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A new spatial interferometry capability using the Arecibo 430-MHz radar

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Abstract. This note describes the new spatial interferometry (SI) capability of the 430-MHz radar system of the Arecibo Observatory (AO). Three limitations exist when the 430-MHz radar is used for observations in the tropospheric and stratospheric regions. First, the AO radar currently has a lower height limitation of approximately 6 km because of the existing transmit/receive switch. Second, fading ground clutter limits the useful data which can be obtained and complicates the analysis. Third, the large mass of the feed system, which slows down beam steering, reduces the temporal resolution of any measurements requiring multiple beam positions. For these reasons, an SI system has been developed which will be shown to reduce these limitations. A brief description of the hardware is provided, and preliminary data are presented.

Introduction

The Arecibo Observatory (AO) 430-MHz UHF radar, although designed for incoherent scatter measurements of the ionosphere, has been used extensively to make wind measurements in the troposphere and stratosphere over the last 2 decades. The earliest application of the system [*Farley et al.*, 1979] came soon after the landmark study by *Woodman and Guillen* [1974] which outlined the technique that has been used extensively in mesosphere-stratosphere-troposphere measurements and in radar wind profiling. An example of more recent measurements made with the radar system can be found in the article by *Cho* [1995].

The Arecibo radar is clearly unique. The combination of a large transmitter power in excess of 2 MW peak and a large antenna aperture of 300 m provide the capability for routine height coverage up to 20-25 km. However, the large size of the system also imposes limitations. The most critical is that movement of the feed needed to change the beam-pointing direction is slow and cumbersome. The capabilities and limitations of the system in this respect have been described by *Cornish and Larsen* [1989] who carried out an extended set of velocity-azimuth-display wind measurements over a period of 5 days. A complete vector wind measurement required approximately 20-30 min.

There are presently two techniques that are used extensively in making radar wind measurements in clear air. The one that has been applied most broadly is the so-called Doppler technique which uses the radial line-of-sight velocity obtained from the Doppler shift. Combining the measurements from various beam directions produces a vector velocity. The other technique is based on a configuration that uses a single transmitting antenna, usually pointed vertically, in combination with three or more receiving antennas. These techniques are generally referred to as multiple-receiver methods. There are a number of variations in the analysis procedures which are known as the spaced antenna (SA), poststatistic steering, or spatial interferometry, among others. *Röttger and Larsen* [1990] have described various techniques and their applications.

The physical layout of the AO radar suggested that some of the limitations of the system can be overcome

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by implementing a multiple receiving antenna capability. By placing a small array of receiving antennas adjacent to the large 300-m antenna, one or more of the multiple receiver techniques can be implemented to provide vector winds with high time resolution. A drawback, of course, is that the gain of the large antenna is lost when receiving. However, the effective gain of the system as a whole can be shown to be the geometric mean of the large and small antennas [*Doviak and Zrnić*, 1993], so the loss in gain is not quite as severe as first impressions might suggest. Of course, this assumes far-field measurements, which is not the case for the transmitting antenna. An additional benefit of the multiple receiving antenna configuration is that the measurements can be made at lower altitudes. Lower atmospheric measurements at Arecibo have been limited by the transmit/receive switch, which produces a lower altitude limitation of approximately 6 km, effectively eliminating lower tropospheric observations. Having separate receiving antennas effectively eliminates that restriction.

The remainder of this note describes the results of a collaborative effort between the University of Nebraska, Clemson University, Cornell University, and the National Atmosphere and Ionosphere Center to design, construct, install, and test a new spatial interferometer system at the Arecibo Observatory.

Brief System Description

The Arecibo spatial interferometry system (ASIS) consists of three Yagi-Uda antenna arrays and a three-channel, superheterodyne receiver. The receive antenna arrays, in relation to the main AO dish, are shown in Figure 1. Each receiving array consists of four high-gain, Yagi-Uda antennas placed on a rectangular grid of size 1.97 m by 2.16 m. Each antenna has a boom length of 5.3 m. All coordinates are provided in three dimensions with respect to the 430-MHz feed of the main AO system, which is at the origin of the coordinate system.

The three receiving arrays are approximately 327 m away from the center of the dish and form an equilateral triangle. The separation between receiving arrays is 5 m and was chosen to minimize any phase ambiguity present in the configuration. Because of the 327 m offset of the receiving arrays, however, a significant phase difference is observed between the three receivers even if the signal originates from the center of the transmitter-illuminated volume [*May*, 1993]. Of course, the configuration is not ideal since the phase difference measurement is integral to the wind calculation in standard multiple-receiver techniques. Other bistatic multiple-receiver measurements have been made but at VHF wavelengths [*Larsen and Röttger*, 1991]. At these longer wavelengths, the phase ambiguity problem is difficult to resolve since aspect sensitivity can modify the phase offset and is difficult to measure. In fact, without precise knowledge of the aspect sensitivity function and in-beam incidence angles, it is impossible to remove the bias caused by a bistatic, multiple-receiver system.

The ASIS operates at the UHF frequency of 430-MHz and is therefore not generally affected by aspect sensitivity [*e.g., Röttger et al.*, 1981]. Furthermore, since the receiver array configuration is precisely known, the expected phase differences between

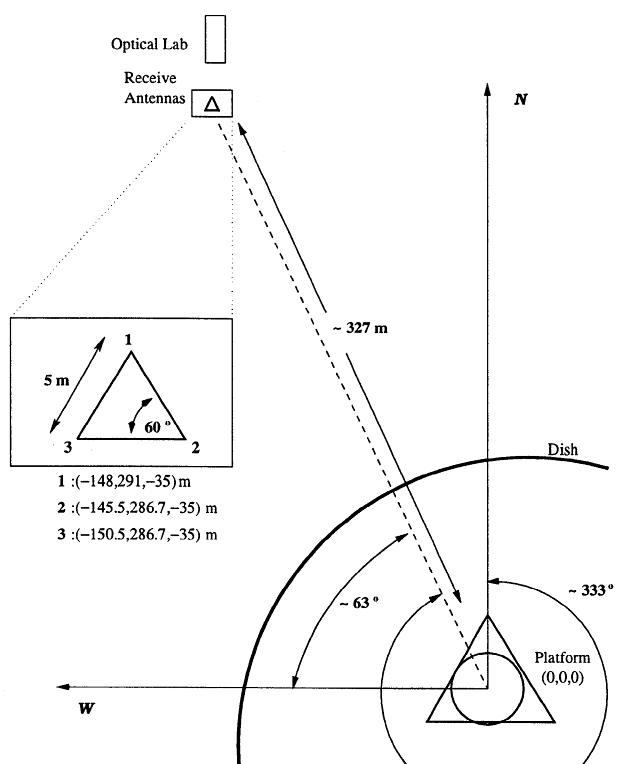

Figure 1. Depiction of antenna configuration used for the multiple-receiver system. The receiving arrays are located approximately 327 m away from the center of the main dish and are configured in an equilateral triangle. The baseline lengths are 5 m with azimuth angles of 150 °, 210 °, and 270 °, corresponding to receiver pairs 1-2, 1-3, and 2-3, respectively.

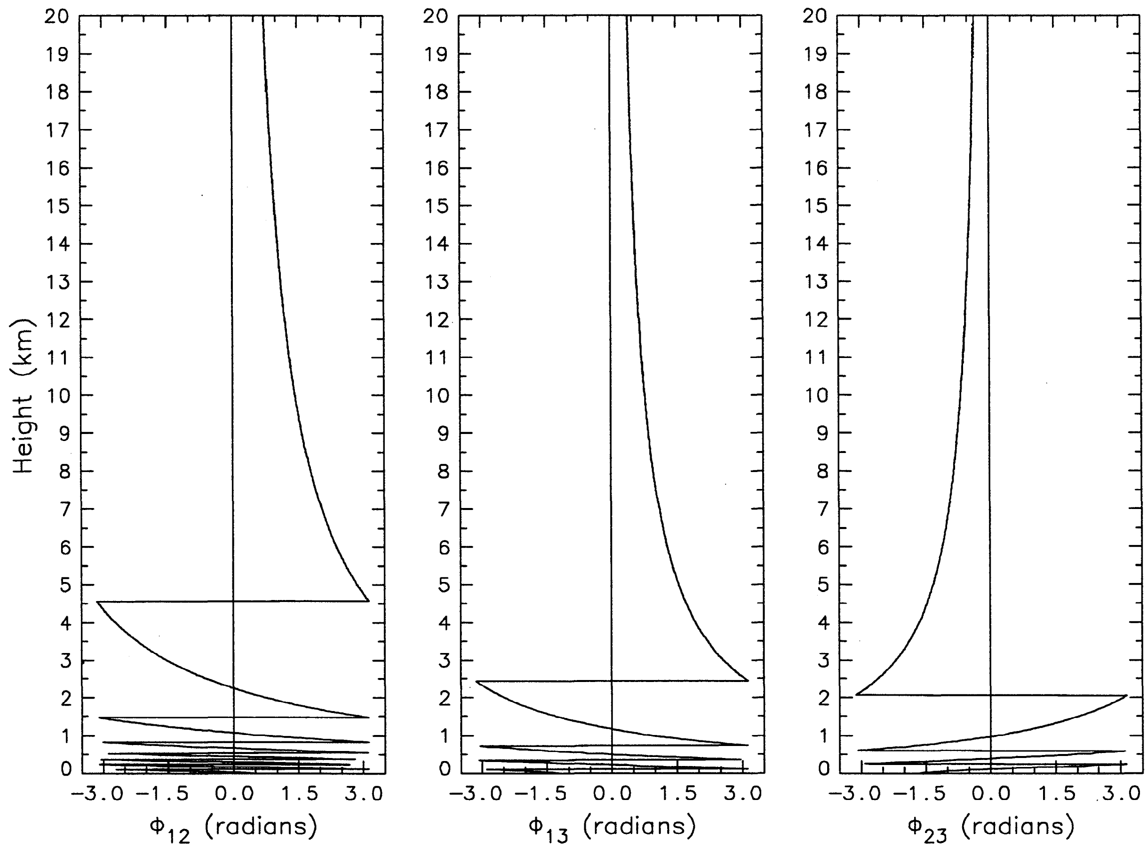

Figure 2. Theoretical phase difference calculations for the three receiver pairs used in the experiment. The offset of the receiving arrays from the transmitter center resulted in this inherent phase pattern. The effect decreases with higher altitudes since the approximate 327-m separation becomes insignificant in comparison to the height. Note that at lower altitudes, the phase wraps around $\pm\pi$ rapidly, which is not completely depicted in the figure.

the three receiver pairs can be calculated. By finding the path length differences, multiplied by the wavenumber k, one can arrive at the expected theoretical phase difference for any antenna pair ij.

$$\phi_{ij}(x,y,z) = k(r_i - r_j) \qquad (1)$$

where

$$r_i = \sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2}$$
$$r_j = \sqrt{(x-x_j)^2 + (y-y_j)^2 + (z-z_j)^2}$$

The antenna array locations are denoted by $x_i y_i z_i$ and are given for the three arrays in Figure 1, in meters. The scatterer location is given by xyz. By setting x and y equal to zero (zenith) and varying z from 0–20 km, profiles of ϕ_{ij} were calculated for the three receiver combinations. The results are shown in Figure 2. At lower altitudes, the phase differences for each baseline vary rapidly and numerous $\pm\pi$ phase wraps are apparent. It is evident that the offset of the receiving arrays from the transmitter of 327 m is less significant at higher altitudes. Orientation of the baseline, with respect to the transmitter, is also important in the calculation of phase. If the baseline is perpendicular to the line connecting the transmitter and the receiving arrays, no phase bias will exist for that baseline. In contrast, an alignment of the baseline along the transmitter-receiver line will result in the full effect of the 327 m offset. The effect of orientation is obvious in Figure 2 where ϕ_{12} has the largest magnitude because it is approximately parallel to the transmit-receive orientation shown in Figure 1. Phase values ϕ_{13} and ϕ_{23} are antisymmetric and are smaller in magnitude because of the acute angle between the baselines and the transmit-receive line. Theoretical phase differences vary relatively slowly above 1.5 km and should therefore be easy to remove from the data. Since aspect sensitivity does not affect the echoes at UHF wavelengths, it should be possible to remove the effects of this phase wrapping in the data taken with the ASIS.

The signals received by the three antenna arrays are preamplified at the antenna mast and then travel via a 5-m, RG/9 coaxial cable to the frontend of the receivers. The receiver system consists of three independent channels with associated bandpass filters, mixers, and amplifiers. An intermediate frequency of 30 MHz was chosen because of the availability of in-phase/quadrature (I/Q) detectors at that frequency and a reference signal from the transmitter. After the signals are mixed to baseband, separate matched filters are used for each I and Q signal from the three channels. These baseband signals are multiplexed and fed to a two-input, 12-bit, analog to digital (A/D) converter, which is controlled by a pc. Coherent integration and data storage are also implemented on the pc.

Preliminary Results

The system was completed and tested on August 26, 1995, over the time span 0130–0500 LT. The main 430-MHz transmitter beam, as well as the re-

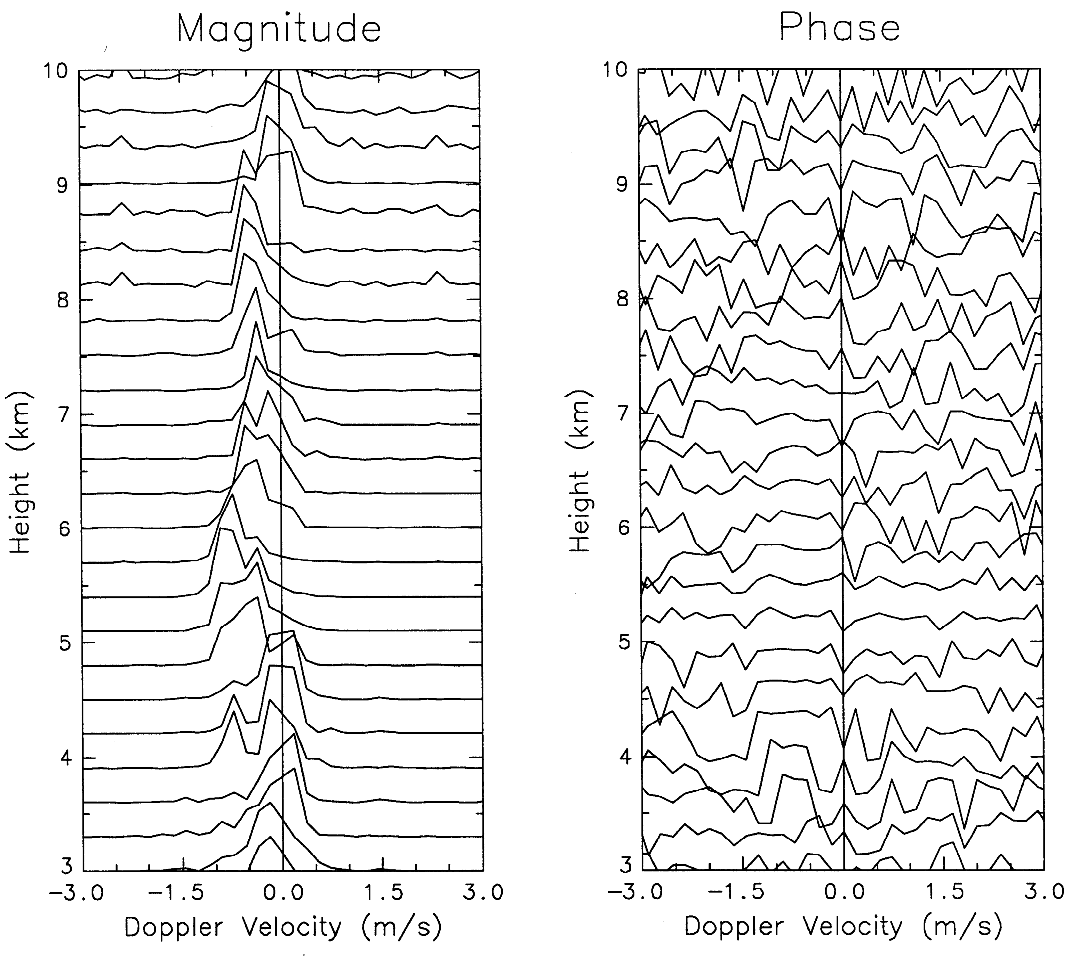

Figure 3. Example of cross-spectral magnitude and phase as a function of height. Notice the linear variation in the cross-spectral phase, which is typical of multiple-receiver measurements. The data were obtained from a 2-min average at 0306 LT on August 26, 1995.

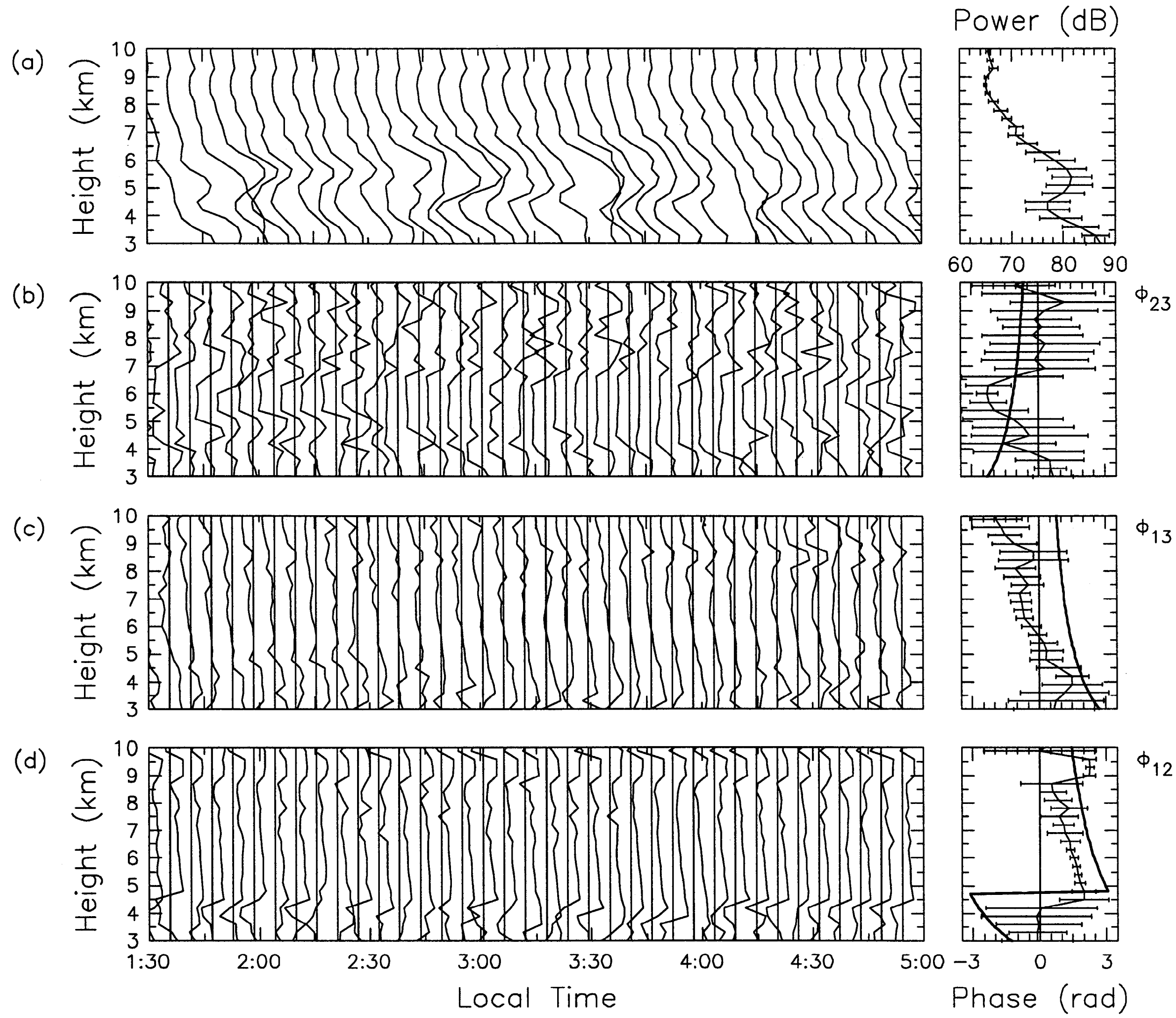

Figure 4. Time histories of (a) echo power and phase difference from the three receiver pairs: (b) ϕ_{23}, (c) ϕ_{13}, (d) ϕ_{12}. The average and error bars over the 3.5-hour period are shown to the right of the time histories. Notice that the theoretical phase values from Figure 2 are shown as a bold line in the average measured phase profiles. Each profile in the time histories corresponds to a 6-min average.

ceiving arrays, were directed vertically. The receiving arrays are presently installed on towers with a support at the top that can be rotated toward the main dish. With the steerable receiving arrays, it was hoped to be able to observe lower altitudes than those which could be obtained with the vertical beam only. Nevertheless, the vertical beam was used for this preliminary experiment.

As a first test of the ASIS, a pulse width of 4 μs was used with an interpulse period (IPP) of 1 ms. This wide pulse width provides a range resolution of 600 m and almost assured a reasonable signal-to-noise ratio (snr). No pulse coding was used for this experiment. A gate spacing of 300 m was chosen in order to oversample the returned signal. With the IPP of 1 ms and the inherent multiplexing that takes place with the data acquisition system, an effective sampling rate of 3 ms is produced. The aliasing velocity would then be approximately 58.1 m s^{-1}. However, five coherent integrations were used to reduce the data rate resulting in the final aliasing velocity of 11.6 m s^{-1}.

During the data analysis, the effect of multiplexing the three channels was removed by simple linear interpolation. These time series points were processed using a fast Fourier transform with no windowing. Cross-spectral estimates were then obtained, one example of which is shown in Figure 3 for baseline 1–2 after 2 min of averaging. Other cross-spectral results are similar. Notice that the Doppler velocity range in the plot has been reduced to ± 3 m s^{-1}in order to show more details in the part of the spectrum with the signal. Data below 3 km were corrupted by the direct transmission signal and numerous reflections from ground sources. In contrast, the cross-spectral magnitude shows virtually no ground clutter above 3 km. Note that only the zero-velocity point was interpolated in Figure 3. Previous tropospheric measurements with the 430-MHz Arecibo system showed strong fading clutter at all heights which hampered the data analysis [*Sato and Woodman*, 1982]. However, we believe that the sidelobes of the ASIS receiving arrays are fortuitously not matched with those of the transmitting feed, thus reducing the effects of ground clutter in the data presented. The cross-spectral phase from the three baselines show the typical characteristics, i.e., a linear variation of phase with Doppler velocity, as is seen in Figure 3.

Again, using 2-min averages, the echo power and in-beam incidence angles were calculated for each baseline from the cross-correlation functions. Echo power profiles for the three antenna pairs were averaged and are displayed in Figure 4a. Note that three additional averages were performed on the profiles of Figure 4. Therefore each profile corresponds to a time period of 6 min. The average over the 3.5-hour observation window and error bars are shown in the right graph. The power profiles show evidence of a wave structure with downward propagating phase at a height of approximately 5 km. The vertical wavelength is of the order of a few kilometers. Similar waves have been seen over Puerto Rico at heights near the tropopause and in the lower stratosphere and are thought to be induced by the interaction of the trade winds with the orography of the island [*Cornish and Larsen*, 1989]. Estimates of the in-beam incidence angles for the three baselines are presented in Figures 4b, 4c, and 4d. Averages and error bars are also given to the right of these time history plots. Notice that a zero-phase reference line is drawn for each profile of the in-beam incidence angle. The results are consistent with time at altitudes where the echo power is relatively strong, as indicated by the error bar size in the phase plots to the right. Phase estimates from baseline 2–3, however, show a more variable characteristic, which may be due to the alignment of the wind field. If the horizontal wind was perpendicular to a particular baseline, the coherence of those data would be reduced, thus causing increased variability. The inherent phase offset due to the system geometry is also shown in Figure 4 by the thick lines. The cross-spectral phase estimates show a similar variation with height as the geometrical phase but appear to be shifted. This shift is presumably a result of a phase offset and is not important for the calculation of the horizontal wind using SA techniques. If radial velocity measurements are desired, however, a simple phase calibration procedure will be performed. The consistency of the phase profiles and similarity to the theoretical phase shows that ASIS is providing reasonable results.

Conclusions and Future Plans

A simple, low-cost (~\$20,000 US), spatial interferometry system has been implemented at the Arecibo Observatory as a means of enhancing the capabilities of the system. In spite of the small size of the receiving arrays, which consist of only four elements each, and the lack of any sophisticated signal processing such as coding, usable signals were obtained over the height range from 3 to at least 10 km. The consistency of the 2-min average cross-spectral phase over a period of several hours is an indication of the quality of the data.

Future improvements in the system will have the goal of increasing the maximum altitude and decreasing the minimum altitude where reliable measurements can be obtained. In order to increase the sensitivity and therefore the height coverage of the ASIS, larger receiving arrays are desirable. As the array size becomes larger, the spatial separation between receiving arrays must increase. The beam size at the higher altitudes and the requirement for unambiguous phase determination limit the spacing and hence the maximum size of the receiving arrays to approximately 8 m. However, that is still considerably larger than the present four-element arrays. The inherent geometric phase offset will be reduced if the the arrays can be moved closer to the center of the dish.

As described earlier, the signals from the receiving arrays are fed by coaxial cable to the receiver and have a length of approximately 5 m. At 430-MHz, losses are inevitable. However, plans are underway to improve the noise figure of the ASIS by simple modifications to the front end of the receiver. Phase coding and the addition of four A/D channels so that multiplexing is not necessary will also improve the snr. All these modifications should make it possible to detect echoes at higher altitudes.

Finally, a well-chosen location and possible shielding of the receiving arrays with a clutter fence should reduce the clutter at the lower altitudes so that the minimum altitude with usable echoes will be reduced.

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