Atmospheric VHF Radar Calibration

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Atmospheric Radars

Used to investigate

- the dynamics of the atmosphere
- the turbulent structure of the atmosphere
- Temperatures in the D-region (60-90 km)
- Electron densities in the D-region
- Meteor Astronomy
- Hydrometeors / Precipitation

To do this they utilise

- partial reflection and backscatter from the neutral and ionized atmosphere
Atmospheric Radars

Generally they

- operate in pulsed mode with
  - duty cycles of 0.2-15 %
  - high peak powers (8 to 500 kW)
- utilise frequencies near
  - 2 MHz (MF)
  - 50 MHz (VHF)
  - 400 MHz (UHF)
  - 1000 MHz (UHF)
- use static antennas at MF and lower VHF
Applications are determined by frequency

<table>
<thead>
<tr>
<th>Type</th>
<th>Frequency</th>
<th>Winds</th>
</tr>
</thead>
<tbody>
<tr>
<td>MF Partial Reflection Radar</td>
<td>1.5-3.5 MHz</td>
<td>60-100 km (day)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80-100 km (night)</td>
</tr>
<tr>
<td>Meteor Radar</td>
<td>27-50 MHz</td>
<td>75-105 km</td>
</tr>
<tr>
<td>Mesosphere Stratosphere Troposphere (MST) Radar</td>
<td>45 – 65 MHz</td>
<td>0.5 – 20 km</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60 – 80 km (day)</td>
</tr>
<tr>
<td>Stratospheric Tropospheric (ST) Radar</td>
<td>45 – 65 MHz</td>
<td>0.5 – 20 km</td>
</tr>
<tr>
<td></td>
<td>440 – 494 MHz</td>
<td>0.5 – 16 km</td>
</tr>
<tr>
<td>Boundary Layer Troposphere (BLT) Radar</td>
<td>45 – 65 MHz</td>
<td>0.2 – 8 km</td>
</tr>
<tr>
<td>Boundary Layer (BL) Radar</td>
<td>915 – 1300 MHz</td>
<td>0.1 – 3 km</td>
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</table>
VHF Radar Array Calibration

• Calibration of:
  – The antenna array polar diagram
    • Satellite beacon
    • Radio “stars”
    • Helicopter / aircraft carrying beacon
    • UAV with beacon / reflector
    • Targets of opportunity
      – Aircraft
      – Radiosondes
      – Meteors
  – The phase paths through the radar system elements
    • Local source / Doppler simulator
    • Radio “stars”
  – The absolute power
    • Noise sources and delay lines
Buckland Park MF/HF Array

An aerial array 1 km in diameter has been constructed near Adelaide, South Australia. It will be used for observations of ionospheric drifts and mesoscale, and for other experiments in ionospheric physics.

Description of the Array

The array consists of 156 dipole antennas arranged as shown in Fig. 1. Each dipole is a wire 7 m long supported 15 m above the ground by two short posts set at the centre to act as a "halo", and is linked to the array in the same way as the 76 dipoles are linked to the main laboratory. The electrical length of the wire is approximately adjusted to that which would be required for the frequency of operation of the array. The basic frequency of the array is 1 MHz, but it can also be operated in two other frequency ranges at 4.5 MHz and 3.5 MHz. The elimination of the radio signals from the secondaries is achieved by the wire slotted along the length of the dipole. The array can be operated to receive only the polarization of the received signals, which can be done in two ways: in one case, with eight-eighths dipoles, one half of the dipoles are excited and the other half are used for reception; in the other case, with eight-eighths and eight-eighths dipoles, one half of the dipoles are excited and the other half are used for reception.

Our present approach to the problem of dipole arrays involves the use of a larger array of vertical dipoles, capable of covering a range of frequencies. The dipole array is designed to give a higher sensitivity to the frequency range of the desired signals. The array is designed to give a higher sensitivity to the frequency range of the desired signals. The array is designed to give a higher sensitivity to the frequency range of the desired signals.
MF receiver channel phase calibration

Doppler simulator signal injected into receiver before each data set acquired. Receiver channel without antennas and feeds.

Angle of arrival data measured over longer period after receiver calibration.
Antenna array phase calibration: Doppler simulator

- Receiving antennas of same symmetry
- Transmitting antennas

Figure 5.6: Grid 2

Figure 5.7: Grid 3

Doppler simulator used as radar “target”
Chung Li VHF Radar

Diagram of Chung Li VHF Radar components including power dividers, phase shifters, transmitters, receivers, and control systems. The diagram also shows the beam positions and Yagi arrays.
Polar diagram Chung Li VHF radar: radio “star”

Fig. 4. Antenna pattern of the 64-Yagi submodule with vertical beam (relative amplitude scale). The projection of the track of the radio source Taurus A is indicated by a thick line; the thin line indicates the latitude 24°58′N of the Chung-Li radar antenna [from Pan, 1987].

Fig. 5. The power density received from the radio source Cygnus A (declination 40.7°N), when the antenna beam is pointed to 16.7° north. The projection of the track of Cygnus A is only one degree toward the south of the northward pointing direction with maximum at 16.7° zenith angle. The computed and measured pattern agree satisfyingly [from Pan, 1987].

Radio sources e.g., Cygnus A, Cassiopeia A
Commercial Aircraft: phase calibration of receivers

Phase calibration of the three receiver channels using commercial aircraft
Tennant Creek operational wind profiler
Buckland Park ST VHF Radar (similar to Tennant Creek)

Radar elements are summed in hardware
Can also use aircraft in special experiments

- Buckland Park ST VHF radar
  - UAV
  - Aircraft

ARA aircraft flyover. Radar transmitting less than 1% power
Hybrid Doppler Interferometry

Multiple receiver system. Radar elements are summed in software. Interferometric operation.
MU → EAR → PANSY Radars

Middle and Upper (MU) Atmosphere Radar (1984)

Equatorial Atmosphere Radar (EAR) (2001)
MU radar polar diagram calibration: satellite beacon

Fig. 15. (bottom) An example of the MU radar TX array pattern (thin line) measured by using the Japanese satellite OIZORA, and the corresponding theoretical antenna gain (thick line) relative to the reference antenna. The reference antenna has almost constant gain for the elevation angles shown in this diagram. (top) Elevation angle of the satellite seen from the MU radar (solid line) and the angle between the direction of the satellite and the axis of the main beam of the MU radar antenna (dashed line) versus time.
Receiver channel phase calibration: Radio star

- Relies on known position of radio source
- Needed for Frequency Domain Interferometry, and
- Spatial Domain Interferometry
- Only require relative phases

**Figure 1.** Depiction of the configuration used for the calibration technique. The vector P points in the direction of Cygnus A and changes with time. The drawing is shown with only two receiving arrays although three are used in the analysis.

**Figure 4.** Height-averaged estimates of (a) source location and (b) noise power, as a function of time. As would be expected, the phase values from each antenna pair vary linearly as Cygnus A traverses the beam of the MU radar. It should be noted that unlike Figure 3, these values are with respect to zenith, which permits the comparison to the astronomical calculation. For reference, Cygnus A is approximately in the center of the beam at 0442 LT.
PANSY VHF MST Radar

**Specifications of the PANSY Radar**

<table>
<thead>
<tr>
<th></th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar System</td>
<td>Monostatic pulse Doppler radar</td>
</tr>
<tr>
<td>Location</td>
<td>Syowa Station Antarctica (69°00'22&quot;S, 39°35'24&quot;E)</td>
</tr>
<tr>
<td>Centre Frequency</td>
<td>47.0 MHz</td>
</tr>
<tr>
<td>Antenna</td>
<td>A quasi-circular array consisting of 1045 crossed Yagi antennas with 3 elements</td>
</tr>
<tr>
<td>Aperture</td>
<td>about 16000 m²</td>
</tr>
<tr>
<td>Beam directions</td>
<td>arbitrary zenith angles less than 30 degrees</td>
</tr>
<tr>
<td>Transmitter</td>
<td>1045 solid-state TR modules</td>
</tr>
<tr>
<td>Peak power</td>
<td>500kW</td>
</tr>
<tr>
<td>Average power</td>
<td>25kW</td>
</tr>
<tr>
<td>Polarization</td>
<td>Circular</td>
</tr>
<tr>
<td>Receiver</td>
<td>55 systems of synchronous quadratic detection</td>
</tr>
</tbody>
</table>

- Array size is now larger than minimum range resolution
- 55 receiver channels
- Multiple frequencies transmitted ($\Delta f \sim 1$ kHz) around centre frequency
Motivation for phase calibration

Transmitting multiple frequencies to observe the atmosphere has become a basic capability of the modern mesosphere-stratosphere-troposphere (MST) radars.

This observational technique started with frequency domain interferometry (FDI) which uses two slightly different frequencies. It was extended using signal-processing algorithms such as the Capon method to deal with echoes received at several carrier frequencies. It is now known as range imaging (RIM) [Palmer et al., 1999] or frequency interferometric imaging (FII) [Luce et al., 2001] in the MST radar community.

The algorithms used with RIM/FII are inversion processes, which were initially introduced to multiple-receiver coherent radar imaging (CRI) to determine multiple echo centres (the angle of arrival) in the radar volume [Palmer et al., 1999].

With similar processing, these algorithms permit recognition of multiple irregularity layers in the radar volume and then give estimates of the altitudes and thicknesses of the layers. Consequently, the range resolution of echo distribution (or the “brightness distribution”) is improved greatly.
Motivation for calibration

Capon is one of several algorithms for DOA estimation that have been proposed in recent years. Others include the maximum entropy method and Multiple Signal Classification (MUSIC). Capon’s method tends to fail if signals that are correlated with the signal of interest are present. It may be computationally expensive for large antenna arrays. For MUSIC, the resolution is better, but in the case of correlated signals (e.g., a multipath scenario) the covariance matrix is not of full rank, and the separation between signal and noise subspace becomes difficult.
Radar absolute power calibration

Figure 2. Hardware configuration during noise-generator calibration. The N-G corresponds to a noise-generator hardware, which can be switched in at point S (as input for the receiver in order to perform a calibration). Others symbols are referred to in the text.

Figure 3. Hardware configuration during sky-noise calibration.
Radar Calibration: precipitation measurements

To fix the absolute value of the number of rain drops, a VHF radar must be calibrated. A radar equation for the equivalent radar reflectivity factor $Z_e$ of the precipitation is derived for a bistatic VHF boundary layer radar takes the form

$$Z_e = \frac{1024 \ln(2) k \lambda^2 BT_N r_0^2 (\text{SNR})_P}{(P_t \varepsilon_x) I^2 c \pi^3 g \theta \theta l \tau |K^2| 10^{-18}}$$

where the variables measured by the radar are $T_N$, the noise temperature; $r^2$, the range to the scatterers; and $r_0^2 (\text{SNR})_P$, the signal-to-noise ratio of the precipitation signal only. The remainder of the terms are assumed to be constant for a given radar. The terms for the antenna beamwidth and the gain, usually written as $\theta^2$ and $g^2$ in traditional formulations, are separated into individual components for the transmitting and receiving antennas, subscripted with $t$ and $r$, respectively.

To obtain the noise temperature $T_N$, a receiver calibration is performed with a noise generator. The results of this calibration from the three different receivers are combined and a linear regression of these data is used to calculate the noise temperature from the observed noise level of an individual spectrum. The equation returns a value of reflectivity that should be expected given the observed strength of the precipitation signal, the range, and the noise level.

This is compared to the reflectivity calculated (from the unmodified spectrum) from the DSD retrieval. The ratio of the expected to the observed is taken as a “calibration factor,” which is applied to the DSD at the end of the calculation a final uncertainty of 30%–40% in this number is estimated.
Table of associated parameters for radar calibration

**Table A1.** Description of radar parameters and constants, their values, and the estimated uncertainties. Dash indicates negligible uncertainty.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Value</th>
<th>Estimated relative uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$</td>
<td>Bandwidth</td>
<td>1 MHz</td>
<td>5</td>
</tr>
<tr>
<td>$\sigma_{tx}$</td>
<td>Transmission line loss</td>
<td>1.75 dB</td>
<td>5</td>
</tr>
<tr>
<td>$g_r$</td>
<td>Receiver antenna gain</td>
<td>15.22 dB</td>
<td>3</td>
</tr>
<tr>
<td>$G_t$</td>
<td>Transmitter antenna gain</td>
<td>19.74 dB</td>
<td>3</td>
</tr>
<tr>
<td>$\theta_r$</td>
<td>Receiving antenna half beamwidth</td>
<td>31°</td>
<td>3</td>
</tr>
<tr>
<td>$\theta_t$</td>
<td>Transmitting antenna half beamwidth</td>
<td>17°</td>
<td>6</td>
</tr>
<tr>
<td>$l_r$</td>
<td>Receiver loss term</td>
<td>2.3 dB</td>
<td>4</td>
</tr>
<tr>
<td>$P_r$</td>
<td>Transmitted power</td>
<td>1000 W</td>
<td>5</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Pulse width</td>
<td>1 μs</td>
<td>—</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Wavelength</td>
<td>5.54 m</td>
<td>—</td>
</tr>
<tr>
<td>$c$</td>
<td>Speed of light</td>
<td>$2.997 \times 10^8$ m s$^{-1}$</td>
<td>—</td>
</tr>
<tr>
<td>$\varepsilon_0$</td>
<td>Dielectric constant of water</td>
<td>0.93</td>
<td>—</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Atmospheric attenuation term</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>$k$</td>
<td>Boltzmann’s constant</td>
<td>$1.38 \times 10^{-22}$ J K$^{-1}$</td>
<td>—</td>
</tr>
</tbody>
</table>
Calibration against other radars
Meteor Radar

Interferometer piggy backed onto an ST radar (55 MHz).
Incompatible operation, so interleaved

Dedicated all-sky meteor radar (near 30 MHz)
Meteor Radar Receiving Array

Tx antenna
Meteor Radar Angle-of-Arrival Estimation

- Antennas spaced at 2.0 and 2.5 times wavelength to avoid mutual coupling, but AoA is ambiguous for $d < 0.5 \lambda$.

- Phase $\phi$ is measured for each antenna using in-phase and quadrature components.

- Angle-of-Arrival is determined by a succession of combinations of antenna-pair phase differences to produce an unambiguous estimate of AoA.

\[
\phi_{0.5\lambda} = \phi_{2.5\lambda} - \phi_{2.0\lambda}
\]
\[
\phi_{4.5\lambda} = \phi_{2.5\lambda} + \phi_{2.0\lambda}
\]
Effect of Phase Biases on Observations

before calibration

after calibration
Observed Detection Heights
Reference: Meteor Phase Calibration

Interferometric meteor radar phase calibration using meteor echoes

David A. Holdsworth, Masaki Tsutsumi, Iain M. Reid, Takuji Nakamura, Toshitaka Tsuda

*Radio Science, vol. 39, 2004*

doi:10.1029/2003RS003026
Meteor Phase Calibration: Biases

- Consider the phase differences of the two pairs of antennas on baseline 13 due to backscatter incident at angle $\psi$.

$$\phi_1 = kd_1 \sin \psi$$

$$\phi_3 = kd_3 \sin \psi$$

$$\phi_3 = \phi_1 \frac{d_3}{d_1}$$

- With biases $\alpha$ in each phase measurement, the observed phases become

$$\phi'_1 = \phi_1 + \alpha_1$$

$$\phi'_3 = \phi_3 + \alpha_3$$
Meteor Phase Calibration: Biases (cont.)

- This produces two ambiguous sets of possible biased AoAs $\Psi'$, such that:

$$\phi'_1 = kd_1 \sin \Psi'_1 \quad \phi'_3 = kd_3 \sin \Psi'_3$$

- For any candidate AoA $\psi'_1$ from the set $\Psi'_1$, the phase difference on antenna pair 3 is then:

$$\varphi_3 = kd_3 \sin \psi'_1$$

- We can now define a mixed bias term for the entire baseline

$$\gamma_3 = \varphi_3 - \phi'_3 = \alpha_1 \frac{d_3}{d_1} - \alpha_3$$

- Furthermore

$$\phi''_3 = \phi'_3 - \gamma_3 = \phi_3 + \alpha_1 \frac{d_3}{d_1}$$
Meteor Phase Calibration: Extracting Biases

- Given \( n \) meteor echoes, there are \( n \) estimates of \( \gamma_3 \) aliased into \( \pm (d_3/d_1-1)\pi = \pm \pi/4 \)

- New distributions de-alias values of \( \gamma \) to allow fitting of a curve to the histogram, where \( \mu = 2(d_3/d_1-1)\pi = \pi/2 \)

\[
\Gamma_3 = [[\gamma_3] - \mu, [\gamma_3], [\gamma_3] + \mu]
\]

- The estimates of \( \gamma \) can then be used to estimate \( \alpha \) using

\[
\phi'_3 = \phi'_3 - \gamma_3 = \phi_3 + \alpha_1 \frac{d_3}{d_1}
\]

- The best values of \( \alpha \) are determined by optimizing the resultant distribution of meteors (minimize height range, center detections on zenith)

From: Holdsworth et al., Radio Sci., vol. 39, 2004
Post-Statistical Steering

- In the event phase data for each antenna is not available, need a method to calibrate radar phases using existing data
  - useful for older/incomplete data sets

- Meteor radars detect “underdense” meteors: Echo strength decays exponentially with time
  - rate of echo decay is determined by the ambipolar diffusion coefficient, a function of temperature and pressure

- Echoes with the same decay time should occur at unique heights
  - adjust phases to calibrate angles-of-arrival
  - minimize differences in heights between echoes with the same decay time
Spherical Cap Fitting using Geophysical Data

- Zenith angle, $\chi$, as a function of the phase differences, $\Phi$ along two interferometer baselines of length $d$ is given by

$$\cos^2 \chi = 1 - \cos^2 \left[ \sin^{-1} \left( \frac{\phi_1 \lambda}{2\pi d} \right) \right] - \cos^2 \left[ \sin^{-1} \left( \frac{\phi_2 \lambda}{2\pi d} \right) \right]$$

$$= \left( \frac{\phi_1 \lambda}{2\pi d} \right)^2 + \left( \frac{\phi_2 \lambda}{2\pi d} \right)^2 - 1$$

- Height can be expressed in terms of the phase angles and errors, $\alpha$, allowing a direct parametric fit of errors to the height function

$$z = \sqrt{R_e^2 + R^2 + 2RR_e \cos \chi} - R_e$$

$$z = \sqrt{R_e^2 + R^2 + 2RR_e \sqrt{\frac{\lambda}{2\pi d} \left( \phi_1 + \alpha_1 \right)^2 + \frac{\lambda}{2\pi d} \left( \phi_2 + \alpha_2 \right)^2} - 1 - R_e}$$
Comparison with Meteor Phase Calibration

- Numerical simulation of meteor radar performance indicates that, with at least 1500 meteor detections, post-statistical steering using meteor echo decay times is accurate to within 1° in the absence of geophysical variability
- Comparison with before/after MPC calibrated data

![Graph comparing bias estimate before and after MPC calibration](image-url)
Mutual Coupling

- The field due to a current in one antenna induces currents in other antennas, producing a coupled system.

- Effects of coupling can be reduced by increasing inter-antenna spacing, at the cost of angle-of-arrival ambiguity.

- The impact of mutual coupling can be characterized by:
  - \( V_i = \) voltage on antenna \( i \) due to currents on antenna \( j \)
  - \( I_j = \) current on antenna \( j \)
  - \( Z_{ij} = \) matrix of impedances between different antennas

\[
V_i = \sum_j Z_{ij} I_j
\]
Assessing the Impact of Mutual Coupling

- Scattering parameters for different antenna-pair combinations can be measured with a vector impedance meter.

- Off-diagonal elements of the S-parameter matrix are the signal transmitted between antennas in a pair; diagonal elements are the amount of signal reflected inside an individual antenna. Assuming reciprocity between antennas in pairs, there are $n(n+1)/2$ unique values.

- S-parameters can be used to obtain $Z_{ij}$
  - $Z_L$ = load impedance ($\sim50\ \Omega$)
  - $S$ = matrix of S-parameters
  - $E$ = identity matrix

$$Z = Z_L \left[(E - S)(E + S)\right]^{-1}$$
Converting $Z$ to Observed Voltage

- The matrix of admittance parameters, $Y$, plays the part of $1/R$ in Ohm’s law
  - current given by $YV$

$$Y = (Z_L E + Z)^{-1}$$

- Vector of observed voltages, $V_O$ can then be calculated using the applied voltage, $V_A$, which is the voltage of the incident electric field.

$$V_O = Z_L E Y V_A$$
Example: Buckland Park 55 MHz Meteor Radar

S-parameter Matrix

<table>
<thead>
<tr>
<th>ant.</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-20.9</td>
<td>-35.8</td>
<td>-38.2</td>
<td>-39.3</td>
<td>-36.7</td>
</tr>
<tr>
<td>1</td>
<td>-35.8</td>
<td>-23.6</td>
<td>-45.8</td>
<td>-44.0</td>
<td>-43.0</td>
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<tr>
<td>2</td>
<td>-38.2</td>
<td>-45.8</td>
<td>-29.6</td>
<td>-46.7</td>
<td>-44.6</td>
</tr>
<tr>
<td>3</td>
<td>-39.3</td>
<td>-44.0</td>
<td>-46.7</td>
<td>-22.4</td>
<td>-47.9</td>
</tr>
<tr>
<td>4</td>
<td>-36.7</td>
<td>-43.0</td>
<td>-44.6</td>
<td>-47.9</td>
<td>-23.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ant.</th>
<th>0</th>
<th>1</th>
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</tr>
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<tbody>
<tr>
<td>0</td>
<td>92.9</td>
<td>-32.6</td>
<td>149.7</td>
<td>-29.2</td>
<td>142.0</td>
</tr>
<tr>
<td>1</td>
<td>-32.6</td>
<td>88.1</td>
<td>157.2</td>
<td>9.3</td>
<td>-43.0</td>
</tr>
<tr>
<td>2</td>
<td>149.7</td>
<td>157.2</td>
<td>63.4</td>
<td>56.7</td>
<td>-44.6</td>
</tr>
<tr>
<td>3</td>
<td>-29.2</td>
<td>9.3</td>
<td>56.7</td>
<td>61.5</td>
<td>-24.4</td>
</tr>
<tr>
<td>4</td>
<td>142.0</td>
<td>-43.0</td>
<td>-44.6</td>
<td>-24.4</td>
<td>87.0</td>
</tr>
</tbody>
</table>
Significance of Mutual Coupling Zenith Errors

- Predicted zenith-angle errors based on measured S-parameters are less than about 0.5°, most of which can be described as a steady gradient across the radar field of view.

- The gradient will be corrected by meteor phase calibration or post-statistical steering. The remaining fluctuations are small in comparison to the inherent uncertainty in the zenith angle due to uncertainty in phase measurements.
Conclusions

• A variety of approaches to calibrating and verifying the antenna and receive channel characteristics of VHF radars have been pursued

• These include
  – Direct known signal input into the receiver itself. This approach is now more or less routine
  – Direct known signal input into the receiver channel (at the antenna)
  – Targets of opportunity
    • Aircraft
    • Meteors
    • The ionosphere
    • Radio sources