# 7. DESIGN CONSIDERATIONS FOR MST RADAR ANTENNAS (Keynote Paper)

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## DESIGN REQUIREMENTS

This paper centers on the design of antenna systems for radar capable of probing the mesosphere. Since the spatial wavelength dependency of turbulently advected ionization cuts off rather rapidly below wavelengths of about 3 m, this implies that we are discussing frequencies of 100 MHz and below; most probably, in the range 40-60 MHz. Also, requirements of sensitivity call for a physical antenna aperture of $10^4$ $m^2$ or more. Taken together, the frequency and aperture requirements point to an array antenna of some kind as the most economical solution. Such an array could consist of dipoles or more directive elements; these elements can be either active or passive.

The use of an array implies severe limitations on steerability, so it is necessary to define carefully just how much steerability is required for the scientific goals of the facility. Is it sufficient to be able to point it vertically and at two fixed directions in the east-west and north-south planes? VINCENT (1982) has shown that momentum fluxes may be deduced if symmetrical pointing directions are available on either side of the zenith. So this represents an additional requirement. If more than one set of angles away from zenith is required (e.g., if different angles are required for stratospheric and mesospheric work) additional complexities result. Finally, one could suppose a capability of pointing at any direction within a limited portion of the sky.

Another requirement may be for modularity: the ability to split the antenna into two or more sections, each pointing at a different part of the sky, to permit simultaneous operation without beam switching. Again, different parts of the antenna may be required to be used for a spaced-antenna drift experiment.

The speed of the rapidity with which the antenna is required to be pointed in a new direction or reconfigured into a new modularity, is an important design consideration, as very rapid switching implies greater electronic complexities.

A final consideration is bandwidth for the antenna. Thin dipoles themselves have a finite bandwidth. If a long array is fed at the end, changing frequency results in swinging the direction of the beam. Impedance matching stubs may lead to a degradation of the VSWR if the design bandwidth is exceeded.

## COST CONSIDERATIONS AND DISTRIBUTED TRANSMITTERS

The signal-to-noise ratio S of an MST radar is given by:

$$S = K_1 PA$$

where P is the transmitter peak pulse power and A is the effective antenna area. The cost $C_T$ of the transmitter is given by

$$C_T = K_2 P + K_3$$

where $K_3$ represents the cost of the low-level drive stages. The antenna cost $C_A$ is

$$C_A = K_4 A$$

where A is the antenna area. Expressing the total cost in terms of a desired signal-to-noise ratio, we have

$$C = K_4 A + \frac{K_2 S}{K_1 A} + K_3$$

This cost is a minimum when

$$K_4 A = \frac{K_2 S}{K_1 A}$$

that is, when the antenna cost is equal to the variable portion of the transmitter cost. This principle is often violated in the construction of MST radar facilities; for example, the Urbana radar antenna cost about $30,000, while the transmitter cost was over $300,000. For the Jicamarca antenna, whose estimated cost was $800,000, the equality was probably nearly satisfied.

It is interesting to extend this simple calculation to the case of a distributed transmitter, consisting of N modules of area A and power P/N. The cost equation becomes:

$$C = K_4 A + \frac{K_2 S}{K_1 A} + K_3 N$$

and the criterion that the total antenna cost should equal the total variable portion of the transmitter cost still applies. The excess cost involved in using a distributed transmitter can be estimated by assuming $K_2$ = \$3/watt, $K_3$ = \$5000. This would make the fixed and variable transmitter costs equal for a peak transmitter power of 1700 watt, suggesting that the individual modules should be for at least that power in order to avoid paying an excessive price for modularity.

## MODULE SIZES

The attainment of phased-array steerability poses limitations on the design of modules for an MST radar antenna. Here, a module is defined as a subset of the array within which all radiating elements are fed in phase. For example, if unlimited steerability is required, the module must consist of no more than a single dipole. At the other extreme, one may consider the antenna at Jicamarca (Figure 1) which has 64 modules each 6 $\lambda$ x 6 $\lambda$, having a 1/2-power beamwidth of 8.24°. So it is possible to phase these modules to any direction within a circle of radius 4.12° (see Figure 2) without excessive degradation of overall gain, simply by rephasing the various modules. The Urbana array (Figure 3) is organized into modules (called "cells" here) also of dimension 6 $\lambda$ x 6 $\lambda$, though the feed system is somewhat different from that at Jicamarca.

The modular design of the Jicamarca antenna gives the possibility of having several simultaneous pointing directions. For example, it is common for mesospheric work to dedicate one polarization of the antenna to the vertical pointing direction, and to dedicate the two halves of the other polarization to an easterly and southerly direction, as shown on Figure 2; so that all three directions may be used simultaneously. Changing this arrangement, however, takes hours to accomplish.

Elements with increased directivity can be substituted for a module without changing the antenna performance. For example, the gain of each module of the

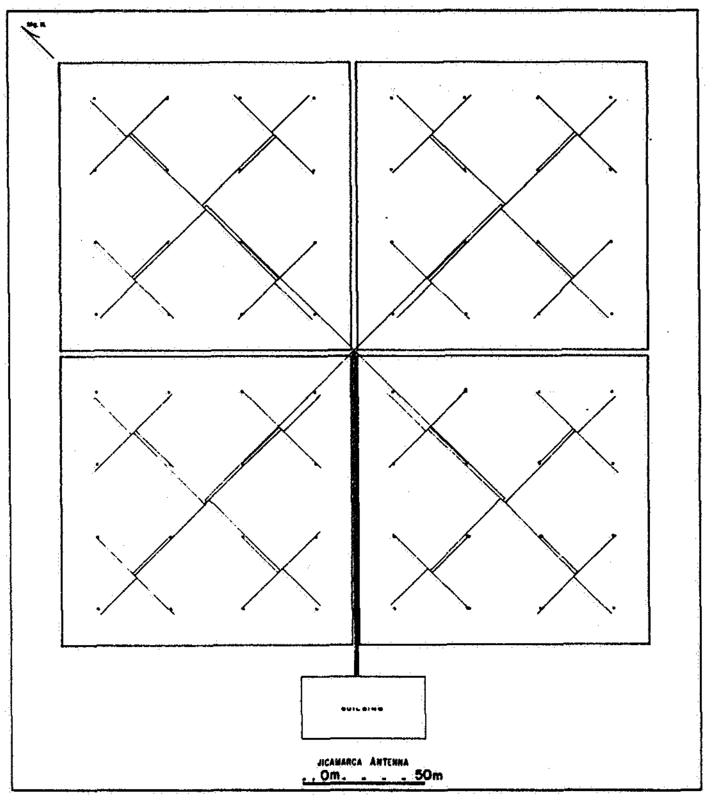


Figure 1. Configuration and the feed arrangement for the Jicamarca antenna (OCHS, 1965).

Jicamarca antenna is 21 dB over an isotropic radiator, so the 64 modules can be substituted by any directive elements with that gain, located at the center of each module. There would be no point in spacing them more closely, since the combined array would have the maximum gain achievable for a filled array. In the Japanese MU-radar, on the other hand, Yagi antennas are used for each module, but spaced only a one-half wavelength in each direction. The Yagi gain cannot contribute to the overall array gain, but additional protection against sidelobes is obtained.

## CHOICE OF POINTING DIRECTIONS

The size of module adopted is determined largely by the choice of pointing directions for the antenna. Given the 8.24° HPBW of the Jicamarca antenna, and its 1.5° tilt toward the southwest, pointing directions 3.5° towards the west and south were easily obtained. With the Urbana antenna, which coincidentally slopes also 1.5° from the vertical, but in this case towards the southeast, pointing directions at 2° to the south and east are obtainable. The modules of the Poker Flat antenna are fixed at 15° from vertical. What are the advantages of the relatively small (less than 5°) or relatively large ($\sim$ 15°) zenith angles?

Three considerations are important for this question. The first of these is the aspect sensitivity of the scattering irregularities. Where this is

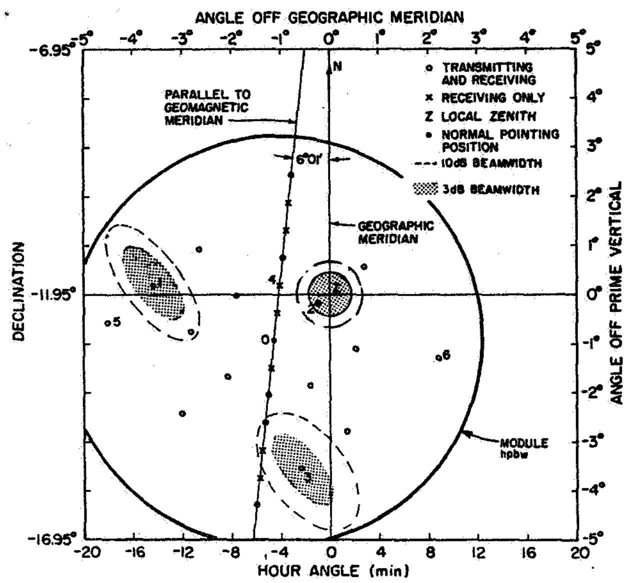


Figure 2. Antenna pointing directions used for mesospheric experiment. Horizontal (3 dB) dimensions of the off-vertical scattering volumes are 1 km by 2 km at 76 km altitude (adapted from RASTOGI and BOWHILL, 1975).

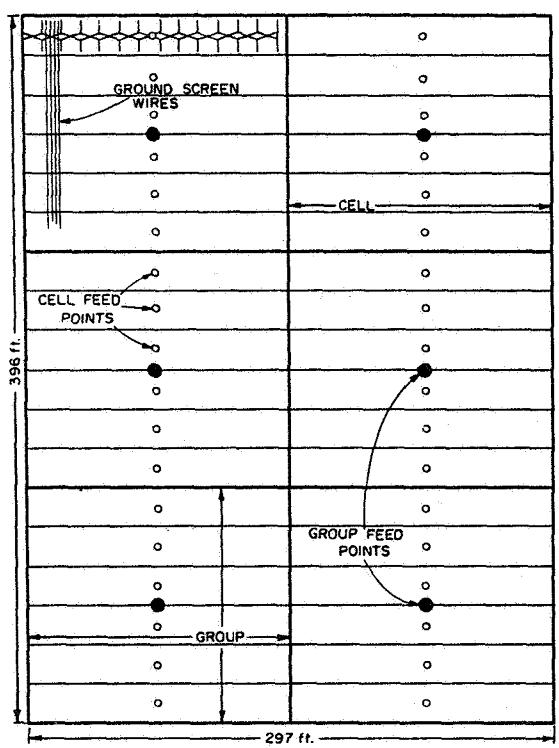


Figure 3. Schematic diagram of the Urbana MST radar antenna.

present, it may penalize the larger zenith angles by 10 dB or more. So one would like to avoid being wedded to a single choice of off-vertical pointing direction. The second consideration is the ability to measure horizontal winds and minimize the contamination from vertical gravity-wave velocities. In a separate paper (3.6-B) I discuss this effect, and show that pointing directions very close to vertical should be avoided, no matter how good the signal-to-noise of each individual measurement. Thirdly, the question arises as to the range of pointing angles which can be covered. Because of the need for symmetrical measurements either side of the zenith, the antenna beam should be centered vertically. The modules should then have polar diagrams such that the extreme pointing directions can be accommodated with no more than 3 dB loss in gain.

Bearing in mind these three compromises, it seems that pointing directions up to 5° away from vertical might be needed, implying a module size approximately the same as that at Jicamarca, namely, $6\lambda \times 6\lambda$.

## FEED SYSTEMS FOR PASSIVE ARRAYS

For feeding energy to the modules of an array, the corporate structure feed used by Jicamarca is attractive, maintaining good bandwidth without beam shifting. For the high voltages required, coaxial lines made from irrigation pipe were successfully used at Jicamarca and have proved successful at Urbana also. Their advantage lies in their large power-handling capability, extremely low loss, and excellent shielding. Open-wire lines are convenient for feeding dipoles within a module, depending whether the array uses end-fed full-wave dipoles (as in Bowles' original Havana array) center-fed full-wave dipoles (as in the Urbana array) or Franklin antennas (as at Jicamarca, Platteville, and Poker Flat). The exact choice depends on impedance-matching considerations.

The choice between these configurations is not particularly easy. The Franklin array has fewer feed lines, but has an awkward crossover at the junctions between the dipoles (Figure 4, OCHS, 1965). It is not clear that this type of coupling would survive anywhere but a very dry environment such as Jicamarca. The use of coaxial cable, as at Poker Flat, carries with it some questions of the ohmic loss in the thin conductor, particularly under conditions of high VSWR.

The question of ground conductor is one which needs careful thought. Wire mesh (as at Jicamarca) is a good solution for a dry climate. Multiple single conductors (as at Urbana) seem to be effective, though in a moist soil it is difficult to determine how much benefit is obtained. Single conductors under each dipole row are very inviting, but it is not clear how applicable this is under varying soil conditions.

## ACKNOWLEDGEMENTS

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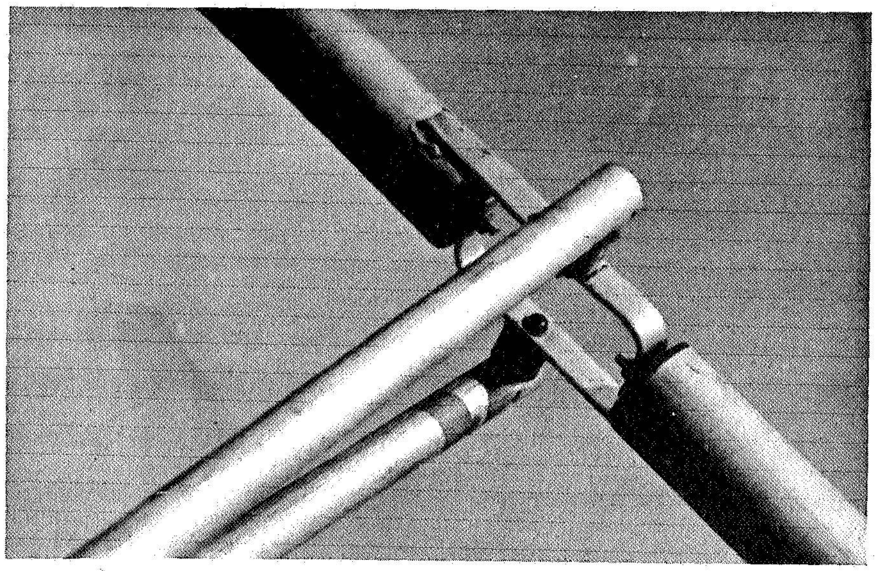

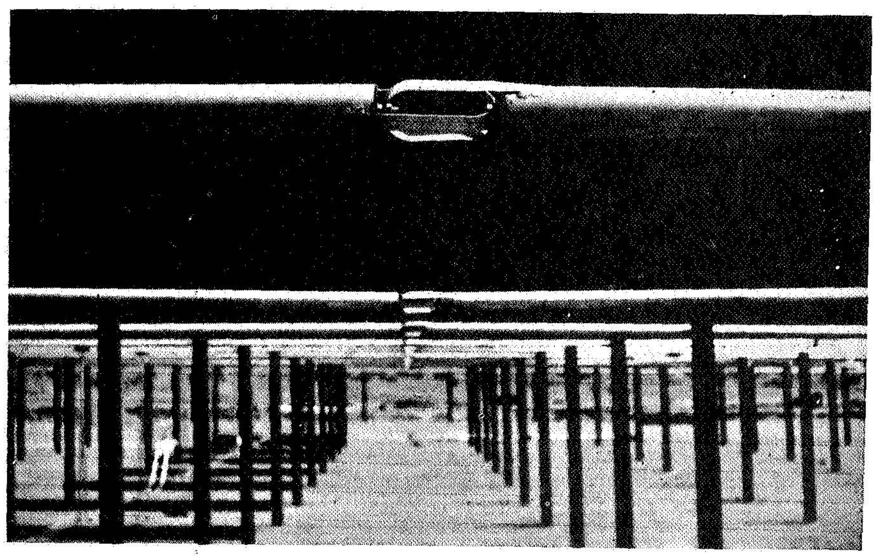

Figure 4. (top) Connection between dipoles (bottom) Central feed point of row of 12 dipoles (OCHS, 1965).

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## SUMMARY OF ADDITIONAL TOPICS

Four topics were added to the list given in the tentative program: site selection, frequency allocation, absolute calibration, and polar diagram verification.

(a) Site Selection

Selection of a site for an MST radar system is subject to several constraints. The requirements of minimizing ground clutter suggests the placement either on very flat terrain (as at Urbana) or in a valley (Jicamarca) or sink hole (Arecibo). In heavy populated areas, the requirement of minimizing interference to other services requires extraordinary measures (as at SOUSY and Kyoto). Finally, it is desirable to select a site with as low a level as possible of natural and man-made noise.

Dr. Chao described noise surveys made for the MU radar in Japan. A vertically pointing Yagi and a field intensity meter monitored the 40-60 MHz band every 30 min for two months, and this formed the basis of the selected frequency band.

Dr. Crochet described the methods used to select the three sites for the ALPEX experiment. He cautioned that a small antenna can fail to see interference which later shows up in a large array located at the same place.

Dr. Rottger indicated that he had good experience using Yagi antennas for site selection. He also pointed out that geophysical reasons dictated that if wind measurements are important, the site should be located far away from mountains.

Dr. Strauch described his criteria for site selection, and prepared the following remarks:

"The general location of the site will usually be governed by the geophysical problem that is to be addressed and often this consideration, that cannot be compromised, places serious restrictions on the choice of the site. Usually, however, there are many local potential sites once the general locations has been determined. Some of the points to consider for site selection are the following:

1. Availability of power, telephone service, and other facilities. The quality of service must also be investigated.
2. The terrain at the site. How much effort will be required to modify the terrain for antenna installation?
3. The near-by terrain. Can it be a natural shield or will its clutter signal be at the same range as the atmospheric phenomena of interest?
4. Aircraft flight paths. Will the antenna pointing angles be close to directions where commercial aviation interference will be troublesome? Are there small airports nearby?
5. Protection. If the site will not be manned at all times, will it be secure? Can it be located on land that is already protected or already has restricted access.
6. Maintenance facilities. Will operations and maintenance people live close enough to the site?
7. Type of vegetation and soil. Is the drainage adequate enough to prevent flooding? Will natural vegetation interfere with the antenna? Is the ground suitable for easy antenna construction?
8. Man-made interference. Will automobile traffic cause a clutter or radiation interference? Will near-by residences cause interference from local oscillators on TV or radio bands? Are there near-by radio amateurs or commercial broadcasting stations?

"Although the actual interference problem will not be known until the antenna and receiver are installed, the prudent experimentor will conduct tests of interference before selecting a site. For large and expensive facilities these tests should be extensive and sensitive. A small directional antenna may be suitable to simulate sidelobe sensitivity of radars, but it should be remembered that sophisticated data-processing methods make system sensitivity extremely good; therefore it would be advisable to use (if possible) the complete data system to look for interference. These measures would certainly be called for before installing expensive, fixed sites."

(b) Frequency Allocation

There was general agreement that two aspects of frequency allocation will become important as increasing numbers of ST or MST radars begin to operate in the low VHF band.

Firstly, there is the difficulty of allocation of frequencies -- almost continuous use by these radars will be made when the band 40-60 MHz is allocated to other services. It was agreed that URSI should be contacted to see if they can make overtures to CCIR concerning this question.

Secondly, there is the problem of interference of MST radars with each other. At the moment, the density of such radars is not sufficient to cause a problem, but some frequency allocation rationale must eventually be decided upon. In this connection, it seems clear that more attention should be paid to the problem of designing MST radar antennas with lower sidelobes which will help both transmitting and receiving.

(c) Absolute Calibration

Dr. Hocking described a technique for absolute calibration which he developed for the SOUSY radar and which is described in an MPI Report, "Absolute Calibration of the SOUSY VHF Stationary Radar". It uses a combination of noise measurement for the receiving system using a standard noise generator, and measurement of the diurnal variation of sky noise for each beam separately.

Dr. Balsley pointed out the difficulty of performing absolute calibrations for a multi-transceiver system, particularly because of the difficulty of estimating cable effects.

Dr. Schmidt described the method of calibration using the Cassiopeia source, and Dr. Bowhill described the Signus-A source.

Dr. Mathews suggested that all MST radars should permit determination of the absolute scattering cross section per unit volume for the given pulse widths used.

(d) Polar Diagram Verification

Several approaches were used for verifying the polar diagram of an MST radar antenna. Dr. Balsley described a method using a number of 1-m diameter spherical earth satellites whose ephemerides are accuately known. The number of these available is such that in a 10-day period as many as 8 passes may be made through a 1-deg-diameter beam. The updated ephemeris is accurate enough that they can be used to determine the direction of the antenna beam, as well as a calibration of the antenna by measurement of the absolute cross section.

Mr. Green described how a probe antenna can be moved through the antenna, accurately measuring the phase and amplitude of the field. The resulting field pattern can be used to synthesize the antenna pattern and to estimate the aperture efficiency.

Dr. Mathews described the use of an aircraft flying at 10,000 feet with a calibrated dipole suspended on a weighted cable. The position of the aircraft was determined by multiple theodolites. When all the theodolites agreed, a time marker was used to calibrate the signal strength record from the receiver. Dr. Balsley used a similar arrangement by using a folded dipole made of RG-58, and using a Hewlett-Packard laser theodolite for position-finding. Dr. Bowhill described a piece of radio equipment using 3 ground-based transmitters which enables a suitably equipped airplane to fly along a known straight line path with about 1-ft accuracy. It is used for crop dusting and for surveying.