approach requires measuring the water vapor column through the atmosphere from each telescope toward the source, ideally to an accuracy of a few microns of precipitable water. Implicit in this approach is the assumption that the water vapor strongly dominates the seeing and that the emission or absorption are related in a known way to the path delay. Precipitated water in the form of cloud droplets or ice crystals has a minor effect on phase, so measurements must discriminate against these forms of water. Different approaches to quantifying the total column of water have been explored, including: monitoring the continuum in the millimeter band; observing the brightness of a microwave or millimeter water line; or, tracking the strength of a relatively stable atmospheric emission line above the tropospheric water layer to reveal the transmission fluctuations due to the variable water content.

The far line wing and continuum absorption associated with telluric water vapor contributes significantly to the sky brightness, even in the millimeter band at frequencies well below the strongest water lines. Early attempts to use water vapor radiometry to infer path variations date back to the mid-60's, and work continued in the 70's mainly for communication applications. Application to radio astronomy started seriously in the late 80's, continuing to the present day. This continuum can be measured using the astronomical receivers. At BIMA the measurement was made with either the 3-mm or the 1-mm receiver, depending on which was required for the astronomy [6], while at IRAM the 1-mm receiver was always used to monitor the water, while simultaneously using either the same receiver or the 3-mm receiver for astronomy [7]. This method has also been applied to VLBI observations [8]. Extremely high gain stability is required of the receiver system. In addition, the method is foiled by the presence of clouds, and perhaps even by 'protoclouds' (concentrations of water dimers or microscopic water droplets) along the line of sight, which increase the atmospheric emission much more than water vapor, but produce little phase delay. Although the method is promising, the move from Schottky mixer receivers to SIS technology was accompanied by reduced gain stability and it became appropriate to develop specific instrumentation for the water measurement. Freedom to choose the frequency for the water-vapor radiometer (WVR) allows water spectral lines to be measured, thus mitigating some of the disadvantages of the continuum.

Many attempts have been made, at the VLA [9], OVRO [10], and other arrays, to measure the water column from the strength of the 22-GHz emission line. Advantages are that this transition is optically thin, and that the WVR components are relatively inexpensive. Disadvantages are that the line is quite weak, so one must measure millikelvin changes in the atmospheric brightness when the total noise power from the sky and receiver is typically ~ 40 K. Thus the 22-GHz radiometers must have extremely high gain stability—of order a part in 10^4—and this has proved difficult to achieve. It also is possible to measure the much stronger 183 GHz transition of water [11], the approach selected for ALMA. The receiver gain stability requirement is greatly reduced, but, since the core of the line is optically thick even at high elevation sites like Chajnantor, one must adaptively fit the line wings in order to infer the water vapor column. These data are combined with other weather information to calibrate an atmospheric model that provides corrections to the observed visibility phases about once per second. The water line data are insensitive to the dry component of the atmosphere, but if there is a significant dry component variation then this will have to be accounted for when calibrating the conversion from measured brightness to actual delay.

The water column can also be probed by monitoring the atmospheric brightness at $\sim \lambda 20$ microns, but this method appears to work best in very dry conditions [12].

An alternative to direct water vapor radiometry for phase correction is currently in early development at the Submillimeter Array (SMA) on Mauna Kea, Hawaii [13]. The proposed method uses stratospheric ozone line emission to probe the water vapor column in the troposphere. The attenuation of the stratospheric line contrast measures the foreground absorption by water vapor. The method is restricted to frequencies well within the overlapping ozone and water vapor pure rotation bands, where many suitably strong ozone lines are available, and where the water vapor line wing and continuum absorption are relatively high. Because of this, the use of ozone radiometry for phase correction is of particular interest for submillimeter interferometers.

For submillimeter interferometers, ozone radiometry offers potential advantages over water vapor emission radiometry. Sensitivity to radiometer gain fluctuations is reduced by the inherently differential nature of the line measurement. Being a transmission measurement, it is a more direct measure of the integrated water vapor column than an emission measurement.

All of these methods have been demonstrated to be successful on a limited number of data sets; in some cases the flux density of test sources is increased by factors of 2 to 3. In most cases the improvement in phase coherence is modest, while in some cases applying the phase corrections actually reduces the coherence. As a result phase corrections are not a completely routine part of radio observing. At IRAM the coherence correction is applied, but not phase linking to the phase calibrator [14]. Since the coherence correction is not sufficiently reliable, parallel coherence-corrected and uncorrected data streams are maintained so that a decision on whether to apply the correction may be made later on the basis of the final data quality.

The above measurements require that the measurements of brightness or attenuation are converted to delay. Physically this scale factor involves the pressure and temperature distribution of the water vapor and other atmospheric constituents. Practically, the factor is determined by correlating the brightness variations with phase fluctuations on a strong astronomical source. It is found that the scale factor can change by almost a factor of two on various time scales depending on atmospheric conditions. Reasons for this are still not clear, but numerical modeling with sophisticated meteorological models indicates that the dry air fluctuations may be correlated positively or negatively with the wet component [15]. This stands as an excellent example of fruitful collaboration between the atmospheric and astronomy communities.

Reference Source Correction

A direct measurement of the delay obviates the need for determining a relationship between the brightness or transparency and the seeing distortions and is analogous to optical adaptive techniques. Although the fundamental concept of removing wavefront distortions by adjusting phases to sharpen a point-like reference source image on short time scales is essentially the same for radio interferometers as for large optical telescopes, the implementations are necessarily quite different for several reasons. Individual antennas do not require deformable surfaces because their diffraction limit is much greater than the seeing limit. (Note that this is not necessarily true for very large single dishes.) There is also no need to have any real-time correction since the phase and amplitude are preserved in the interferometer data products. As well as allowing a *post facto* correction, this opens the possibility of adapting the correction to the prevailing conditions using some metric based on the entire observation.

The relative paucity of potential radio 'guide stars' at millimeter and submillimeter wavelengths means that there is often no suitable source in the observing field of view (for which conventional 'self-calibration' could be applied). No artificial radio guide stars have yet been developed, and in any case at the typical ~ 100 km height of optical laser stars a radio source would not be in the field of view of all antennas of an array since their beams do not overlap until many times that height. A loss of observing time is thus unavoidable if the interferometer has to be redirected to the calibrator at frequent intervals. Alternatively, a separate monitoring instrument may be implemented. In either case the measurement on the calibration source may be made at a different frequency from the science observation. As will be seen in the following sections this degree of freedom has some advantages. In particular, the choice of a relatively low (15–40 GHz) frequency avoids many problems of phase wrap ambiguities. Dispersion in the millimeter and submillimeter bands is small enough that only a small correction need be applied to apply the low frequency delay to the observing frequency.

Fast Switching

Full correction of the coherence requires very fast sampling of the atmospheric fluctuations. For this reason, ALMA antennas are required to move 2° on the sky in under 1.5 s to fully sample atmospheric temporal delay variations. Tests at the VLA [16] demonstrated the principle of the method. On the long baselines the long time scale variations dominate, and the fast changes have a small enough amplitude to be unimportant at the low frequencies. The relatively slow motion of the large VLA antennas is therefore not a big problem and the correction has been routinely applied for several years. At millimeter and submillimeter wavelengths, however, the faster components are large enough to induce significant phase errors so faster antenna motion is mandated. This becomes a problem for existing arrays, such as CARMA, that were not designed with the required drive capabilities, so other techniques are required.

Paired Antennas

By augmenting the science array with a dedicated atmospheric monitoring interferometer array the main array can commit all its time to science observations. Ideally, each science antenna is paired with a monitoring antenna so that the atmospheric delay fluctuations on all baselines are determined directly. A proof of concept was shown by Asakai *et al.* [17, 18] using a satellite as the reference source. This was a short demonstration since it relied on the serendipitous transit of 3C279 very close to the satellite direction. CARMA had the unique opportunity to carry out tests in a true science configuration by assigning the eight 3.5-m elements of the SZA array to the 10-m or 6-m CARMA antennas and using the low-noise receivers and 8-GHz correlator of the SZA to monitor atmospheric delays on nearby sources at centimeter wavelengths. This was very successful when only the paired CARMA/SZA baselines were used and the phase reference calibrator was close-by [19]. Progress was made towards including non-paired baselines using a covariance matrix approach. Some technical issues relating to transferring phases from phase calibrators with larger offsets were identified but not resolved.

The monitoring array has to have a phase measurement accuracy sufficient to correct the highest science observation frequency. Nevertheless, the monitoring frequency can be much lower, and the design can be optimized to minimize the cost. Parameters that can be traded off are frequency, bandwidth, antenna size, source flux versus frequency, available antenna and receiver technologies, and correlator configuration. Given the pay-off of high-resolution measurements, this approach can still be a cost-effective solution.

The Future

This is still very much an active field and significant work is required before a single technique or combination of techniques can be demonstrated to solve the atmospheric seeing problem. This radio astronomy equivalent of adaptive optics is in a similar state to that of infrared and optical techniques of a decade ago. Continued work in this area is required to enable the high-resolution images that astronomers need to answer many of the important questions in astronomy, including the mechanisms of formation of many structures, from planetary systems to massive galaxies.

Broadly, the three areas for development are the instrumentation, understanding the atmospheric physics, and algorithm development. Considerable effort has already been devoted to construction of water vapor radiometers which are now ready for extensive testing. A prototype ALMA system was demonstrated on the SMA but for various reasons the tests were not ideal. Nonetheless the indications were that it should work, but the critical phase transfer step still has to be demonstrated. WVRs will be implemented on 54 of the 66 antennas in the ALMA array. Similarly, a first prototype 22-GHz WVR has been demonstrated for the EVLA, but final prototyping and production are not yet funded.

At the SMA, back-ends for two ozone line measurement systems have been fabricated. Construction for all eight antennas is funded, but the accuracy of correcting phase fluctuations is yet to be demonstrated.

Relatively little effort has been put into paired antennas. There is, for example, room for pushing the precision of the SZA centimeter system to the level required for millimeter observing. If this proves as successful as expected, design and construction of a dedicated system can proceed.

All of the techniques can benefit from improved understanding of the physics of the atmosphere, and collaboration with atmospheric physicists could prove mutually beneficial. Finally, algorithm development needs to be directed towards robust automatic application of correction data. It is clear that there is much to be learned from the meteorological community, specifically those who have been using radiometry to measure properties of the Earth atmosphere (see for example, references in [20]). The hardware and techniques they have been developing in that community, while not identical to what we need, and applied in a different field, are similar and hence collaboration is warranted. The atmospheric physics are of course the same, though our interest in the refraction rather than the water vapor *per se* requiring some additional interpretation. Early efforts at such collaboration were very fruitful, including a number of joint sessions at scientific meetings designed specifically to pass knowledge between the various groups.

The space communication community, notably those at the Jet Propulsion Laboratory have been producing 20–30 GHz radiometers for atmospheric water measurement for some time. While they are keenly interested in absolute radiometry, where we are interested in relative radiometry, once again the hardware and techniques, e.g., [21], should transfer quite well.

Effort

Most centimeter, millimeter and submillimeter interferometry groups around the world are working on various approaches to this difficult problem as outlined above. ALMA, VLA, SMA, JPL and CARMA are in various stages of proposing, designing, implementing or testing different atmospheric phase correction techniques. These groups have made good progress but often do not have the resources to push a given technique through to reaching conclusions that will translate into a robust solution to the atmospheric delay correction problem throughout the radio spectrum. What is missing is a coordinated effort to evaluate and understand the applicability and limitations of these techniques. In addition there is a significant body of knowledge about the atmosphere that could help us understand how to use metrological data to predict the atmospheric seeing, as well as determining the scale factor for converting the radiometer measurements into delay. In particular more work along the lines described in ALMA memo 517 [15] is required to relate the measurements to the atmospheric physics.

The effort will necessarily be distributed among the various groups active in this field with a few people whose primary responsibility it is to work on and understand the atmospheric delay correction problem and develop robust procedures for using the existing or planned instrumentation. A three year project involving three people with expertise in atmospheric physics, instrumentation and data analysis plus computers, travel and miscellaneous supplies would greatly help in moving adaptive optics for radio interferometers from the testing phase into routine use for making high resolution and high fidelity images. The result would be a clear understanding of what systems are required to make adaptive atmospheric delay corrections work across the radio spectrum from cm to sub-millimeter wavelengths. The total cost for this effort would be **~ $1.8M**.

This effort would be in support of the already planned, funded and existing projects to add instrumentation to the VLA, VLBA, ALMA, SMA and CARMA with the goal of maximizing the benefit from the large capital investment in these instruments.

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