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Bistatic Measurement Facility

User's Manual

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Chapter 1

Introduction

Traditional radar systems operate in the monostatic mode in which the transmit and receive antennas are located very close to each other or a single antenna is used for both functions. Monostatic scattering, also called backscattering, is a special case of the more general case of bistatic scattering which includes all possible combinations of illumination and scattering direction. Whereas extensive backscattering data exists in both the open literature and in classified data bases for point and distributed targets, bistatic data is practically nonexistent by comparison. Moreover, our current understanding of the applicability and ranges of validity of available scattering models and theoretical formulations to the general case of bistatic scattering is equally poor, primarily because these models have not been tested against accurate bistatic scattering data. This manual describes the operation of an indoor X-band Bistatic Measurement Facility (BMF) designed to measure the bistatic scattering matrix of distributed targets over a large range of illumination and scattering directions, including the backscattering case.

1 Bistatic Scattering

1.1 Wave Polarization

Figure 1.1 depicts an object, which may be a point or a distributed target, located at the center of an (x, y, z) coordinate system. In bistatic scattering, we have an incident wave generated by a transmit antenna pointed towards the target along the wave direction $\hat{\mathbf{k}}_t$, as well as a receive antenna whose boresight is pointed towards the target along the direction $-\hat{\mathbf{k}}_r$. Both $\hat{\mathbf{k}}_t$ and $\hat{\mathbf{k}}_r$ are unit vectors. The transmit direction propagation vector $\hat{\mathbf{k}}_t$ is specified by the incidence angle θ_t, defined as the angle between $-\hat{\mathbf{k}}_t$ and the positive z-axis, and the incident azimuth angle ϕ_t, defined as the angle in the x-y plane between the x-axis and the projection of $\hat{\mathbf{k}}_t$ onto the x-y plane,

$$\hat{\mathbf{k}}_t = \cos\phi_t \sin\theta_t \hat{\mathbf{x}} + \sin\phi_t \sin\theta_t \hat{\mathbf{y}} - \cos\theta_t \hat{\mathbf{z}} \tag{1.1}$$

A similar definition applies to $\hat{\mathbf{k}}_r$ in terms of the scattering (receive) angle θ_r:

$$\hat{\mathbf{k}}_r = \cos\phi_r \sin\theta_r \hat{\mathbf{x}} + \sin\phi_r \sin\theta_r \hat{\mathbf{y}} + \cos\theta_r \hat{\mathbf{z}} \tag{1.2}$$

The incident wave is represented by an electric field vector $\mathbf{E}$ which may lie anywhere in the plane orthogonal to the direction of propagation $\hat{\mathbf{k}}_t$. We characterize $\mathbf{E}$ in terms of a horizontal polarization components, $E_h^t \hat{\mathbf{h}}_t$, and a vertical polarization component, $E_v^t \hat{\mathbf{v}}_t$, where $\hat{\mathbf{h}}_t$ and $\hat{\mathbf{v}}_t$ are unit vectors denoting the directions of the respective polarizations. The direction $\hat{\mathbf{h}}_t$ is parallel to the x-y plane and is given by:

$$\hat{\mathbf{h}}_t = \frac{\hat{\mathbf{k}}_t \times \hat{\mathbf{z}}}{|\hat{\mathbf{k}}_t \times \hat{\mathbf{z}}|} = \sin\phi_t \hat{\mathbf{x}} - \cos\phi_t \hat{\mathbf{y}} \tag{1.3}$$

and the vector $\hat{\mathbf{v}}_t$ completes the orthogonal set $(\hat{\mathbf{k}}_t, \hat{\mathbf{v}}_t, \hat{\mathbf{h}}_t)$. Thus,

$$\hat{\mathbf{v}}_t = \hat{\mathbf{h}}_t \times \hat{\mathbf{k}}_t = \cos\phi_t \cos\theta_t \hat{\mathbf{x}} + \sin\phi_t \cos\theta_t \hat{\mathbf{y}} + \sin\theta_t \hat{\mathbf{z}} \tag{1.4}$$

The electric field of the incident wave, $\mathbf{E}^t$, is given by:

$$\mathbf{E}^t = E_v^t \hat{\mathbf{v}}_t + E_h^t \hat{\mathbf{h}}_t, \tag{1.5}$$

or in matrix notation as:

$$\mathbf{E}^t = \begin{bmatrix} E_v^t \\ E_h^t \end{bmatrix}. \tag{1.6}$$

Similarly, the received electric field, $\mathbf{E}^r$, is given by:

$$\begin{aligned} \mathbf{E}^r &= E_v^r \hat{\mathbf{v}}_r + E_h^r \hat{\mathbf{h}}_r \\ &= \begin{bmatrix} E_v^r \\ E_h^r \end{bmatrix}, \end{aligned} \tag{1.7}$$

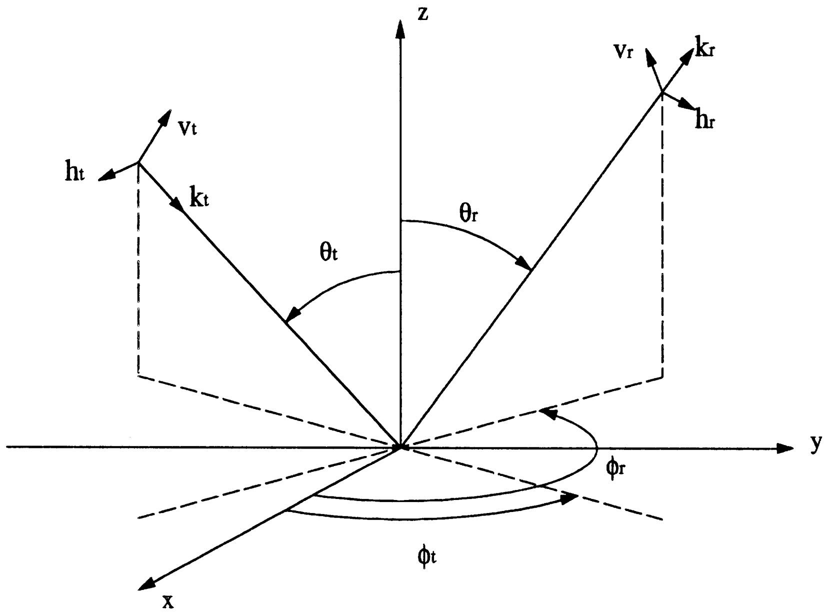


Figure 1.1: General Bistatic Coordinate System

with the polarization unit vectors given by:

$$\hat{\mathbf{h}}_r = \frac{\hat{\mathbf{k}}_r \times \hat{\mathbf{z}}}{|\hat{\mathbf{k}}_r \times \hat{\mathbf{z}}|} = \sin\phi_r\hat{\mathbf{x}} - \cos\phi_r\hat{\mathbf{y}} \qquad (1.8)$$

$$\hat{\mathbf{v}}_r = \hat{\mathbf{h}}_r \times \hat{\mathbf{k}}_{\mathbf{r}} = -\cos\phi_{\mathbf{r}}\cos\theta_{\mathbf{r}}\hat{\mathbf{x}} - \sin\phi_{\mathbf{r}}\cos\theta_{\mathbf{r}}\hat{\mathbf{y}} + \sin\theta_{\mathbf{r}}\hat{\mathbf{z}} \qquad (1.9)$$

1.2 Azimuthally Symmetric Targets

In general, the bistatic-scattering geometry is specified in terms of the four angles θ_t, ϕ_t, θ_r and ϕ_r. For azimuthally symmetric targets, it is often convenient to choose the $\hat{\mathbf{x}}$-axis such that $\phi_r = 0$, as shown in Figure 1.2, thereby reducing the angular set to three. In this case, the propagation directions and associated polarization unit vectors for the receive antenna simplify to:

$$\hat{\mathbf{k}}_r = \sin\theta_r\hat{\mathbf{x}} + \cos\theta_r\hat{\mathbf{z}} \qquad (1.10)$$

$$\hat{\mathbf{h}}_r = -\hat{\mathbf{y}} \qquad (1.11)$$

$$\hat{\mathbf{v}}_r = -\cos\theta_r\hat{\mathbf{x}} + \sin\theta_r\hat{\mathbf{z}} \qquad (1.12)$$

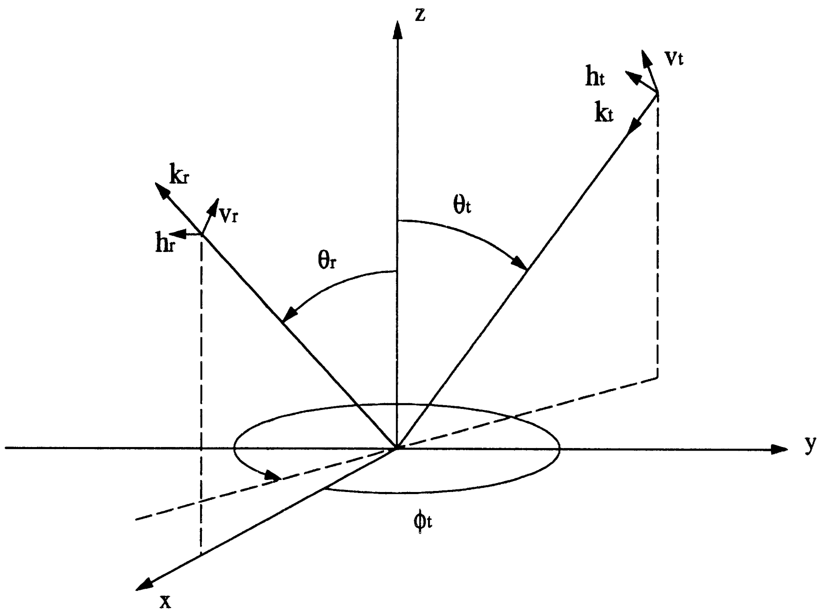


Figure 1.2: Receiver Aligned Bistatic Coordinate System for Azimuthally Symmetric Targets

and those for the transmit antenna, given by (1.1), (1.3), and (1.4), remain unchanged.

The three angles (θ_r, θ_t, ϕ_t) are collectively known as the bistatic angles. When the Bistatic Measurement Facility is in bistatic mode, θ_r corresponds to the Horn Elevation, or as it is sometimes referred in this Manual, the Outer Arch Elevation, θ_t corresponds to the Dish Elevation (or Inner Arch Elevation), and ϕ_t corresponds to the Dish Azimuth (or Inner Arch Azimuth). However, when the BMF is in backscatter mode, the Dish and the entire Inner Arch are not used. For backscattering, $\theta_r = \theta_t$, and this angle corresponds to the Horn Elevation (or Outer Arch Elevation), and $\phi_t = 180°$.

1.3 Scattering Matrix

When a q-polarized transmit antenna, where $q = h$ or v, illuminates a target in the direction (θ_t, ϕ_t) with an electric field E_q^t, and a p-polarized receive antenna at a distance r from the target receives a field E_p^r (where $p = h$ or v) in the direction (θ_r,ϕ_r), the two fields are related to one another by the scattering amplitude of the target $S_{pq}(\theta_r, \phi_r; \theta_t, \phi_t, \theta_j, \phi_j)$:

$$E_p^r(\theta_r, \phi_r) = \frac{e^{ikr}}{r} S_{pq}(\theta_r, \phi_r; \theta_t, \phi_t; \theta_j, \phi_j) E_q^t(\theta_t, \phi_t) \tag{1.13}$$

where the direction (θ_j, ϕ_j) denotes the orientation of the target relative to a reference coordinate system, and $k = 2\pi/\lambda$ is the propagation wavenumber. Note that the first subscript of S_{pq} denotes the polarization of the received antenna and the second one denotes the polarization of the transmit antenna. In the $(\hat{h}, \hat{v})$ polarization space, there are four complex scattering amplitudes: S_{vv}, S_{vh}, S_{hv}, and S_{hh}. To accommodate the general case wherein the incident wave may have any polarization, and therefore may consist of both vertical and horizontal polarization components, we use the matrix form:

$$\begin{bmatrix} E_v^r \\ E_h^r \end{bmatrix} = \frac{e^{ikr}}{r} \begin{bmatrix} S_{vv} & S_{vh} \\ S_{hv} & S_{hh} \end{bmatrix} \begin{bmatrix} E_v^t \\ E_h^t \end{bmatrix} \tag{1.14}$$

or equivalently,

$$\mathbf{E}^r = \frac{e^{ikr}}{r} \mathbf{S}\mathbf{E}^t \tag{1.15}$$

The matrix **S** is called the scattering matrix of the target.

1.4 Radar Cross Section (RCS)

The scattering matrix **S** completely specifies the bistatic scattering behavior of the target for the specified incident and scattering direction. The *pq*-polarized radar cross section (RCS) of a point target is given by:

$$\sigma_{pq} = 4\pi |S_{pq}|^2 \tag{1.16}$$

The RCS for transmit and receive polarization combinations other than horizontal and vertical (such as circular and elliptical) can be calculated in terms of **S** using polarization synthesis [5].

1.5 Bistatic Scattering Coefficient

For a distributed target, such as a soil surface, the quantity of interest is the RCS per unit area, also called the bistatic scattering coefficient σ°. Because a distributed target is a collection of many scattering points, the scattered signal exhibits scintillation effects as a function of spatial position. Hence, to determine σ°, it is necessary to perform measurements of $\mathbf{S}$ for many spatial locations across the surface and then calculate the variance. If N observations are performed, then

$$\sigma^\circ_{pq} = \frac{4\pi}{A_{ill}} \sum_{i=1}^{N} \left(|S_{pq}|^2 \right)_i \tag{1.17}$$

where A_{ill} is the total effective illuminated area of the distributed target (see Section 5 of Chapter 3). In equation (1.17), $\mathbf{S}$ is assumed to have zero mean.

2 System Specification

The Bistatic Measurement Facility (BMF) uses an X-band bistatic radar system mounted on rotatable arches in order to measure the RCS of point targets or the bistatic scattering coefficient of distributed targets over a wide range of incident and scattering directions. Table 1.1 provides a summary of the system specifications. The sweet spot refers to the region near the center of the Bistatic Measurement Facility where the incident field is sufficiently planar to accurately measure a radar cross section. Refer to Section 1.1 of Chapter 2 for more details on using the sweet spot. The noise equivalent measurements refer to the values that the BMF reports when there is no scattering target observed, and represent the minimum values which are obtainable. The bistatic noise equivalents are measured in the specular direction, and the incidence angle is given. The noise equivalent measurements in the specular direction with the angle of incidence at 70° exhibits a higher value than does the similar measurement at 30° because some power leaks directly from the transmitter to the receiver. The noise equivalent measurements at 30° should be indicative of typical noise equivalents at most combinations of the bistatic angles where the antennas are not nearly pointed directly at each other.

A block diagram of the microwave components of the Bistatic Measurement Facility is shown in Figure 1.3. The horn serves as both the bistatic receiver and the backscatter antenna, and is mounted on the outer arch. The dish,

Table 1.1: Bistatic Measurement Facility system specifications

User supplied Network Analyzer	NWA	Hewlett-Packard 8510 or 8720
Network Analyzer Measurement Response		S21
Frequency Bandwidth	B	1.52 GHz
Center Frequency	f_c	9.25 GHz
Frequency Sweep Type		linear, 201 freq. pts.
Calibration Accuracy		±1 dB
Positional Accuracy (all axes)		$\pm 0.1^\circ$
Bistatic Transmitter:		
Antenna Type		Dish reflector
Polarizations	q	v and h
v-pol. Elevation One Way FWHP Beamwidth	β_{tv}^{el}	5.0°
v-pol. Azimuth One Way FWHP Beamwidth	β_{tv}^{az}	4.7°
h-pol. Elevation One Way FWHP Beamwidth	β_{th}^{el}	4.6°
h-pol. Azimuth One Way FWHP Beamwidth	β_{th}^{az}	4.6°
Range, aperture to BMF center	R_{t0}	2.11 m
Raw Polarization Isolation		>30 dB
Bistatic Receiver / Backscatter Antenna:		
Antenna Type		Horn with lens
Polarizations	p	v and h
v-pol. Elevation One Way FWHP Beamwidth	β_{rv}^{el}	9.8°
v-pol. Azimuth One Way FWHP Beamwidth	β_{rv}^{az}	11.3°
h-pol. Elevation One Way FWHP Beamwidth	β_{rh}^{el}	11.1°
h-pol. Azimuth One Way FWHP Beamwidth	β_{rh}^{az}	9.7°
Range, aperture to BMF center	R_{r0}	3.36 m
Raw Polarization Isolation		>30 dB
Bistatic Mode:		
Maximum Transmit Power Level	P^t	20 dBm
Approximate Diameter of "Sweet Spot"		9 cm
Noise Equivalent RCS at 30°	σ_{min}	<-50 dBsm
Noise Equivalent RCS at 70°	σ_{min}	<-30 dBsm
Approximate Effective Illuminated Area	A_{ill}	$266 \text{ cm}^2 \sec\theta_t$
Noise Equivalent Scattering Coefficient at 30°	σ_{min}^0	<-45 dB
Noise Equivalent Scattering Coefficient at 70°	σ_{min}^0	<-30 dB
Backscatter Mode:		
Maximum Transmit Power Level	P^t	10 dBm
Approximate Diameter of "Sweet Spot"		>15 cm
Noise Equivalent RCS	σ_{min}	<-40 dBsm
Approximate Effective Illuminated Area	A_{ill}	$2720 \text{ cm}^2 \sec\theta_r$
Noise Equivalent Scattering Coefficient	σ_{min}^0	<-30 dB

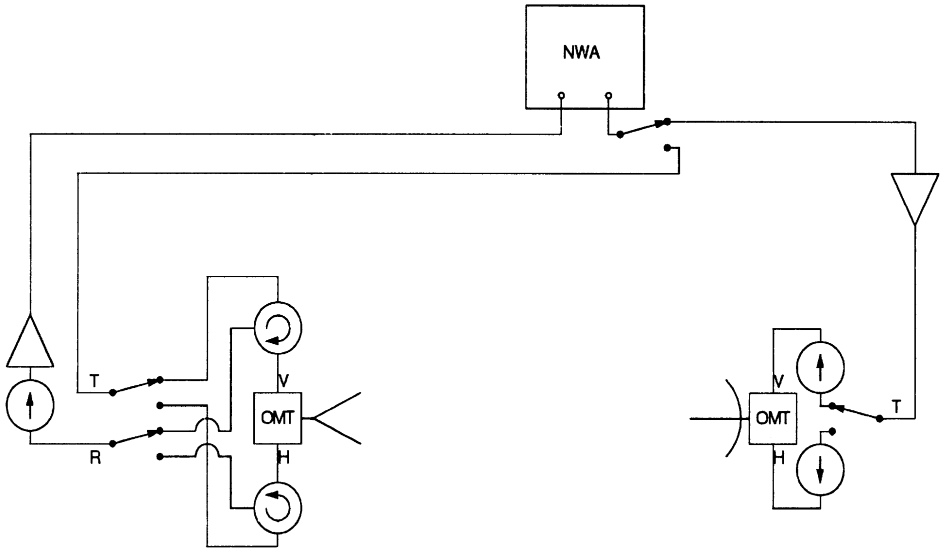


Figure 1.3: Bistatic System Microwave Block Diagram

mounted on the inner arch, is the transmitter when the BMF is in bistatic mode. Details of the microwave components, including the antenna patterns for horn and dish, are given in Chapter 6.

Chapter 2

Operation

1 Target Preparation

The proper preparation of targets is important to insure that measurements made by the Bistatic Measurement Facility are accurate. This section gives a number of helpful hints for this preparation.

1.1 Point Targets

The definition of a radar cross section σ for a point target assumes that the target is illuminated by a plane wave. For this assumption to be true, the target must be sufficiently small so that it fits within the "sweet spot." In both modes the sweet spot is approximately spherical and located at the center of the BMF, but the diameter differs in those two modes as shown in Table 1.1.

Locating the Center of the Facility

The center of the Bistatic Scattering Facility is that point at which the two antenna boresights intersect. It is also the point at which the three bistatic axes intersect. The center is exactly 30 inches off the floor, and the line which passes vertically though the center can be found with the following technique:

Move the inner arch elevation to 0° and the inner arch azimuth to 90°. Move the outer arch elevation such that its uprights are vertical. This should be at -1.5° for this axis. The two pairs of uprights can now be used as visual aids in locating the center of the Bistatic Measurement Facility. Stand close to one of the arch uprights, in the plane of the arch, but not inside the arch. Look across the plane of the arch, from the near upright to the far upright. The plane defined by the left (right) edge of the near upright and the right (left) edge of the far upright of the same arch goes directly through the center the Bistatic Measurement Facility. So does the similar plane defined by the other arch. Since the two arches are now perpendicular to each other, a vertical line going directly through the center of the Bistatic Measurement Facility is well defined. Place the target in the facility such that its center is exactly 30 inches above the floor. Move the target around until it can be verified to be in both planes defined by the two arches.

Using the Calibration Plate with Image Theory

The primary purpose of the calibration plate is for the proper calibration of the system. Another use of the calibration plate, used in conjunction with another object, is for verifying the ability of the Bistatic Measurement Facility to measure radar cross sections. The calibration plate shields the BMF from any objects underneath it, which can be a very useful property since the removal of a bulky distributed target is often very inconvenient. The only catch is that the object placed on the plate is now subject to two properties of image theory: first, the object and its mirror image appear in the receiver's field of view, and second, the target (and its mirror image) are illuminated simultaneously by the transmitter and a mirror image of the transmitter. Probably the most useful target to use with image theory is the hemisphere, because its RCS can be computed exactly and therefore it can be used to verify the operation of the BMF.

1.2 Distributed Targets

For distributed targets, the main issues involved in the preparation for a measurement is the proper use of the illuminated area and methods for producing a flat surface.

The Illuminated Area

Distributed targets are assumed to be very large with respect to the radar's beamwidth. The region which contributes to scattering is much larger than the sweet spot used for measuring point targets. Since the antenna illumination does not drop off instantly outside the beamwidth, this region is technically infinite in extent, but for almost all scattering situations it suffices to say that the region is where the transmitter and receiver gain pattern product, $G_r G_t$, is within 6 dB of the maximum gain product, which is the gain product at the center of the BMF. This region is known as the illuminated area and is denoted by A_{ill}. A_{ill} depends primarily on the antenna with the smallest beamwidth-range product, βR, and depends on the angle of incidence of this antenna, θ, as $1/\cos\theta$. Therefore, for bistatic mode, the illuminated area is determined by the transmit antenna and its incidence angle, while for backscatter mode, which uses only the horn antenna, the illuminated area is determined solely by the horn antenna and the backscattering angle.

The illuminated area is not directly calculated by the software. Rather, it calculates a quantity closely related to it, the illumination integral, I_{ill}. See Section 5 of Chapter 3 for further discussion of the illumination integral and the formulas used to calculate it.

While A_{ill} is the source of the scattering, it is important to keep all objects which are, or could be, very strong scatterers nowhere near the illuminated area. This is particularly important when the distributed target is a weak scatterer for the bistatic angles and/or polarizations desired, because strong scatterers, even though they might be in sidelobes of the antennas many tens of dB down from boresight, might still contribute the majority of the power received. Such objects include metal objects or anything with metal, water and wet objects (including living things), edges, and objects with planar sides which could specularly reflect from the transmit direction to the receive direction.

Making a Flat Surface

An important starting point for many distributed targets is the creation of a flat surface. For measuring volume scattering, a flat surface is useful because it does not scatter in any direction other than the specular direction, thus preventing contamination of the measured volume scattering with surface scattering. For measuring surface scattering, making a flat surface is a good starting point for making rough surfaces because the mean of the rough surface is then more likely to be flat, a requirement of most surface scattering theories.

For distributed targets made from a powdery solid, like sand or soil, the following technique has been found to be the best for creating a flat surface. Level the material as best as one can by hand, then create the final flat surface with a flat surface tool. Such a tool consists of a metal blade, from a strip of sheet metal or angle iron or similar material with a very straight and rigid edge, which is suspended horizontally over the sample holder while the turntable is made to rotate slowly but continuously. The blade acts like a plow, removing material when it is too high and filling in where it is too low. After one rotation it should be evident where the center of the sample holder is located, as it will be in the center of a small circle of unleveled material. Reposition the blade to pass through the center of that small circle and rotate the turntable again. Repeat the process of locating the center until it is found.

Once the center is found, the blade should be raised or lowered at one or both ends so that it carves a plane on the material instead of a cone. It is also desirable to get the surface as close to 30 inches above the floor as possible. Material may need to be added or removed from the center or the ends of the blade as the turntable rotates. Near the end of this procedure the surface will be flat and level but with a small amount of material being plowed by the blade. At this point the blade should be raised a tiny amount (approximately 1/16 inch) to enable this last material to be incorporated evenly into the flat surface. Once the surface is smooth and the blade no longer plows any material, it can be removed and the flat surface is complete.

2 Power Up

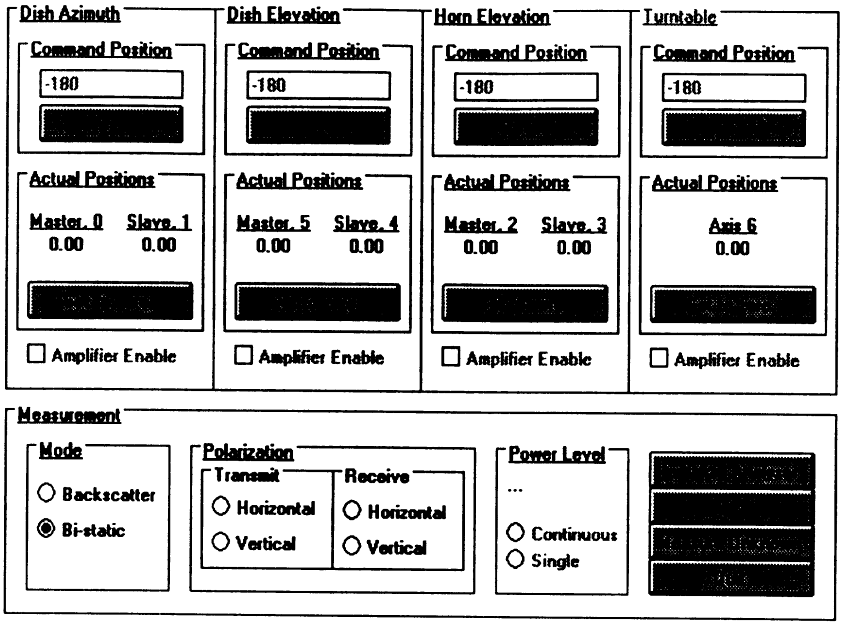
The following steps will quickly bring the Bistatic Measurement Facility to its operational state and insure that the bistatic angles are accurate.

2.1 Inspection

Make sure no cables have been snagged, disconnected or damaged before attempting to power up the facility. The rail should be cleared of all debris. If the HP-IB or the microwave plumbing is not attached to the network analyzer, do so now.

2.2 Apply Power

Power up the instruments in this order: network analyzer, computer monitor, printer (if connected), motor amplifiers, microwave relays, microwave



Dish Azimuth
Command Position: -180
Actual Positions: Master. 0 0.00 Slave. 1 0.00
☐ Amplifier Enable

Dish Elevation
Command Position: -180
Actual Positions: Master. 5 0.00 Slave. 4 0.00
☐ Amplifier Enable

Horn Elevation
Command Position: -180
Actual Positions: Master. 2 0.00 Slave. 3 0.00
☐ Amplifier Enable

Turntable
Command Position: -180
Actual Positions: Axis 6 0.00
☐ Amplifier Enable

Measurement
Mode: ○ Backscatter ● Bi-static
Polarization: Transmit ○ Horizontal ○ Vertical; Receive ○ Horizontal ○ Vertical
Power Level: ...
○ Continuous
○ Single

Figure 2.1: The Main Form, as it appears when the Bistatic Measurement Facility software is launched.

amplifiers, computer cpu. Nothing disastrous will happen if this order is not followed, but the components will have the longest life if this order is used.

2.3 Launch The Software

Once the Gateway 2000 PC has booted and produced a DOS prompt, type "win" and press the enter key to launch Windows. After Windows displays the Program Manager, double click the "Visual Basic 3.0" icon to open the Visual Basic directory. In that directory, launch the Visual Basic application by double-clicking the "Microsoft Visual Basic" icon. From the "File" menu, select "Open Project..." The project to open is "sigzero.mak" in the "c:\bistatic" directory. Press the F5 key or select "Start" under the "Run" menu to execute the Bistatic Measurement Facility software. The software will display the main form, as shown in Figure 2.1, and await user instructions.

In the following discussion, a number of terms, like "radio button" or "form," are used. These are the Visual Basic terms for these standard Graphical User Interface (GUI) software items and the user is referred to that documentation for detailed explanations of their appearance and properties.

2.4 Zero Axes

The physical axes of the system do not have absolute encoders, home or limit switches, or other means of determining absolute position without user intervention. Thus the axes must have their zero positions set by the user. The following paragraphs describe how to put the three bistatic axes into the zero position manually. The software should be running during this process, so that the axes, once in the correct position, can be powered up and thus prevent any inadvertent motion from taking them from the zero position. This is done in the main form of the software by clicking the "Set to Zero" button for the appropriate axis, then clicking the "Amplifier Enable" checkbox to apply power to the motors, thus keeping them at the correct zero position. If the axes have have not had their amplifiers disabled since the last time the axes were zeroed, they do not need to be re-zeroed at this time.

Inner-arch Azimuth

The inner arch azimuth axis zero position is where the inner arch axis of rotation is aligned with the outer arch axis of rotation, and the cables go around the sample holder. (The facility is designed to have the cars in the exact same position, but with the cables going around a spool on the floor instead. That is the 360° position.) Since it is hard to align the axes themselves (the big sprockets obstruct vision), the alignment can be checked by making sure the edges of the inner arch car are in line with the edges of the outer arch stand. The cars cannot be pushed directly into position because the cars' driven wheels are directly attached to a worm gear, which locks when torque is applied to the output shaft. Therefore, if a car needs to be moved, the driven wheel must be used to move it or the driven wheel must be lifted off the floor to allow the other wheels to roll. If a car needs to be moved for proper alignment, pick it up near the driven wheel until the driven wheel is not in contact with the floor and slide the car around on the rail. Be careful to put the car back down on the rail properly. When both cars are properly aligned with the stands, the "Dish Azimuth" axis may be "set to zero" with the softkey. Then enable the amplifiers for this axis to prevent any inadvertent motion, such as that induced by manually zeroing the inner arch elevation.

Inner-arch Elevation

For the inner arch, the zero position is with both arch uprights in the vertical position. If the center of the arch, where the antenna is located, can be reached, move the arch toward vertical by applying an upward force on the arch at that point. Do not apply any force directly to the antenna, as that may misalign it. After the arch is sufficiently upright that the center of the arch is out of reach, the arch uprights can be moved toward vertical with the aid of an assistant (one person on each upright near the axis), or solo, if one is careful to move each side only a little at a time. Do not move one side so hard as to "pull" the other side along with it. Confirm that the arch uprights are both vertical with the aid of a carpenter's level. If one upright needs adjustment, be sure to remeasure both uprights with the carpenter's level before proceeding. Once the inner arch has been set to vertical, the "Dish Elevation" axis may be "set to zero" via the softkey. Then enable the amplifiers for this axis to prevent any inadvertent motion.

Outer-arch Elevation

For the outer arch elevation, the procedure is the same as for the inner arch elevation, except for a few additional steps after the arch has been "set to zero." The software recognizes the outer arch as the "Horn Elevation," so that is the axis which now must be "set to zero" and "enabled." Because the antenna on the outer arch is mounted on the side of the arch instead of the center like the antenna on the inner arch, it is now not at vertical, but instead is off by a few degrees. After the amplifiers have been enabled, type "1.5" in the command position for the "Horn Elevation," then hit the "Move" softkey. Wait until the actual positions agree with each other and are within one count of the command position (for both elevation axes, one count is about 0.05°). Then disable the "Horn Elevation" axis, set it to zero, and re-enable the axis.

3 Using the Software

Now that the Bistatic Facility's axes have been aligned and the motor amplifiers for each axis have been enabled, all interactions between the user and the bistatic facility itself (not including the targets) can be done with the software.

3.1 Moving the Antennas

Each bistatic axis has a frame in the main form (see Figure 2.1) which has exclusive control over the motion of that axis. In addition to the "Set to Zero" command button and the "Amplifier Enable" checkbox, both explained in Section 2.4, there is a text box and "Move" command button for the motion of the axis. The "Actual Position" frame has labels which display the logical axis numbers for the master and slaved axes associated with the bistatic axis, as well as their current positions (in degrees).

3.2 Set the Mode

The mode, backscatter or bistatic, must be set using the radio buttons on the lower left side of the main form. The default mode is bistatic. Pressing one of these radio buttons will cause the software to initialize the network analyzer for the appropriate mode, but will also erase all calibration data and invalidate the current calibration. The system is ready for either making raw measurements or for calibrating.

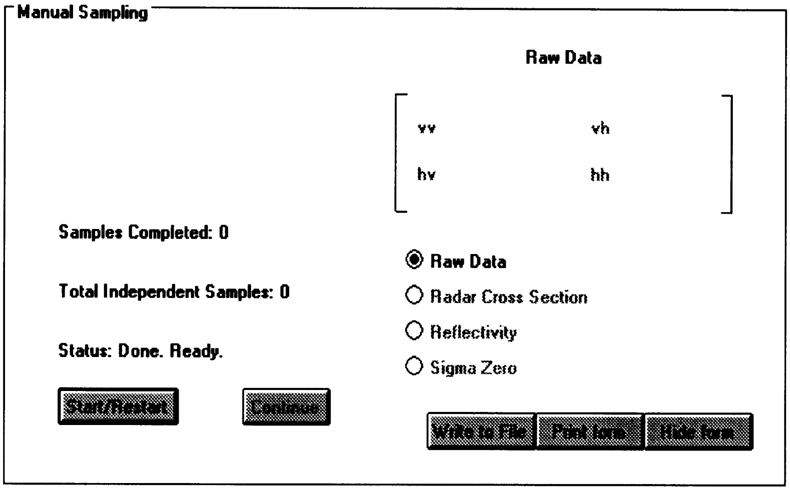
If the system is in backscatter mode, the entire inner arch is superfluous to the operation of the system. Therefore, it should be moved to a position such that it is out of the way for making measurements. Moving the inner arch elevation to +90° or -90° will keep it entirely out of the field of view of the backscatter antenna, regardless of the backscattering angle of incidence.

3.3 Initialize the Network Analyzer

If the mode was not explicitly set, that is, it was left in bistatic mode, the network analyzer must be initialized by clicking the "Initialize Analyzer" command button. This command button puts the network analyzer into a known state, but does not, by itself, invalidate a completed calibration. Anytime the front panel of the network analyzer has been accessed, re-initializing the network analyzer with this command button before doing anything else with the software is highly encouraged.

3.4 Raw Measurements

Raw measurements can be done in two ways, manually from the main form, or with all the polarizations done at once in the measurement form. Either



Samples Completed: 0

Total Independent Samples: 0

Status: Done. Ready.

● Raw Data
○ Radar Cross Section
○ Reflectivity
○ Sigma Zero

Figure 2.2: The Measurement Form, for manual sampling, as it appears when the Bistatic Measurement Facility is not calibrated.

way, the bistatic angles must be set using the axis controls in the main form. Within the main form, the user also has control of the polarization state of the facility via the polarization frame, and the raw power level of the signal received at the network analyzer may be read with the power level frame.

Within the power level frame, which is enabled only after the NWA has been initialized, there are two command buttons. The "Single" command button takes a single trace of the network analyzer and reports the power at the center frequency. The "Continuous" command button repeatedly makes single traces and updates the power at the center frequency as it gets it. The "Continuous" command button may be turned off by clicking the "Single" command button, or by doing various other actions (such as starting a calibration or measurement).

The radio buttons in the polarization frame control the settings of the polarization switches that are part of the antenna assemblies. The software cannot detect whether the power is applied to the microwave switches, so it is the user's responsibility to ensure that the microwave relay power switch is on.

By clicking the "Measure Unknown" command button and then clicking

"Manual" in the menu, the measurement form appears as shown in Figure 2.2. The only type of measurement enabled at this point is the raw data, which measures the center frequency power for each polarization and reports the value without applying any calibration, conversion or statistical analysis. The major difference between this measurement and that done from the main form, other than the fact that all four polarizations are done, is that measurements made in the measurement form have an averaging factor set to 8 on the network analyzer, while that done from the main form has the averaging off (which is the same as an averaging factor of 1). Thus raw measurements done in the measurements form has a signal to noise ratio 9 dB greater than that made from the main form.

Raw measurements have limited usefulness, as their numbers can only be compared to other numbers generated in exactly the same fashion, ie. on that particular bistatic facility. Thus the raw measurements are useful primarily in troubleshooting. For example, the operation of the polarization switches can be easily verified by moving the antennas into the specular angles for a calibration plate, then measuring the plate in the different polarization states.

3.5 Calibration

In order to make meaningful measurements, the system must be calibrated. This can be done by clicking the "Calibrate" command button on the main form, which loads the calibration form appropriate for the mode the system is in. Refer to Chapter 3 for the appropriate calibration instructions to calibrate the system.

3.6 Calibrated Measurements

Upon first entering the measurement form, only the menu is visible. One of the two items on the menu, "Manual" or "Automatic," must be clicked, which will show the measurement form.

Manual sampling refers to the fact that the software waits for the user to modify the target in some fashion between measuring independent samples. The user must acknowledge to the software (via the "Continue" command button) that the target has been set to a new independent sample before the BMF will make further measurements.

In automatic sampling, the software rotates the target on the turntable to generate new spatial independent samples between measurements, thus not requiring user intervention. However, entering automatic sampling without the proper turntable controller attached will cause the software to go into a loop which can be escaped only by stopping the program.

These two menu items may be clicked any time the measurement form is open.

Manual Sampling

The measurement form for manual sampling, as shown in Figure 2.3, displays information in two columns side by side:

On the left, from top to bottom, is a display of the spatial samples completed, the total number of independent samples measured for the current measurement sequence, the current status of the Bistatic Measurement Facility, and finally two command buttons, one for (re-)starting a measurement and a second for continuing a measurement already started.

On the right, from top to bottom, is a 2×2 array of the measured data, four radio buttons showing the type of information to be displayed in the array, and three command buttons. The radio buttons are entitled "Raw Data", "Radar Cross Section", "Reflectivity", and "Sigma Zero." The title of the array matches that of the radio button which has been selected. The three command buttons, which are always visible and enabled, are, from left to right, "Write to File," "Print Form," and "Hide Form."

When the "Radar Cross Section" radio button is selected, as in Figure 2.3, an additional command button and check box appear which have to do with background subtraction. The command button is captioned "Measure Bkgnd" and is used to measure the background for a point target (ie. the scene with just the target itself removed, but with all support structures and bistatic angles unchanged). The measurement of a background occurs in the same fashion as any other measurement, and it takes the same time to complete, but the data is stored in a temporary array. If this check box, captioned "Subtract Bkgnd", is turned on (off), the RCS is recalculated and displayed with the background subtracted (ignored).

The "Start/Restart" command button on the left side of the form is used to reset the statistics used to generate the reflectivity and the scattering coefficient, and start the measurement of the first sample. The "Continue" command button is used to measure an additional sample, and can be used repeatedly to measure an arbitrary number of samples.

Clicking the "Write to File" command button will cause certain information

Table 2.1: Integer codes in the final column of output files

measurement type	integer code
Raw Data	0
RCS	1
Reflectivity	2
Sigma Zero	3

on the current measurement to be written as a single line at the the end of the file *c:\patterns\bmf.dat.* The information is written in ASCII in this order: outside arch elevation, inside arch elevation, inside arch azimuth, the four elements of the array of measured data (vv, vh, hv, hh), and an integer indicating which of the radio buttons is active (and therefore, what kind of data is being written to the file). The bistatic angles are recorded in degrees, the measured data is recorded in dB or dBsm, as appropriate, and the integer has one of the four values given in Table 2.1.

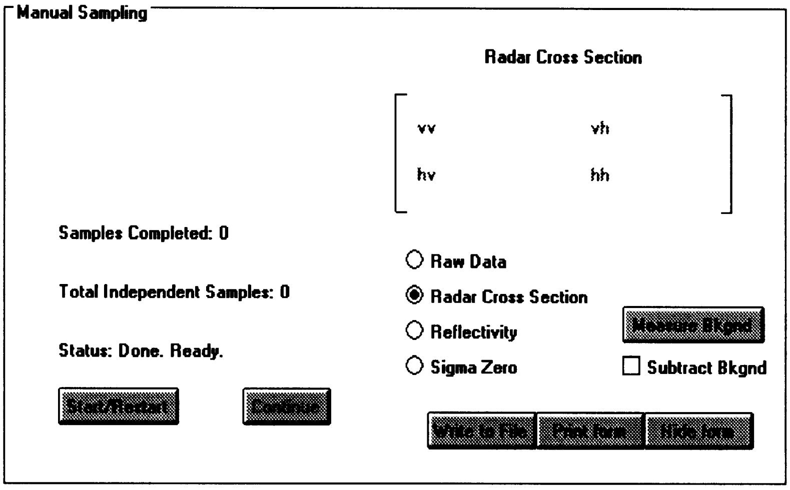
Clicking the "Print Form" command button will cause the measurement form to be printed on a properly configured printer which is connected in some fashion to the computer. The computer system is delivered with the assumption that a printer is attached to the printer port LPT1, but the user may reconfigure the default printer with other software provided with Windows. If no printer is attached, any attempt to use this command button will be ignored.

Clicking the "Hide Form" command button will cause the measurement form to be hidden, returning the user to the main form.

See Section 5 of Chapter 3 for explanations of the precise meanings of the different types of data that the Bistatic Measurement Facility can produce.

Automatic Sampling

Clicking the "Automatic" menu option brings up the same form as does clicking the "Manual" menu option, but with a few additional pieces of information: two text boxes and an additional command button. The measurement form for automatic sampling is shown in Figure 2.4. Refer to the manual sampling section above for explanations of the form elements that appear in common between the two sampling methods.



Samples Completed: 0

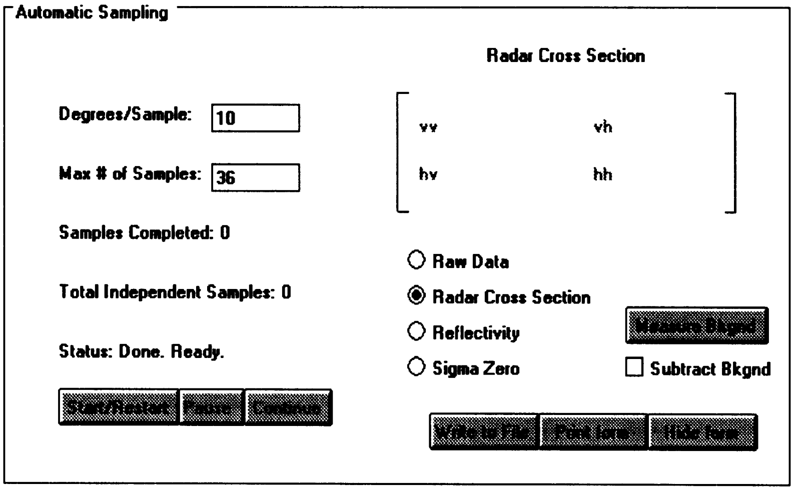
Total Independent Samples: 0

Status: Done. Ready.

○ Raw Data
● Radar Cross Section
○ Reflectivity
○ Sigma Zero

☐ Subtract Bkgnd

Figure 2.3: The Measurement Form, for manual sampling, as it appears when the Bistatic Measurement Facility has been calibrated and RCS is the chosen measurement unit.



Automatic Sampling

Degrees/Sample: 10

Max # of Samples: 36

Samples Completed: 0

Total Independent Samples: 0

Status: Done. Ready.

Radar Cross Section

○ Raw Data
● Radar Cross Section
○ Reflectivity
○ Sigma Zero

☐ Subtract Bkgnd

Figure 2.4: The Measurement Form, for automatic sampling, as it appears when the Bistatic Measurement Facility has been calibrated and RCS is the chosen measurement unit.

On top of the left hand side are two text boxes for entering information regarding the use of the turntable. The first text box is for entering the number of degrees the turntable should rotate between independent samples, and the second is for entering the maximum number of independent spatial samples (the number of times the turntable is rotated and the target is measured).

There is an additional command button on the left side of the form, with the caption of "Pause." Clicking this command button will cease program execution, but only after the current sample measurement has been completed. This allows the user to do something with the target or the BMF without invalidating a measurement or having to wait for the measurement sequence to complete. Anytime the software has been paused, and the measurement of that particular spatial location has been completed, the measurement sequence can be continued indefinitely with the "Continue" command button or restarted with the "Start/Restart" command button.

Manual sampling is the same as Automatic sampling except that the turntable is ignored, and that the software tells itself to pause anytime "Start/Restart" or "Continue" has been clicked.

Chapter 3

Calibration

The network analyzer measures only the the ratio of received to transmitted power. This ratio is dependent on the polarization state, the geometry of the Bistatic Measurement Facility, and, of course, the target. This ratio can be converted into a useful quantity, such as the bistatic radar cross section σ or the scattering coefficient σ^0, only after calibration. The calibration procedures are described in Section 3.2 and Section 4.2. But first, a brief introduction is presented to acquaint the reader with the general concept of distortion matrices and associated terminology.

1 Distortion Matrix Model

The distortion matrix model [6] was developed to analyze the relationships between the ideal scattering characteristics of a point target and the actual signals measured by a NWA. The method is very similar to the S-parameter analysis method used in conjunction with microwave networks. A review of the calibration documentation for a typical NWA is very instructive towards the general approaches that are described in this chapter.

The Bistatic Facility, regardless of whether it is in bistatic or in backscatter mode, can measure four quantities for each target position. These are four complex voltage ratios corresponding to four combinations of the transmit and receive polarizations. The transmitter is equipped with a polarization switch which can be actuated to cause the antenna to transmit a nominally horizontally polarized or nominally vertically polarized wave. Similarly, the receiver is equipped with a similar polarization switch that causes the receive antenna to accept a nominally vertically or nominally horizontally polarized wave. Deviations from the perfect polarization state are called distortions, and the purpose of the calibration procedure is to correct them.

The four measurements constitute a 2×2 scattering matrix, denoted $\boldsymbol{M}$ (for the *measured* scattering matrix), with elements denoted M_{rt}, where r represents the nominal receive polarization (either v or h), and t represents the nominal transmit polarization (again, either v or h). $\boldsymbol{M}$ can be considered to consist of two terms, an undesired signal $\boldsymbol{B}$ due to *background* effects, and a desired signal due to the target $\boldsymbol{S}$ distorted by an imperfect transmitter $\boldsymbol{T}$ and an imperfect receiver $\boldsymbol{R}$, and scaled by a constant:

$$\boldsymbol{M} = \boldsymbol{B} + k_{cal}\boldsymbol{RST} \tag{3.1}$$

or,

$$\begin{aligned}\begin{pmatrix} M_{vv} & M_{vh} \\ M_{hv} & M_{hh} \end{pmatrix} &= \begin{pmatrix} B_{vv} & B_{vh} \\ B_{hv} & B_{hh} \end{pmatrix} \\ &+ k_{cal}\begin{pmatrix} R_{vv} & R_{vh} \\ R_{hv} & R_{hh} \end{pmatrix}\begin{pmatrix} S_{vv} & S_{vh} \\ S_{hv} & S_{hh} \end{pmatrix}\begin{pmatrix} T_{vv} & T_{vh} \\ T_{hv} & T_{hh} \end{pmatrix}\end{aligned} \tag{3.2}$$

where all the matrix elements are complex. Thermal noise is assumed to be negligibly small.

The background term $\boldsymbol{B}$ can be directly measured in the absence of a target (i.e., when $\boldsymbol{S} = 0$) and then, if not already negligibly small, subtracted from the measured scattering matrix to give the distorted signal from the desired target:

$$\boldsymbol{N} = \boldsymbol{M} - \boldsymbol{B} = k_{cal}\boldsymbol{RST} \tag{3.3}$$

If a measurement of $\boldsymbol{B}$ results in the measurement of noise (i.e., the measurements of $\boldsymbol{B}$ are not repeatable), then the background should be ignored by assigning all the elements of $\boldsymbol{B}$ to zero.

$\boldsymbol{S}$ is the 2×2 polarimetric scattering matrix of the target under examination. Its complex elements are functions of the bistatic angles $(\theta_t, \theta_r, \phi_t)$ as well as the target's orientation (θ_j, ϕ_j). When $\boldsymbol{S}$ is theoretically known, as for calibration targets, it will be denoted $\boldsymbol{P}$.

$\boldsymbol{R}$ is the 2×2 distortion matrix for the receive antenna, and represents the effects (gain, loss, phase delay, etc) of the horn, orthomode, circulators, transitions, and plumbing up to and including the microwave switch. For example, R_{pq} is the signal measured at the common terminal of the microwave switch while it is in the p-polarized position and the antenna is illuminated with a perfect unit amplitude q-polarized plane wave. Since the target is designed to always reside in the receive antenna's far field, the R_{pq} elements incorporate the $\frac{e^{ikR_r}}{R_r}$ range dependence. The matrix elements also incorporate the antenna gain by being functions of the directions from the antenna (as measured from boresight). Within the main beam, $|R_{pq}| \ll |R_{qq}|$. $\boldsymbol{R}$ is the same regardless of whether the system is in backscatter or bistatic mode, since the same hardware is used to receive in both modes.

$\boldsymbol{T}$ is the 2×2 distortion matrix for the transmit antenna, and represents the effects (gain, loss, phase delay, etc) of the feed horn, dish and supports, orthomode, transitions, isolators, and plumbing up to and including the microwave switch. T_{pq} is the amplitude and phase of the p-polarized component of the transmitted wave when the microwave switch is in the q-polarized position and a unit amplitude signal applied to the common terminal of the switch. Unlike $\boldsymbol{R}$, $\boldsymbol{T}$ depends on measurement mode of the system. For backscattering, $\boldsymbol{T}$ has very similar range and direction characteristics as does $\boldsymbol{R}$. The bistatic transmit module, however, is not designed to operate with the target in its far field, and thus the T_{pq} elements are more complicated functions of direction (as measured from boresight) and range from the antenna. Within the main beam, $|T_{pq}| \ll |T_{qq}|$.

k_{cal} is a complex constant accounting for the change in amplitude and phase of the signal due to elements in common for all measurement polarizations. This includes all the active elements (amplifiers and the NWA), as well as the microwave plumbing up to the antenna modules. If some of the plumbing has been damaged or if plumbing connections have come loose, it may change with respect to the bistatic angles, but the system was designed such that this constant remains unchanged over long periods of time, regardless of the measurements made.

Calibration then is the measuring of a set of targets with theoretically known $\boldsymbol{P}^{cal}$ and using the corresponding $\boldsymbol{N}^{cal}$ to determine an unknown $\boldsymbol{S}^{unk}$ from a measurement $\boldsymbol{N}^{unk}$. The resulting $\boldsymbol{S}^{unk}$ has the same units as $\boldsymbol{P}^{cal}$. In other words, if a sphere is used as a calibration target, then $\boldsymbol{S}^{unk}$ will be reported as a radar cross section, whereas if a large conducting plate is used as a calibration target the unknown targets will be reported in units of reflectivity. No reliable distributed targets have been developed for the purpose of calibration, so if the unknown targets are distributed the measurements must be translated into a differential radar cross section σ^0.

2 General Calibration Technique

Whitt and Ulaby [6] developed a calibration technique, known as the General Calibration Technique, with which the matrices $\boldsymbol{R}$ and $\boldsymbol{T}$ can be determined by using three calibration targets with known characteristics $\boldsymbol{P}_1, \boldsymbol{P}_2, \boldsymbol{P}_3$ and the following conditions:

(1) $\boldsymbol{P}_1$ (at least) is an invertible matrix.

(2) Both $\boldsymbol{P}_1^{-1}\boldsymbol{P}_2$ and $\boldsymbol{P}_1^{-1}\boldsymbol{P}_3$ must have distinct eigenvalues; i.e., $\lambda_1 \neq \lambda_2$.

(3) $\boldsymbol{P}_1^{-1}\boldsymbol{P}_2$ and $\boldsymbol{P}_1^{-1}\boldsymbol{P}_3$ must have no more than one common eigenvector.

(4) Both $\boldsymbol{P}_1^{-1}\boldsymbol{P}_2$ and $\boldsymbol{P}_1^{-1}\boldsymbol{P}_3$ must have eigenvalues which are not negatives of each other; i.e., $\lambda_1 \neq -\lambda_2$.

If the first 3 conditions are not met, the calibration targets are not sufficiently different to determine $\boldsymbol{R}$ and $\boldsymbol{T}$. The last condition is not described in [6] and if it is not met the solutions for $\boldsymbol{R}$ and $\boldsymbol{T}$ are not unique. The incorrect solutions may or may not be obvious.

Examples of a set of targets which fulfill these criteria for backscatter are: a sphere, a 45° oriented metallic cylinder, and a horizontally oriented metallic cylinder. The corresponding theoretical scattering matrices of these targets are (in the limit as the cylinder diameter becomes very small):

$$\boldsymbol{P}_1 = \boldsymbol{P}_{sphere} = c_1\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \tag{3.4}$$

$$\boldsymbol{P}_2 = \boldsymbol{P}_{45^\circ\ cyl} = c_2\begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} \tag{3.5}$$

$$\boldsymbol{P}_3 = \boldsymbol{P}_{horiz\ cyl} = c_3\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \tag{3.6}$$

where c_1,c_2, and c_3 are constants which depend on the size and wavelength.

Kähny [2] uses a fixed set of calibration targets to solve the calibration problem in a similar fashion. However, he employs a unique "twist": He measures two physically different targets, but obtains a third by rotating one of the bistatic antennas 90° about its boresight direction. For this purpose, the Bistatic Facility Transmitter Module has been designed to rotate about its boresight direction. When the transmitter is rotated by θ about its boresight, the target's scattering matrix gets modified from $\boldsymbol{P}$ to $\boldsymbol{P}' = \boldsymbol{P\theta}$ where

$$\boldsymbol{\theta} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \tag{3.7}$$

(If the Receiver Module were capable of such rotations, the new target scattering matrix would be $\boldsymbol{\theta}^{-1}\boldsymbol{P}$). The reader is referred to [6] for details of the General Calibration Technique.

The improvement in a backscatter antenna's cross polarized isolation (the minimum value of *measured* $\left|\frac{S_{vv}}{S_{vh}}\right|^2, \left|\frac{S_{vv}}{S_{hv}}\right|^2, \left|\frac{S_{hh}}{S_{vh}}\right|^2$ and $\left|\frac{S_{hh}}{S_{hv}}\right|^2$ for a target whose *theoretical* $P_{vh} = P_{hv} = 0$) is a good indicator of the quality of a calibration technique. The GCT improves the isolation from a raw value of 20 dB (i.e., assuming $R_{vh} = R_{hv} = T_{vh} = T_{hv} = 0$) to a corrected value of 50 dB. A perfect calibration technique would make the isolation infinite.

While the technique is exact, its application is somewhat cumbersome. The targets require very accurate positioning and orientations to prevent small errors from overwhelming the minute corrections that the technique provides. The General Calibration Technique is therefore reserved for situations requiring very accurate polarimetric measurements. Other more convenient approaches are discussed in the following sections, first for the backscatter case and next for the bistatic case.

3 Backscatter Calibration

3.1 Single Target Calibration Technique

The Single Target Calibration Technique (STCT) was developed by Sarabandi and Ulaby [3] for a backscatter antenna for which the distortion was small, but not negligible. It starts by taking the distortion model and further separating some of the physical processes contained in the distortion elements, in particular the electrical differences in plumbing (length of coaxial tubing, different circuit elements, etc.) for the different polarizations as separated from the depolarizations caused by geometrical imperfections (in the dish, feed, horn, etc.). Mathematically, these are represented as:

$$\boldsymbol{R} = \boldsymbol{R}_p\boldsymbol{C}_r \tag{3.8}$$

$$\boldsymbol{T} = \boldsymbol{C}_t\boldsymbol{T}_p \tag{3.9}$$

where

$$\boldsymbol{R}_p = \begin{pmatrix} R_v & 0 \\ 0 & R_h \end{pmatrix} \tag{3.10}$$

$$\boldsymbol{T}_p = \begin{pmatrix} T_v & 0 \\ 0 & T_h \end{pmatrix} \tag{3.11}$$

$$\boldsymbol{C}_r = \begin{pmatrix} 1 & C_{rv} \\ C_{rh} & 1 \end{pmatrix} \tag{3.12}$$

$$\boldsymbol{C}_t = \begin{pmatrix} 1 & C_{th} \\ C_{tv} & 1 \end{pmatrix} \tag{3.13}$$

Since the same physical antenna is used for transmitting and receiving, the geometric distortions for transmit and receive are identical. Thus, $C_{th} = C_{rh}$ and $C_{tv} = C_{rv}$ (let us denote them as C_h and C_v respectively). Then, this technique assumes that all these crosstalk terms are identical; i.e., $C_h = C_v$, which is then denoted as C. The justification for this assumption is described in [3], and requires that $|C_h| \ll 1$ and $|C_v| \ll 1$. Most dual-polarized antennas are built such that both $|C_h|$ and $|C_v|$ are approximately on the order of -20 dB.

The calibration is achieved by measuring a single target with a theoretical scattering matrix proportional to the identity matrix:

$$\boldsymbol{S}_{cal} = s_{cal} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \tag{3.14}$$

Such targets include a sphere in freespace, and a large conducting plate. If a sphere is used, the calibration results in measurements reported in radar cross section; if the plate is used the measurements are reported in term of reflectivity. These units can be converted into each other or into differential radar cross sections with the appropriate knowledge of the antenna pattern, as discussed in Section 5.

After background subtraction (if necessary), we achieve a set of four complex values: $\boldsymbol{N}^{cal}$. From this single set of measurements we generate a complex parameter a:

$$a = \frac{N_{vh}^{cal} N_{hv}^{cal}}{N_{vv}^{cal} N_{hh}^{cal}} \tag{3.15}$$

Since we assume that the crosstalk is small to begin with, and the measured target has no cross-polarized scattering, we can expect $|a| \ll 1$. In fact, it can be shown that a and C are related by

$$C = \pm\frac{1}{\sqrt{a}}\left(1 \pm \sqrt{1-a}\right) \tag{3.16}$$

which has four solutions. Fortunately, two of the solutions result in a value of C which is not small, and can be discarded. These large incorrect values are a consequence of the fact that $P^{cal}_{vv} = P^{cal}_{hh}$ and therefore the calibration cannot, by itself, tell the difference between $\hat{v}$ and $\hat{h}$ at the target. Then, since a is small, we can expand the expression for C in a Taylor series to avoid division by a small number:

$$C = \frac{b}{2}\left(1 + \frac{a}{4} + \frac{a^2}{8} + \cdots\right) \tag{3.17}$$

where $b = \pm\sqrt{a}$.

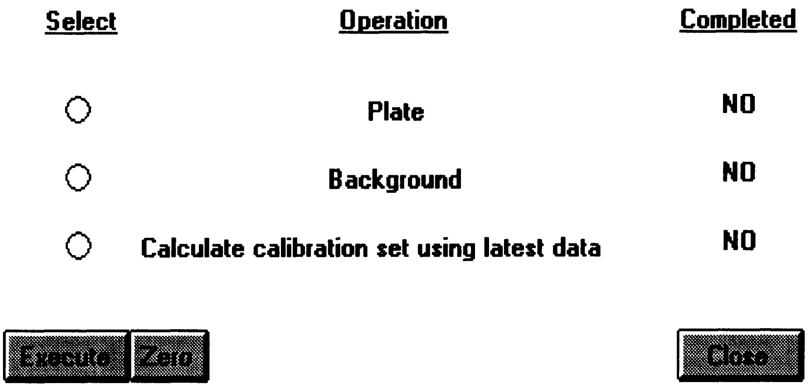
We cannot solve directly for R_h, R_v, T_h or T_v. However, given a measurement of an unknown target $\boldsymbol{N}^{unk}$, we can solve for the scattering matrix $\boldsymbol{S}^{unk}$ that would result in such a measurement for this antenna under this set of (reasonable) assumptions:

$$\begin{aligned} \boldsymbol{S}^{unk} &= \begin{pmatrix} S^{unk}_{vv} & S^{unk}_{vh} \\ S^{unk}_{hv} & S^{unk}_{hh} \end{pmatrix} \qquad (3.18) \\ &= s_{cal}\frac{1+C^2}{(1-C^2)^2}\begin{pmatrix} 1 & -C \\ -C & 1 \end{pmatrix}\begin{pmatrix} \frac{N^{unk}_{vv}}{N^{cal}_{vv}} & b\frac{N^{unk}_{vh}}{N^{cal}_{vh}} \\ b\frac{N^{unk}_{hv}}{N^{cal}_{hv}} & \frac{N^{unk}_{hh}}{N^{cal}_{hh}} \end{pmatrix}\begin{pmatrix} 1 & -C \\ -C & 1 \end{pmatrix} \end{aligned}$$

The result is unambiguous in S_{vv} and S_{hh}, but there is a 180° ambiguity in the phase of S_{hv} and S_{vh}, as evidenced by the choice of sign in the calculation of b. Another measurement is required to determine the sign, but is unnecessary if magnitudes of the scattering matrix are all that is desired.

3.2 Backscatter Calibration Procedure

With the software displaying the backscattering calibration form, which is shown in Figure 3.1, three radio buttons and either two or three command buttons appear. The radio buttons are labelled "Plate", "Background", and "Calculate calibration set using latest data". They are used to determine the next object upon which the software will act, but selecting them in and



Select	Operation	Completed
○	Plate	NO
○	Background	NO
○	Calculate calibration set using latest data	NO

Figure 3.1: The Calibration Form, as it appears when the Bistatic Measurement Facility is in backscatter mode.

of themselves does not do anything. To the right of the radio buttons is a column displaying the status for each object. Possible messages in the status column are: “NO”, meaning that no action has yet taken place with that object; “Working”, meaning that the software is busy with that object; and a time, which indicates when the last action on that object was completed. The background has an additional status: “0’d” and a time, indicating that the last action on the background was a deletion of the background data and when it happened.

The command buttons are used for telling the software to do something, and are labelled “Execute”, “Zero”, and “Close”. The “Close” command button is used to exit the form and return to the main form, and can be used at any time during the calibration procedure. The “Execute” command button is used to either measure the plate or background, or to calculate the calibration set. The “Zero” command button only applies to the “Background” radio button, so it only appears if that radio button is selected, and is used to erase the measured data for the background target. In effect, it returns the background data to the state it was when the calibration form was first entered; that is, the background is unmeasured.

The following order of steps is recommended for backscattering calibration.

Position Calibration Target

Place a large sheet of aluminum at the center of the Bistatic Facility. It must be flat and level, and at a height equal to the axis of rotation of the bistatic facility (30 inches off the floor).

Position The Backscattering Antenna

From the main form in the software, move the antenna to 0°. If the inner arch is positioned such that it is between -20° and +20°, it will also need to be moved to prevent it from affecting the calibration measurement.

Measure The Calibration Target

Make sure the "Plate" radio button is selected, then click on the "Execute" command button. The status column will show "Working" for about 30 seconds then display the time when the measurement was completed.

Measure The Background (optional)

The object of this measurement is to determine how much of the calibration measurement is due to scattering from other than the calibration target. We have found that the calibration measurement on this bistatic facility has such a large signal to background ratio that this measurement is not necessary for accurate calibration. However, should the system change so that the signal to background ratio be substantially reduced (to 30 dB or less), this measurement would be essential. About the only thing which could cause such a reduction is damage to microwave components, which could then introduce internal reflections within the microwave plumbing and multipath with the same length as the direct path involving the calibration target.

With the same aluminum plate in the same location, the background can be measured by moving the outer arch away from the specular direction. We recommend that it be moved to more than 30° away from nadir for a valid background measurement. In this position, the plate will not scatter any energy back toward the antenna, and the time-gating on the network analyzer will prevent other nearby objects from being measured. Again, the inner arch must not be within the field of view of the backscattering antenna. Select the "Background" radio button, and then select the "Execute" command button.

The status will display "Working" for about 30 seconds then display the time the measurement was completed.

Calculate The Calibration Set

Anytime a valid "plate" measurement has been completed, the calibration set may be calculated. Select the "Calculate calibration set using latest data" radio button then select the "Execute" command button. The software will then calculate the calibration set using the STCT algorithm and display the time it was completed.

Leave The Calibration Form

Remove the calibration plate (unless it is going to be used for measurements) and select the "Close" command button to return to the main form. The bistatic system is now calibrated in backscatter mode and is ready for measurements, as described in Section 3.6 of Chapter 2.

4 Bistatic Calibration

4.1 Bistatic Calibration Theory

The basic bistatic calibration procedure is based on the Isolated Antenna Calibration Technique (IACT) developed for backscattering by Sarabandi *et al.*[4]. The IACT is a precursor to the STCT described in Section 3.1, and it does not account for antenna cross-talk. In other words, C is assumed to be not just small, but to be zero.

In addition, the transmitter is made to rotate about its boresight direction. For a rotation of θ degrees, the transmit distortion matrix for a distortionless antenna becomes:

$$\boldsymbol{T} = T_v \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & T'_h \end{pmatrix} \tag{3.19}$$

where $T'_h = \frac{T_h}{T_v}$. The receiver distortion matrix becomes

$$\boldsymbol{R} = R_v \begin{pmatrix} 1 & 0 \\ 0 & R'_h \end{pmatrix} \tag{3.20}$$

where $R'_h = \frac{R_h}{R_v}$.

Up to two measurements of the same target are required with this technique, one with the transmitter module in the normal position, and an optional one with the transmitter module rotated by approximately 45°. The calibration target must be diagonal, ie. in the bistatic measurement configuration

$$\boldsymbol{P}^{cal} = \begin{pmatrix} P_{vv}^{cal} & 0 \\ 0 & P_{hh}^{cal} \end{pmatrix} \tag{3.21}$$

For the usual calibration targets, namely a sphere and conducting plate, this condition can be made true. For the sphere, the bistatic system must have the receiver in the the plane of incidence, ie. $\phi_t = 0°$ or $\phi_t = 180°$. For the plate, the specular position, where $\theta_r = \theta_t$ and $\phi_t = 0°$, must be used, in which case the theoretical scattering matrix is not just diagonal, but $P_{vv}^{cal} = P_{hh}^{cal}$.

Then, for a measurement of arbitrary θ,

$$\begin{aligned} \boldsymbol{N} &= \begin{pmatrix} N_{vv} & N_{vh} \\ N_{hv} & N_{hh} \end{pmatrix} \\ &= k\boldsymbol{RP\theta T} \\ &= k'\begin{pmatrix} P_{vv}\cos\theta & P_{vv}T'_h\sin\theta \\ -R'_hP_{hh}\sin\theta & R'_hP_{hh}T'_h\cos\theta \end{pmatrix} \end{aligned} \tag{3.22}$$

where $k' = kR_vT_v$. Then the following relations are easily shown:

$$\frac{R'_hP_{hh}T'_h}{P_{vv}} = \frac{N_{hh}}{N_{vv}} \tag{3.23}$$

$$\frac{R'_hP_{hh}}{P_{vv}T'_h} = \frac{-N_{hv}}{N_{vh}} \tag{3.24}$$

$$k'^2P_{vv}R'_hP_{hh}T'_h = N_{vv}N_{hh} - N_{vh}N_{hv} \tag{3.25}$$

$$k'^2P_{vv}R'_hP_{hh}T'_h\cos 2\theta = N_{vv}N_{hh} + N_{vh}N_{hv} \tag{3.26}$$

$$T'_h\tan\theta = \frac{N_{vh}}{N_{vv}} \tag{3.27}$$

$$\frac{-\tan\theta}{T'_h} = \frac{N_{hv}}{N_{hh}} \tag{3.28}$$

and, for the measurement at 45°,

$$\tan\theta_{45} = +\sqrt{\frac{-N_{vh}(45°)N_{hv}(45°)}{N_{vv}(45°)N_{hh}(45°)}} \tag{3.29}$$

From these relations the quantities of interest can be derived:

$$T'_h = \frac{N_{vh}(45°)}{N_{vv}(45°)\tan\theta_{45}} \tag{3.30}$$

$$R'_h = -T'_h \frac{P_{vv}}{P_{hh}} \frac{N_{hv}(45°)}{N_{vh}(45°)} = \frac{1}{T'_h} \frac{P_{vv}}{P_{hh}} \frac{N_{hh}}{N_{vv}} \tag{3.31}$$

$$k'^2 = \frac{N_{vv}N_{hh} - N_{vh}N_{hv}}{R'_h T'_h P_{vv} P_{hh}} \tag{3.32}$$

$$\cos\theta_0 = +\sqrt{\frac{N_{vv}(0°)N_{hh}(0°)}{N_{vv}(0°)N_{hh}(0°) - N_{vh}(0°)N_{hv}(0°)}} \tag{3.33}$$

$$\sin\theta_0 = -T'_h \cos\theta_0 \frac{N_{hv}(0°)}{N_{hh}(0°)} \tag{3.34}$$

The positive sign in (3.29) and (3.33) indicates that the square root which yields a positive real part for the complex quantities $\tan\theta_{45}$ and $\cos\theta_0$ should be used.

It can be seen from this development that the need for calibration with the antenna rotated is only necessary to prevent a multiplication and division by small numbers in the calculation of T'_h. A rotation by 45° is best to eliminate such difficulties, but it may be that using a lesser or greater rotation, or even using no rotation at all, may be satisfactory.

Then, the scattering matrix $\boldsymbol{S}^{unk}$ can be determined from a measurement $\boldsymbol{N}^{unk}$ as follows:

$$\boldsymbol{S}^{unk} = \boldsymbol{R}^{-1}\boldsymbol{N}^{unk}\boldsymbol{T}^{-1}\boldsymbol{\theta}^{-1}/k' \tag{3.35}$$

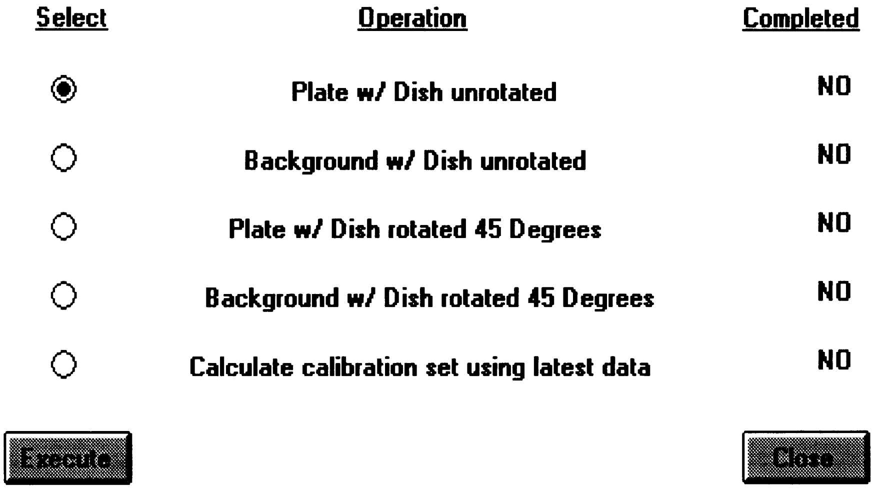
where

$$\boldsymbol{R}^{-1} = \begin{pmatrix} 1 & 0 \\ 0 & 1/R'_h \end{pmatrix} \tag{3.36}$$

$$\boldsymbol{T}^{-1} = \begin{pmatrix} 1 & 0 \\ 0 & 1/T'_h \end{pmatrix} \tag{3.37}$$

$$\boldsymbol{\theta}^{-1} = \begin{pmatrix} \cos\theta_0 & -\sin\theta_0 \\ \sin\theta_0 & \cos\theta_0 \end{pmatrix} \tag{3.38}$$

and k' is the square root of (3.32) that is closest to $N_{vv}(0°)/(P_{vv}\cos\theta_0)$.



Select	Operation	Completed
●	Plate w/ Dish unrotated	NO
○	Background w/ Dish unrotated	NO
○	Plate w/ Dish rotated 45 Degrees	NO
○	Background w/ Dish rotated 45 Degrees	NO
○	Calculate calibration set using latest data	NO

Figure 3.2: The Calibration Form, as it appears when the Bistatic Measurement Facility is in bistatic mode.

4.2 Bistatic Calibration Procedure

With the software displaying the bistatic calibration form, which is shown in Figure 3.2, five radio buttons and either two or three command buttons appear. The radio buttons are labelled “Plate w/ Dish unrotated”, “Background w/ Dish unrotated”, “Plate w/ Dish rotated 45 degrees”, “Background w/ Dish rotated 45 degrees”, and “Calculate calibration set using latest data”. These are used to determine the next object upon which the software will act, but selecting them in and of themselves does not do anything. To the right of the radio buttons is a column displaying the status for each object. Possible messages in the status column are: “NO”, meaning that no action has yet taken place with that object; “Working”, meaning that the software is busy with that object; and a time, which indicates the when the last action on that object was completed. The three middle objects have an additional status: “0’d” and a time, indicating that the last action on that object was a deletion of the measured data and when it happened.

The command buttons are used for telling the software to do something, and are labelled “Execute”, “Zero”, and “Close”. The “Close” command button is used to exit the form and return to the main form, and can be used at any time during the calibration procedure. The “Execute” command button is used to either measure the plate or background, or to calculate the calibration set. The “Zero” command button only applies to the three middle radio buttons, so it only appears if one of those radio buttons is selected, and is used to erase the measured data for those targets. In effect, it returns the data for that object to the state it was when the calibration form was first entered, that is, unmeasured.

The only measurement essential for calculating the calibration coefficients is the “Plate with dish unrotated” measurement. The “Plate with dish rotated 45 degrees” is used to insure that the calculation of the calibration coefficients does not involve the division by very small numbers (see the previous section on the bistatic calibration theory). Experience has shown that those small numbers are not sufficiently small (compared to the noise in those numbers) to necessarily cause problems. The object of the two background measurements associated with each plate measurement is to determine how much of the calibration measurement is due to scattering from other than the calibration target. We have found that calibration measurements on this bistatic facility has such a large signal to background ratio that these measurements are not necessary for accurate calibration. However, should the system change so that the signal to background ratio be substantially reduced (to 30 dB or less), this measurement would be essential. About the only thing which could cause such a reduction is damage to microwave components, which could then introduce internal reflections within the microwave plumbing and multipath with the same length as the direct path involving the calibration target.

The following order of steps is recommended for bistatic calibration.

Position The Calibration Target

Place a large sheet of aluminum at the center of the Bistatic Facility. It must be flat and level, and at a height equal to the axis of rotation of the bistatic facility (30 inches off the floor).

Rotate The Dish (optional)

Lower the dish antenna to an elevation where the the bolt holding the dish assembly to the I-beam of the arch is accessible. Depending on the height of the user, this can be done by sending the dish elevation to about 70° or so. Use a 7/16 inch nut driver or wrench to loosen the bolt about one turn. Do not remove the bolt, as it is the only thing holding the Dish antenna assembly onto the arch. Rotate the Dish assembly about its boresight direction, that is, rotate it around the shaft of the bolt, about 45° counterclockwise (as viewed with the bolt visible). The cables attached to the dish assembly should prevent it from being rotated in the wrong direction. Tighten the bolt which holds the dish assembly onto to the arch.

Position The Antennas In The Specular Direction (optional)

From the main form in the software, move the Horn Elevation to some angle θ_{rc} where $20^\circ < \theta_{rc} < 60^\circ$. An angle of 35° is recommended. The Dish Azimuth must be set at 0° and the Dish Elevation must be the same as the Horn Elevation. This is the specular direction; with the antennas in these positions and the plate properly located, the measured scattered power will be at a maximum.

Measure The Plate With Rotation (optional)

Make sure the "Plate w/ dish rotated" radio button is selected, then click on the "Execute" command button. The status column will show "Working" for about 30 seconds then display the time when it was completed.

Measure The Background With Rotation (optional)

With the same aluminum plate in the same location, the background can be measured by moving both antennas in elevation equal amounts but in opposite directions. This allows the direct path between antennas to be unaffected while removing the calibration target. We recommend that the antennas be moved by more than 30° away from specular direction for a valid background measurement. In this position, the plate will not scatter any energy back toward the antenna, and the time-gating on the network analyzer will prevent other nearby objects from being measured. Select the "Background w/ dish rotated 45 degrees" radio button, and then select the "Execute" command button. The status will display "Working" for about 30 seconds then display the time the measurement was completed.

Unrotate The Dish (optional)

Following similar procedures used to rotate the dish, return the dish to its normal orientation. Remember to tighten the bolt which holds the dish assembly onto the arch.

Measure The Background Without Rotation (optional)

With the same aluminum plate in the same location, the background can be measured by moving both antennas in elevation equal amounts but in opposite directions away from the specular direction. This allows the direct path between antennas to be unaffected while removing the calibration target. We recommend that the antennas be moved by more than 30° away from the specular direction for a valid background measurement. In this position, the plate will not scatter any energy back toward the antenna, and the time-gating on the network analyzer will prevent other nearby objects from being measured. Select the "Background w/ dish unrotated" radio button, and then select the "Execute" command button. The status will display "Working" for about 30 seconds then display the time the measurement was completed.

Move The Antennas To The Specular Direction

From the main form in the software, move the Horn Elevation to some angle θ_{rc} where $20^\circ < \theta_{rc} < 60^\circ$. An angle of 35° is recommended. The Dish Azimuth must be set at 0° and the Dish Elevation must be the same as the Horn Elevation. This is the specular direction; with the antennas in these positions and the plate properly located, the measured scattered power will be at a maximum.

Measure The Plate Without Rotation

Make sure the "Plate w/ dish unrotated" radio button is selected, then click on the "Execute" command button. The status column will show "Working" for about 30 seconds then display the time when it was completed.

Calculate Calibration Set

Anytime a valid "Plate w/ dish unrotated" measurement has been completed, the calibration set may be calculated. Select the "Calculate calibration set using latest data" radio button then select the "Execute" command button. The software will then calculate the calibration set and display the time it was completed.

Leave The Calibration Form

Remove the calibration plate (unless it is going to be used for measurements) and select the "Close" command button to return to the main form. The bistatic system is now calibrated in bistatic mode and is ready for measurements, as described in Section 3.6 of Chapter 2.

5 Target Types

The Bistatic Facility can characterize three classes of objects: point targets, distributed targets, and reflectors. Point targets are small objects (when compared to the cross section of the radar beam) and scatter energy coherently in many directions. They are characterized by a radar cross section σ, which has the units of area and is usually measured in dBsm (sometimes written as dBm^2), which is an area expressed in decibels relative to 1 square meter.

Distributed targets are large (when compared to the cross section of the radar beam) random objects and scatter energy incoherently in many directions. They are characterized by a differential radar cross section σ^0, which is defined as the ratio of the surface's radar cross section to its physical area, and is thus dimensionless. It is usually expressed in dB. Reflectors are large (when compared to the cross section of the radar beam) objects which scatter energy into a finite set of directions. They are characterized by the reflection coefficient R_{pq}, which is dimensionless complex ratio of the p-polarized coherent field amplitude scattered from the reflector to the q-polarized field amplitude incident upon it. It is also often characterized by the reflectivity Γ_{pq}, which simply the magnitude squared of the reflection coefficient. This quantity is also dimensionless and is expressed in dB.

The conversion of a calibration using one target into a measurement of another target starts with the radar equation for each target:

$$P_p^{pt} = P_q^t \frac{G_r G_t \lambda^2}{(4\pi)^3 R_r^2 R_t^2} \sigma_{pq} \tag{3.39}$$

$$P_p^{inc} = P_q^t \frac{\lambda^2}{(4\pi)^3} \int_{A_{ill}} \frac{G_r G_t}{R_r^2 R_t^2} \sigma_{pq}^0 dA_{ill} \tag{3.40}$$

$$P_p^{coh} = P_q^t \frac{G_r G_t \lambda^2}{(4\pi)^2 (R_r + R_t)^2} \Gamma_{pq} \tag{3.41}$$

where P^{pt} is the received coherent power scattered by a point target, P^{inc} is the received incoherent power scattered by a distributed target, and P^{coh} is the received coherent power scattered by a distributed target. In addition, λ is the radar wavelength in a vacuum, G_r and G_t are the antenna gains of the receiver and transmitter in the direction to the target, R_r and R_t are the ranges from the receiver and transmitter to the target, P^t is the transmitted power, the subscripts p and q indicate the received and transmitted polarizations, respectively, and A_{ill} is the area of illumination on the distributed target.

Point targets are deterministic, so only one measurement need be made for every combination of bistatic angles $(\theta_t, \theta_r, \phi_t)$ and target orientation angles (θ_j, ϕ_j).

Distributed targets, however, are statistical. Therefore, accurate determination of the coherent and incoherent power, and thus the reflectivity Γ and the scattering coefficient σ^0, require the measurement of many independent realizations of statistically identical targets. There are numerous ways to do this, but the easiest is to make a distributed target which is much larger than illuminated area A_{ill}, and to move the target between measurements so that different portions of the target correspond to the radar's illuminated area during a measurement. For this reason the Bistatic Measurement Facility is equipped with the capacity to include a turntable and 215 cm diameter sample holder. (It is important that the turntable be positioned with its axis of rotation offset from the center of the BMF by at least the diameter of the area of illumination, so that different portions of the distributed target can be rotated into and out of the illuminated area. This is in contrast to a turntable which might be used to control ϕ_j for point targets, which should be located at the center of the BMF so that the point target stays at the same location within the sweet spot.)

The separation the coherent and incoherent powers measured by the radar can be achieved by applying complex statistics on the calibrated scatter matrices $\boldsymbol{S}$. The calibrated scatter matrix elements S_{pq} represent a complex voltage ratio which is proportional to the scattered electric field for each polarization state at each spatially independent sample of the surface. Because the scattered electric field is composed of a coherent component from the mean surface and an incoherent component from the distributed target, the measured voltage ratio will also have a coherent and incoherent component: $S_{pq} = S_{pq}^{coh} + S_{pq}^{inc}$. These two components can be separated because the incoherent component has a zero mean: $\overline{S_{pq}^{inc}} = 0$ (where $\overline{x}$ indicates the mean of x). Provided a large number of independent samples are measured, the coherent power P_{coh} is proportional to the square of the complex average of the measured voltages:

$$P^{coh} = \left|S_{pq}^{coh}\right|^2 = \left|\overline{S_{pq}}\right|^2 \qquad (3.42)$$

The incoherent power P_{inc} is then proportional to the variance of the fluctuating component of the measured voltage:

$$P^{inc} = \overline{\left|S_{pq}^{inc}\right|^2} = \overline{\left|S_{pq} - \overline{S_{pq}}\right|^2} = \mathrm{Var}(S_{pq}) \qquad (3.43)$$

These averages and variances are calculated on the fly by means of the following equations. For the first independent spatial sample, $\left(\overline{S_{pq}}\right)_1 = S_{pq}$ and $\mathrm{Var}(S_{pq})_1 = 0$ and for the nth spatial independent sample,

$$\left(\overline{S_{pq}}\right)_n = \frac{n-1}{n}\left(\overline{S_{pq}}\right)_{n-1} + \frac{1}{n}S_{pq} \qquad (3.44)$$

$$\mathrm{Var}(S_{pq})_n = \frac{n-2}{n-1}\mathrm{Var}(S_{pq})_{n-1} + \frac{1}{n}\left(S_{pq} - \left(\overline{S_{pq}}\right)_{n-1}\right)^2 \qquad (3.45)$$

Provided that calibration is achieved with a large flat metal plate, for which

$$\boldsymbol{P}^{cal} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \qquad (3.46)$$

it can be readily shown that

$$\sigma_{pq} = \frac{4\pi R_{r0}^2 R_{t0}^2}{(R_{r0} + R_{t0})^2}|S_{pq}|^2 \qquad (3.47)$$

$$\Gamma_{pq} = \left|\overline{S_{pq}}\right|^2 \qquad (3.48)$$

$$\sigma_{pq}^0 = \frac{4\pi}{(R_{r0} + R_{t0})^2 I_{ill}}\mathrm{Var}(S_{pq}) \qquad (3.49)$$

where R_{t0} and R_{r0} are the boresight ranges from the transmitter and receiver, respectively, to the center of the Bistatic Measurement Facility and the illumination integral I_{ill} is given by

$$I_{ill} = \int_{A_{ill}} \frac{G_r G_t}{R_r^2 R_t^2} dA_{ill}. \tag{3.50}$$

and has been implemented with the following approximation:

$$I_{ill} \approx \frac{\pi \tan \frac{1}{2}\beta_t^{az} \tan \frac{1}{2}\beta_t^{el}}{R_{r0}^2 \cos \theta_t} \tag{3.51}$$

The values of some of these parameters in equations 3.47 thru 3.51 depend on whether the BMF is in bistatic or backscatter modes. Technically, some of the variables in equation 3.51 also depend on the polarization state, but that dependence is sufficiently weak that it has been neglected.

6 Independent Samples

The total number of independent samples is an indicator of the quality of the measurement of Γ or σ^0. Generally, 20 to 30 independent samples should be considered a minimum for a valid measurement; 50 to 100 independent samples would constitute a good measurement.

The total number of independent samples for σ^0 is not always the same as the number of spatial independent samples. A single spatial independent sample may have more than one independent sample due to a phenomenon known as "frequency averaging." We can consider a radar with bandwidth B to be equivalent to a pulse radar operating at a single frequency but with a pulse duration of $\tau = 1/B$. For each point in the illuminated area there is a path r going directly from the transmitter to that point, then continuing from that point directly to the receiver. The propagation time associated with these paths is $t = r/c$, where c is the speed of light. One of the points has the longest such path r_{max}, and one has the shortest such path r_{min}. Therefore, for each instant that the radar transmits power, it is receiving energy from the distributed target for a total duration $\Delta t = \Delta r/c$ where $\Delta r = r_{max} - r_{min}$. If $\Delta t > \tau$, then different portions of the illuminated area are distinct, that is, they are independent samples. Thus, the number of independent samples per spatial sample, denoted N_f, is

$$N_f = \frac{\Delta t}{\tau} = \frac{B \Delta r}{c} \tag{3.52}$$

The number of independent samples per spatial sample is never less than one, nor is it greater than the number of frequencies sampled (for the BMF, while 201 frequency points are measured by the network analyzer, only 21 equally spaced frequency points are used by the software). For the backscatter mode,

$$\Delta r \;=\; 4R_{r0}\frac{\sin 2\theta_r \sin \frac{1}{2}\beta_r^{el}}{\cos 2\theta_r + \cos \beta_r^{el}} \tag{3.53}$$

and for bistatic mode

$$\begin{aligned}\Delta r \;=\; & 2R_{t0}\left|\sin \tfrac{1}{2}\phi_t\right| \times \\ & \left(\frac{\tan \frac{1}{2}\beta_t^{el}}{\cos \theta_t}(\sin \theta_t - \sin \theta_r \cos \phi_t) + \tan \tfrac{1}{2}\beta_t^{az}(1 + \cos \phi_t)\sin \theta_t\right)\end{aligned} \tag{3.54}$$

Generally, for a given θ_r, the backscattering direction provides the greatest Δr. Also, $N_f = 1$ for the specular direction.

The reported scattering coefficient is the average scattering coefficient over all 21 frequency points used by the software. Reflectivities do not average well over frequencies, so the reported reflectivity is just that at the center frequency and the total number of independent samples for the reported reflectivity is the same as total number of spatial samples. The reported radar cross section, of course, involves neither spatial nor frequency averaging.

Measuring Sample Independence

The maximum number of spatial independent samples, and thus the amount of rotation required between measurements, can be determined by the finding the angle of rotation of the turntable necessary for decorrelating the measured power. This is achieved by measuring the RCS of a distributed target, preferably a relatively strong scattering target which has many random variations within each possible illuminated area, at many close but equally spaced rotations of the turntable. Let N_ρ be the number these close but equally spaced samples. Then the amount of turntable rotation per (non-independent) sample ϕ_{rot} would be $\phi_{rot} = 360°/N_\rho$. N_ρ should be on the order of 100 or more. Then the resultant measurements at position n, namely $\sigma_{pq}(n\phi_{rot})$ for the pq polarization, are used to find the autocorrelation of the measured signal ρ:

$$\rho(n\phi_{rot}) \;=\; \sum_{m=0}^{N_\rho - 1} 10^{\sigma_{pq}(m\phi_{rot})/10} 10^{\sigma_{pq}((m+n)\phi_{rot})/10} \tag{3.55}$$

where it is recognized that angles greater than 360° are equivalent to an angle between 0° and 360°. The smallest angle ϕ_s at which $\rho(\phi_s)/\rho(0^\circ) < e^{-1}$ is the decorrelation angle. The total number of spatial independent samples N_s to be used per rotation of the sample holder is then $N_s = 360^\circ/\phi_s$.

The value for ϕ_s should be a weak function of the bistatic angles, since it will change only with the extent of the illuminated area. Formula 3.55 will only work, however, if the target measured produces much more incoherent power than coherent power for the bistatic angles chosen. Therefore, care must be taken to use a scattering target with sufficient randomness and physical fluctuations, especially if this is to be measured at or near the specular direction.

Chapter 4

Examples of Measurements

The following two examples demonstrate the use of the software to make specific measurements. In addition, some practical hints for setting up measurements are given. The hemisphere measurement is useful for confirming the operation of the Bistatic Measurement Facility. The rough surface measurement is a typical measurement of an unknown target and demonstrates the ability of the BMF to separate reflectivity from a scattering coefficient.

1 Backscattering RCS of hemisphere on a conducting half-space

The hemisphere and its mirror image create a sphere, for which the scattering characteristics are known exactly. The formulation of the scattering from a sphere is given in Bohren and Huffman [1], Chapter 4, and a Fortran 77 program which calculates the RCS of a hemisphere on a ground plane is provided with the BMF. This code has as its heart a subroutine "bhmie" based on the fortran code in the appendix of [1]. In addition, the software provided includes a subroutine "scatter", which calls "bhmie" and converts the scattering coefficients from the coordinate system in [1] to the coordinate system shown in Figure 1.2. The main routine calls these subroutines and applies image theory to calculate the RCS of a hemisphere as it would be measured with the BMF. This code, which runs (at least) under f77 on a Sun 4, likely needs only minor modifications to run under the local fortran compiler. As described in Section 1.1 of Chapter 2, the radar cross section is then given by the interference pattern of the sphere illuminated by the transmitter (a plane wave incident at

θ_t) and its image (another plane wave incident at 180° $-$ θ_t). A copy of the Fortran source code is in *c:\patterns\mie.f* and is listed in Appendix B.

Upon launching the BMF software, select the Backscatter mode in the main form, and set up the calibration sheet. Move inner arch out of the way; make sure the outer arch is at 0° and calibrate (without a background). Refer to Section 3.2 of Chapter 3 for the backscatter calibration procedure. Do not remove the calibration sheet, it will become part of the measurement. The system is now ready for making measurements and the only trick is to properly position the target. Find the center of the BMF as described in Section 1.1 of Chapter 2. Once the hemisphere is located at the center of the BMF, marking a circle on the plate with a mechanical pencil around the circumference of the hemisphere can be helpful to quickly but precisely relocate the hemisphere at the center of the BMF without having to use the arches.

Again, move the inner arch out of the way. Move the outer arch to the desired angle and enter the measurement form. Choose manual sampling. Click the RCS radio button and click the Start/Restart command button. When the measurement is complete and an RCS is displayed, remove the hemisphere and click the "Measure Bkgnd" command button. When this is complete, the RCS of the hemisphere at this angle can be viewed both with and without background subtraction by checking or unchecking the "Subtract Bkgnd" check box. The order in which the target and its background are measured can be reversed. The system is ready to be moved to a new backscattering angle for a new measurement.

By this technique it can be easily shown that the background is very significant at angles near nadir, where the specular flash from the plate is large, but is negligible at angles far from nadir.

Typical results of the measurement of a hemisphere on the calibration plate are shown in Figure 4.1. The points show the measured Radar Cross Section, and the curves are results of the software listed in Appendix B.

2 Reflectivity and Specular Scattering Coefficient of a rough surface

Prepare a smooth surface as outlined in Section 1.2 of Chapter 2. Place the calibration plate directly onto the surface in the region of the illuminated area. Put the BMF into bistatic mode and calibrate as described in Section 4.2 of

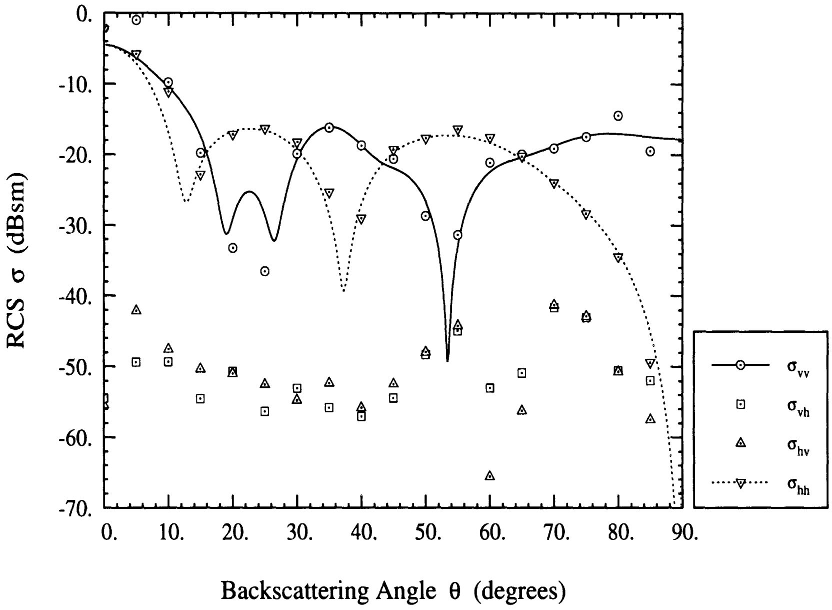


Figure 4.1: Typical Bistatic Measurement Facility results for a conducting 3-3/16 inch diameter hemisphere on a calibration plate. The curves show the theoretical results as computed by the code listed in Appendix B. The corrected system isolation is evident from the reported values for cross-polarization, since their theoretical values are zero. The agreement near nadir is poor because the hemisphere shields part of the calibration plate which contributes significantly to the background. The agreement for σ_{vv} near grazing is poor because the time-gate does not eliminate interactions between the hemisphere and the edge of the calibration plate (the same interaction for *hh* polarization is extremely small).

Table 4.1: Hemisphere Measurement Cross Reference and Checklist

Chapter	Section	Task
2	2.1	Inspect the BMF
2	2.2	Power up the BMF
2	2.3	Launch the BMF software
2	2.4	Zero the BMF axes
2	3.1	Move the Dish Elevation to +30°
2	3.2	Click Backscatter Mode radio button
2	3.5	Click Calibrate command button
3	3.2	Position Calibration target
3	3.2	Click Plate radio button and Execute
3	3.2	Click Calculate radio button and Execute
3	3.2	Click Close command button
2	3.1	Move the Dish Elevation to 0°
2	3.1	Move the Dish Azimuth to +90°
2	3.1	Move the Horn Elevation to -2°
2	1.1	Place the hemisphere at the center of the BMF
2	3.1	Move the Dish Elevation to +30°
2	3.1	Move the Horn Elevation to desired backscatter angle
2	3.4	Click the Measure Unknown command button
2	3.6	Click Manual in the menu
2	3.6	Click the Radar Cross Section radio button
2	3.6	Click the Start/Restart command button
2	3.6	Remove the hemisphere
2	3.6	Click the Measure Bkgnd command button
2	3.6	Click the Subtract Bkgnd check box
2	3.6	Read the RCS in the array

Chapter 3, with the antennas in the (or in one of the) elevation angles to be used for measuring. Carefully remove the calibration plate, so as not to disturb the smooth surface underneath (an assistant at this point is invaluable). Perturb the surface to the desired roughness.

The surface is now ready for measuring. If the automatic sampling is working, enter the measurement form, click on "Automatic" in the menu, enter the desired number of spatial samples and their angular separation in the appropriate text boxes, and click the start command button. If automatic sampling is not usable, use manual sampling in the measurement form, and click the start command button. When the measurement is completed, rotate the sample holder by the amount of the desired angular separation between independent samples and click the continue command button. Repeat the instructions in the last sentence until the desired number of independent samples have been measured.

By clicking the "Reflectivity" radio button, the reflectivity matrix is displayed. Clicking the "Sigma Zero" radio button displays the scattering coefficient matrix. These radio buttons can be clicked at any time during the measurement cycle to show how the variations in these numbers decrease as the number of independent samples increases.

If the reflectivity and/or scattering coefficient are desired at other angles, move the bistatic arches (via the controls in the main form), and repeat the directions in the last two paragraphs. The reflectivity does not have a scientific meaning for a surface away from the specular direction, however.

Once the measurement is complete, the surface may be characterized by inserting a long piece of sheet metal edgewise into the surface, and tracing the intersection of the surface and the sheet metal onto the sheet metal with a pencil or with spray paint. Remove the sheet metal and digitize the traced curve. Use the data to estimate the rms surface height and correlation length. This technique is not the most accurate, as it disturbs the surface which is measured, but it is one of the easiest. The accuracy can be improved somewhat by taking several "slices" of the surface.

Table 4.2: Rough Surface Measurement Cross Reference and Checklist

Chapter	Section	Task
2	2.1	Inspect the BMF
2	2.2	Power up the BMF
2	2.3	Launch the BMF software
2	2.4	Zero the BMF axes
2	1.2	Prepare a smooth target surface
2	3.2	Click Bistatic Mode radio button
2	3.1	Move the Dish Elevation to 35°
2	3.1	Move the Horn Elevation to 35°
2	3.1	Move the Dish Azimuth to 0°
2	3.5	Click Calibrate command button
3	3.2	Position Calibration target
3	3.2	Click Plate radio button and Execute
3	3.2	Click Calculate radio button and Execute
3	3.2	Click Close command button
4	2	Remove the Calibration Target
4	2	Make a rough surface
2	3.1	Move the Dish Elevation to desired angle
2	3.1	Move the Horn Elevation to the same angle
2	3.4	Click the Measure Unknown command button
2	3.6	Click Manual in the menu
2	3.6	Click the Reflectivity radio button
2	3.6	Click the Start/Restart command button
2	3.6	Move target & click the Continue command button (repeat for independent samples)
2	3.6	Read the Reflectivity in the array
2	3.6	Click the Sigma Zero radio button
2	3.6	Read the Scattering Coefficient in the array

Chapter 5

Safety

1 Mechanical Safety

The Bistatic Measurement Facility contains many moving parts, some of which involve forces which could cause personal injury. The Facility has been designed such that nothing is overpowered, but the power needed for proper operation may nonetheless cause injury to the careless user or observer.

The simplest safety precaution is to stay out of the bistatic facility while arches are moving. While the software has been written to turn off motion if somehow motion is interrupted, and the slip clutches are set such that the arches should start slipping very shortly after an arch collides with something, it is possible that both of these safety features are insufficient to prevent injury. Far from the axis of rotation, the arches should be incapable of crushing anything (except, perhaps, the antennas), but close to the axis of rotation, not only are there many different ways to entrap body parts between the upright and the car or stand, but the force required to overcome the slip clutch is much larger. Do not ever count on being able to overcome the slip clutches as it is within the realm of possibility that they get stuck. Similarly, the drive wheels on the cars should slip on the floor if a car is driven into something. However, the car likely would not stop if it were given the opportunity to ride over a hand or a foot.

Most important, **keep your hands far from the elevation drive chains** anytime the motors are enabled or if the arches might be moved manually. The action of the moving chain on either the big sprocket or the slip clutch can produce a very severe injury very quickly to fingers caught between the chain and the sprocket teeth.

2 Electrical Safety

Do not plug or unplug any cables coming from the back of the control box unless the power is off to all three switches and the computer. The motors can take a considerable current, and the sudden connection or disconnection of a motor cable will cause a spike which could cause damage to motor amplifiers and possibly damage to other electronic system components or give a shock to the user. While the encoder cables handle only TTL signals, disconnecting an encoder cable with computer on will send encoder counts to the MEI motion control card, and if the motor amplifiers are on and enabled the one of the motors will start to run.

3 Microwave Safety

The American safety standard for exposure to microwave fields is 10 $\mathrm{mW/cm^2}$ and is the highest in the world. Near this intensity fluorescent lights start to glow. While the BMF has been designed to produce no freespace fields larger than the American safety standard, it is recommended that users minimize their exposure to the fields that it generates. Obviously, the fields the BMF produces exist everywhere near it (this is necessary for the BMF to work), but the fields with the largest intensity are in the beam transmitted by the antennas. It is best to avoid intercepting the transmitted beam with the human body. Remember, the antenna which is producing the transmitted beam depends on whether the BMF is in bistatic or backscatter mode.

Chapter 6

Hardware Care and Maintenance

1 Microwave Components

The microwave components require minimal maintenance, per se, but do require appropriate attention and care to prevent damage.

1.1 Antennas

The two antennas are of very different type, but both share the fact that they are hand-crafted precision instruments. While a large dent or gash in one of the antennas might not effect its performance, a tiny cut or dimple in the right place might render it useless.

The antenna patterns, measured at the operating ranges given in Table 1.1, are given in Figures 6.1 thru 6.4. The patterns for the Dish are measured with the dish as the transmitter; the patterns for the Horn are measured with the horn as the receiver. The patterns for the Horn as transmitter are the same as for the Horn as receiver.

Dish Antenna

The construction of the Dish Antenna, which is used as the bistatic transmitter, is such that the most important element, namely the dish, is not visible. The polystyrene which conceals most of the elements of the dish comprises a rigid and strong support which holds the active components precisely in their

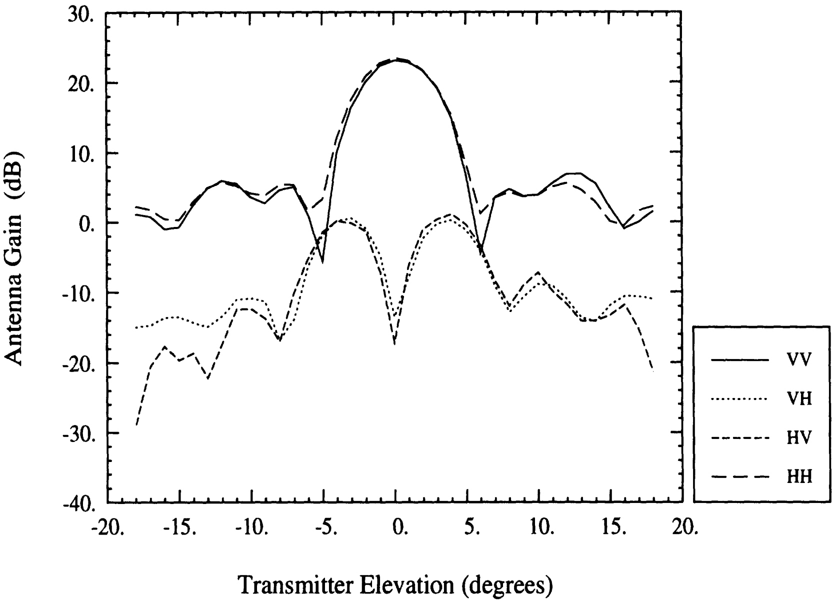


Figure 6.1: Dish Elevation One-Way Patterns.

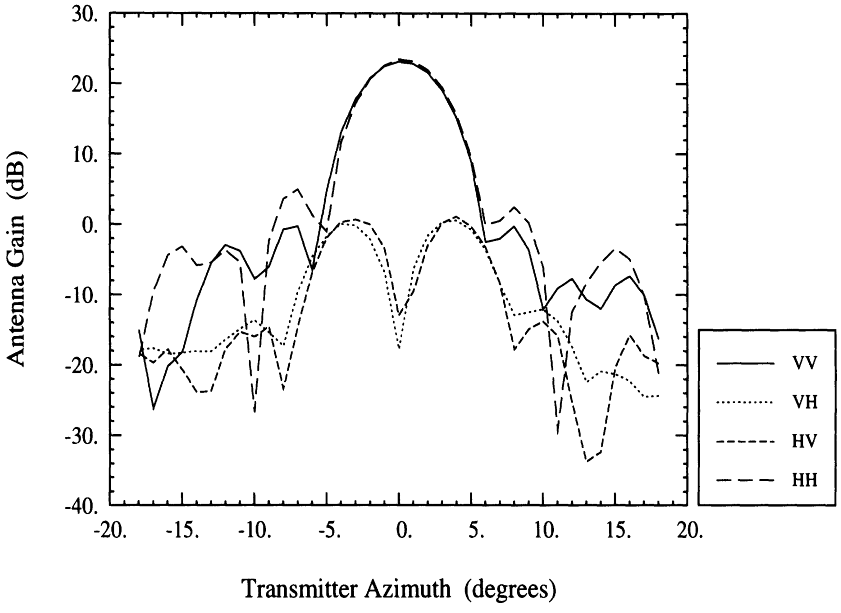


Figure 6.2: Dish Azimuth One-Way Patterns.

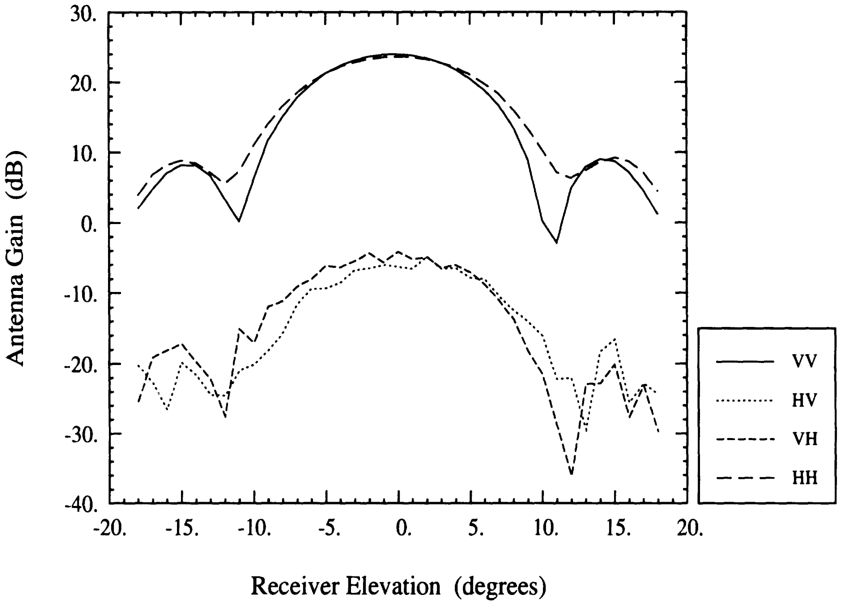


Figure 6.3: Horn Elevation One-Way Patterns.

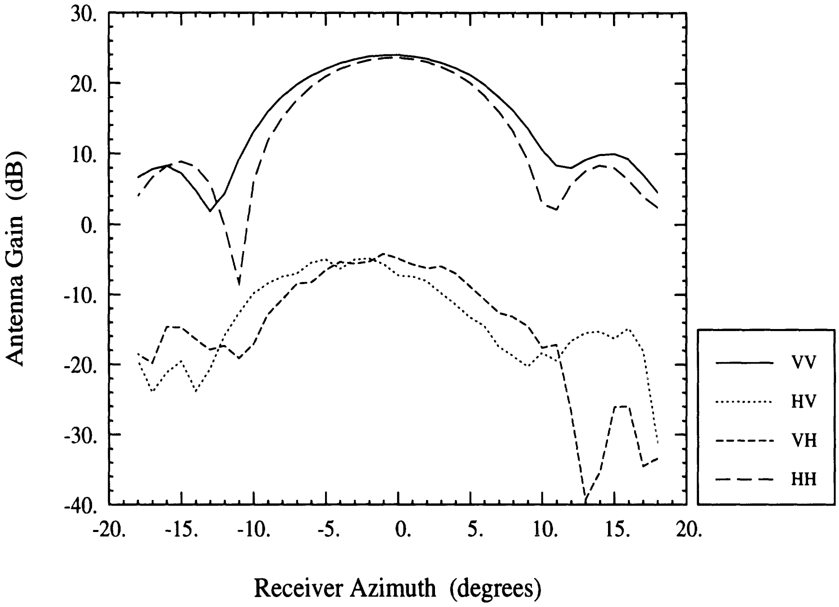


Figure 6.4: Horn Azimuth One-Way Patterns.

correct locations, yet is practically invisible to microwaves. The dish feed, of which the orthomode and waveguide-to-coax transitions are visible in front, is held in its location relative to the dish via the polystyrene block. The dish and feed are attached to the polystyrene block via foam polyurethane (the kind sold over-the-counter for sealing cracks and openings in homes for purposes of insulation). The polystyrene block is in turn attached to the back plate via wood screws, which should not be removed since the fasteners will not hold as well in a reused hole as they do in a new hole. The Dish assembly is not designed to be taken apart and reassembled; if this is attempted the components will need to be precisely relocated, and new antenna patterns will need to be measured.

If the antenna assembly needs to be disconnected from the arch, the following precautions are in order. Note the orientation of the antenna before disconnecting; the antenna patterns and polarizations are not identical upon rotation around boresight and measurements of targets with the antenna installed in the wrong orientation might not agree with previous measurements. All connections (microwave and control) should be disconnected before attempting to remove the assembly from the arch. The arch should be rendered immobile before attempting to completely undo the single 1/4 inch bolt holding the antenna in place: the weight of the dish assembly keeps the arch balanced. The arch will lurch toward nadir if the antenna is removed and the arch is not physically restrained. The slip clutches on the arches are set to slip on the minimum applied torque for the purposes of maintaining personal safety. If the mass of the antenna changes significantly (from added or removed components), or if the antenna assembly is replaced by a different one, the arch will have to be retuned so that motion is smooth and accurate.

Horn Antenna

The most impressive feature of the Horn antenna is the polystyrene lens placed in the aperture. It narrows the horn antenna one-way beamwidth from approximately 17° without a lens to about 10° with the lens. This object is fragile and should be treated with the utmost care. Never rest the antenna on the lens; never apply pressure to the polystyrene as it crushes easily, nor ever apply torque to the lens as it is very brittle and can snap off easily. The lens itself is very simple. It is made from two polystyrene cones (one outside the horn and one inside it) and a piece of 1 inch thick polystyrene sheet cut to the size of the aperture. The pieces are held together with epoxy cement. Should the lens be damaged and need to be replaced, these polystyrene pieces are sold in nurseries (for flower arrangements). It is held onto the horn aperture with ordinary duct tape. The antenna patterns should be remeasured if the lens is replaced.

If the antenna assembly needs to be disconnected from the arch, the following precautions are in order. Unlike the Dish antenna, which can only go in one location but be attached in any orientation, the Horn can only be attached in two orientations but in any location on the arch. Note the orientation of the antenna before disconnecting; the antenna patterns and polarizations are not identical if the horn is reattached on the other side of the I-beam, and measurements of targets with the antenna installed in the wrong orientation might not agree with previous measurements. Mark the location of the antenna on the I-beam with a mechanical pencil at the edges where the assembly meets the I-beam. This will help in placing the antenna assembly back onto the I-beam in the correct location. All connections (microwave and control) should be disconnected before attempting to remove the assembly from the arch. There are two microwave connections which are not interchangeable. Mark or record the connections so that they are correctly reconnected later. Do not flex the microwave cables as they are removed or reattached: they are designed to be bent only once into their final configurations and will fail if repeatedly flexed. The arch should be rendered immobile before attempting to completely undo the four 1/4 inch bolts holding the antenna in place: the weight of the horn assembly keeps the arch balanced. The arch will lurch toward nadir if the antenna is removed and the arch is not physically restrained. The slip clutches on the arches are set to slip on minimum applied torque for the purposes of maintaining personal safety. If the mass of the antenna changes significantly (from added or removed components), or if the antenna assembly is replaced by a different one, the arch will have to be retuned so that motion is smooth and accurate.

The circulators on the horn antenna use permanent magnets. Do not store the horn antenna assembly near strong or fluctuating magnetic fields, lest the circulators be demagnetized and be rendered useless.

The mounting plate is attached to the horn antenna itself via three 1/4-20 bolts. The bolt farthest from the horn aperture has several washers between the antenna and the mounting plate. These washers are essential, as they point the antenna toward the center of the Bistatic Measurement Facility. Without them, the horn would point parallel to the plane of the outer arch and not at the axis of rotation of that arch.

1.2 Cables

There are three types of coaxial cables used in the Bistatic Measurement Facility: flexible, semi-flexible, and semi-rigid. These cables are precision products, and should be treated with great respect. In particular, the cables have a minimum bend radius, which should never be exceeded. While some bending is expected on all three types of cables, they should never be torqued around their axis. Also, they are sensitive to crushing. Since a number of these cables run along the floor, it is imperative that all BMF users get into the habit of never stepping on any cables.

The cables all have a slight change in loss and phase with respect to temperature. If the BMF is not located in a climate controlled room, temperature variations will be an important parameter in deciding when to recalibrate the system.

Flexible Cables

The flexible cables are used at the points where cables absolutely need to flex, such as at the stands/carts and at the dish antenna assembly. They are manufactured by Quality Microwave Interconnects (QMI) and distributed by Compucon Distributors under the model name "Workhorse." A typical model number is WH18-3636-XXX where XXX is the length of the cable in inches. The pieces used on the Bistatic Measurement Facility use 24 inch long cables, (except for the one on the floor around the turntable, which is 216 inches). This brand has a minimum repeatable bend radius of 4 inches, which is approaching the radius that it will experience in use at the stand/cart for certain angles. While this is not expected to decrease the cable's lifetime (which is long but finite), when these cables fail, they should be replaced with cables with smaller bend radii or with longer Workhorses. If the replacement cables were twice as long they could make one loop around the axis of rotation at each such position and experience only half the bending as the current ones.

Semi-Flexible Cables

The semi-flexible cables are used at the points where it is most convenient to flex a cable into its final position but there is no need to ever flex it again. They are used primarily on the antenna assemblies. They are manufactured by Quality Microwave Interconnects (QMI) and distributed by Compucon Distributors under the model name "SemiFlex." A typical model number is 1-

3636-601-52XX where XX is the length of the cable in inches. This brand has a minimum bend radius of 1 inch.

Semi-Rigid Cables

Semi-rigid cable is used where microwave signals need to be transported over some distance, and the geometry is simple. They are manufactured by Precision Tube, Inc, and distributed by Compucon Distributors under the model number RA50141. This type of cable is ordered in 10 foot lengths or 50 foot spools. The cable does not come with connectors on it; they must be added by the end user. Connectors are sold separately as Omni Spectra part number 2001-7943-02. While these cables have a relatively sharp minimum bend radius of 5/8 inch, they must be bent with a special tool. Attempts to bend this cable by hand can very easily result in ruin of the cable.

1.3 Microwave Switches

The microwave switches are manufactured by Teledyne Microwave, and, of all the microwave components, require the least maintenance or care. Their most common failure mode is to not have repeatable insertion loss between the normally open terminal and the common terminal when power is applied to the switch. Operating the switch outside its recommended voltage range, or mechanical shocks to the case (as when dropped), can cause a switch to occasionally fail.

1.4 Microwave Amplifiers

The microwave amplifiers are manufactured by MITEQ and have a model number of AMF-4B-0812-20P. They are driven by 15VDC and draw about 300mA. Microwave amplifiers are very expensive and rather sensitive. They can be easily damaged by overvoltage conditions and from high temperatures.

Extreme care is appropriate anytime the amplifiers are to be handled, to prevent electrostatic discharge. A little homework should also be done before connecting them to any other power supply than the one provided. Spiking voltages when power is applied (or disconnected) can destroy the amplifier, so be sure this will not happen with the new power supply before first connecting the amplifier to it. Also, the amplifier will modulate the microwave signal with any ripple that is present on the power supply, so a well regulated power supply should be used.

The amplifier needs to be heat-sinked in normal operation. Without sufficient heat sinking, the amplifier can cook itself to death. Generally, an amplifier which is too warm to hold is too warm. Like the microwave cables, the amplifiers have characteristics which can change with temperature in its normal operating range of temperatures. Refer to the section on cables regarding the appropriate precautions for operation in a variable temperature environment. Also, the characteristics of the amplifier will change from when it is first powered up to when it reaches its ambient operating temperature. The system should not be used for precision measurements (such as calibration) for the first 15 minutes after the power is applied to the microwave amplifiers since they have not yet reached their operating temperature.

2 Moving Parts

The Bistatic Facility has a number of moving parts which need periodic lubrication. These parts need to be oiled, greased, and/or to be kept clear of debris.

2.1 Grease

The following parts have grease fittings and should be greased every 500 hours of operation:

Eight (8) pillow block bearings holding the elevation shafts.
Six (6) undriven wheels below the cars.
Any grease fittings associated with the turntable.

2.2 Oil

The following parts should be oiled:

Two (2) drive wheels for the inner arch azimuth and the worm gears associated with each. Change the oil in the oil cover every 500 hours of operation.

Four (4) drive chains for the elevation control. (Do not get oil on slip clutch). Oil as needed; clean as instructed below.

Four (4) gearboxes at each elevation control. Initial oil change at 500 hours or 5 weeks. Subsequent oil changes every 2500 hours or 6 months. Use SAE140 grade gear lubricant.

2.3 Cleaning

The entire Bistatic Facility should be kept clean to insure the longest possible life of operation. Certain parts, however, are particularly susceptible to damage due to dirt or other contaminants.

The rail should be kept clear of all debris. The azimuthal feedback and constraint systems contain precision moving parts which must be kept free of dirt and dust.

The azimuthal encoders must be kept both clean and dry. Wipe off any oil or water that may come in contact with the azimuthal feedback and constraint system.

Dust will settle and stick to the elevation control drive chains. Every 1000 hours of operation, or when the chain is showing signs of losing its flexibility due to dirt and dust, it should be removed and cleaned in a petroleum-based solution. Do not use gasoline. Clean the chain in a well ventilated location only. Do not clean the chain near any sparks or open flames. Each chain has one key link which can be disassembled, allowing the chain to be removed. Before reinstalling the chain, thoroughly lubricate it with oil or a paraffin-based chain lubricant.

2.4 Tuning

Tuning is the process by which optimum movement of the motorized pieces of the BMF is achieved. Should the motion of the one of the axes become jerky, or if it fails to arrive at its destination, that axis is in need of a tune-up. Please contact the University of Michigan for tune-up procedures.

2.5 Drive Wheel Assembly

This section includes instructions for assembling the drive wheels that are located under the cars. It is not expected that the user should ever have to disassemble or reassemble these units, but if for some reason it should become necessary, the assembly procedure is given below. Trying to assemble the drive wheels without instructions resembles trying to solve Rubik's Cube without knowing how: frustration comes quickly, and the temptation to force something which shouldn't be forced can be overwhelming.

Put the key for the wheel in its keyway on the wheel shaft.

Put the wheel in the fork.

Put the wheel shaft through the wheel with the key locking the wheel to the wheel shaft.

Put two (2) 1/8" spacers on the wheel shaft on the side nearest the worm gear.

Put one (1) 1/8" spacer and one (1) 1/16" spacer on the side away from the worm gear.

Put a bearing on each side.

Check the spacing. Hold the bearing flanges down on the fork. They should both touch with minimal movement of the wheel. Adjust spacing as needed.

Put a 1/16" spacer outside the bearing on the end away from the gear. Add a circlip to the same end.

Add spacers to the gear end of the shaft so that with the circlip installed, a minimum of motion (endplay) is possible (approx. 5 mils acceptable).

Install the worm wheel with its key but do not tighten the set screw.

Install the worm on its shaft with the roll pin end down. Drive or press the roll pin in.

Insert the worm shaft in to the holes in the frame, add bearings, a 1/16" spacer on each end and circlips. Adjust spacers for minimum endplay. Make sure the circlips are fully seated in their grooves; they are important.

Check by turning the worm shaft that the wheel does not bind at any point in its rotation. There will be some backlash.

Add the coupling to the worm shaft and its roll pin. Be careful not to damage the coupling shaft or bearings when driving or pressing the pin in.

Mount the oil pan with 100 cc of new oil.

Bolt the motor, motor adapter, motor plate and wheel assembly to the frame. Be sure the motor and worm shafts are well aligned. They turn freely by hand; the only resistance should be from the motor. It is the relative positions of the motor plate and wheel assembly that determine alignment; the motor adaptor position is fixed. The rubber part of the coupling should not be compressed.

The drive wheel is now ready to use.

Chapter 7

Troubleshooting

1 Multipath

Multipath is best detected by moving or shielding objects and comparing measurements before and after. For example, measuring a bistatic target and then placing radar absorbing material (RAM) on the transmitter side of a suspect object and remeasuring will reveal if the direct path from the transmitter to the suspect object contributes to the measurement. Or, measuring a target which is known not to change its scattering pattern very rapidly with a change in bistatic angles, and repeating the measurement with a small change in bistatic angles, may change the path length of an unwanted signal and dramatically change the measured signal.

For some sets of angles, a direct path from transmitter to receiver may carry sufficient energy to distort the desired signal. Software gating may help, but for some geometries it may not be useful, and a baffle may need to be constructed.

Multipath may also come from objects near to the target. The edge of the sample holder may diffract signals, for example. In this case, possible solutions include lining the sample holder edge with RAM, or replacing the sample holder with one of a different (larger) size, and choosing a different set of bistatic angles.

Background subtraction is a technique very useful for small but not negligible multipath problems. A background measurement is made for each set of bistatic parameters without a target. This background measurement is then subtracted from every measurement of a target (calibration, validation, or unknown) for those sets of parameters. Then the resultant data contains the target but not the multipath signals which do not involve the target. Care must be used in this technique to not introduce new unwanted signals in the background measurement; also, the technique has a limitation in that multipath which involves the target of interest is not corrected. For example, if an aluminum sphere is placed on a styrofoam pedestal as a calibration target, the background measurement would consist of the styrofoam pedestal alone. The technique of background subtraction will remove the effect of the scattering from the styrofoam pedestal, but it will not remove the effect of the interaction of the sphere with the pedestal, and it will amplify the effect of any scatterer which was shadowed by the sphere. Also, small errors, such as slightly moving the pedestal when removing the sphere, will make the subtraction worse than if it were ignored.

2 Noise

The cause might be a noisy electrical environment; low frequency cables (like DC power to the amplifiers) might be picking up unwanted signals (like pulses caused by nearby motors being turned on or off). Many shielding techniques may be employed, but even a short list is beyond the scope of this section. At worst, the Facility may need to be moved to a more quiet location.

The Network Analyzer may need service. Disconnect the rest of the Facility and see if similar noise persists.

Under rare circumstances, large sets of measurements contain occasional data points which are obviously in error (usually much too low in power). One possible cause is failure of the microwave switches to open or close identically each time. The switches should be removed and tested for repeatability if they are suspected, and repaired or replaced if they show problems. Faulty switches are very rare but not unknown. Another, more likely cause, is interference from an occasionally changing environment; most often it is an operator who forgets that measurements are being taken and walks into the beam. Discard the data point and lash the idiot with a wet noodle.

3 No repeatability of identical measurements

3.1 Has anything changed?

Disconnecting and reconnecting any cables that carry rf signal may change the amplitude and phase of the received signal. Recalibrate.

Cables are very easily damaged and must be handled with care. A damaged cable may invalidate a calibration every time the bistatic angles are changed. If measurements at a particular angle are repeatable when the Facility is not moved but not repeatable if it is moved (away and then back to the same set of angles), then the cables should be inspected and/or tested for damage. The cause may be a just a loose connection, but damage can easily occur. Damaged cables should be replaced.

Target positioning may appear identical to a previous measurement effort, but some targets have such rapidly changing patterns that a slight error in positioning (either in position or in orientation) may significantly change the measurement. It may be necessary to refine the technique used to position the target.

3.2 Is everything warmed up?

The amplifiers and the network analyzers need a finite amount of time after power-up for their rf characteristics to stabilize. This time varies from as short as a half hour to 24 hours, depending on the condition of the active equipment. If the equipment is defective, it may never stabilize.

Temperature variations can also change rf characteristics of active and passive elements in a system, especially cables. For an indoor measurement facility, these temperature variations are usually sufficiently small that it rarely causes any problems.

4 Calibration cannot be validated

4.1 Are either or both measurements repeatable?

See Section 3 for repeatability problems.

4.2 Are the measurements noisy?

See Section 2 on noise.

Targets must appear at least 10 dB above any noise floor in order to provide any confidence in the data. Calibration targets should have at least 20 dB signal to noise ratio. Look at the time domain of the network analyzer or compare the calibration measurement with a background measurement to determine the signal to noise ratio of a target. If the noise cannot be eliminated, the calibration target could be replaced with one of a larger radar cross section.

4.3 Has multipath been removed?

See Section 1 on multipath.

4.4 Are the targets calculated correctly?

The literature often contains several different conventions for the same quantities of interest. Make sure the same conventions and definitions for quantities are used for both targets.

A number of targets use approximations in determining their theoretical properties. Most important of these is the far-field approximation. Make sure the approximations are valid.

The nastiest of calculation errors is the software bug. Make sure the code agrees with the derivation.

4.5 Could uncontrollable errors be at fault?

The bistatic facility is not ideal. For example: the antennas have a beamwidth while calibration and verification targets are not points, but have a size; thus measurements for a particular set of bistatic angles is really a weighted sum of measurements over a small range of bistatic angles. If the target has scattering properties which vary rapidly with respect to the bistatic angles, even the most accurate positioning techniques will not help the user recover the calculated properties from measurements. Also, constitutive parameters are sometimes not known very accurately; small changes in the "known" value of the dielectric of a target may dramatically affect the expected result of a measurement. Scattering characteristics at microwave frequencies are not sensitive to the value of the conductivity for a conductive target, so these are often the best targets for calibration and verification.

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[5] F. T. Ulaby and Editors C. Elachi. *Radar Polarimetry for Geoscience Applications.* Artech House, Norwood, MA, 1990.

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Appendix A

Documentation

In addition to this document, a number of other documents accompany the Bistatic Facility.

1 Manufacturer Documents

Wiring diagrams
Installation drawings
mechanical drawings of completed system
Calibration papers: GCT, IACT, Kähny.

2 OEM Documents

Gateway documents: User's Guide.

Colorado Backup Systems: User's Guide for DOS, Jumbo Tape Backup System Hardware Guide.

Microsoft DOS/Windows documents

Microsoft Project documents

Visual Basic books: Programmer's Guide, Language Reference, Professional Features Books 1 and 2.

Hewlett Packard documents: Installing the HP-IB Interface, Using the HP-IB Interface and Command Library with DOS, Using the HP-IB Interface with Microsoft Windows, Using the HP-IB Interface with Printers and Plotters.

MEI Motion Engineering, Inc. books: DSP-Series Motion Controller Installation, version 2.1c; DSP-Series Motion Controller C-Programming, version

2.1c.

Advanced Motion Controls Catalog.
microwave components spec sheets

3 Original Diskettes

All diskettes are 3.5" DD-HD (DOS 1.44 MB) unless noted.

Hewlett-Packard: HP-IB Tools – Install/Winstall rev. B.01.00 (1 disk).

Intel: EtherExpress 16 and 16TP LAN Adaptor Diskette v. 2.0.3 (1 1.2 MB disk).

Microsoft: MS Project for Windows v. 3.0 (3 disks); MS-DOS 6 Plus Enhanced Tools v. 6.0 (3 disks); MS Visual Basic for Windows, Professional Edition v. 3.0 (9 disks); MS Windows v. 3.1 (6 disks); MS OEM Mouse Drivers & Utilities Disk (1 disk); MS Mouse Setup v. 9.0 (1 disk).

Gateway: AnyKey Keyboard Utility Disk (1 disk); ATI Local Bus ULTRA PRO v. 2.0 (2 disks).

Appendix B

Hemisphere Scattering Code

The fortran code used to model the RCS of a hemisphere on a ground plane is listed here. Refer to Sections 1 and 1.1 of Chapter 2 and Section 1 of Chapter 4 for more details of the use of this code.

This file contains the driver routines and executes the image theory:

```
      program mie5driver
c   this program calculates the
c   bistatic pattern of a hemisphere on gnd plane
      implicit undefined (a-z)
c  spdlite is the speed of light in m/ns
      real pi,spdlite
      parameter(pi=3.14159265357989,spdlite=0.29979)
      complex refrel
c     real refr,refi
      real chi,radius,fghz,k,lam
      real thetas,thetai,phi
c f is scatter amplitude as in Ishimaru...
c m is scatter amplitude as in Bohren&Huffman
c  Es=(e^ikr)/r f Ei          : Ishimaru
c  Es=(e^ikr)/(-ikr) m Ei     : B & H
      complex m1(2,2),m2(2,2),m(2,2),f(2,2)
c  sigd= abs(f^2)    Ishimaru's differential scattering coefficient
c  sigbi = 4 pi sigd   Ishimaru's bistatic radar cross section
      real sigd(2,2),sigbi(2,2)
      integer r,t,v,h
```

```
      parameter(v=1,h=2)
      logical verbose
      parameter (verbose=.false.)
      external scatter
      real d2r, db, x
      db(x)=10.*log10(x+1.e-45)
      d2r(x)=x*180./pi
c     if (verbose) write(6,*) 'input radius in inches'
      read(5,*) radius
c     radius=3.1875/2.
c  convert from inches to meters
      radius=radius*2.54/100.
c     if (verbose) write(6,*) 'input frequency, in GHz'
c     read(5,*) fghz
      fghz=9.25
c     if (verbose) write(6,*) 'input relative index of refraction'
c     read(5,*) refr,refi
c     refrel=cmplx(refr,refi)
c  use refractive index of a good conductor
      refrel=cmplx(1.,100.)
      if (verbose) write(6,*) 'elevation angle of incidence, in deg'
      read(5,*) thetai
      if (verbose) write(6,*) 'elevation angle of scattering, in deg'
      read(5,*) thetas
      if (verbose) write(6,*) 'azimuth angle b/t scat & inc, in deg'
      read(5,*) phi
c  make freespace wavelength
      lam=spdlite/fghz
c  make freespace wavenumber
      k = 2. * pi / lam
c  make sphere size parameter
      chi=k*radius
      if ( abs(thetas+cos(d2r(phi))*thetai) .gt. 1.e-7 ) then
c  calculate scattering from real transmitter
          call scatter(m1,phi,thetas,thetai,chi,refrel)
c  calculate scattering from image transmitter
          call scatter(m2,phi,thetas,180.-thetai,chi,refrel)
          do r=v,h
```

```
c  calculate real and image scattering interference via image theory
            m(r,v)=m1(r,v)+m2(r,v)
            m(r,h)=m1(r,h)-m2(r,h)
            do t=v,h
c  convert scatter coefficients to RCS
              f(r,t)=m(r,t)/(-cmplx(0.,1.)*k)
              sigd(r,t)=abs(f(r,t))**2
              sigbi(r,t)=db(4.*pi*sigd(r,t))
            enddo
          enddo
c  output results
          write(6,*) sigbi(v,v),sigbi(v,h),sigbi(h,v),sigbi(h,h)
      endif
      stop
      end
c
c----------------------------------------------------------------------------
c
```

This file contains the routines "bhmie", which calculates the scattering coefficients, and "scatter" which calls "bhmie" and converts the scattering coefficients into the coordinate system used in this documentation:

```
c            mie.ftn          ( bohren and huffman,1983 )
c     input x      = ka          normalized radius
c           refrel = ns/nb       relative refractive index
c           amu    = cos(theta)  angle b/t incident & scattered directions
c    output s1,s2  complex scattering amplitudes for e-field perpendicular
c                  & parallel directions
      subroutine bhmie2(x,refrel,amu,s1,s2)
      real amu,pi,tau,pi0,pi1
      complex d(3000),refrel,xi,xi0,xi1,an,bn,s1,s2,dd
      real*8 psi0,psi1,psi,dn,dx
      dx = x
c**** series summation terminated after nstop terms
      nstop = x + 4.0*x**0.3333 + 2.0
      nmx = amax1(float(nstop),cabs(x*refrel)) + 15
c**** logarithmic derivative d(j) calculated by downward
```

```
c**** recurrence beginning with the initial value 0 + i0 at j = nmx
      dd = cmplx(0.0,0.0)
      do 120 n=1,nmx - 1
        rn = nmx - n + 1
        dd = (rn/(x*refrel)) - (1./(dd+rn/(x*refrel)))
        if (nmx-n.le.nstop) d(nmx-n)=dd
  120 continue
      pi0 = 0.0
      pi1 = 1.0
      s1 = cmplx(0.0,0.0)
      s2 = cmplx(0.0,0.0)
c**** riccati-bessel fct w/ real argument x, calculated by upward recurrence
      psi0 = dcos(dx)
      psi1 = dsin(dx)
      chi0 = -sin(x)
      chi1 = cos(x)
      apsi0 = psi0
      apsi1 = psi1
      xi0 = cmplx(apsi0,-chi0)
      xi1 = cmplx(apsi1,-chi1)
      do 200, n=1,nstop
        dn = n
        rn = n
        fn =(2.0*rn+1.0)/(rn*(rn+1.0))
        psi = (2.0*dn-1.)*psi1/dx-psi0
        apsi = psi
        chi = (2.0*rn-1.0)*chi1/x - chi0
        xi = cmplx(apsi,-chi)
        an=((d(n)/refrel+rn/x)*apsi-apsi1)/((d(n)/refrel+rn/x)*xi-xi1)
        bn=((refrel*d(n)+rn/x)*apsi-apsi1)/((refrel*d(n)+rn/x)*xi-xi1)
        pi = pi1
        tau = rn*amu*pi - (rn+1.)*pi0
        s1 = s1+fn*(an*pi+bn*tau)
        s2 = s2+fn*(an*tau+bn*pi)
        psi0 = psi1
        psi1 = psi
        apsi1 = psi1
        chi0 = chi1
```

```
        chi1 = chi
        xi1 = cmplx(apsi1,-chi1)
        rn = n+1
        pi1 = ((2.*rn-1.)/(rn-1.))*amu*pi -rn*pi0/(rn-1.)
        pi0 = pi
 200  continue
      return
      end
c
c-----------------------------------------------------------------------------
c
      subroutine scatter(m,phi,thetas,thetai,chi,refrel)
c  this routine calculates scatter coefficients by calling bhmie,
c  then rotates them from para & perp coordinates to V & H
      implicit undefined (a-z)
      complex m(2,2),refrel
      real phi,thetas,thetai,chi
c
c   in m(r,t), v=1, h=2  r-receive index, t-transmit index
      real amu,rotin(2,2),rotout(2,2),sina
      real rthes,rthei,rphi
      real coss,cosi,sins,sini
      complex s(2), zero
      real pi
      parameter(zero=cmplx(0.,0.),pi=3.14159265357989)
      integer i,j,k
      external amod2,bhmie2
      real x,d2r,amod2
      d2r(x)=x*pi/180.
c
c  convert angles to radians, phi to range of +/- pi
c   no need to fix negative theta's here...
      rthes=d2r(thetas)
      rthei=d2r(thetai)
      rphi =d2r(amod2(phi,360.,180.))
c
c  calculate scatter matrix in b&h's perp/para notation
c   perp x para = k  \   rules used by bohren &
```

```
c   perps = perpi    /    huffman,  except to a common sign
      amu=cos(rthei)*cos(rthes)+sin(rthei)*sin(rthes)*cos(rphi)
c  amu is now cosine of angle b/t -ki and ks, by spherical trig
      amu=-amu
c  amu is now cosine of angle b/t ki and ks
      call bhmie2(chi,refrel,amu,s(1),s(2))
c       s(1) is S_perp  ;  s(2) is S_para
c  note:  sperp=+spara @ amu=+1.  ie. fwd scatter  (thei=pi-thes, phi=pi)
c         sperp=-spara @ amu=-1.  ie. backscatter  (thei=thes, phi=0)
c
c  make incident/scattered wave rotation matricies to get to V/H pol
      if (abs(amu).ge.1.00-1.e-7) then
        m(1,1)=s(1)
        m(1,2)=zero
        m(2,1)=zero
        m(2,2)=s(2)
      else
c  more spherical trig...
        sina=sqrt(1.-amu*amu)
c
        sini=sin(rthes)*sin(rphi)/sina
        cosi=(sin(rthei)*cos(rthes)-cos(rphi)*sin(rthes)*cos(rthei))
     &      /sina
        rotin(1,1)= sini
        rotin(1,2)=-cosi
        rotin(2,1)= cosi
        rotin(2,2)= sini
c
        sins=sin(rthei)*sin(rphi)/sina
        coss=(sin(rthes)*cos(rthei)-cos(rphi)*sin(rthei)*cos(rthes))
     &      /sina
        rotout(1,1)= sins
        rotout(1,2)= coss
        rotout(2,1)=-coss
        rotout(2,2)= sins
c
c  compute scatter matrix in V/H notation.  V always points "up", (for the>0)
c     V x H = k       m=rotout*s*rotin     s is a diagonal matrix
```

```
        do i=1,2
         do j=1,2
            m(i,j)=zero
            do k=1,2
              m(i,j)=m(i,j)+rotout(i,k)*s(k)*rotin(k,j)
            enddo
          enddo
        enddo
      endif
c
      end
c
c-----------------------------------------------------------------------------
c
      function amod2(x,y,z)
      real amod2,x,y,z
c  x modulo y, with specified range of output
c  x is dividend, y is divisor, z defines greatest possible remainder
c  output is in range of (y-z,z]
c
c  offset x
      x=x+z
c  take x modulo y
      amod2=x-anint(x/y-.4999999)*y
c  unoffset amod2
      amod2=amod2-z
c  no side effects: unoffset x
      x=x-z
      return
      end
c
c-----------------------------------------------------------------------x------
c
```