A longstanding problem in radar and electromagnetic scattering measurements is the reconstruction of object shape and detail, i.e., an image, from far field scatter data to be used in object identification and classification. During the period covered by this report we have been able to demonstrate in a feasibility study the first reconstruction of a 3-D image of a perfectly reflecting object from its wave-vector diversity (multifrequency and multi-aspect) scatter data making use of a new Weighted Fourier Domain Projection...
Theorem (WFDPT) and establish a relationship between holography with wavelength diversity and inverse scattering. Coherent wave vector diversity radar techniques are used to access a finite volume of the 3-D Fourier space (also known as reciprocal space or p-space) of the scattering object. The WFDPT permits the use of hybrid (digital/optical) computing that enables the retrieval and display of 3-D image information in parallel slices or cross-sectional outlines. The major attributes of this approach as compared to totally digital computing are its potential for displaying a true 3-D image in real-time. Wave-vector diversity methods appear suitable for the imaging of two classes of practical objects namely non-dispersive perfectly reflecting objects of the type often encountered in radar (and sonar) and semitransparent weakly scattering objects such as certain ultrasound and light scattering objects encountered in biology and medicine. The method has several unique characteristics. It furnishes true super-resolution, i.e. resolution exceeding the classical Rayleigh Limit of the available recording aperture, in this case a highly thinned (widely dispersed) broad-band coherent receiver array. True super-resolution is achieved because of an inherent aperture synthesis due to frequency diversity (frequency scanning, stepping or comb illumination) and conversion of spectral degrees of freedom into spatial image detail. Accordingly, when applied to the imaging of a dispersive object, a target signature rather than a geometrical image should be expected. Such a target signature could still be useful in object identification and classification since it contains information pertaining to the material composition of the object intermixed with geometrical image detail. The use of frequency diversity was found to lead to a unipolar impulse response. This is very useful in suppressing coherent noise (speckle) which is known to be the major drawback of coherent imaging.

Preliminary work on 3-D image display has yielded encouraging results on 3-D display from a series of weighted projection holograms of various slices of a test object. The projection holograms were viewed in rapid succession using the virtual Fourier transform.

To identify optimal and practical approaches to wave-vector diversity data acquisition a unique microwave measurement system has been assembled, installed and tested in our anechoic chamber facility. The system was used also in the study of TDR (target derived reference) methods in which a reference for phase measurement can be furnished by the scattering object eliminating thus the need for costly local oscillator distribution networks and eliminating at the same time undesirable range phase ambiguities from the collected data. The measurement facility is computer aided furnishing thereby semi-automatic control of object positioning or orientation, frequency stepping, data acquisition and storage, and final data correction and analysis. A high resolution CRT display enables the display of weighted projection holograms computed from the p-space data making use of the WFDPT. Preliminary results of this measurement system capabilities included in this report confirm its tremendous versatility. At this stage, the program strongly suggests the practical feasibility of a new generation of cost effective, real-time, super-resolving 3-D imaging radars that can because of their 3-D image slicing characteristic be appropriately referred to as Tomographic Radars (Tomos=Slice in Greek).

Finally, a study of 3-D imaging using other forms of broadband radiation such as impulsive, random noise and particularly thermal emission for passive 3-D wavelength diversity imaging has been also initiated.
The findings in this report are those of the authors and are not to be interpreted as the official position of the Air Force Office of Scientific Research or the U.S. Government.
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FINAL REPORT

SUPER RESOLUTION IMAGERY
BY FREQUENCY SWEEPING

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NE
BUILDING 410 BOLLING AIR FORCE BASE
WASHINGTON, D.C. 20332

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PREPARED BY
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HIGH RESOLUTION FREQUENCY SWEPT IMAGING

1. Introduction

The aim of the research work outlined in this final report was the analysis and investigation of methods by which frequency or wavelength diversity techniques can be employed to impart to a highly thinned, and therefore cost-effective, longwave (microwave or ultrasound) imaging aperture resolution capabilities better than its monochromatic classical (Rayleigh) limit achieving thereby super-resolution by means of frequency synthesized apertures. This approach to longwave imaging gains practical significance when one considers the current highly developed state of the art of broadband microwave gear suitable for use in a new generation of cost-effective high resolution microwave imaging radars utilizing frequency diversity techniques.

It is well known that the development of longwave holographic imaging systems possessing resolution and image quality approaching those of optical systems is hampered by three factors: (a) prohibitive cost and size of longwave imaging apertures, (b) rapid deterioration of longitudinal resolution with range, (c) inability to view a 3-D image as with optical Fresnel holograms because of a wavelength scaling problem and (d) degradation of image quality by speckle or coherent noise because of the low numerical apertures attainable with present techniques. For example, a longwave imaging aperture operating at a wavelength of 3 cm should be about 3 km in size in order to achieve image resolution comparable to an ordinary photographic camera. In addition to inconvenient size, the cost of filling such a large aperture with suitable coherent sensors is clearly prohibitive. Furthermore, recall that in conventional longwave holography when optical image retrieval is utilized, it is necessary to store the longwave hologram data (fringe pattern) in an optical transparency suitable for processing on the optical bench using laser light. In order to avoid longitudinal distortion* of the reconstructed image, the size of the optical hologram replica must be \( m = \frac{X_{long}}{X_{laser}} \) times smaller than the longwave recording aperture. For the example cited earlier, this means an optical hologram replica of less than a millimeter in size. It is certainly not possible to view a virtual 3-D image through such a minute hologram even with optical aids since these tend to introduce their own longitudinal distortion. As a result, longwave holographers have long learned to forgo 3-D imagery and settled instead for 2-D imagery obtained by projecting the reconstructed real image on a screen. This permits lowering of the reduction factor \( m \) and consequently relaxing the resolution requirements of the photographic film which allows in turn the use of highly convenient Polaroid transparency film for preparation of the optical hologram replica. Because of the small size (measured in wavelength) of longwave apertures attainable in practice and the above methods of viewing the real image, speckle noise is always present leading to degradation in image quality.

* Longitudinal distortion causes for example the image of a sphere to appear elongated in the range direction like a very long ellipsoid.
In this report we summarize the main results of our investigation under this grant. Our findings show that frequency diversity techniques not only circumvent the limitations discussed above but provide a means of viewing true 3-D images of distant objects such as satellites and aircraft. It is worthwhile to point out that our studies of wave-vector diversity imaging (or frequency swept imaging) were motivated to some extent by evidence of super-resolved "imaging" capabilities in the dolphin and the bat which are known to use frequency swept (chirp) signals in their "sonar" to discern small objects in their environment.

2. Summary of Important Results

The main findings of the study, details of which are given in the appendices and our publications (see list of publications), are outlined next.

(a) Wave-vector diversity (multifrequency and multiaspect) techniques can be used to enhance the amount of object information collected by a broadband coherent aperture deployed in the far field of the scattering object. Thus the data collected by a highly thinned array of coherent receivers intercepting the wavefield scattered from a distant 3-D reflecting object, as the frequency of its illumination (and/or its direction of incidence) are changed (see Fig. 1-a for example), can be stored as a 3-D data manifold in \( p \)-space (Fig. 2) from which an image of the object can be retrieved by means of a 3-D Fourier Transform. The size and shape of the 3-D data manifold, and therefore the resolution, depend on the relative positions of the object, the transmitter (illuminator), and the receiving array and on the spectral width of the illumination utilized.

(b) The data collected must be corrected for a quadratic phase factor \( F \) (caused by the unequal distances between the object and the receiving stations forming the widely dispersed imaging array) before it is stored in a 3-D manifold in \( p \)-space and an undistorted image of the 3-D reflecting object reconstructed through the 3-D Fourier transform operation. A bothersome range-azimuth ambiguity is also avoided through elimination of this quadratic phase term.

The most promising methods for data acquisition and correction is that which utilizes a target derived reference (TDR) at the synchronous detectors of the various receivers to correct for the unequal phase shifts or propagation time delays from the object to each receiver. In this approach the data furnished by the various receivers of the recording array is free of the undesired factor \( F \). Therefore no additional processing by a computer will be necessary before filing the data at the appropriate locations in \( p \)-space. The TDR method has several advantages which include:

(i) Elimination of the need for a costly and unreliable central local oscillator distribution network.

(ii) Because TDR results in a recording configuration similar to that of a lensless Fourier Transform hologram, the resolution requirements from the recording device are greatly relaxed*.

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In longwave holography this fact is translated into a significant reduction of the number of receiving elements in the recording aperture. In addition the use of TDR allows us to place all the resolving power of the recording aperture on the target. This means that high resolution images of distant isolated targets should be feasible with array apertures consisting of tens of elements. The ability to synthesize a 2-D receiving aperture with a Wells array consisting of two orthogonal linear arrays one of transmitters and the other of receivers provides further means of reducing the number of stations needed for data acquisition without sacrifice in resolution. A frequency swept Wells array of 10 transmitters and 10 receivers using a (2-4) GHz sweep should be able to easily furnish $10^4$ 3-D distinguishable resolution cells on the target which is more than sufficient for discerning the scattering centers on practical targets.

(i) Greater immunity to phase fluctuations arising from turbulence and inhomogeneities in the propagation medium because both the reference and imaging signals arriving at each receiving element of the aperture travel roughly over the same path.

(v) TDR eliminates the range azimuth ambiguity and excessive bandwidth problems that arise in fast frequency swept imaging when the reference signal for the array aperture is distributed instead from the illumination source or a centrally located local oscillator phase locked to it.

Two TDR methods have been considered to some extent in our work to date. In one method which we term LFTDR (Low Frequency Target Derived Reference), the object is assumed to be illuminated simultaneously with a high frequency imaging signal and a low frequency signal that is a subharmonic of the illuminating frequency. The subharmonic reference frequency $\omega_r$ is chosen such that $k_{r} l \ll c$, $l$ being the maximum linear dimension of the object and $k_{r} = \omega_r/c$, $c$ being the velocity of light. This places scattering from the object in the Rayleigh region where the object behaves as point scatterer with zero phase contribution. The far field phase of the reference signal at any receiver is therefore entirely due to propagation between a reference point formed at the object to the receiver. A method for measuring this reference signal phase and using it to correct the imaging signal phase due to propagation has been proposed by Porter* and analyzed for a one-dimensional object geometry. The reference signal phase and the imaging signal phase are measured separately at each receiving station with the aid of two receivers whose local oscillators (L.O)'s, one at the reference frequency and one at the imaging frequency, are phase-locked only to each other and not to a central local oscillator as would be the case were we to use a conventional receiver array. Phase locking of the two L.O's can be accomplished by simply making the imaging L.O a harmonic of the

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reference L.O. This would eliminate the difficulties encountered in the implementation of large or giant thinned coherent receiving arrays of the type required here, namely the distribution of a central local oscillator signal. A great reduction in cost and effort associated with installation of a central L.O. distribution network can thus be achieved. This cost reduction should be compared however with the cost of implementing a LFTDR. Because of the large difference between the high frequency imaging frequencies and the low frequency reference frequency required for the high resolution imaging of practical objects, the same microwave gear can not be used for both frequencies. This could increase system cost. In addition since the measured reference phase must be multiplied by a factor $\beta$ equal to the ratio of the imaging to the reference frequency before being used as a reference phase in the imaging signal measurement, any errors in the reference phase measurement will also be amplified by this ratio. The precision of the reference phase measurement and phase error analysis are important and will have therefore to be examined further.

Another TDR methods which we call the Frequency Displaced Target Derived Reference (FDTDR) also shows promise. In this method, the analytical details of which are outlined in appendix I, the object is illuminated simultaneously during the sweep with two phase locked imaging frequencies $\omega_1$ and $\omega_2 = \omega_1 + \Delta \omega$, $\Delta \omega$ being a small incremental frequency. This can be realized also by single side band modulation of the swept signal or by phase locking two sweep oscillators. Measurement of the differential phase between the signals scattered from the target at these frequencies yields

\[ \frac{\Delta \omega}{c} \left( R_T + R_R \right), \]

where $c$ is the speed of light, $R_T$ is the distance from the transmitter to the object and $R_R$ is the distance from the object to the receiver. Multiplication of this phase by $\omega_1/\omega_2$ yields the phase factor $F$ at frequency $\omega_1$ which would be used to correct the phase measured at $\omega_1$. At first look this method would appear to still require a reference local oscillator. However this is not so since the procedure outlined above need not involve explicit phase measurements and multiplications. For example by mixing the two received signals at $\omega_1$ and $\omega_1 + \Delta \omega$ in a square law detector at each receiver a beat signal at frequency $\Delta \omega$ is derived whose phase is equal to

\[ \frac{\Delta \omega}{c} \left( R_T + R_R \right) \]

This phase shift of the signal due to the object is effectively zero because the wavelength at $\Delta \omega$ is much larger than the object extent making it behave effectively as a point scatterer. Harmonic mixing of the signal $\omega_1$ received at each receiver with this beat signal should yield the corrected p-space data at $\omega_1$. Because of the small difference $\Delta \omega$ between the two frequencies $\omega_1$ and $\omega_2$ utilized, the effect of phase errors due to system and atmospheric propagation could be more completely cancelled in this method than in the low frequency TDR methods. The small difference $\Delta \omega$ means also that unlike the LFTDR case the same microwave gear (antennas, transmission lines and other microwave circuit components) can be utilized in the handling of the reference and imaging signals. A variation of the TDI technique involving double side-band modulation is also possible and appears to be more simple to implement than the single side-band method.
(c) Because in addition to being dependent on geometry, the dimensions of the 3-D data in p-space shown in Fig. 2 are dependent on the spectral range of the illumination, super-resolution (i.e. resolution beyond the classical limit of the available physical aperture) is achieved. This aperture synthesis by wave-vector or frequency diversity helps cut down array cost (since a thinned array can be used to frequency synthesize a large array with higher filling factor).

(d) Fourier Domain Projection Theorems (see appendixes II and III for details) enable the generation of two dimensional holograms from projections (or weighted projections) of the corrected p-space 3-D data manifold of Fig. 2 permitting thereby optical image retrieval of the 3-D object in slices parallel to the projection plane one at a time. For example, Fig. 1-b shows the projection hologram for the p-space data obtained in a computer simulation of the arrangement shown in Fig. 1-a. The central cross-sectional outline of the object (the two 1 m diameter reflecting spheres of Fig. 1-a) retrieved from this projection hologram by means of a 2-D Fourier transform carried out on the optical bench is shown in Fig. 1-c. A similar example is shown in Figs. 3 and 4. Figure 3 shows a second test object consisting of 3-D distribution of a set of 8 point scatterers with locations and spacings given in the Figure. Figure 4 shows the projection holograms corresponding to the three slices of the object containing the point scatterers and the image retrieved from each. The sweep width in this example, as in the previous example, was (2-4) GHz however the number of receivers in the recording array has been reduced from 50 to 16. These computer simulations demonstrate that a 3-D (lateral and longitudinal) resolution of the order of twenty centimeters is easily achieved with a frequency sweep covering only (2-4) GHz using a broad-band array of 16 receivers and one transmitter. Wider-spectral windows should yield better resolution. It is worthwhile to note in this respect that commercial microwave sweepers and synthesizers are available with a spectral coverage of (.1-25) GHz indicating a potential for practical resolutions of the order of possibility few centimeters with cost-effective broad-band apertures consisting of tens of receivers operating with one central illuminator.

(e) The viewing or the display of a true 3-D image of the various slices or cross-sectional outlines should be possible by reconstruction of the various projection holograms in rapid succession while projecting the reconstructed real images of the corresponding slices on a rapidly moving projection screen. The screen would be displaced rapidly (together with the Fourier transforming lens) on the optical bench in the axial directions by small amounts proportional to the distances between the various slices. In another approach we have found that the 2-D virtual Fourier transform of a projection hologram can be carried out by simply viewing (with the unaided eye) a transparency containing an array of reduced replicas of the projection hologram arranged side-by-side with a point source. The image retrieved in this fashion would lie in the plane of the point source. This approach has the potential for 3-D display by viewing the virtual images retrieved from a series of projection holograms corresponding to different slices or cross-sectional outlines

*This means $10^3$ distinguishable 3-D resolution cells in the $(2 \times 2 \times 2) m^3$ volume of the assumed object.
of the object passed in front of the eye in rapid succession while moving the reconstruction point source axially back and forth at a suitable rate of incremental axial displacements. A proposed electro-optical scheme that permits carrying out this procedure in real-time using a rapidly recyclable spatial light modulator (SLM) operating in a reflection mode is shown in Fig. 5. The computer, the high resolution CRT and the projection optics are used to project reduced noncoherent images of the various projection holograms in rapid succession on the SLM while the axial position of the reconstruction point sources is altered rapidly also under computer control. The point source need not be derived from a laser in order to yield an image but could also be a miniature "grain of wheat" light bulb. Details of this task are found in Appendix III.

(f) As seen in (e), unlike monochromatic longwave holographic imaging, there is no specific scaling requirements imposed on the projection holograms in order to avoid longitudinal distortion in the optical reconstruction circumventing thus the wavelength scaling problem.

(g) Because of the broad spectral extent of the illumination used and ability to display the reconstructed image in separate slices, speckle or coherent noise, which is known to plague coherent imaging systems, is suppressed making the system behave in as far as image noise is concerned like a noncoherent imaging system but at the same time enjoy the superior detection characteristics associated with synchronous detection techniques.

(h) The broad-band nature of the imaging process also helps suppress undesirable image detail that could arise from object resonance, which could seriously degrade image quality in a monochromatic imaging system.

(i) The data collected at every receiver, represents after correction, essentially the frequency response of the scattering object measured from a different aspect angle. Assuming the scattering process is linear, this frequency response is related to the impulse response of the object by a Fourier transform (see ref. 5 in List of publications). This suggests that impulse illumination can be utilized instead of frequency swept illumination. When this is done, the 3-D data manifold in p-space may be generated by Fourier transforming the impulse response at each receiver, correcting the data for the Factor F mentioned in (b), and storing the result in the appropriate p-space locations for each receiver. The resulting p-space volume accessed in this fashion can then be employed as described earlier to yield 3-D image information. Impulse illumination is desirable in certain instances of rapid target motion but may be more difficult to implement than frequency swept illumination. Since the impulse response of a time invariant linear system can also be deduced from white noise excitation and corellation of the output response with the input as described elsewhere in more detail (see 5 in list of publications), it follows that the techniques described in this report for coherent broadband radiation should be equally applicable with minor signal processing modification to noise-like broadband
radiation including passive black-body radiation.

(j) Experimental verification for both the principle of frequency diversity imaging and the TDR concept were obtained with the aid of a semi-automated network analyzer configured and installed in a recently refurbished anechoic chamber within the scope of this program (see Figs. 6 and 7). This versatile system is capable of vector (amplitude and phase) measurements of wavefields scattered from test objects situated in the anechoic chamber over any frequency range lying in the (.1-18)GHz range for a variety of polarizations. A test object consisting of two parallel cylinders 25 cm apart each 5 cm in diameter and 50 cm long was mounted on a rotating styrofoam pedestal that is under computer control and illuminated as shown in Fig. 8. The distance from the center of the object to the illuminating parabolic antenna to the left and the receiving horn feeding the network analyzer was 2.5 m. The complex frequency response of this object was measured in the (5-14)GHz range and the data stored for 128 object orientation covering 360°. The stored data was corrected for range-phase with a synthetic TDR generated in the computer and the corrected data displayed and photographed yielding the frequency swept hologram shown in Fig. 9 (c). The image retrieved from this hologram via an optical Fourier transform carried out on the optical bench is shown in Fig. 9 (d). For reasons of comparison a computer simulation of this experiment assuring a (2-18)GHz sweep was performed. The resultant range-phase corrected hologram and the image retrieved from it optically are shown in Fig. 9 (a) and (b). Further detail on this phase of the program were reported in an MSc. thesis made part of this report in Appendix IV. This part of the program is being continued with the aim of further enhancing measurement accuracy and demonstrating imaging of a nonsimple 3-D test object such as a model aircraft utilizing polarization diversity to further enhance image quality.

3. Conclusions.

The primarily analytical and numerical study of frequency diversity imaging performed under this grant demonstrates conclusively the feasibility of a new generation of coherent broadband imaging radars capable of furnishing 3-D image detail of distant target with cost effective giant apertures and efficient digital/optical signal processing.

Future work in this area will focus more on the analysis and identification of optimal methods for data acquisition, processing and 3-D display. The ultimate aim is the generation of design criteria for a prototype system and its assessment in the 3-D imaging of low flying aircraft passing within range of our facilities on route for landing at the Philadelphia Airport.
List of Publications


10. C.K. Chan and N.H. Farhat, "Frequency Swept Imaging of Three Dimensional Perfectly Reflecting Objects", IEEE Trans. on Antennas and Propagation - Special Issue on Inverse Scattering. (Accepted for publication.)


Related Publications


6. N.H. Farhat and J. Bordogna, "An Electro-Optics and Microwave-Optics Program In Electrical Engineering", IEEE Trans. on Education - Special Issue on Optics Education (accepted for publication).

Fig. 1. Computer Simulation of Wave-vector Diversity Imaging, (a) Geometry, (b) Projection Hologram, (c) Retrieved Central Cross-sectional Image.
Three dimensional \( \beta \)-space data generated by frequency sweeping and collected by a 2-D array of receivers.
Fig. 3. 3-D object consisting of a set of eight point scatterers shown in isometric and \( R'_x-R'_y \) plane views at \( R'_z=-z_0,0,z_0 \). \( x_0=y_0=z_0=100^\circ \text{cm} \).
Fig. 4. Projection holograms and their optical reconstructions for the set of point scatterers in Fig. 7.10 at different $R'$ planes. (a) Hologram and reconstructed image of scatterers at $R' = -z_0$ plane. (b) Hologram and image at $R' = 0$ plane. (c) Hologram and image at $R' = z_0$ plane. $x_0 = y_0 = z_0 = 100$ cm.
Fig. 5. True 3-D image reconstruction based on the virtual Fourier transform.
Fig. 6. Block diagram of automated microwave network analyzer showing interface to MINC II computer via IEEE 488 standard interface bus.
Fig. 7. View of Microwave Anechoic chamber showing illuminator antenna and a calibration sphere in background.
Fig. 8. Two views of dual-cylinder test object in Anechoic chamber. (a) View showing illuminator to the left and the receiving horn on the right separated by absorbing barrier. (b) View showing test object mounted on rotating styrofoam pedestal. Cylinders are 5 cm in diameter, 50 cm long, 25 cm apart.
Fig. 9. Frequency swept holograms and retrieved images for a dual-cylinder test object. (a) Computed frequency swept hologram for a (2-18)GHz sweep and (b) retrieved image; (c) measured frequency swept hologram for a (5-14)GHz sweep and (d) retrieved image.
APPENDIX I

The Frequency Displaced Target Derived Reference

A second TDR method which we refer to as a Frequency Displaced Target Derived Reference (FDTDR) method also shows promise. This method involves simultaneous illumination of the object with two phase locked imaging frequencies $\omega_1$ and $\omega_2 = \omega_1 + \Delta \omega$ that differ by a small frequency increment $\Delta \omega$. Referring to eq. (9) of ref. 10 (see list of publications) we can write for the far field at a given receiver location $R_R$,

$$\psi_1(k_1, R_R) = \frac{jk_1}{2\pi R_R} e^{jk_1(R_T + R_R)} \int U(\vec{r}) e^{-j \vec{p}_1 \cdot \vec{r}} d\vec{r}$$  (1)

$$\psi_2(k_2, R_R) = \frac{j(k_1 + \Delta k)}{2\pi R_R} e^{-jk_1(R_T + R_R)} e^{-j\Delta k(R_T + R_R)} \int U(\vec{r}) e^{-j \vec{p}_1 \cdot \left(1 + \frac{\Delta \omega}{\omega_1}\right) \vec{r}} d\vec{r}$$  (2)

where $k_1, 2 = \omega_1, 2/c$ and $\Delta k = \Delta \omega/c$.

By making $\Delta \omega/\omega << 1$ the integral in (2) will approach that in (1). The only difference between the far fields $\psi_1$ and $\psi_2$ at the receivers is then the phase term $\Delta k(R_T + R_R)$. Measurement of this phase difference yields $(R_T + R_R)$ since $\Delta k$ is known. This information can be used to correct the phase of either the $\psi_1$ or $\psi_2$ signals to obtain the required $\vec{p}$-space information.

$$\Gamma(\vec{p}) = \int U(\vec{r}) e^{j \vec{p} \cdot \vec{r}} d\vec{r}$$  (3)
Appendix II

HOLOGRAPHY, WAVE-LENGTH DIVERSITY
AND INVERSE SCATTERING

ABSTRACT

The use of wavelength diversity to enhance the performance of thinned coherent imaging apertures is discussed. It is shown that wavelength diversity lensless Fourier transform recording arrangements that utilize a reference point source in the vicinity of the object can be used to access the three-dimensional Fourier space of non-dispersive perfectly reflecting or weakly scattering objects. Hybrid (opto-digital) computing applied to the acquired 3-D Fourier space data is shown to yield tomographic reconstruction of 3-D image detail either in parallel or meridional (central) slices. Because of an inherent ability of converting spectral degrees of freedom into spatial 3-D image detail true super-resolution is achieved together with suppression of coherent noise. The similarity of the key equations derived to those of inverse scattering theory is pointed out and the feasibility of using other forms of broadband radiation such as impulsive, noise and thermal is discussed. Finally, the potential of utilizing wavelength diversity imaging in microscopy and telescopy are discussed.

INTRODUCTION

A frequently encountered question in the science of image formation is how to make an available aperture collect more information about the scene or object being imaged in order to enhance its resolving power beyond the classical Rayleigh limit. This process is known as super-resolution and is relevant to all imaging systems whether holographic or conventional. There are five known methods for achieving super-resolution. These include: weighting or apodization of the aperture data; analytic continuation of the wavefield measured over the aperture; use of evanescent wave illumination; maximum entropy method; and use of the time channel. Weighting and analytical continuation techniques are known to become rapidly ineffective as the signal to noise ratio of the data collected decreases. Maximum entropy techniques are known to be more robust as far as noise is concerned but involve usually extensive computation. Illumination with evanescent waves is practical in limited situations where full control of the recording arrangement exists as in microscopy for example.
This leaves the time channel approach in which one can collect in
time more information about the object through the available recording
aperature by altering the object aspect relative to the aperature by
means of rotation or linear motion, or by altering the parameters of
the illumination such as directions of incidence, wavelength and/or
polarization. These later operations are known to increase the degrees
of freedom of the wavefields impinging on the recording aperature
enhancing thereby their ability to convey information about the nature
of the scattering object. Sophisticated imaging systems endeavour to
convert the nonspatial degrees of freedom of the wavefield, e.g.,
angular, spectral and polarization to spatial image detail enhancing
thereby the resolution capability beyond the classical Rayleigh limit
of the available physical aperature. Obviously such procedures involve
more signal processing than that performed by conventional imaging
with lens systems or holography.

In this paper we consider generalizing the holographic concept to
include wavelength diversity as a means of enhancing resolution. A
quick examination of the basic equations of holography reveals that
the lensless Fourier transform hologram recording arrangement is
amenable to this generalization. This conclusion is used then as a
starting point for a Fourier optics formulation of wavelength diversity
imaging of 3-D (three dimensional) nondispersive objects. The results
show that measurement of the multiaspect or multistatic frequency (or
wavelength) response of the 3-D object permits accessing its 3-D
Fourier space. The resulting formulas are identical to those obtained
from a multistatic generalization of inverse scattering\textsuperscript{10,11,12}
establishing thus a clear connection between holography and the inverse
scattering imaging problem. The inclusion of wavelength diversity in
holography is shown to have several important features: (a) the
availability of the 3-D Fourier space data permits 3-D image retrieval
tomographically in parallel or meridional (central) slices or cross-
sectional outlines by the application of Fourier domain projection
theorems, (b) suppression of coherent noise and speckle in the retrieved
image, (c) removal of several longstanding constraints on longwave
(microwave and acoustical) holography such as the impractically high
cost of the aperatures needed, the inability to view a true 3-D image
as in optical holography because of a wavelength scaling problem, and
minimization of the effects of resonances on the object.

WAVELENGTH DIVERSITY

We start by inquiring into the conditions under which the data
from $N$ holograms of the same nondispersive object recorded over the
same aperature, each at a different wavelength, can be combined to
yield a single image superior in quality to the image retrieved
from any of the individual holograms.
One approach to answering the question posed above would be to determine the conditions under which the well known formulas for the focusing condition, magnification and image location in holography can be made independent of wavelength. This quickly leads to the conclusion that wavelength independence can be met if a reference point source centered on the object is used and proper scaling of the individual holograms by the ratio of recording to the reconstruction wavelength is performed before super-position. The former condition is that for recording a lensless Fourier transform hologram where the presence of the reference point source in the object plane leads to the recording of a Fraunhofer diffraction pattern of the object rather than its Fresnel diffraction pattern because of the elimination of a quadratic phase term in the object wavefield in the recorded hologram. This is known to result in a highly desirable reduction in the resolution required from the hologram recording medium and is therefore of practical importance especially in nonoptical holography. More detail of the processing involved in combining the data in multi wavelength hologram can be found elsewhere.

Additional insight into the process of attaining super-resolution by wavelength diversity is obtained by considering the concept of wavelength or frequency synthesized aperture. The synthesis of a one dimensional aperture by wavelength diversity is based on the simple fact that the Fraunhofer or far field diffraction pattern of a nondispersive planar object changes its scale, i.e. it "breathes", but does not change its shape (functional dependence), as the wavelength is changed. A stationary array of broadband sensors capable of measuring the complex field variations deployed in this breathing diffraction pattern at suitably chosen locations would sense different parts of the diffraction pattern as the wavelength is altered collecting thereby more information on the nature of the diffraction pattern and therefore on the object that gave rise to it than if the wavelength was fixed (stationary diffraction pattern). Each stationary sensor in the array is thus able to collect as the wavelength is changed, and the breathing diffraction pattern sweeps over it, the same set of data or information collected by a movable sensor mechanically scanned over the appropriate part of the diffraction pattern when it is kept stationary by fixing the wavelength. Hence the term wavelength or frequency synthesized aperture.

The orientation and location of the wavelength synthesized aperture for any planar distribution of sensors deployed in the Fraunhofer diffraction pattern of a planar object and the retrieval of an image from the data collected has been treated earlier. It was clear, however, that extension of the wavelength diversity concept to the case of 3-D objects is necessary before its generality and practical use could be established.
For this purpose we considered as shown in Fig. 1(a) an isolated planar object of finite extent with reflectivity $D(\mathbf{p}_o)$, where $\mathbf{p}_o$ is a two dimensional position vector in the object plane $(x_o, y_o)$. The object is illuminated by a coherent plane wave of unit-amplitude and of wave vector $\mathbf{k}_i = k \mathbf{i}_k$ produced for example by a distant source located at $R_T$. The wavefield scattered by the object is monitored at a receiving point designated by position vector $\mathbf{R}_R$ belonging to a recording aperture lying in the far field region of the object. The receiving point will henceforth be referred to as the receiver and the source point at the transmitter. The position vectors $\mathbf{p}_o$, $\mathbf{R}_T$ and $\mathbf{R}_R$ are measured from the origin of a cartesian coordinate system $(x_o, y_o, z_o)$ centered in the object. The object is assumed to be nondispersive i.e., $D$ is independent of $k$. However, when the object is dispersive such that $D(\mathbf{p}_o, k) = D_1(\mathbf{p}_o)D_2(k)$ and $D_2(k)$ is known, the analysis presented here can easily be modified to account for such object dispersion by correcting the data collected for $D_2(k)$ as $k$ is changed.

Referring to Figure 1(a) and ignoring polarization effects, the field amplitude at $\mathbf{R}_R$ caused by the object scattered wavefield may be expressed as,

$$\psi(k, \mathbf{R}_R) = \frac{jk}{2\pi} \int D(\mathbf{p}_o) e^{-j \mathbf{k}_i \cdot \mathbf{r}_T} e^{\frac{-jk \mathbf{r}_R}{\mathbf{r}_R}} d\mathbf{p}_o \quad (1)$$

where $d\mathbf{p}_o$ is an abbreviation for $dx_0 dy_0$ and the integration is carried out over the extent of the object. Noting that $\mathbf{r}_T = \mathbf{p}_o - \mathbf{R}_T$, $\mathbf{R}_T = -R_T \mathbf{i}_k$, and using the usual approximations valid here: $\mathbf{r}_R = \mathbf{R}_R + \mathbf{p}_o^2/2\mathbf{R}_R - \mathbf{I}_R \cdot \mathbf{p}_o$ for the exponential in (1) and $\mathbf{r}_R = \mathbf{R}_R$ for the denominator in (1) where $\mathbf{I}_R = \mathbf{R}_R/\mathbf{R}_R$ and $\mathbf{I}_k = \mathbf{k}_i/k$ are unit vectors in the $\mathbf{R}_R$ and $\mathbf{k}_i$ directions respectively, one can write eq. (1) as,

$$\psi(k, \mathbf{R}_R) = \frac{jk}{2\pi R_R} e^{-jk(\mathbf{R}_T + \mathbf{R}_R)} \int D(\mathbf{p}_o) e^{-j \mathbf{p}_o \cdot \mathbf{p}_o} d\mathbf{p}_o \quad (2)$$

where we have used the fact that the observation point is in the far field of the object so that $\exp(-jk\mathbf{p}_o^2/2\mathbf{R}_R)$ under the integral sign can be replaced by unity. In eq. (2), $\mathbf{p} = k (\mathbf{I}_k - \mathbf{I}_R) \mathbf{p}_x \mathbf{I}_x + \mathbf{p}_y \mathbf{I}_y + \mathbf{p}_z \mathbf{I}_z$ is a three dimensional vector whose length and orientation depend
Fig. 1. Geometries for wavelength diversity imaging. (a) Two dimensional object, (b) Three dimensional object with the n-th meridional (central) slice and cross sectional outline c shown.
on the wavenumber \( k \) and the angular positions of the transmitter and the receiver. For each receiver and/or transmitter present, \( \vec{p} \) indicates the position vector for data storage. An array of receivers for example would yield therefore as \( k \) is changed (frequency diversity) or as \( k = k_l k_j \) is charged (wave-vector diversity) a 3-D data manifold.

The projection of this 3-D data manifold on the object plane yields \( \psi(k, R_R) \) because \( \rho - \rho_0 = \vec{p}_t \cdot \vec{p}_o = p_x x_o + p_y y_o \) where \( p_x = k(\vec{R}_l - \vec{R}_e) \) and \( p_y = k(\vec{R}_l - \vec{R}_e) \) are the cartesian components of the projection \( \vec{p}_t \) of \( \vec{p} \) on the object plane. Accordingly eq. (2) can be expressed as,

\[
\psi(k, R_R) = \frac{jk}{2\pi R_R} e^{-jk(R_T + R_R)} \int D(x_o, y_o) e^{-j(p_x x_o + p_y y_o)} dx_o dy_o \tag{3}
\]

Because of the finite extent of the object, the limits on the integral can be extended to infinity without altering the result. The integral in (3) is recognized then as the two dimensional Fourier transform \( D(p_x, p_y) \) of \( D(x_o, y_o) \). It is seen to be dependent on the object reflectivity function, the angular positions of the transmitter and the receiver and on the values assumed by the wavenumber \( k \) but is entirely independent of range. Information about \( D \) can thus be collected by varying these parameters. Note that the range information is contained solely in the factor \( F = jk \exp[-jk(R_T + R_R)]/2\pi R_R \) preceding the integral. The field observed at \( R_R \) has thus been separated into two terms one of which, the integral \( \tilde{D} \), contains the lateral object information and the other \( F \), contains the range information. The presence of \( F \) in eq. (3) hinders the imaging process since it complicates data acquisition and if not removed, gives rise to image distortion because \( R_R \) is generally not the same for all receivers. To retrieve an image of the object via a 2-D Fourier transform of eq. (3), the factor \( F \) must first be eliminated. Holographic recording of the complex field amplitude given in (3) using a reference point source located at the center of the object will result in the elimination of the factor \( F \) and the recording of a Fourier transform hologram. This operation yields \( \tilde{D} \) over a two dimensional region in the \( p_x, p_y \) plane.

The size of this region, which determines the resolution of the retrieved image depends on the angular positions of the transmitter and the receiver and on the values assumed by \( k \), i.e. the extent of the spectral window used. The later dependence on \( k \) implies super-resolution imaging capability because of the frequency synthesized dimension of the 2-D data manifold generated. Because of the dependence of resolution on the relative positions of the object, the transmitter, and receiving aperture, the impulse response is clearly spatially variant. In fact a receiver point situated at \( \vec{R}_R \) for which \( \vec{p} \) is normal to the object...
plane can not collect any lateral object information because for this condition ($\hat{p} \cdot \hat{p}_o = 0$) the integrals in (2) and (3) yield a constant. Such receiving point is located in the direction of specular reflection from the object where the diffraction pattern is stationary i.e. does not change with $k$. In this case the observed field is solely proportional to $F$ containing thus range information only. Obviously this case can easily be avoided through the use of more than one receiver which is required anyway when 2-D or 3-D object resolution is sought.\textsuperscript{20,21}

The analysis presented above can be extended to three dimensional objects by viewing a 3-D object as a collection of thin meridional or central slices as depicted in Fig. 1(b) each of which representing a two dimensional object of the type analyzed above. With the $n$-th slice we associate a cartesian coordinate system $x_0, y_0, z_0$ that differ from other slices by rotation about the common $x_0$ axis. Since the vectors $\hat{p}, \hat{R}_T$ and $\hat{R}_R$ are the same in all $n$-coordinate systems, eq. (3) holds. $\psi_n(k, R)$ is then obtained from projection of the three dimensional data manifold collected for the 3-D object on the $x_0, y_0$ plane associated with the $n$-th slice. An image for each slice can then be obtained as described before. An inherent assumption in this argument is that all slices are illuminated by the same plane wave. This is a reasonable approximation when the 3-D object is weakly scattering and the Born approximation is applicable or when the 3-D object is perfectly reflecting and does not give rise to multiple reflections between its parts. In the later case the two dimensional meridional slices $D_n(\hat{p}_o)$ deteriorate into contours, such as C in Fig. 1(b) defined by the intersection of the meridional planes with the illuminated portion of the surface of the object. Accordingly we can write for the $n$-th meridonal slice or contour,

$$\psi_n(k, R) = F \int D_n(\hat{p}_o) e^{-j\hat{p} \cdot \hat{p}_o} \, d\hat{p}_o$$

We can regard $D_n(\hat{p}_o)$ as the $n$-th meridional slice or contour of a three dimensional object of reflectivity $U(\hat{r})$ where $\hat{r}$ is a three dimensional position vector in object space. This means that $D_n(\hat{p}_o) = U(\hat{r}) \, \delta(z_0)$ where $\delta$ is the Dirac delta function.

Consequently eq. (4) becomes,
\[
\psi_n(k_r R) = F \int U(\vec{r}) \, \delta(z_{o_n}) \, e^{-j \vec{p} \cdot \vec{r}_o} \, d\vec{r}_o
\]
\[
= F \int U(\vec{r}) \, \delta(z_{o_n}) \, e^{-j \vec{p} \cdot \vec{r}} \, d\vec{r}
\]  \hspace{1cm} (5)

where \(d\vec{r}\) designated an element of volume in object space and where the last equation is obtained by virtue of the sifting property of the delta function.

Summing up the data from all slices or contours of the object we obtain,

\[
\sum_n \psi_n = F \int U(\vec{r}) \, e^{-j \vec{p} \cdot \vec{r}} \, d\vec{r} = \psi(\vec{p})
\]  \hspace{1cm} (6)

because

\[
\int U(\vec{r}) \, \delta(z_{o_n}) = U(\vec{r}).
\]

Assuming that the Factor \(F\) in eq. (6) is eliminated as before, equation (6) reduces to

\[
\psi(\vec{p}) = \int U(\vec{r}) \, e^{-j \vec{p} \cdot \vec{r}} \, d\vec{r}
\]  \hspace{1cm} (7)

which is the 3-D Fourier transform of the object reflectivity \(U(\vec{r})\). Wavelength diversity permits therefore accessing the 3-D Fourier space of a nondispersive object providing thereby the basis for 3-D Lensless Fourier transform holography. An alternate formulation to that given above of super-resolved wave-vector diversity imaging of 3-D perfectly conducting objects is possible\(^{22}\) by extending the formulation of the inverse scattering imaging problem\(^{10,11}\) to the multistatic case, along lines that are similar but somewhat different than those given by Raz\(^{12}\). The resulting scalarized formulas are identical to (7) establishing thus the connection between the holographic and the inverse scattering approaches to the imaging problem.

THREE DIMENSIONAL IMAGE RETRIEVAL

The above considerations of multiwavelength holography have lead us to determining a means by which the 3-D Fourier space of the object can be accessed employing synchronous detection. It is clear that once the 3-D Fourier space data is available, 3-D image detail can be retrieved by means of an inverse 3-D Fourier transform which can be carried out digitally. Alternately, holographic techniques
Fig. 2. 3-D object consisting of a set of eight point scatterers shown in isometric and $R'_x-R'_y$ plane views at $R'_z=-z_0, 0, z_0$. $x_0=y_0=z_0 = 100$ cm.
Fig. 3. Projection holograms and their optical reconstructions for the set of point scatterers in Fig. 2 at different $R_z$ planes. 
(a) Hologram and reconstructed image of scatterers at $R_z=-z_0$ plane. 
(b) Hologram and image at $R_z=0$ plane. 
(c) Hologram and image at $R_z=z_0$ plane. $x_0=y_0=z_0=100$ cm.
Fig. 4. Arrangement used in computer simulation of wavelength diversity imaging.
Fourier domain projection theorems\textsuperscript{23} that are dual to the spatial domain projection theorem\textsuperscript{25,26} can be applied to the Fourier space data to produce a series of projection holograms from which 2-D images of meridional or parallel slices of the object can be retrieved on the optical bench\textsuperscript{20}. This procedure does not involve any specific scaling of the size of the optical hologram transparency relative to the size of the original recording aperture by the ratio of the recording to the reconstruction wavelengths as in longwave holography where the scaling necessary for viewing a 3-D image free of longitudinal distortion usually leads to an impractically minute equivalent hologram transparency that cannot be readily viewed by an observer. The lateral and longitudinal resolutions in the retrieved image depend now on the dimensions of the volume in Fourier space accessed by wavelength diversity. This volume depends on the wavelength range and on the recording geometry. Thus the longitudinal resolution does not deteriorate now as rapidly with range as in conventional monochromatic imaging systems.

An example of computer simulations of frequency diversity holographic imaging of a 3-D object consisting of eight point scatterers distributed as shown in Fig. 2 is given in Fig. 3. Shown in Fig. 3 are three weighted Fourier domain projection holograms and the corresponding optically retrieved images for three equally spaced parallel slices of the object containing distinguishable 2-D distributions of scatterers. The simulated recording arrangement shown in Fig. 4 consisted of an array of 16 receivers equally distributed on an arc extending from $\phi = 40^\circ$ to $\phi = 77.5^\circ$ surrounding a central transmitter capable of providing plane wave illumination of the object. The results shown were obtained with microwave imaging in mind assuming a frequency sweep of (2-4)GHz. They clearly indicate a lateral and longitudinal resolution capability of the order of 25 cm. Wider sweep widths yield better resolution. For example a (1-18)GHz sweep would yield a 3-D resolution of the order of 1.5 cm.

**DISCUSSION AND CONCLUSIONS**

Seeking means by which the information content in a hologram can be increased for example by wavelength diversity we have arrived at a formulation of 3-D Lensless Fourier transform holography capable of furnishing 3-D image detail tomographically. This ability of producing 3-D images in slices from coherently detected wavefields enable us to regard the method also as coherent tomography. The Fourier space accessed in the above fashion by wavelength diversity can be viewed as a generalized 3-D hologram in which one dimension has been synthesized by wavelength diversity. Such a generalized hologram contains not only spatial amplitude and phase data as in conventional holography but also spectral information and hence can yield better
resolution than the classical Rayleigh limit of the available aperture operating at the shortest wavelength of the spectral window used. This super-resolving property is further enhanced through an inherent suppression of the effects of object resonances and coherent noise in the retrieved image, the latter being so because frequency diversity tends to make the impulse response of the system unipolar resembling that of a non-coherent imaging system that is free of speckle and coherent noise artifacts. Further enhancement of information content and resolution can be achieved by polarization diversity where the \( p \) space can be multiply accessed for different nonredundant polarizations of the illumination and the receivers and the resulting polarization diversity images added either coherently or non-coherently in order to achieve a degree of noise averaging as discussed elsewhere.

The removal of several longstanding constraints on conventional longwave (microwave and acoustic) holography attained through the use of wavelength diversity as described here leads to a new class of imaging systems capable of converting spectral degrees of freedom into 3-D spatial image detail furnishing thereby true super-resolution. Wavelength diversity is applicable to the imaging of two classes of objects: perfectly reflecting objects of the type encountered in radar and sonar and weakly scattering objects of low or known dispersion of the type encountered in biology and medicine. The practical application of the concepts presented here to optical wavefield is presently under consideration. The availability of tunable dye lasers and electronic imaging devices suggest interesting possibilities of three dimensional wavelength diversity microscopy. Here one can conceive of an arrangement in which a minute semitransparent object with homogeneous or known dispersion is transilluminated by a collimated coherent light beam from a tunable dye laser which can also be made to provide a coherent reference point source in the immediate vicinity of the object. The resulting reference and the object scattered wavefields are intercepted by the photocathode of an electronic imaging device of known spectral response such as a vidicon. Because of the minute size of the object, the photocathode can easily be situated in the far field of the object. Thus nearly a lensless Fourier transform hologram recording arrangement results. The spatial frequency content in the resulting hologram is therefore expected to be sufficiently low to be resolved by a high resolution electronic imaging device. By recording and digitally storing the resulting detected hologram fringe pattern as a function of dye laser wavelength one can gain access to the 3-D Fourier space of the object since \( I_{k_1} \) and \( I_R \) for the recording geometry are precisely known.

A similar recording arrangement can be envisioned in the active coherent imaging of a distant reflecting object (active telescopy) where the object can be made to furnish a reference point source situated on its surface like a wavelength independent stationary glint point or an intentionally placed retroreflector. Because in such an arrangement the reference and the object wavefields travel over the same path, atmospheric effects are expected to be minimized. The generation of an
object derived reference geometry in longwave (microwave and acoustic) wavelength diversity imaging has been described elsewhere\textsuperscript{20,27}.

Finally it is worthwhile to note that since the scattering process is linear the multiaspect or multistatic frequency or wavelength response measurements referred to in this paper can be obtained also by measuring the multiaspect impulse response followed by Fourier transformation of the individual impulse responses measured\textsuperscript{19}. This means that impulsive illumination can also be utilized. Because the impulse response of a linear system can be measured by using random noise excitation and cross-correlating the output with the input\textsuperscript{19}, a possibility of using random noise (white light) illumination and cross-correlation detection techniques as a means for accessing the 3-D Fourier space of the object also emerges.
REFERENCES


APPENDIX III

THE VIRTUAL FOURIER TRANSFORM
AND ITS APPLICATION IN THREE DIMENSIONAL DISPLAY

ABSTRACT

In contrast to the well known and widely used instantaneous Fourier transforming property of the convergent lens in coherent (laser) light, the "Virtual Fourier Transform" (VFT) capability of the divergent lens is less widely known or used despite many advantages. We will review the principle of the VFT and discuss its advantages in certain applications. In particular a method for viewing the virtual Fourier transform of a two dimensional function with the naked eye using an ordinary point source will be presented. A scheme for three-dimensional image display based on a "Fourier domain projection theorem" utilizing varifocal VFT is described and a discussion of the properties of the displayed image given.

INTRODUCTION

Several sophisticated three dimensional (3-D) imaging techniques such as x-ray tomography\(^1\), electron microscopy\(^2\), crystallography\(^2\), wave-vector diversity imaging and inverse scattering\(^3\), involve measurements that give access to a finite volume in the 3-D Fourier space of a 3-D object function. A 3-D image of the original object can then be reconstructed by computing the inverse 3-D Fourier transform. The retrieved image normally represents the spatial distribution of a relevant parameter of the object such as absorption, reflectivity, scattering potential, etc.

Obviously, the required inverse transform can be performed digitally. Digital techniques however often preclude real-time operation particularly when the object being imaged is not simple but contains considerable resolvable intricate detail. More importantly, because of the inherent two dimensionality of CRT computer displays, direct true 3-D image display is not possible. Present day computer graphic displays are capable of displaying 3-D image detail either in separate cross-sections or slices, or in a computed perspective (isometric) view of the object, or in some instances stereoscopically where an illusion of a 3-D scene is created in the mind of the observer who is required usually to use special viewing glasses\(^4,5\).
Hybrid (opto-digital) computing techniques offer an alternate approach to 3-D image retrieval from 3-D Fourier space data. They furnish as shown in this paper the ability to display true 3-D image detail. The approach is based on "Fourier Domain Projection Theorems" that are dual to "Spatial or Object Domain Projection Theorems" used in radio-astronomy and tomography. These theorems permit the reconstruction of 3-D image detail tomographically, i.e., in slices from 2-D projections of the 3-D Fourier space data. Although the required 2-D Fourier transform can be carried out digitally, the emphasis in this paper is on coherent optical techniques for performing the 2-D Fourier transform, with particular attention to implementations that permit the execution of the necessary 2-D optical transforms of the various projection holograms sequentially in real-time. Specific attention is given to a technique that utilizes the virtual Fourier transform which permits the viewing of a virtual 3-D image in real-time.

FOURIER DOMAIN PROJECTION THEOREMS

There are two Fourier domain projection theorems. One leads to tomographic object reconstruction in parallel slices and is called the "weighted Fourier domain projection theorem"; the other leads to tomographic object reconstruction in meridional or central slices and can therefore be called the "meridional or central slice Fourier domain projection theorem."

We begin by considering a 3-D object function \( f(\mathbf{r}) \) with \( \mathbf{r} = x\hat{x} + y\hat{y} + z\hat{z} \) being a position vector in object space. Let \( F(\mathbf{w}) \) be the 3-D Fourier transform of \( f(\mathbf{r}) \) defined by,

\[
F(\mathbf{w}) = \int f(\mathbf{r}) e^{-j\mathbf{w} \cdot \mathbf{r}} \, d\mathbf{r}
\]

(1)

where \( d\mathbf{r} = dx \, dy \, dz \) and \( \mathbf{w} = w_x \hat{x} + w_y \hat{y} + w_z \hat{z} \) is a position vector in the Fourier or spatial frequency domain.

Consider next the projection of \( F(\mathbf{w}) \) on the \( w_x, w_y \) plane defined by,

\[
F_p(w_x, w_y) = \int \int F(\mathbf{w}) \, dw_z
\]

(2)

and combining eq. (1) and (2),

\[
F_p(w_x, w_y) = \int \int \int f(x,y,z) e^{-j(w_x x + w_y y + w_z z)} dx \, dy \, dz \, dw_z
\]

(3)

*From the Greek work Tomos meaning slice.
Integrating with respect to \( w_z \) first and assuming that the volume in \( \tilde{w} \) space occupied by \( F(\tilde{w}) \) is sufficiently large we obtain,

\[
F_p(w_x, w_y) = \int \int \int f(x, y, z) \delta(z)e^{j(w_x x + w_y y)} \, dx \, dy \, dz
\]

\[
= \int \int f(x, y, o) \, e^{j(w_x x + w_y y)} \, dx \, dy
\]

The 2-D Fourier domain projection \( F_p(w_x, w_y) \) and the central slice \( f(x, y, o) \) through the object form thus a Fourier transform pair. This may be symbolically expressed as,

\[
F_p(w_x, w_y) \leftrightarrow f(x, y, o)
\]

Other parallel slices through the object at \( z = z_n \), \( z_n \) being a constant describing the \( z \) coordinate of the \( n \)-th parallel slice, can in a similar manner be related to "weighted" Fourier domain projections of \( F(\tilde{w}) \) defined by,

\[
F_{p,n}(w_x, w_y) = \int_{\tilde{w}_z}^{j z_n} F(\tilde{w}) e^{n \tilde{w}_z} \, d\tilde{w}_z
\]

Making use of eq. (1) and again performing the integration with respect to \( \tilde{w}_z \) first we obtain,

\[
F_{p,n}(w_x, w_y) \leftrightarrow f(x, y, z_n)
\]

which indicates that the weighted projection \( F_{p,n}(w_x, w_y) \) and the \( n \)-th parallel object slice \( f(x, y, z_n) \) form a Fourier transform pair. Equation (6) is seen to be a special case of eq. (8) when \( z_n = 0 \).

Given the 3-D Fourier space data manifold \( F(\tilde{w}) \) one can digitally compute and display a set of "weighted projection holograms" \( F_{p,n}(w_x, w_y) \). A corresponding set of images of parallel slices or cross-sectional outlines of the 3-D object can then be retrieved via 2-D Fourier transform operations which can most conveniently be carried out optically from photographic transparency records of the weighted projection holograms displayed by the computer.
Returning to eqs. (1) and (2) one can also show that projections of \( F(\mathbf{w}) \) on arbitrarily oriented planes other than the \( w_x, w_y \) plane chosen for eq. (2), yields "meridonal projection holograms" that are 2-D Fourier transforms of corresponding meridional (central) slices of the object. This is the "meridonal Fourier domain projection theorem. It furnishes the basis for angular multiplexing of the resulting meridional projection holograms into a single composite hologram which can be used to form a 3-D image of the object in a manner similar to that in integral holography* which is increasingly being referred to as Cross holography.

**THE VIRTUAL FOURIER TRANSFORM**

In contrast to the well known spatial Fourier transforming property of the convergent lens widely used in coherent optical computing, the complementary virtual Fourier transform capability of a divergent lens is less widely known or used despite many attractive features. This is surprising since the power spectrum associated with the VFT is a phenomenon that is frequently observed in daily life when one happens to look at a distant point source such as a street light through a fine mesh screen or the fine fabric of transparent curtain material. The spectrum of the screen transmittance appears then as a virtual image in the plane of the point source.

The VFT concept of the divergent lens is easily derived from the Fourier transform expression of the convergent lens. Figure 1 illustrates the well known process of forming a real Fourier transform with a convergent lens. The object transparency, with complex transmittance \( t(x, y) \), is placed at a distance \( d \) in front of a convergent lens of focal length \( F \) and illuminated with a normally incident collimated laser beam. The complex field amplitude of the wavefield in the back focal plane, the transform plane, is given by the well known formula

\[
T(x, y) = \frac{j}{\lambda F} e^{-j \frac{k}{2F} [(1 - \frac{d}{F})(x^2 + y^2)]} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} t(x_o, y_o) e^{j \frac{k}{F} (x x_o + y y_o)} \, dx_o \, dy_o
\]

in which the integral is recognized as the two dimensional Fourier transform of the object transmittance. \( T(x, y) \) becomes the exact Fourier transform of \( t(x_o, y_o) \) when \( d = F \) that is when the object transparency is placed in the Front focal plane of the lens. The power spectrum associated with the transform is real and can be projected on a screen placed in the back focal plane. It is also well known that a scaled version of the transform can be obtained in the back focal plane by placing the object transparency in the converging laser beam to the right of the lens.

*Named after Lloyd Cross the originator of integral holography.
Fig. 1. Real Fourier transform formed with a convergent lens

Fig. 2. Virtual Fourier transform formed with a divergent lens
Noting that eq. (1) does not change when we replace $d$ by $-d$, $F$ by $-F$, $x_0$ and $y_0$ by $-x_0$ and $-y_0$ respectively, we can arrive at the complementary VFT arrangement illustrated in Fig. 2. An inverted transparency $t(x_0, y_0)$ is placed now in the divergent coherent beam to the right of the divergent lens (of focal length $-F$) and a VFT given by eq. (1) is observed in the virtual focal plane of the lens. The same VFT can be seen by removing the divergent lens and replacing the laser beam with a point source placed at the origin of the VFT plane as depicted in Fig. 3. Thus a simple way of viewing the power spectrum associated with the VFT of a given diffracting screen (which is usually a Fourier transform hologram or a projection hologram of the type described above) is to hold the screen close to the eye and look through it at a distant bright point source. The point source used need not be derived from a laser. In fact it is preferable for safety purposes to use an LED or a spectrally filtered minute white light source such as a "grain-of-wheat" subminiature incandescent lamp or a miniature Christmas tree decorating lamp covered by a color or interference filter. This has the added advantage of furnishing a measure of control over the coherence properties of the wavefield impinging on the screen providing thereby a means for reducing coherent noise in the observed VFT and also, as will be discussed below, a means for coherent or noncoherent superposition of VFT's. As the distance of the point source from the diffracting screen is decreased in order to make it compatible with typical laboratory or optical bench dimensions, the size of the observed VFT decreased because of the change in the curvature of the wavefield illuminating the diffracting screen. To compensate for this effect it is necessary to reduce the size of the diffracting screen or transparency often to such a scale where viewing the VFT through the small available aperture becomes difficult. To overcome this limitation the displacement property of the Fourier transform can be utilized. A composite transparency containing an ordered or random array of reduced replicas of the transmittance function $t(x_0, y_0)$ arranged side by side as illustrated in Fig. 4 is prepared. When such a composite transparency is viewed with the point source, the VFT's formed by the individual elements will overlap in the virtual Fourier plane. The VFT's are identical except for Linear phase dependence on $x, y$ which depends in each VFT on the central position of each element in the composite transparency. This leads to a desirable noise averaging effect and the appearance of fine checkered texture in the image detail. All this leads to an enhancement of the quality of the observed power spectrum. Both coherent and noncoherent superposition of the overlapping VFT's is possible using this scheme by varying the coherence area of the wavefield illuminating the composite transparency. When the coherence area is roughly equal to the size of the individual elements of the composite transparency noncoherent superposition results, while a coherence area equal or greater than the size of the composite transparency would yield coherent superposition.
Fig. 3. Arrangement for viewing a virtual Fourier transform with a point source.

Fig. 4. A composite screen consisting of an ordered array of identical Fourier transform projection holograms.
THREE DIMENSIONAL DISPLAY

The VFT concept and the "weighted Fourier domain projection theorem" discussed above can be combined in an attractive scheme for the reconstruction and display of a 3-D image from a series of weighted projection holograms corresponding to different parallel slices through the object. The scheme is based on viewing a series of weighted projection holograms sequentially in the proper order of the occurrence of their corresponding slices in the original object while displacing the point source axially for one hologram to next by an axial increment proportional to the spacings between adjacent object slices. In this fashion the reconstructed virtual images of the various slices are seen in depth at different VFT planes that are determined by the positions of the axially incremented point source. Repeated rapid execution of this procedure by displacing the point source back and forth leads the observer to see a virtual 3-D image tomographically in parallel slices or sections as he looks through the series of projection holograms passed rapidly, as in a motion picture film, in front of his eyes.

More specifically the scheme is based on preparing a series of N weighted Fourier domain projection holograms from the 3-D Fourier domain data $F(\omega)$ of a given object $f(\tau)$ as described in the preceding sections. Each of the projection holograms would correspond to a different parallel slice through the object. A composite transparency similar to that shown in Fig. 4 is formed for each projection hologram. In fact Fig. 4 is an example of a computer generated composite hologram containing an array of identical weighted projection holograms corresponding to one slice of the test object shown in Fig. 5. The test object chosen consisted of eight point scatterers arranged as shown. The 3-D Fourier space of this test object was accessed in a computer simulation of wavelength diversity imaging as described in a companion paper in this volume*. The resulting computer generated Fourier space data manifold $F(\omega)$ was used to compute three weighted projection holograms corresponding to the three planes $R^2=\lambda m, 0, \lambda m$ of Fig. 5 containing the three different distributions of point scatterers. A composite array such as that of Fig. 4 was formed and displayed by the computer for each of the three projection holograms, each was photographed yielding a set of three projection hologram composite transparencies. Copies of these were then mounted on a rotating wheel as shown in Fig. 6 (a) and viewed with an axially scanned point source. Four sets of transparency copies of these three composite projection holograms were mounted in the order 1, 2, 3, 2, 1, 2 ... on the periphery of a rotating wheel as shown in Fig. 6 (a). The wheel is driven by a computer controlled stepper motor. The axially scanned point source was produced by scanning a focused laser beam back and forth on a length of fine nylon thread with the aid of a deflecting mirror mounted on the shaft of a second computer controlled stepper motor as shown in Fig. 6 (b). The laser and optical bench arrangement for forming the scanned focused beam appear in the background of Fig. 6 (a). The computer controlled steppers enable precise positioning of the secondary point source on the scattering thread in synchronism with the hologram.

*See paper entitled "Holography, Wavelength Diversity Inverse Scattering" in this volume.
Fig. 5. A three-dimensional test object consisting of a set of eight point scatterers shown in isometric and $R'_x-R'_y$ plane views at $R'_z=-z_0, 0, z_0$. $x_0=y_0=z_0=100$ cm.
Fig. 6. Quasi real-time three-dimensional image reconstruction and tomographic display in successive slices from a series of projection holograms mounted on rotating wheel seen in forefront of (a); Detail of laser scanner used to produce linearly scanned point source is shown in (b).
Fig. 7. Photographs of three slices of the virtual 3-D image of the test object of Fig. 5 obtained by photographing the VFT's formed from corresponding Fourier domain projection holograms.
being viewed so that the VFTs are formed in their proper planes. A viewer looking at the axially displaced point source through each transparency mounted on the wheel as it passes in front of his eye will see a 3-D virtual image. Photographs of the three virtual images seen by an observer in this fashion are shown in Fig. 7. An opto-digital scheme for rapid real-time implementation of the procedure realized above is shown in Fig. 8. This scheme, presently under study, utilizes a rapid recyclable spatial light modulator (SLM) such as the Itek PROM in order to form VFT's of the projection holograms displayed by the computer in real-time.

CONCLUSIONS

We have presented the basic principles of tomographic 3-D image display based on Fourier domain projection theorems. One possible implementation of the principle using the virtual Fourier transform and a series Fourier domain projection holograms has been described. There are several advantages for using the VFT rather than the real Fourier transform (RFT), the most important of which is the ease with which the position of the VFT plane can be moved axially by simply moving the position of the reconstruction point source. The VFT approach was adopted in the present study because it is much easier to move a point source rapidly than to move the display screen needed in the RFT approach. Furthermore focusing in the VFT approach is carried out by the observer while in the RFT approach it must be performed by the system. Other attractive features of the VFT are:

(a) Simplicity - enables direct viewing of the power spectrum of a transparency or a hologram with a variety of simple point sources.

(b) The scale of the observed VFT can be easily altered by changing the distance between the projection hologram transparency and the reconstruction point source.

(c) Lower speckle noise and therefore higher reconstructed image quality can be attained by using nonlaser point sources in the reconstruction such as LED or miniature spectrally filtered incandescent lamps. Further reduction in speckle noise occurs when an array of the projection hologram rather than a single hologram is used and when the hologram is slightly vibrated or is in motion because of a noise averaging effect.

(d) Coherent and noncoherent superposition of VFT's is possible by altering the coherence area of the reconstruction wavefield.

(e) Because of the Fourier transform nature of the projection holograms utilized, the resolution requirements from the storage medium (photographic film or the CRT/SLM system of Fig. 8) are much lower than would be needed in the recording of a Fresnel hologram of the object as a means of 3-D image display. The 3-D image detail contained in the single Fresnel hologram is now distributed over a series of lower resolution projection holograms which are used to form the 3-D image sequentially in time in individual slices.
Fig. 8. Opto-digital scheme for the reconstruction and display of 3-D images using a recyclable spatial light modulator and a point source to view the VFT in real-time.
(f) Because 3-D image reconstruction is tomographic (in separate slices) there is no interference between the wavefields forming the various slices.

(g) Permits other forms of 3-D image display involving spatial or angular multiplexing in a fashion similar to integral holography.
REFERENCES


APPENDIX IV

AN AUTOMATED FREQUENCY RESPONSE AND
RADAR CROSS-SECTION MEASUREMENT FACILITY
FOR MICROWAVE IMAGING
UNIVERSITY OF PENNSYLVANIA

THE MOORE SCHOOL OF ELECTRICAL ENGINEERING

AN AUTOMATED FREQUENCY RESPONSE AND RADAR CROSS-SECTION MEASUREMENT FACILITY FOR MICROWAVE IMAGING

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AN AUTOMATED FREQUENCY RESPONSE AND RADAR CROSS-SECTION MEASUREMENT FACILITY FOR MICROWAVE IMAGING

ABSTRACT

This thesis investigates the development of a broadband microwave holographic imaging facility. Different methods for the correction of microwave target scatter data are discussed and implemented. A minicomputer automates all system functions including data acquisition, storage, calculation, and graphic display. The effects of range phase shift on holographic frequency diversity imaging is considered and techniques for the removal of this phase shift in a laboratory environment. The frequency dependent backscatter of several test targets is derived analytically and simulations done of the corresponding holograms. These holograms are compared to those measured experimentally. Finally both simulated and experimental holograms are optically reconstructed to yield target images using optical Fourier transforms and shown to be in excellent agreement.

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Appendix II.....Microwave imaging programs-acquisition and display
I INTRODUCTION

Frequency diversity imaging has been under study at the Electro-Optics and Microwave Optics laboratory of the Moore School Graduate Research Center. [1], [2], [3], [4]. This study has established the theoretic feasibility of imaging objects by means of their multiaspect frequency response. For the purpose of experimentally studying frequency diversity imaging, an experimental measurement system has been assembled and installed in the Moore School anechoic chamber. In this thesis we will describe the automation of this measurement system and characterize its performance in the measurement of complex field amplitudes of scattered fields. A system block diagram fig.1.1, shows the major system components. The central element is the DEC MINC LSI 11/2 minicomputer. This computer performs several important functions. The MINC controls laboratory instrumentation via the IEEE-488 bus protocol standard. This allows the Hewlett-Packard 8620C microwave sweeper to be precisely tuned to any frequency in the 2.0 to 18.0 GHz range (fig.1.2). The computer collects data from the HP 8410B network analyzer through the four analog input channels available. These analog values are proportional to the amplitude in db and phase in the range (-π) to (+π) radians relative to the reference signal supplied to the network analyzer. The computer stores Experimental data on floppy discs. The available storage capacity is large, over 500,000 measurement pairs of complex field amplitude and
Fig. 1.1 System block diagram.

Fig. 1.2 HP 8620C microwave sweeper and HP 1410B network analyzer.
phase may be stored on a single disc. This data can be accessed for both processing and display on a Tektronix 606A high resolution CRT monitor. The disc system allows the MINC to operate under a sophisticated software system, DEC RT-11 V3.0B permitting programing in MINC BASIC, FORTRAN IV, and MACRO languages.

The processing capability of the system allows the removal of system response errors due to anechoic chamber clutter, antenna cross-coupling and receiver channel characteristics. The data may be processed for target range calculations and the removal of the phase shift due to the target range. In addition the collected data may be filtered to improve imaging and finally displayed on a high resolution Tektronix 606A X-Y CRT monitor using the MINC system D/A converter module.

The second part of this thesis will describe the simulation and actual operation of a holographic radar system verifying the theory of frequency diversity imaging. This is done using the system described in the first section. The scattering of various targets is derived and holograms using these results are generated for comparison with experimental data. Finally a system for the experimental measurement of the scattering for these targets is outlined and the results from this system compared to theory.
II SYSTEM OPERATION AND ERROR REMOVAL

This chapter will cover the operation of the microwave backscatter data acquisition system. This will include actual interfacing information and an analysis of the types of errors encountered when making microwave measurements. The error correction techniques developed are later used in the experimental verification of the frequency diversity imaging theory. [4]

2.1 Microwave sweeper operation

The first task in the development of an automated data acquisition system is the implementation of a data communications link between the intelligent controller and instrumentation. The IEEE-488 bus protocol is utilized in this application for the transfer of data to the Hewlett-Packard 8620C microwave sweeper from the MINC LSI 11/2 computer. This bus is a high speed 8 bit wide bidirectional data path with 5 additional lines dedicated to control. Data is transferred in ASCII format over the bus. For example the number 1 is transmitted as the ASCII code for the character '1'. Certain sequences of characters make the sweeper perform different functions or enter different modes of operation via its IEEE-488 interface.

In order to set the frequency of the sweeper a number must be sent to the IEEE-488 interface in the range 1-10000. Each sweeper frequency band has been split into 10000 frequency points. The frequency of operation is controlled
by an internal analog voltage that varies between 0.0 and 10.0 volts. A D/A converter on the 8620C IEEE-488 interface changes the data transmitted from the MINC into the frequency controlling voltage. The correspondence between voltage and output frequency is essentially linear. In order to obtain the interpolating function for frequency versus control voltage; a microwave frequency counter was used to measure the voltage-frequency characteristic function. Using the MINC-BASIC program CALAB.BAS a least squares fit for both linear and quadratic functions was made on the frequency vs voltage data. This type of program is used for determining the best polynomial fit to the frequency-voltage characteristic of the sweeper. Sample output and program listings are in appendix I along with an explanation of program operation. The results from this work indicate that the quadratic fit was statistically superior for all bands on the microwave sweeper. The FORTRAN subroutine SWEEP was written which utilizes the quadratic interpolation polynomial for each of the four bands of the 8620C. This subroutine automatically calculates the control voltage and band to generate any frequency in the 2-18 GHz range and transmits the appropriate commands over the IEEE-488 bus. The variance of the frequency setting using the quadratic fit for the three bands are as follows: .6 MHz in the 2.0-6.3 GHz band; 1.2 MHz in the 6.3-12.0 GHz band; and 1.6 MHz in the 12.0-18.0 GHz band. For higher accuracy the sweeper may be phase
locked to the reference in a locking frequency counter yielding very high accuracy as precise as the frequency reference itself. The EIP 371 locking counter may be used in this application to lock the HP 8620C sweep oscillator to the correct frequency once it is within 20 MHz of the desired frequency. The auxiliary output of the HP 8620C supplies a sample of the signal generated by the fundamental 2.0-6.3 GHz oscillator module within the sweeper to the locking counter. Sweeper output on higher bands is this fundamental multiplied by a factor of 2 or 3 for the 6.3-12.0 and 12.0-18.00 GHz bands respectively. For example the locking frequency for a 10.0 GHz sweeper output on band 2 would be 5.0 GHZ. In operation, subroutine SWEEP will set the frequency of the sweeper within 2.0 MHz of the desired frequency and subroutine SLOCK will be called to calculate the locking frequency, lock the HP 8620C and return to the main calling routine when lock will have occurred. Lock time varies from .1 to 3 seconds and resolution is 100 KHZ. These subroutines are called whenever the sweeper must be set to a particular frequency or the sweeper must be placed in or be released from computer control.

2.2 Network analyzer-computer interface

The Hewlett-Packard 8410B network analyzer is the focus of the measurement capabilities of the microwave measurement system. It can make vector (amplitude and phase) measurements in the (.1-18.0)GHz range. The range of amplitude measurement is 80 db and phase may be measured
modulo \((2\pi)\). The system reference signal is fed from a 20db directional coupler to the HP8411A harmonic converter sampling head of the network analyzer. This reference is compared to the backscatter from the illuminated target; both in amplitude and phase. The reference signal amplitude is kept constant by leveling the sweeper with a feedback signal derived from its amplified output by means of a crystal detector. This allows the sweeper-TWT (Traveling Wave Tube) system to yield nearly constant output in the \((2.0-16.5)\) GHz range; see fig.2.1. TWT power output is on the order of 1 watt over these frequencies.

The complex field amplitude measurements are available as analog voltages from the back panel of the 8410B. The outputs are proportional to amplitude and phase: \(25\text{ MV/db}\) and \(10\text{ MV/DEGREE}\) These values are digitized by the MINC using its built in analog to digital conversion channels. The MINC A/D converters digitize voltages lying in the range of \(-5.12\) to \(+5.12\) volts to the range of \(0-4096\) yielding 12 bit resolution. If the signal is corrupted by noise; the user has the option of employing signal averaging to cancel the effects of noise uncorrelated to the received signal.

A difficulty encountered when measuring phase angle modulo \((2\pi)\) occurs when the phase is close to \((+\pi)\) or \((-\pi)\). At this point a small change in the signal phase may cause the phase to flip between these two equivalent extremes rapidly. If a data sample is taken close to \((+\pi)\) or \((-\pi)\) it may be in transition between them and therefore incorrect.
Since such points occur infrequently in a typical measurement they may be ignored; their presence does not seriously hinder any holographic imaging due to the inherent redundancy and therefore noise immunity of the holographic reconstruction process.[5] If it is desired that these points be identified and removed it is necessary to estimate the mean and variance of the samples taken at each frequency point. At frequencies where the phase is flipping between $(+\pi)$ and $(-\pi)$, the variance will be much larger than at other frequencies. The mean of the samples when this is occurring will be near zero. Hence to resolve the ambiguity problem it is necessary to decide if the variance exceeds a predetermined threshold when the mean in the neighborhood of zero. Two FORTRAN subroutines PHAMP and PHAMP2 which implement these algorithms are listed in appendix I.
Since such points occur infrequently in a typical measurement they may be ignored; their presence does not seriously hinder any holographic imaging due to the inherent redundancy and therefore noise immunity of the holographic reconstruction process.\[5\] If it is desired that these points be identified and removed it is necessary to estimate the mean and variance of the samples taken at each frequency point. At frequencies where the phase is flipping between $(+\pi)$ and $(-\pi)$, the variance will be much larger than at other frequencies. The mean of the samples when this is occurring will be near zero. Hence to resolve the ambiguity problem it is necessary to decide if the variance exceeds a predetermined threshold when the mean in the neighborhood of zero. Two FORTRAN subroutines PHAMP and PHAMP2 which implement these algorithms are listed in appendix I.
2.3 Implementation of the data acquisition system

In an experimental environment it is important to be aware of the various types of errors inherent in the equipment and the experimental procedure adopted. Conditions and equipment always vary from theoretical ideals. A clear understanding of the error removal process leads to the development of practical implementations of theoretical concepts and enhancement of measurement accuracy unattainable otherwise.

Errors in complex field amplitude measurement may be caused by several factors. These may be grouped into two categories. Errors caused by the instruments themselves fall into the first class. Such factors as measurement variations caused by electronic noise, inaccurate A/D and logarithmic conversions, and inaccuracy and instability in the microwave source make up this category. The second group of errors is caused by the test set, antennas, cables, connectors, amplifier, and room clutter. All these factors interact with each other in the microwave region and are the significant cause of error in microwave measurements. Little can be done about the first class of errors since they are inherent in the characteristics of the equipment used. The second group of errors can be removed through the use of automated measurement of system parameters in the frequency range of interest. These errors can be removed form any measurements of scattering objects by digital processing and the results stored for later recall. This
essentially provides an automated and improved version of the conventional two antenna radar cross-section measurement technique [6]; in which a microwave bridge is balanced in the absence of the target and the degree of imbalance is measured when the target is introduced into the microwave field.

Let us look at the first class of errors more closely since these errors will set the ultimate performance limits on the system. The characteristics of the signal source are important in this regard. In this case the signal source is a Hewlett-Packard 8620C microwave sweeper. Since the sweeper is not phase locked frequency and stability problems exist. The carrier also has significant FM noise which appears as phase noise in the scattered signal. The phase shift of the scattered signal as a function of frequency for small frequency variations is given by:

$$\Delta \Theta = \Delta k \cdot R$$

where \(k=(2\pi/\lambda)\) and \(R\) is the path length. For \(R\) greater than a few tens of meters, the FM noise on the signal source causes measurable variations in the phase of the scattered signal. The stability of a synthesizer is required for the implementation of a holographic radar system when target ranges are in terms of kilometers.

Another limit on the ultimate accuracy of the system is the resolution of the A/D conversions and the accuracy of the network analyzer. Given the 2.2MV resolution of the MINC A/D converter and the network analyzer analog output of
50 MV/db, the system can resolve .048 db steps. This resolution limit restricts the minimum signal to system error ratio. If the error signal consisting of clutter, antenna coupling, system directivity and noise exceeds the scattered target signal the resolution of the target signal suffers. For example, if the system error signal and target scattered signal are of equal intensity, then a 1 db change in the scattered signal causes a .53 db change in the total received signal vector. When the system error is 13 db above the scattered signal it becomes impossible to resolve a 1 db change in the target signal given the resolution capabilities of the system. This difficulty is further compounded by errors in the network analyzer. These too are amplified when the clutter exceeds the target scatter signal. In fig.2.1 is a plot of the minimum system resolution in order to detect a 1 db change in the target return signal versus the system error signal to scattered signal level in db. In fig.2.2 is plotted the target signal resolution versus the noise to signal level in db. When the system error is 20 db below the target signal then the resolution of the target scatter signal is very close to the ultimate resolution, .048db. Clutter is the component of the received signal not scattered by the target but that signal that is the result of coupling between antennas and signal scattered by the anechoic chamber walls. As the clutter/signal ratio increases the target scatter signal resolution decreases exponentially. Clutter may be reduced
Fig. 2.1 The required resolution in dB for a data acquisition system to detect a 1 dB change in the desired signal vs. signal/error -signal ratio.

Fig. 2.2 Minimum change in desired signal level detectable versus signal/error signal level given .048 dB system data acquisition resolution.
by improving the isolation between the transmitter and receiving antennas with the introduction of absorbing foam panels such as Emerson and Cummings' Ecosorb panels between the antennas.

2.4 System error correction

Turning next to the second class of errors; those directly measurable and therefore removable; define the following quantities which are functions of frequency:

- $I(f)$ -- Isolation of reference to test channels
- $T(f)$ -- Transfer characteristic of system
- $A(f)$ -- Attenuator characteristic
- $A_l(f)$ -- Antenna system characteristic
- $S(f)$ -- Corrected backscatter for target
- $C_1(f)$ -- Uncorrected antenna clutter and coupling
- $C_2(f)$ -- Corrected antenna clutter and cross-coupling
  (uncorrected for antenna system response)
- $C(f)$ -- Corrected antenna clutter and coupling
- $R_1(f)$ -- Uncorrected reference target backscatter
- $R_2(f)$ -- Corrected reference target data
  (uncorrected for antenna system response)
- $R(f)$ -- Corrected reference target data

Several possible techniques exist for the removal of system errors. The particular technique is dependent on the relative signal levels involved, the accuracy desired, ease of implementation, and computational speed. The first technique described here is similar to that used by Weir et al. [7]
The first step in the correction procedure measures the transfer function of an attenuator $A(f)$ as a function of frequency. The equipment setup for this procedure is shown in fig. 2.3. The two ports of the reflection-transmission unit connected through a precision HP 11605A flexible coaxial arm. The MINC then steps the sweeper to a number of frequency points and stores the system response (log amplitude and phase vs. frequency) in memory. When this completed the attenuator is placed in series with the arm and another set of measurements is made at the same frequency points as before. The system response characteristic is subtracted from the combined attenuator plus system response measurement made on the second sweep. An example of this procedure is shown in fig 2.4. Computer subroutine PAD performs this operation. It is listed in appendix I along with all other computer program listings and output pertaining to system response measurement and removal.

The next step in the calibration process is measurement of the reference to test channel isolation $I(f)$. This characteristic is dependent on the directivity of the network analyzer harmonic converter, and the reflection transmission unit. For the Hewlett-Packard 8411A harmonic converter the isolation is greater than 50 db. In this measurement the ports of the reflection-transmission unit are terminated in the cables used for the later target scatter measurement. These coaxial cables are terminated in
Fig. 2.3 Equipment setup for attenuator measurement.

Fig. 2.4 30 db attenuator characteristic for 8.0-8.5 GHz.
50 ohm resistive loads as shown in fig.2.5. The results of a typical run are shown in fig.2.6. Computer subroutine IST automates this stage in the correction procedure. As can be seen the coupled signal is well in the noise of the system and would not affect later scatter data. If the isolation effect is ignored later calculation would be simplified greatly; but is included here to be consistent with the procedure outlined in the literature.[7]

The next stage in generating the data for correction of scatter data is measurement of the system transfer function T(f). This consists of the characteristics of the traveling wave tube amplifier, system cables and connectors. This is done by connecting the cable from the transmitting antenna to the receiving antenna cable in fig.2.6 and placing the 30 db attenuator characterized previously in the line to avoid damage to the harmonic converter. The raw measurement MT(f) is a combination of several factors:

\[ MT(f) = T(f) * A(f) + I(f) \]  

Solving for T(f):

\[ T(f) = \frac{(MT(f) - I(f))}{A(f)} \]  

The equipment setup for this procedure is shown in fig 2.7 and typical uncorrected and corrected transfer function data in fig.2.8 and 2.9.

Measurement of the antenna cross-coupling and room clutter is the next step in the correction process. In this procedure shown in fig.2.7b, the target is removed from the anechoic chamber and the antennas pointed to the target.
Fig. 2.5 System configuration for measuring isolation between reference and unknown ports.

Fig. 2.6 Isolation between ports of reflection-transmission unit; 8.0-8.5 GHz.
Fig. 2.7 a) System configuration for transfer characteristic measurement. b) Connection to antennas for scattering and clutter measurement. c) Transmitting antenna with spiral AEL antenna and parabolic dish. d) Receiving dual polarization horn; EMI A6100 with Norsal 90 hybrid.
Fig. 2.7 (contd.)  a) system configuration for transfer characteristic measurement.  b) Connection to antennas for scattering and clutter measurement  c) Transmitting antenna with spiral AEL antenna and parabolic dish.  d) Receiving dual polarization horn; EMI A6100 with Norsal 90 hybrid.
Fig. 2.8 Uncorrected transfer characteristic of system; 8.0-8.5 GHz.

Fig. 2.9 Transfer characteristic corrected for attenuator response; 8.0-8.5 GHz.
A high gain parabolic dish antenna is used for illumination of the target since the narrow beam pattern of the antenna places most of the radiated power on the target area. A smaller dual polarization horn is used for receiving in order to sample a small area of the scattered field. The uncorrected clutter $C_1(f)$ is given by:

$$C_1(f) = C_2(f) * T(f) + I(f)$$

(2.3)

Solving for the corrected clutter and coupling:

$$C_2(f) = (C_1(f) - I(f)) / T(f)$$

(2.3a)

Subroutine ANTEN does the system clutter and coupling removal. Examples of the uncorrected and corrected clutter $C_1(f)$ and $C_2(f)$ are shown in figs.2.10 and 2.11. The corrected clutter represents the actual signal reflected from the anechoic chamber walls and that signal coupled between the antennas with the system response removed.

These subroutines: PAD, IST, TRANS, and ANTEN, were combined into a program SYSRES. Data from each of these subroutines may be stored on disc for later recall or display. Theoretically if the system is not disturbed then the system response will remain constant. Then only the target data need be recorded in any run for a new corrected backscatter measurement.

The transfer function of the system and the range clutter-antenna cross coupling data are utilized the the next step of the error correction process. A reference object of known constant cross section is measured and the result stored. This data includes all the errors previously
Fig. 2.10 Uncorrected system clutter; 8.0-8.5 GHz.

Fig. 2.11 System clutter corrected for transfer function; 8.0-8.5 GHz.

22.
described but also takes into account the antenna system variations as a function of frequency:

\[ R_1(f) = C_2(f) * T(f) + I(f) + R_2(f) * T(f) \]  

(2.4)

Here \( C_2(f) \) and \( R_2(f) \) contain the antenna system response multiplying the actual values of corrected reference target and system clutter data.

\[ R_2(f) = R(f) * A_1(f) \]  

(2.5)

\[ C_2(f) = C(f) * A_1(f) \]  

(2.6)

This response \( A_1(f) \) takes into account the varying amount of power received and transmitted as a function of frequency in the antenna system. If the reference target is chosen to have a constant cross section and linear phase over the frequency range of interest then \( R(f) \) is of constant amplitude and linear phase. Solving for \( R_2(f) \):

\[ R_2(f) = \frac{(R_1(f) - I(f) - C_1(f))}{T(f)} \]  

(2.7)

This leaves \( R_2(f) \) proportional to \( A_1(f) \) shifted by a linear phase corresponding to the reference target range.

When the actual target is measured; it is corrected for system errors as was the reference target data and this result is divided the corrected reference target data to yield the final target scatter data.

\[ S_2(f) = \frac{(S_1(f) - I(f) - C_1(f))}{T(f)} \]  

(2.8)

\[ S(f) = \frac{S_2(f)}{R_2(f)} \]  

(2.9)

This technique may be simplified considerably in the laboratory environment given the signal to noise ratio is greater than 10 db for the scattered signals. In this case only multiplicative errors remain and the additive errors
are masked by the high target scatter signal amplitude. Hence:

\[ I(f), C_1(f) \rightarrow 0 \]

\[ R_1(f) = R_2(f) \cdot T(f) \] (2.10)

and therefore:

\[ S(f) = S_1(f) / R_1(f) \] (2.11)

Weir and his group have reported that this technique has reduced equivalent range clutter to -45 db below 1 sq. meter.

There remains one source of error in the scattered signal measurement that cannot be removed by calculation. This error comes from multipath scattering from the object. The target scatters power in all directions. Some of this signal may be reflected off the walls or floor of the anechoic chamber. The signals reflected off the walls is over 48 db down from the incident wave amplitude in the 6.0-12.0 GHz range. However if the target is small in cross section; on the order of 100 sq. cm.; then it is possible for the walls (on the order of 100 000 sq. cm.) to contribute a significant component to the received signal.

In order to analyze the effect of the multipath scattering, let the directly received signal be written:

\[ S_d(t) = A \cos(\omega t \cdot \psi) \] (2.12)

and the indirectly received signal:

\[ S_i(t) = B \cos(\omega t \cdot \psi + \theta) \] (2.13)

Then the total received signal is given by:

\[ S_r(t) = (A^2 + 2AB \cos \theta \cdot \cos \psi) \cos(\omega t \cdot \psi + \theta \cdot \tan^{-1} \left( \frac{B \sin \theta}{A + B \cos \theta} \right)) \] (2.14)
Since theta is a function of the indirect path length differences and frequency, it will lead to a periodic variation in the amplitude of the scattered signal. As an example; if the paths differ in length by 1 meter then the amplitude oscillations will occur every 300 MHz given all other factors remain constant.

A series of programs was written to test these various techniques of error removal. They differ in the only in the error removal technique employed; not in file storage or display formats nor in range calculation and removal to be described. These programs used together:

1) Measure and correct the reference target data with files of transfer function and clutter data generated by SYSRES.
2) Measure and correct the target data and finally take the corrected reference target data and remove the antenna system response from the target data.
3) Alternately for high SNR; calculate the correct scattered target signal directly using the reference target data.
4) Calculate and remove phase shift due to range from the target signal after error correction

These programs are briefly described and differ in the mentioned categories:

SPHERE—Reads transfer function and clutter data files generated by SYSRES; takes the reference or object data and corrects for errors in the
equipment.

SPHER2—Measures clutter and reference target data. It then subtracts clutter and divides the target data by the reference target transfer function.

SPHER3—Measures reference target and object signals ignoring clutter, and divides the object data by the reference target complex field amplitude data.

In order to implement the complete error correction process program SPHERE would be run twice; once for the reference target and then again for the test object. This data would be stored for later retrieval. Program SPHER3 would read these files and process them such that the test object complex field data would be divided by the reference target data. For high SNR cases; program SPHER3 alone would be run: first measuring the reference target and then the test target and finally dividing them yielding the final result.

Listings and a more complete description of program operation is given in the program appendix I.
III RANGE PHASE SHIFT ANALYSIS

This chapter contains an analysis of the effects on the phase shift due to target range on coherent imaging of a target. It includes a discussion of some of the available techniques for the removal of this phase shift and the required performance of these systems based on bandwidth and signal to noise ratio.

3.1 The effects of range phase on imaging

As previously described by Farhat and Chan ;[4]; the scattered field of the scattering target is given by:

\[ \psi(\mathbf{R}_t, \mathbf{R}_r, \mathbf{R}_s) = \frac{j}{2\pi} e^{-j\mathbf{k}(\mathbf{R}_t - \mathbf{R}_r)} \int_{-\infty}^{\infty} \mathcal{U}(\mathbf{r}) e^{-j\mathbf{k}(\mathbf{R}_r + \mathbf{R}_s) \cdot \mathbf{r}} d\mathbf{r} \]  \hspace{1cm} (3.1)

Where \( \mathbf{R}_t \) and \( \mathbf{R}_r \) are the vectors from the receiving and transmitting antennas to the target respectively and \( \mathbf{k} \) is the wave vector of the illuminating wave. In this case the integration is over the extent of the object. The integral term is independent of the range of the target. While the term preceding the integral is target independent and contains range information. The argument of the complex exponential is a linear phase function of frequency.

In the single receiver-transmitter pair arrangement; shown in fig.3.1, the spatial frequency domain (\( \mathbf{p} \) space) data is collected in a plane perpendicular to the axis of rotation. In this case the multiplication of the range phase factor leads to the convolution of the transforms of the range and target functions in the spatial domain. The real part of the range frequency domain function is a
Fig. 2.12 a) Target and antenna placement relative to target considered in analysis. b) Experimental configuration in anechoic chamber; note target on rotating pedestal in forefront.
radially symmetric sinusoidal function:
\[ R \{ e^{-jA(R_t, R_r)} \} = \cos A(R_t, R_r) \]  \hspace{1cm} (3.2)

This transforms to a circular ring of radius \((R_t + R_r)\). This indicates that each point of the reconstructed image is convolved with this circular ring pattern; seriously degrading the target image. In fact any error in the removal of phase will distort the image in this manner. The effect of removing the range phase factor is equivalent to the focusing of the system on the target.

There are several other reasons for the removal of the factor:
\[ \frac{jA}{2\pi(R_t + R_r)} e^{-jA(R_t, R_r)} \]  \hspace{1cm} (3.3)

from the received data. If the data is discrete then the considerations of aliasing and sufficient data sampling rate are introduced. When the sampling rate in the frequency domain is \( f \) then the maximum target range before aliasing will occur is \((c/4\pi f)\). However if the phase factor is removed and the target is of smaller dimension \( L \) than the range, then the sampling rate in the frequency domain need only be sufficient to prevent aliasing over the dimensions of the object:
\[ \Delta f \leq \frac{c}{4L} \]  \hspace{1cm} (3.4)

This allows the entire resolution capability of the system to be placed on the target itself greatly reducing the data
volume.

Another reason for the removal of this phase factor term can be seen in systems involving multiple receiver-transmitter pairs. For each pair \((\mathbf{R}_i)\) and \((\mathbf{R}_j)\) is different and in order for the data to be coherent all phase centers must be equal for an image to be formed.

Several methods have been suggested for the removal of the range phase factor. [4] In all cases it is required that the range removal technique be accurate to within \((\lambda/5)\) for there not to be serious image degradation. It is important to investigate the constraints on the ranging system parameters necessary to attain the required accuracy.

From the scaling theorem in Fourier analysis; a signal cannot be both of narrow bandwidth and short duration. [8]

\[
a_{f(at)} \rightarrow F\left(\frac{\omega}{a}\right)
\]  

(3.5)

We define the duration and the bandwidth of the signal in the following manner:[ ]

\[
(\Delta t)' = \frac{1}{E} \int_{-\infty}^{\infty} |f(t)|^2 dt \quad (\Delta \omega)' = \frac{1}{2\pi E} \int_{-\infty}^{\infty} \omega |F(\omega)|^2 d\omega \quad (3.6a,b)
\]

where:

\[
E = \int_{-\infty}^{\infty} |f(t)|^2 dt = \frac{1}{2\pi} \int_{-\infty}^{\infty} |F(\omega)|^2 d\omega
\]  

(3.6c)

is the signal energy. Then if:

\[
\lim_{|t| \to \infty} \sqrt{t} f(t) = 0
\]  

(3.6d)

When applied to signals scattered by a target this may be translated to range uncertainty:

\[
\Delta R \Delta f \leq \frac{\lambda}{4\pi}\]  

(3.7)
This represents a limit when the durations of the signal pairs are as previously defined. However it may be possible to improve the range resolution given that the signal to noise ratio is greater than 10 db.

Consider a sinusoid in narrow band gaussian noise:

\[ r(t) = A \cos \omega t + n_c(t) \cos \omega t - n_s(t) \sin \omega t \]

where \( n(t) \) is the noise signal and \( n_s(t) \) and \( n_c(t) \) are the quadrature components of the noise signal. The amplitude and phase may be expressed as:

\[ |r(t)| = \sqrt{(A + n_s(t))^2 + n_c(t)^2} \]  

\[ \text{Arg}(r(t)) = \tan^{-1}\left( \frac{n_c(t)}{A + n_s(t)} \right) \]

Since the noise is gaussian \( n_c(t) \) and \( n_s(t) \) are gaussian. Assuming that the SNR is high the phase may be approximated by:

\[ \text{Arg}(r(t)) = \tan^{-1}\left( \frac{n_s(t)}{A} \right) \approx \frac{n_s(t)}{A} \]

Also since the noise is white \( n_s(t) \) may be related to the bandwidth of the receiving system.

\[ \sigma_{n_s}^2 = 2N_s B \]

where \( \sigma_{n_s}^2 \) is the variance of the \( n_s(t) \) quadrature phase component. The probability density of the phase may be written as:

\[ f(\phi) = \frac{A}{\sqrt{2\pi}N_sB} e^{-\frac{A^2\phi^2}{4N_sB}} \]

This leads to an interesting result; the variance of the phase.
phase is the inverse of the SNR:

\[
\varphi = \frac{1}{\text{SNR}} \tag{3.13}
\]

Translating this result to an uncertainty relationship the phase uncertainty may be expressed:

\[
\Delta \omega \Delta t \geq \sqrt{\frac{\text{SNR}}{A}} \tag{3.14}
\]

The uncertainty in phase is the product of the time and frequency uncertainties. This leads to an expression for the range resolution as a function of the SNR.

\[
\Delta f \Delta R \geq \frac{c}{2\pi \sqrt{\text{SNR}}} \tag{3.15}
\]

Wide band ranging systems measure range by calculating the propagation delay of the signal. In one such system a high speed code is transmitted. The received signal is correlated with the original coded signal in a delay locked loop. The value of the control signal in the loop is proportional to the target range. Obviously the resolution is only as good as the period of one of the code bits (chips). Other wide band systems use other signals for ranging (chirps, Walsh functions) to obtain high range resolution.\cite{4,11,12}

The system implemented here at the Graduate Research center of the Moore school is a coherent amplitude-phase measurement facility. Ranging techniques that may be integrated into this system are therefore of special interest. The phase of a point scatterer is a linear function the frequency. This directly corresponds to the
phase factor preceding the scattering integral in eq ( ). If the target consists of multiple scattering centers; then each of these will be represented as a delta function in the in the reconstructed image. This suggests a technique using Fourier analysis to determine range. First place the reference target in the microwave field and measure the phase/amplitude response over as wide a frequency range as possible. Then inverse transform this one dimensional collection of data. This will transform to essentially a delta function occurring at the time corresponding to the propagation delay. This will occur when the target has a single scattering center such as a sphere. Even when the object is more complex the inverse transform will be centered around the transit time. In this Fourier technique for range determination the resolution \( \Delta x \) is inversely related to the frequency sweep width.

\[
\Delta x = \frac{c}{2\pi f}
\]  

(3.16)

The factor of 1/2 results from the fact that the range is half the signal propagation path length.

A factor to be considered is that different scattering centers are visible from different receiver positions. It is imperative that all when several receivers are used simultaneously that all choose the same scattering center; the phase center for range removal. If the various centers do not coincide, the fringes of the hologram be skewed. The data sets from each of the receivers brought into alignment using an adaptive
SUPER-RESOLUTION IMAGERY BY FREQUENCY SWEEPING, (U)
AUG 80 N H FARMAT, C WERNER
AFOSR-TR-80-1068
Information is lost in the hologram if the phase centers for the scan lines are separated.

When this process is automated the sweep is done by measuring the response at discrete frequency points. The amplitude and phase are stored at \( N \) frequency points in the sweep range. The range at which aliasing will occur is given by:

\[
R_{\text{alias}} = \frac{c}{4 \Delta f}
\]  

(3.17)

This system exhibits processing gain; a quality of all systems which spread a baseband signal into a wide spectrum. For this system the processing gain is a function of the number of measurements and the sweep width.

\[
\text{Gain} = \frac{\Delta f}{\text{stepsize}} = n
\]  

(3.18)

\[
\text{Gain (db)} = 10 \log_{10} n
\]

As an example, for 256 measurement points, this would give 24 db of processing gain.

A set of subroutines was written to test this range removal technique. In one of them, RANGE, the range of the strongest scattering center is calculated and in the other, RANCOR, the phase factor is calculated and removed from the target data. These subroutines are used in programs SPHERE, SPHER2, and, SPHER3.

The time domain equivalent of this technique is fitting a linear trend to the phase signal from the network analyzer. Since the phase signal is modulo \((2\pi)\); this means
estimating the frequency of a ramp waveform; either using a least squares approximation or implementing the equivalent of a phase locked loop. The slope of the ramp waveform is proportional to the range of the target. The accuracy to which the range may be determined depends on the sweep width, the target structure and the noise in the system. If the sweep is wide, then there will be more data with which to estimate the slope. Noise in the data will obviously interfere with the estimation process as will any phase shifts due to the target structure.

Another type of system for generating a reference signal utilizes a Target Derived Reference. This system has been extensively studied at the Electro-Optics and Microwave Optics laboratory. [11] A brief review of the ideas developed to date in this regard are given below. The complex exponential in the integral term of scattered signal remains constant when the target is small relative to the illuminating signal wavelength.

\[
\psi(\phi) = \int \mathcal{U}(\phi) e^{-j\phi^2} d\phi \approx e^{-j\phi^2} \int \mathcal{U}(\phi) d\phi
\]  

(5.19)

This is true if \( L_{\text{eq}} \) is sufficiently small such that \( \phi \cdot \phi < a \). In this case the integral value approaches a constant multiplied by a linear phase; i.e. a point scatterer. It will only occur when the target dimensions are less than a tenth wavelength of the illuminating signal, placing it in the Rayleigh scattering region. The TDR signal is mixed harmonically with a phase locked scattered signal.
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\[
\psi(\theta) = \int \mathcal{U}(\cdot) e^{-j \frac{2\pi}{\lambda} \cdot \cdot} d\tau = e^{j \frac{2\pi}{\lambda} \cdot \cdot} \int \mathcal{U}(\cdot) d\tau 
\]  

(3.19)

This is true if \((L_{\text{in}})\) is sufficiently small such that \((\cdot \cdot \cdot \approx \cdot \cdot \cdot)\). In this case the integral value approaches a constant multiplied by a linear phase; i.e. a point scatterer. It will only occur when the target dimensions are less than a tenth wavelength of the illuminating signal, placing it in the Rayleigh scattering region. The TDR signal is mixed harmonically with a phase locked scattered 35
signal at the imaging frequency. Here the two signal sources are phase locked by a phase synchronizer. The high frequency sweeper acts as the slave signal source. These two signals simultaneously illuminate the target. Harmonic mixing of the suitably limited TDR and imaging signals will yield the desired phase corrected data.

Another technique which is useful for ranging is the frequency displaced reference method. Here the carrier is displaced \((\Delta f)\). It is important that the object not contribute to the phase shift; hence the displacement must satisfy the following condition:

\[
\Delta f < \frac{2c}{L}
\]  \(3.20\)

In this case the target structure will not contribute to the net phase shift. The range to the target phase center is given by:

\[
R = \frac{\Delta \phi c}{\Delta f \pi n}
\]  \(3.21\)

Where \((\Delta \phi)\) is the change in phase for the carrier and displace carrier signals respectively. If the frequency shift is small then the phase shift will not be large. The resolution of the system then is directly related to the SNR in the receiver channel since the accuracy to which the phase may be measured is a function of the channel noise. If the displacement is large then the phase shift is increased and the SNR requirements on the signal for a specific resolution is decreased. This relationship may be expressed:

\[
R_{\text{resolution}} = \frac{\Delta \phi c}{4\pi A \Delta f}
\]  \(3.22\)
The factor of 2 comes about due to the phase uncertainty existing in both the carrier and displaced carrier signals.

An alternate method for implementation of the displaced frequency ranging system is a swept frequency chirp system. The ranging signal frequency is given by:

\[ f(t) = f_0 (1 + \frac{\Delta t}{T}) \]

where \( \Delta = \frac{f_2 - f_0}{T} \)

- \( T \) - Sweep period
- \( f_0 \) - Initial frequency for sweep
- \( f_2 \) - Final frequency

The scattered signal from the target is given by:

\[ f_s(t) = f_0 + \frac{df}{dt} - \frac{f_2 - f_0}{R_T \cdot R_r} \]

where \( \frac{df}{dt} \) is the change in frequency due to the target structure. The range of the target may then be simply calculated using a frequency counter and sweep time \( T \) and sweep width \( (f_2 - f_0) \). This method could be used in an analog imaging system.

Other Target Derived Reference systems simulate the low frequency reference carrier by measuring the change in phase of the imaging frequency over a narrow band. Over this small band the phase shift is assumed to be linear. In one system a series measurements is made for each frequency point. The first displaced down by a small amount, \( \Delta f \); the second at \( f \); and the final measurement at \( f + \Delta f \). Phase and amplitude are measured at each frequency and processed to obtain the target range. In a similar system the three
signals are transmitted simultaneously by amplitude modulation of the carrier. These systems are presently under intense investigation by other workers at the Electro-Optics and Microwave Optics Laboratory of the Moore School.

3.2 Practical considerations for range phase removal

Several factors influence which of these systems would be of value in a long range imaging radar system versus a controlled laboratory environment. The distribution of the reference signal for complex field amplitude measurement makes implementation of system requiring a central reference difficult to implement. Techniques are being considered in the E.O. laboratory for reference distribution using fiber optic that might remove this limitation. Reference distribution is accomplished in the lab readily since the distances are small.

Typical transmitter-receiver pattern arrangements might be the Wells array [14], an orthogonal pattern of receivers and transmitters, a circular array of receivers with central transmitter or a random array. Each combination of receiver and transmitter contributes another line in the frequency domain 3D data volume. For this reason it is advantageous that all combinations of the receivers and transmitters are utilized for data collection. Reference signal distribution difficulty therefore leaves the TDR systems as the only practical alternatives for long range imaging systems. The AM TDR system eliminates
reference distribution by transmitting the reference signal along with the imaging signal and automatically corrects for the target range. TDR systems have the additional advantage that they have immunity to turbulence and inhomogeneities in the propagation medium since both the reference and imaging signals follow the same path.

There are several considerations for determining the best TDR system. Narrow band systems yield only a weighted average of the range to the phase center of the object while wide band system can resolve individual scatters on the target body. A wide band system could adaptively choose one of the scattering centers for the phase reference of the system. A narrow band system could not do this, and any error would introduce image distortion. The narrow band systems have the advantage of automatically correcting the target data for the range phase factor.

For the laboratory imaging experiments a TDR system would not yield the correct phase factor since in this arrangement the object rotates about an axis and the correct phase factor would be a constant, representing the phase shift to the axis of rotation, not the target. The TDR system looks only at the range to the strongest specular reflector on the target surface.

If movement of the target is utilized for aperture synthesis then only one receiver-transmitter pair is required for 3-D imaging and the adaptive system is not required.
Knowledge of the placement of the data in the 3-D frequency domain volume is necessary for the reconstruction of the hologram. The azimuth and elevation angle of the target can be obtained from a conventional radar located at a central location where the data processing and reconstruction is taking place.
IV  SYSTEM IMPLEMENTATION OF SWEPT FREQUENCY IMAGING

This section of the thesis will describe the research that was done in order to obtain a clear understanding of system performance. Following this will be a section of the thesis devoted to the experimental verification of the swept frequency imaging theory. The theory is applied in the simulation of the experiments performed.

4.1 System repeatability

An important parameter of system performance is the repeatability of an experimental measurement. The frequency range over which this possible for the equipment used indicates the bandwidth for which imaging is possible. There are several feedback loops in the system which allow it to track variations in the transmitted signal level. The traveling wave tube amplifier characteristic is shown in fig.4.1. This plot is on a logarithmic scale, indicating that the TWT amplifier gain drops off exponentially below 7.0 GHz and above 15.0 GHz. This measurement was done by first measuring the system response (cables, connectors, attenuator) less the TWT amplifier and then subtracting this response from the TWT amplifier plus system data. A sample of the amplifier output is sampled using a 20 db directional coupler and this is fed to the RF input of the HP 8743A reflection-transmission (R-T) unit. A crystal detector at the 'unknown' port of the R-T unit rectifies a portion of this signal. The detector output is brought to the external signal leveling input of the HP 8620C sweeper.
Fig. 4.1 a) Traveling Wave Tube amplifier gain characteristic in db; 4.0-16.0 GHz.  b) Varian VA 618G TWT amplifier (bottom) and HP 8743A reflection-transmission unit (top).
The leveling circuit of the sweeper can level the output over a 20 db range. In addition the AGC in the HP 8410B network analyzer can track the reference signal amplitude over a 40 db dynamic range. System performance may be seen in fig.4.2 for a cylindrical target 7 meters distant from the receiving and transmitting antennas. Two consecutive measurements of the target were made and the results divided. The ideal response would be 0 db flat amplitude and 0 degree phase difference over the entire frequency sweep. With few exceptions due to phase noise at the (+/- ) transition point, the system has the desired repeatability in the 5.5 to 16.0 GHz range. Below 4.5 GHz there are phase errors due to insufficient reference power whereas above 15 GHz errors come about due to the low amplitude of the received signal. Noise may be cancelled by taking multiple measurements and finding the mean. These results indicate the useful data can be recorded in the 5.5-16.0 GHz range.

### 4.2 Computer control of target rotation

When implementing a frequency diversity system with just one pair of receiving and transmitting antennas, the target must then be rotated in the electromagnetic field and the scattering measured for different rotation angles. The target used in the experimental system rotates on a stepper motor driven pedestal. The column of the pedestal is 1 1/2 meters in length and is made of styrofoam material with minimal cross section. A stepper motor controls table rotation precisely. In order for the pedestal to rotate one
Fig. 4.2 System repeatability for two consecutive scattering measurements of a 80 cm long cylinder 7 cm in diameter; 4.0-16.0 GHz.
revolution the motor must be stepped 10 000 times. The motor is under direct computer control using the digital output port the MINC. A FORTRAN subroutine STEP2 was written for control of the stepper motor. It calculates the number of steps required for a specified angular rotation and moves the table clockwise or counter clockwise based on the direction parameters passed in the subroutine call. The stepper and pedestal are shown in fig.4.3.

4.3 Sphere Simulation

For the calibration of a radar system a reference target is required. The most commonly used reference target is the conducting sphere since its high degree of symmetry does not favor any particular polarization for the incident illumination. Both the bistatic and monostatic scattering of a metallic sphere was simulated.

The general solution for the plane wave electro-magnetic scattering of the sphere was first done by Mie in 1908.[15],[16] In the far field approximation, the scattered field is given by:

\[ E_s(r, \theta, \phi) = \frac{j k r}{4 \pi} \left[ \cos \phi S_r(\theta) \hat{\phi} - \sin \phi S_\theta(\theta) \hat{\theta} \right] \]  

(4.1)

where

\[ S_r(\theta) = \sum_{n=0}^{\infty} (-1)^n \left[ A_n \frac{P_n'(\cos \theta)}{\sin \theta} + i B_n \frac{d}{d \theta} \left( P_n'(\cos \theta) \right) \right] \]  

(4.2)

and

\[ S_\theta(\theta) = \sum_{n=0}^{\infty} (-1)^n \left[ A_n \frac{d}{d \theta} \left( \frac{P_n'(\cos \theta)}{\sin \theta} \right) + i B_n \frac{P_n'(\cos \theta)}{\sin \theta} \right] \]
Fig. 4.3 Stepper motor and rotating pedestal.
$S_1(\chi)$ and $S_2(\chi)$ are called the complex far field amplitudes for the (\hat{e}) and (\hat{\phi}) polarizations respectively. The quantity in the square brackets of eq. 4.1 is called the scattering function.

$$F(\theta, \phi) = \cos \phi S_1(\theta) \hat{e} - \sin \phi S_2(\theta) \hat{\phi}$$

(4.4)

The scattering cross section in any arbitrary polarization ($\hat{n}$) for an incident wave polarized in the ($\hat{r}$) direction may be written:

$$\sigma_n(\theta, \phi) = \frac{4\pi}{k^2} |F(\theta, \phi)|^2 |\hat{r} \cdot \hat{n}|^2$$

(4.5)

Where ($\hat{\eta}$) is the polarization of the incident wave and ($\hat{\phi}$) is the polarization vector of the receiving system.

For the perfectly conducting sphere the coefficients $A_n$ and $B_n$ are:

$$A_n = -(-i)^n \frac{2n+1}{n(n+1)} \frac{J_n(k_\eta a)}{k_\eta(k_\eta)}$$

(4.6a)

$$B_n = (-i)^n \frac{2n+1}{n(n+1)} \frac{J_n(k_\eta a)}{k_\eta(k_\eta)}$$

(4.6b)

$J_n(k_\eta a)$ - Spherical Bessel function

$h_n'(k_\eta a)$ - Spherical Hankel function

$P_n(x)$ - Associated Legendre function

$k_\eta$ - Wave number of incident wave

$a$ - Sphere radius

The prime on the expression for $B_n$ denotes differentiation with respect to ($k_\eta a$).

Polynomial approximations exist for the Mie series exact solution. [15] Different polynomials are used for the three frequency regions for scattering. These are: low
frequency or Rayleigh region $(k_a)<0.4$; the resonance region $0.4<(k_a)<20$; and finally the high frequency or physical optics region $(k_a)>20$. Two programs BISCAT and SPSCAT implement both bistatic and monostatic cases in the three frequency regions. Fig. 4.4 shows the monostatic scattering of the sphere as calculated. This is exactly the same answer for the scattering of the sphere as the exact solution. The horizontal axis is in terms of the dimensionless quantity $(k_a)$. Figure 4.5 a, b, c and d show the bistatic scattering of the metallic sphere of bistatic angles of $30^\circ, 60^\circ, 90^\circ$, and $120^\circ$ degrees. Note that the approximation are only valid in the range:

$$\xi < \theta' < \pi - \xi$$

where

$$\xi = O\left(\frac{1}{k_a}\right)$$

which leads to the discontinuities for small $(k_a)$ at large bistatic angles. BASIC programs BIDISP and SDISP generate the graphs for the sphere simulations. These programs are in appendix II.

An important result from these simulations is that at high frequencies the scattered signal is of constant amplitude and linear phase irrespective of the bistatic scattering angle. The only exception to this is the forward scattering case when $(\theta)$ equals $(\pi)$, where the cross section grows without bound as $k$ increases. This indicates that the only portion of the sphere that is scattering for large $(k_a)$ is the front face closest to both the receiver and transmitter; and therefore a ray optics approximation
Fig. 4.4 Monostatic scattering for the perfectly conducting sphere. $(k/a)$ varies from 0.2 to 10.5 which corresponds to the scattering of a 20 cm. diameter sphere in the frequency range of 0.1 to 5.0 GHz. Log normalized cross section: $\log(\ )$. 
Fig. 4.5 Bistatic scattering of a 20 cm. diameter conducting sphere in the frequency range .1 to 6.0 GHz; \(0.2 < (k, a) < 12.6\); polarization of the receiver equal to scattered wave polarization. a) Geometry for scattering expression. b) Bistatic angle 30°. c) Bistatic angle 60°. d) Bistatic angle 89°. e) Bistatic angle 120°.
Fig. 4.5 (contd.) Bistatic scattering of a 20 cm. diameter conducting sphere in the frequency range .1 to 6.0 GHz; \(0.2 < (k_a) < 12.6\); polarization of the receiver equal to the scattered wave polarization. a) Geometry for scattering expression. b) Bistatic angle 30°. c) Bistatic angle 60°. d) Bistatic angle 89°. e) Bistatic angle 120°.
Fig. 4.5 (contd.) Bistatic scattering of a 20 cm. diameter conducting sphere in the frequency range 0.1 to 6.0 GHz; $0.2 < (k_a) < 12.6$; polarization of the receiver equal to the scattered wave polarization. 

a) Geometry for scattering expression.  
b) Bistatic angle 30°.  
c) Bistatic angle 60°.  
d) Bistatic angle 89°.  
e) Bistatic angle 120°.
may be applied to find the scattered field.

\[ S_x(o) = S_y(o) = -\frac{1}{2} \lambda_0 a e^{-i2\lambda_0 a \cos \phi} \]  

(4.8)

for the bistatic case. In the monostatic case this reduces to:

\[ E(o) = -\frac{1}{2} \lambda_0 a e^{-i2\lambda_0 a} \]  

(4.9)

For targets with features larger than a few wavelengths in size resonance effects become minimal.

Another possible reference target is the long cylinder \((l >> a)\). The scattering of the cylinder in the high frequency region when it is oriented vertically yields an answer similar to that of the sphere. For \((k a) > 5\) where \(a\) is the cylinder radius, resonance effects disappear and the copolarized scattered field is given by:

\[ E_3 = E_1 \left( \sqrt{\frac{\lambda_0 \cos \phi}{2\pi r}} \right) \exp \left( i \frac{\lambda_0 a \cos \phi}{2} \right) \]  

(4.10)

\[ r = (R_T + R_r) \]

The equation for the scattering of the cylinder is used for the computer simulations of frequency swept holography.

### 4.4 Simulation of frequency swept imaging

A series of frequency swept hologram simulations were done of targets that would later be imaged experimentally. The basic arrangement consists of separate receiving and transmitting antennas which measure the scattering of a target that rotates about an axis. The center of rotation is chosen as the phase center of the imaging system. For this configuration the frequency domain data lies in a plane
perpendicular to the axis of rotation. Therefore the transforms of the holograms will be slices in this plane. The first object hologram simulated was comprised of two cylinders equidistant from the rotational axis. This target is shown in fig. 4.6. Approximations for the various distances were derived:

\[ r_1 = r - \frac{d}{2} \sin (\frac{\theta}{2} - \theta) \]  \hspace{1cm} (4.11a)  
\[ r_2 = r + \frac{d}{2} \sin (\frac{\theta}{2} - \theta) \]  \hspace{1cm} (4.11b)  
\[ \chi_1 = r + \frac{d}{2} \sin (\frac{\theta}{2} + \theta) \]  \hspace{1cm} (4.11c)  
\[ \chi_2 = r - \frac{d}{2} \sin (\frac{\theta}{2} + \theta) \]  \hspace{1cm} (4.11d)  

the waves striking cylinders Cl and C2 are given by:

\[ E_{Cl} = E_0 e^{-i A_0(\chi_1)} \]  \hspace{1cm} (4.12a)  
\[ E_{C2} = E_0 e^{-i A_0(\chi_2)} \]  \hspace{1cm} (4.12b)  

The scattered waves from the two cylinders including the cylinder response then follows:

\[ E_{Sc1} = E_0 \sqrt{\frac{A_0 \cos \phi}{2(\pi)}} e^{-i A_0(r_1 - 2a \cos \phi)} \]  \hspace{1cm} (4.13a)  
\[ E_{Sc2} = E_0 \sqrt{\frac{A_0 \cos \phi}{2(\pi)}} e^{-i A_0(r_2 - 2a \cos \phi)} \]  \hspace{1cm} (4.13b)  

This is further simplified by combining terms:

\[ E_s = 2 E_0 e^{i A_0(2a \cos \phi)} \sqrt{\frac{A_0 \cos \phi}{2(\pi)}} \left\{ \cos \alpha \cos \phi \right\} \]  \hspace{1cm} (4.14b)  

Finally take the real part of this function for display:

\[ R(E_s) = C \cdot \cos (2a \cos \phi) \cos (A_0 \rho \cos \phi \sin \theta) \]  \hspace{1cm} (4.14b)  

This was done for a two cylinder target with cylinders 5 cm.
Fig. 4.6 Bistatic scattering of two cylinder target.
in radius, separated by 25 cm. using program CYLIN. The results were displayed by program CDISP on a Tektronix 606A CRT display. CDISP gives the option of varying the gray scale compression of the hologram either logarithmically or by constant multiplication. These programs are listed in appendix II. The resultant hologram and the reconstructions obtained through Fourier transformation on the optical bench appear in figs. 4.7 a, b. The hologram simulated a sweep from 2.0 to 18.0 GHz in 64 frequency steps. The target in the simulation rotated 360 degrees in 128 steps.

Another target simulated which did not have the symmetry of the first target was comprised of two cylinders both mounted to one side of the rotational axis, as shown in fig. 4.8. Two simulations were done of this target with varying diameter cylinders. In the first case 7 cm radius cylinders were used. The hologram for this case and the Fourier transform reconstructions are shown in figs. 4.8 b, c, d. For the second simulation the target was two cylinders 3.5 cm in radius. In both cases the cylinders were located 10 cm from the center of rotation and the simulation was for a 2.0 to 18.0 GHz sweep. The hologram and the transformed images are shown in figs. 4.9 a, b, c. The two cylinder off axis target was simulated by first calculating the copolarized scattered field for a single cylinder:

\[ \mathbf{\tilde{E}}_s = 2 \mathbf{E}_e e^{i k z a} e^{-i k d \cdot \mathbf{e}} \]  

(4.15)

56
Fig. 4.7 a) Simulation Hologram of two cylinder target; 10 cm. diameter, 25 cm. apart. Frequency range: 2.0-18.0 GHz; 128 lines, 64 points/line. b) Optical Fourier transform of hologram.
Fig. 4.8 a) Geometry of two cylinder off-axis target. b) Hologram simulation two cylinder off-axis target; 2.0-18.0 GHz; 64 points/line; 128 lines. b) Transform with zero order term. c) Transform with zero order removed.
Fig. 4.9 a) Hologram simulation of off-axis two cylinder target with cylinders 7 cm. in diameter; 2.0-18.0 GHz b) Optical Fourier transform with zero order. c) Transform with zero order term removed.
taking the real part:
\[ R[E_i] = 2E_z \left\{ \cos(2a) \cos \theta \sin \Theta \left( z \sin \theta \sin \Theta \cos \phi \right) \right\} (4.15a) \]
\[ = 2E_z \cos \left( a \sin \Theta \right) \]

For the two cylinder off axis target, one cylinder is at \( \Theta = 0 \) and the other at \( \Theta = 90^\circ \), therefore the scattered field is given by:
\[ R[E_i] = C \left\{ \cos \left( a \sin \Theta \right) + \cos \left( a \sin \Theta \right) \right\} (4.16) \]

In general for an arbitrary set of circular scatterers of radius \( a \) and distance \( l \) from the origin; the scattered field may be written:
\[ R[E_i] = \sum_n \cos \left\{ \frac{2a}{l} \sin \Theta \cos \Theta \right\} (4.17) \]

This gives the capability to simulate the scattering of any target given that it can be decomposed into \( N \) spherical scattering centers.

4.6 Experimental results

An experimental system for the implementation of swept frequency imaging was setup in the anechoic chamber at the Graduate Research Center in the Moore School. The frequency range for these experiments was from 6.3 to 16.0 GHz in 64 discrete steps. The targets were rotated 360 degrees in 128 steps. These holograms were then identical in form to the simulations previously done.

The system for error correction and range phase shift removal was that used for high signal to noise ratio signals. The reference target was a cylinder positioned so
that its front face was located on the axis of rotation as in fig. 4.10. A plot of system response is shown in fig. 4.11. This data represents the combined characteristics of the antennas, amplifier, cables and clutter. In addition it contains the linear phase shift that is the range phase factor. As an example for the two cylinder target shown in 4.12 the raw data, magnitude and phase is shown in fig. 4.13. Figure 4.14 shows how this data has been corrected for range phase and system response. This data was generated using the Fortran program SPHER3.

The experimental properties of the two cylinder target were studied extensively. Both the scattering as a function of frequency for a specific orientation of the target and the scattering as a function of angular rotation at specific frequencies was obtained. In figs. 4.15 a, b, c are shown the corrected frequency response of the target for orientations of 45°, 90° and 135° degrees.

Another computer program ANTPAT was written to obtain the radiation pattern of an arbitrary target or antenna. In the two cylinder case the pattern was measured at 5.0, 10.0 and 15.0 GHz. Note that when the cylinders are collinear all that is seen is the front surface specular reflection of the one cylinder hence the pattern of a point scatterer in the vicinity of 0° degrees. These patterns are shown in figs. 4.16 a, b, c. At high frequencies the lobe spacing is much closer than at low frequencies, consistent with the theoretical result for the pattern. To see this examine the
Fig. 4.10 Reference target on pedestal; 80 cm. long cylinder, 7 cm. in diameter.

Fig. 4.11 Reference target response including system response and range phase shift; 6.3-16.0 GHz.
Fig. 4.12 Two cylinder target geometry.
Fig. 4.13 Uncorrected scatter data for symmetrical two cylinder target; \((\theta)=0^\circ\), 6.3-16.0 GHz.

Fig. 4.14 Corrected two cylinder target data using system response of Fig. 4.11.
Fig. 4.15  a) Corrected two cylinder symmetrical target response; 6.3-16.0 GHz, (θ)=45°. b) (θ)=90°. c) (θ)=135°.
Fig. 4.16 Scattering pattern of a two cylinder target of Fig. 4.12 at different frequencies as a function of target rotation angle.  

a) 5.0 GHz  

b) 10.0 GHz  

c) 15.0 GHz
expression for the monostatic scattering of the symmetrical two cylinder target:

\[ E_s = C \left\{ e^{j2\pi \omega t} \cdot \cos \theta \cdot \sin \theta \right\} \quad (4.18) \]

The expression for the scattering of the target at a given frequency as a function of angular rotation may be written:

\[ E_s(\theta, \omega) = C \cdot \cos \omega \cdot \sin \theta \quad \text{C-constant} \quad (4.19) \]

As for the swept frequency response; \( 1 \sin(\theta) \) remains constant, and the hence the swept frequency response is sinusoidal with period dependent on \( \lambda \) and 1.

The final test for the system was the generation of actual holograms. The first target measured was the two cylinder target shown in fig.4.17a. The cylinders are of aluminum, 80 cm. in length and 7 cm. in diameter. The real part of the corrected swept frequency data in the range 6.3 to 16.0 GHz was stored and displayed on the CRT. The targets were rotated 360 degrees in 128 steps yielding a total of 8192 points in the hologram (64 points/line * 128 lines). The center of the hologram is at 0 Hz with radial distance directly proportional to frequency. An example is shown in fig.4.17b and the reconstructions in figs.4.17c and d. These Fourier transforms were done optically. [17]

This procedure was followed for other targets not having the symmetry of the first object used. The target type was the same as the simulations done previously. The
Fig. 4.17  a) Two cylinder target in anechoic chamber on rotating pedestal.  b) Hologram of target measured between 5.3 and 16 GHz corrected for range and system response; 128 lines, 64 points/line.  c) Optical Fourier transform of hologram.  c) Optical Fourier transform without zero order term.
first of these was a single cylinder mounted off axis as shown in fig.4.18a. This cylinder was the same as the others used and the frequency range and angular sweep were identical to that of the two cylinder target. The hologram and reconstructions are shown in figs.4.18 b,c,d. The final target was the two off axis cylinder target pictured in fig.4.19a. The frequency diversity hologram and transforms are in figs.4.19 b,c,d.
Fig. 4.18 a) Single cylinder off-axis target and position in anechoic chamber. b) Experimental hologram of target; 6.3-16 GHz; 128 lines, 64 points/line; corrected for range and system response. c) Optical Fourier transform of hologram. d) Optical Fourier transform without zero order term.
Fig. 4.19  a) Two cylinder off-axis target geometry and position in anechoic chamber, corrected for range and system response.  
c) Optical Fourier transform of hologram.  
d) Optical Fourier transform without zero order term.
V Conclusion

This thesis has described an automated swept frequency measuring system. This system may be used for radar cross section measurement, antenna pattern measurement and swept frequency holography. The system has a useful range of 5.0-17.0 GHz in which amplitude and phase of the scattered microwaves from targets in the anechoic chamber of the Graduate Research Center may be recorded and stored. A DEC MINC LSI-11/2 completely automates the data acquisition process. A complete error correction algorithm was implemented using the data storage and processing capabilities of the minicomputer.

The effect of range phase shift on swept frequency holograms was investigated and various techniques for its removal were investigated. It is believed that a TDR system for range phase removal is required for implementation of a practical radar system. This system must have extremely high resolution for coherent imaging. The relationship between TDR system bandwidth, receiver channel bandwidth and resolution was derived:

\[ \text{Resolution} = \frac{\sigma \cdot C}{\Delta f \cdot 2\pi} = \frac{\sqrt{2 \pi \Delta f}}{4 \pi A \Delta f} \]

where \((\Delta f)\) is the imaging bandwidth, \((R)\) the range uncertainty, \(B\) the receiver channel bandwidth and \(N\) the noise power spectral density.

Simulations were performed for the scattering of various radar targets which include the conducting sphere,
V Conclusion

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$$\text{Resolution} = \frac{\sigma \frac{\Delta f}{z \pi}}{\Delta f} = \frac{\sqrt{2 \pi N B C}}{4 \pi A \Delta f}$$

where (\Delta f) is the imaging bandwidth, \(R\) the range uncertainty, \(B\) the receiver channel bandwidth and \(N\), the noise power spectral density.

Simulations were performed for the scattering of various radar targets which include the conducting sphere,
infinite cylinder and combinations of these. The holograms recorded from these analytical results reconstruct the targets extremely well and set a goal for practical system performance. An expression was derived for the scattering of \( N \) spherical/cylindrical cylinders in a plane passing through their centers:

\[
\Re\{E_d^2\} = \sum_n \omega \left\{ \frac{z n}{\theta_n} - \frac{\ell_n}{\omega_n} \sin (\theta + \theta_n) \right\}
\]

where \( l \) is the distance from the axis of rotation (\( \theta_n \)) the angle relative to some reference for the target angular position and \( a \) the target radius.

Finally experimental swept frequency holograms were generated using a rotating pedestal under computer control to scan the target in one dimension. The experiments done indicate the feasibility of implementing a practical holographic radar system. The holograms obtained for various targets agree well with theory even though the error correction and range phase shift removal techniques used were robust in nature. It is believed that better images are possible given that the error correction techniques previously outlined are implemented.

Further work can be done in testing the TDR techniques for their suitability for an imaging system. The system may also be expanded to include scanning in the \( \phi \) direction to give true 3-D imaging capability. This may be implemented by adding a stepper motor controlled azimuthal scanner to the top of the rotating column.
infinite cylinder and combinations of these. The holograms recorded from these analytical results reconstruct the targets extremely well and set a goal for practical system performance. An expression was derived for the scattering of N spherical/cylindrical cylinders in a plane passing through their centers:

$$R[E_3] = \sum_n \cos \left( -\frac{\pi}{2} \frac{\alpha}{\alpha_n - \alpha} \sin (\theta + \theta_n) \right)$$  (4.17)

where \(l\) is the distance from the axis of rotation \(\theta_n\), the angle relative to some reference for the target angular position, and \(a\) the target radius.

Finally, experimental swept frequency holograms were generated using a rotating pedestal under computer control to scan the target in one dimension. The experiments done indicate the feasibility of implementing a practical holographic radar system. The holograms obtained for various targets agree well with theory even though the error correction and range phase shift removal techniques used were robust in nature. It is believed that better images are possible given that the error correction techniques previously outlined are implemented.

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BIBLIOGRAPHY


[13] CHi Keung Chan,"Analytical and Numerical Studies of
BIBLIOGRAPHY


10 DIM A(25): B(25)
20 PRINT "THIS PROGRAM WILL CALIBRATE THE MICROWAVE SPECTRUM." 
30 PRINT "ENTER NEW DATA (Y OR N)?"
40 LINPUT 28
50 IF D="Y" THEN GO TO 120
60 PRINT "WHAT FILE NAME?": LINPUT 28
70 OPEN 28 FOR INPUT AS FILE 28
80 FOR I=1 TO 25
90 INPUT A(I). B(I)
100 NEXT I
110 GO TO 240
120 SEND (M1. 4)
130 PRINT "WHAT FILE NAME?": LINPUT 28
140 OPEN 28 FOR OUTPUT AS FILE 81
150 FOR I=1 TO 25
160 A(I)=SQR(A(I)'-1.1)
170 C(A)=SQR(A(I)'-1.1)
180 PRINT "COMMAND:" (C
190 SEND (M8. 4)
200 PRINT "INPUT THE COUNTER FREQUENCY:" 
210 INPUT B(I)
220 PRINT B(I): A(I) = PRINT 81.B(I)
230 NEXT I
240 U0=V2=O: C=O: N=O: N2=O
250 FOR I=1 TO 25
260 N=I+2(I)  
270 NEXT I
280 FOR J=1 TO 25 PRINT A(J): B(J) NEXT J
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330 CONTINUE (RETURN):" LINPUT 28
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LOGICAL UNIT 12 THE NAME WILL BE ASSIGNED USING THE ASSIGN
SUBROUTINE IN THE LIBRARY. THIS IS A NEW FILE ON THE DISC AND

FORTAN IV VO2.1-1 THU 09-AUG-79 00 46 59 PAGE 002

WILL BE SAVED WHEN THE FILE IS CLOSED

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AND NOT THE ACTUAL PAD TO BE MEASURED
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TYPE 902 STARTING FREQUENCY IN GHZ

ACCEPT +, FSTART

CALL SWEP (1, FSTART, 1, 1.4)
TYPE 903 ENDING FREQUENCY IN GHZ

ACCEPT +, FEND

TYPE 904 PASE

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DO 200 K = 1, NPOINT

FREQ = FSTART + FLOAT (K - 1) * STEP

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IF (IPHA (12) LT 720) IPHA (12) = IPHA (12) + 1440

CONTINUE

CALL SWEP (10, FREQ, 1, 1.4) 'RESET IEEE BUS

WRITE (12, *) FSTART

WRITE (12, *) FEND

WRITE (12, *) NPOINT

DO 400 K = 1, NPOINT

WRITE (12, *) IPHA (K)

CONTINUE

CALL CLOSE (12)

DO TO 700

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**************************************************************************
SECTION TO OBTAIN CHARACTERISTICS OF ARM
AND NOT THE ACTUAL PADS TO BE MEASURED
**************************************************************************

TYPE 901 NUMBER OF POINTS IN SYSTEM RESPONSE

ACCEPT +, NP0INT

TYPE 902 STARTING FREQUENCY IN GHZ

ACCEPT +, FSTART

CALL SWEP (1, FSTART, 1, 1.4)

ACCEPT +, FEND

CALL (FEND-FSTART)/FLOAT (NPOINT)

DO 200 K = 1, NPOINT

FREQ = FSTART + FLOAT (K - 1) * STEP

CALL SWEP (1, FREQ, 1, 1.4)

CALL IPHA (12, 1, IPHA, NSAMP)

IF (IPHA (12) = 1) IPHA (1)

IF (IPHA (12) GT 720) IPHA (12) = IPHA (12) + 1440

IF (IPHA (12) LT 720) IPHA (12) = IPHA (12) + 1440

CONTINUE

CALL SWEP (10, FREQ, 1, 1.4) 'RESET IEEE BUS

WRITE (12, *) FSTART

WRITE (12, *) FEND

WRITE (12, *) NPOINT

DO 400 K = 1, NPOINT

WRITE (12, *) IPHA (K)

CONTINUE

CALL CLOSE (12)

DO TO 700

RETURN

FORMAT (/10.6, 'ENTER THE PAD RESPONSE FILE NAME

FORMAT (/10.6, 'ENTER NUMBER OF POINTS IN PAD #', CONE

FORMAT (/10.6, 'ENTER START FREQUENCY IN GHZ', CONE

FORMAT (/10.6, 'ENTER ENDING FREQUENCY IN GHZ', CONE

FORMAT (/10.6, 'CONNECT THE FLEXIBLE ARM PLUS 6 DB PAD ', CONE

RETURN

RETURN
SUBROUTINE 1ST

VERSION 1.3

THIS SUBROUTINE WILL MEASURE THE ISOLATION BETWEEN THE TWO C
CHANNELS OF THE NETWORK ANALYZER. THE PHASE AND AMPLITUDE OF THE L
INPUTS WILL BE PASSED THROUGH COMMON BLOCKS. THE OUTPUT WILL BE THE VALUE OF THE SENSING
SYSTEM ATTACHED TO THE SECONDARY AMPLITUDE AND THE MAGNITUDE AND PHASE OF THE LEGEND SIGNAL ARE MEASURED AT THE SAME POINT AS THE SYSTEM MEASUREMENTS.

IAMP2  ARRAY WITH AMPLITUDE OF LEAKED SIGNAL

IPH2  ARRAY WITH PHASE OF LEAKED SIGNAL

IFLAG2  FLAG TO INDICATE IF NEW DATA IS GENERATED

NPOINT  NUMBER OF SAMPLE POINTS TAKEN AT EACH FREQUENCY

COMMON/RADA/, LW, DP, IPH, IFLAG, FSTART, FEND, NPOINT, Nsamp

COMMON/IST/A, IAMPP, IPH2, IF, PL, Nsamp

LOCAL AND COMMON ARRAYS

NAME  TYPE  SECTION OFFSET  SIZE  Dimensions

IAMPP  INT  unknown  000000  000000 ( 512 ) (512)

IPH2  REAL  unknown  020000  020000 ( 512 ) (512)

NPOINT  INT  unknown  040002  040002

NSAMP  INT  unknown  04016  04016

LOCAL AND COMMON ARRAYS

NAME  TYPE  NAME  OFFSET

IAMPP  INT  PADA  000000  000000 ( 512 ) (512)

IPH2  REAL  PADA  020000  020000 ( 512 ) (512)

FSTART  REAL  FP  040000  040000

FEND  REAL  FP  040002  040002

NPOINT  INT  FP  04016  04016

NSAMP  INT  FP  04020  04020

SUBROUTINES, FUNCTIONS, STATEMENT AND PROCESSOR-DEFINED FUNCTIONS.

NAME  TYPE  NAME  TYPE  NAME  TYPE  NAME  TYPE  NAME  TYPE

ASSIGN  REAL  R4  04  FLOAT  R4  04  PHAMP2  R4  04  SLEEP  R4  04

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0001  SUBROUTINE 1ST

0002  COMMON/RADA/, LW, DP, IPH, IFLAG, FSTART, FEND, NPOINT, Nsamp

0003  COMMON/IST/A, IAMPP, IPH2, IF, PL, Nsamp

0004  LOCAL AND COMMON ARRAYS

0005  NAME  TYPE  SECTION OFFSET  SIZE  Dimensions

0006  IAMPP  INT  unknown  000000  000000 ( 512 ) (512)

0007  IPH2  REAL  unknown  020000  020000 ( 512 ) (512)

0008  FSTART  REAL  FP  040000  040000

0009  FEND  REAL  FP  040002  040002

0010  NPOINT  INT  FP  04016  04016

0011  NSAMP  INT  FP  04020  04020

0012  SUBROUTINES, FUNCTIONS, STATEMENT AND PROCESSOR-DEFINED FUNCTIONS.

0013  NAME  TYPE  NAME  TYPE  NAME  TYPE  NAME  TYPE  NAME  TYPE

0014  ASSIGN  REAL  R4  04  FLOAT  R4  04  PHAMP2  R4  04  SLEEP  R4  04

0015  FORTRAN IV  V03  1-1  THU 09-AGO-79  00  57  36  PAGE 002

0023  CONTINUE

0024  CALL SLEEP(10,FSTART,1.4)

0025  DO 100 Y=1,NPOINT

0026  DO 200 K=1,NPOINT

0027  CALL SLEEP(1,FSTART,1.4)

0028  CONTINUE

0029  CALL SLEEP(10,FSTART,1.4)

0030  WRITE(12,*) FSTART

0031  CALL SLEEP(10,FSTART,1.4)

0032  WRITE(12,*) FEND

0033  CALL SLEEP(1,FSTART,1.4)

0034  WRITE(12,*) FEND

0035  CALL SLEEP(1,FSTART,1.4)

0036  WRITE(12,*) FEND

0037  CALL SLEEP(1,FSTART,1.4)

0038  WRITE(12,*) FEND
La (-r. ~ ~ ~ i 0' - ~ ~ W . , . 1 0 ~ - . W- fgd -0r IL'J''0 K J -0 ka jwW a m ~ ZZwJ w - 4K Cetz. C . C- L-t ccz xr-- C I W > 0. U, U uu v' -C- 0 or a. CL.. iI HO u Q U..-N~- a.wjWiC 1- II t0 0 KK A.L 0 . £N 0 04. J 471x343) 156x300) >rg 3-ad t to JA i. 0 ' 8U IL Q- #A W ........ 142x154} Ir 4 IL 00 00 a 0 462x152 I0
0012 DO 200 K=1,NPOINT
0013 PRED=PSTART+FL2AT(K-1)+STEP
0014 CALL SWEEP1,FRED,I.4)
0015 CALL PHRM2(10,IPR3MP3)
0016 IMP3(K)=(IM3+2040)
0017 IPH(K)=(IP-2040)
0018 CONTINUE
0019 CALL SWEEP(10,START,1.4)
0020 TYPE=902
0021 CALL ASSGNC(NNEW,NC,1)
0022 STORE THE UNCORRECTED DATA
0023 WRITE(12,*) FSTART
0024 WRITE(12,*) FEND
0025 WRITE(12,*) NPOINT
0026 WRITE(12,*) IMP3(K)
0027 WRITE(12,*) IPH3(K)
0028 CONTINUE
0029 CALL CLOSE(12)
0030 OPEN FILE WITH CORRECTED DATA
0031 TYPE=903
0032 CALL ASSGNC(NNEW,NC,1)
0033 WRITE(12,*) FSTART
0034 WRITE(12,*) FEND
0035 WRITE(12,*) NPOINT
0036 GENERATE CORRECTED DATA AND STORE
0037 PI=3.1415926
0038 DO 400 K=1,NPOINT
0039 PSTART=25+FLOAT(IPR3MP3(K))
0040 ADRMP=25+FLOAT(IPH3(K))
0041 AIST=AIST+05+FLOAT(IPR3MP3(K))
0042 CONVERT TO DEGREES AND DB
0043 PIST=25+FLOAT(IPR3MP3(K))
0044 ADRMP=25+FLOAT(IPH3(K))
0045 CONVERT TO WATTS
0046 AIST=AIST+05+FLOAT(IPR3MP3(K))
0047 ATRMP=AISTR+05+FLOAT(IPR3MP3(K))
0048 FIND REAL AND IMAGINARY PARTS
0049 FORTRAN IV 111 PAGE 004
0050 FORMAT(1X,15)
0051 BACK TO DEGREES AND DB
0052 ATRMP=AISTR+05+FLOAT(IPR3MP3(K))
0053 ATRMP=AISTR+05+FLOAT(IPR3MP3(K))
0054 ATRMP=AISTR+05+FLOAT(IPR3MP3(K))
0055 ATRMP=AISTR+05+FLOAT(IPR3MP3(K))
0056 ATRMP=AISTR+05+FLOAT(IPR3MP3(K))
0057 ATRMP=AISTR+05+FLOAT(IPR3MP3(K))
0058 ATRMP=AISTR+05+FLOAT(IPR3MP3(K))
0059 ATRMP=AISTR+05+FLOAT(IPR3MP3(K))
0060 ATRMP=AISTR+05+FLOAT(IPR3MP3(K))
0061 ATRMP=AISTR+05+FLOAT(IPR3MP3(K))
0062 ATRMP=AISTR+05+FLOAT(IPR3MP3(K))
0063 CONTINUE
0064 CONTINUE
0065 CONTINUE
0066 CONTINUE
0067 CONTINUE
0068 CONTINUE
0069 CONTINUE
0070 CONTINUE
0071 CONTINUE
0072 CONTINUE
0073 CONTINUE
0074 CONTINUE
0075 CONTINUE
0076 CONTINUE
0077 CONTINUE
0078 CONTINUE
0079 CONTINUE
0080 CONTINUE
0081 CONTINUE
0082 CONTINUE
0083 CONTINUE
0084 CONTINUE
0085 CONTINUE
0086 CONTINUE
0087 CONTINUE
0088 CONTINUE
0089 CONTINUE
0090 CONTINUE
0091 CONTINUE
0092 CONTINUE
0093 CONTINUE
0094 CONTINUE
0095 CONTINUE
0096 CONTINUE
0097 CONTINUE
0098 CONTINUE
0099 CONTINUE
0100 CONTINUE
0101 CONTINUE
0102 CONTINUE
0103 CONTINUE
0104 CONTINUE
0105 CONTINUE
0106 CONTINUE
0107 CONTINUE
0108 CONTINUE
0109 CONTINUE
0110 CONTINUE
0111 CONTINUE
0112 CONTINUE
0113 CONTINUE
0114 CONTINUE
0115 CONTINUE
0116 CONTINUE
0117 CONTINUE
0118 CONTINUE
0119 CONTINUE
0120 CONTINUE
0121 CONTINUE
0122 CONTINUE
0123 CONTINUE
0124 CONTINUE
0125 CONTINUE
0126 CONTINUE
0127 CONTINUE
0128 CONTINUE
0129 CONTINUE
0130 CONTINUE
0131 CONTINUE
0132 CONTINUE
0133 CONTINUE
0134 CONTINUE
0135 CONTINUE
0136 CONTINUE
0137 CONTINUE
0138 CONTINUE
0139 CONTINUE
0140 CONTINUE
0141 CONTINUE
0142 CONTINUE
0143 CONTINUE
0144 CONTINUE
0145 CONTINUE
0146 SUBTRACT ISOLATION FROM TRANSFER+ISOLATION
0073 READ(12,*) IAMP5(K)
0074 READ(12,*) IPHM(K)
0075 600 CONTINUE
0076 CALL CLOSE(12)
0077 TYPE 903
0078 CALL ASSIGN(12,-4,'OLD','NE',1)
0079 READ(12,*) FSTART
0090 READ(12,*) FEND
0091 READ(12,*) NPOINT
0092 DO 450 K=1,NPOINT
0093 READ(12,*) IAMP6(K)
0094 READ(12,*) IPHM6(K)
0095 650 CONTINUE
0096 CALL CLOSE(12)
0097 700 RETURN
C
C
0088 900 FORMAT(/'SUBROUTINE ANTEM DETERMINES THE ANTENNA/'
C 1/','CHARACTERISTICS AND'/,'ANTENNA CROSS COUPLING'/'
C 2/,'CONFIGURE THE SYSTEM IN ITS K-NAL PUNK'/')
0089 901 FORMAT(/'ENTER THE ANTENNA SYSTEM RESPONSE NEW FILE'/'
C 1 NAME '')
0090 902 FORMAT(/'ENTER THE ANTENNA CLUTTER DATA FILE NAME '')
0091 903 FORMAT(/'ENTER THE ANTENNA ANTENNA CLUTTER DATA OLD FILE'
C 1 NAME '')
0092 904 FORMAT(/'ENTER THE ANTENNA SYSTEM RESPONSE OLD FILE'
C 1 NAME '')
0093 STOP
0094 END

FORTRAN IV STORAGE MAP FOR PROGRAM UNIT ANTEM
LOCAL VARIABLES. PSEET DDATA. SIZE = 000216 ( 111 WORDS)
NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
ANNT R4 000110 ANNT K4 000124 ANNT K4 000130
AEMN R4 000100 AEMN R4 000074 AEMN R4 000154
AIST R4 000104 AIST R4 000114 AIST R4 000120
ARES R4 000160 ARES R4 000150 ARES R4 000124
ATEMPY R4 000140 ADEK R4 000060 FREQ R4 000044
IA R4 000050 IP R4 000052 K R4 000042
PANT R4 000070 PI R4 000054 PIST R4 000044
PREQ R4 000114 PTEMP R4 000144

COMMON BLOCK /PADA / SIZE = 004022 ( 1033 WORDS)
NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
IAMPAD 1=2 IPHA 1=2 IFLAG 1=2 004000
FSTART 1=4 004002 FEND R4 004006 STEP R4 004012

COMMON BLOCK /ISTA / SIZE = 004004 ( 1026 WORDS)
NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
IAMP 1=2 IPH 1=2 IFLAG 1=2 004000
NSAMP 1=2 IFLAG 1=2 004020

COMMON BLOCK /TRANSA / SIZE = 010004 ( 2050 WORDS)
NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
IAMP5 1=2 IPH 1=2 002000 IFLAG0 1=2 004000
NSAMP5 1=2 IFLAG 1=2 004000

COMMON BLOCK /ANTA / SIZE = 010004 ( 2050 WORDS)
NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
IAMP6 1=2 IPH 1=2 002000 IFLAG0 1=2 004000
NSAMP6 1=2 IFLAG 1=2 004000

LOCAL AND COMMON ARRAYS:
NAME TYPE SECTION OFFSET -----SIZE----- DIMENSIONS
IAMPAD 1=2 IPHA 000000 002000 ( 512 ) (512)
IAMP 1=2 IPH 000000 002000 ( 512 ) (512)
IAMP5 1=2 TRANSA 004004 002000 ( 512 ) (512)
IAMP6 1=2 ANTA 000000 002000 ( 512 ) (512)
IAMP 1=2 IPHA 002000 002000 ( 512 ) (512)
IAMP5 1=2 TRANSA 004004 002000 ( 512 ) (512)
IAMP 1=2 IPH 002000 002000 ( 512 ) (512)
IAMP5 1=2 IPHA 002000 002000 ( 512 ) (512)
IAMP6 1=2 ANTA 006004 002000 ( 512 ) (512)

FORTRAN IV STORAGE MAP FOR PROGRAM UNIT ANTEM
SUBROUTINES, FUNCTIONS. STATEMENT AND PROCEDURE-DEFINED FUNCTIONS
NAME TYPE NAME TYPE NAME TYPE NAME TYPE
AL0010 R4 4 ASSIGN R4 ATAN2 R4 CLOSE R4 COS R4
FLOAT R4 IFIX 1=2 PHAMP2 R4 SIN R4 SORT R4
SWEEP R4
PROGRAM SPHERE

VERSION 1.2

THIS PROGRAM WILL TAKE EXPERIMENTAL DATA FOR THE SPHERE
AND CORRECT IT FOR THE SYSTEM RESPONSE. IT WILL PRINT
BOTH THE CORRECTED AND UNCORRECTED DATA AND FINALLY DISPLAY
IT ON THE HIGH RESOLUTION CRT.

ALSO IT DESIRED IT WILL GENERATE IF DESIRED ANALYTICAL
DATA FOR THE SPHERE AND STORE IT IN A FILE. IT WILL ALSO
PRINT THIS DATA IF DESIRED TO A FILE AND ALSO DISPLAY IT ON
THE HIGH RESOLUTION CRT MONITOR.

COMMON/RANGE,DIST,IRFLAG,UNIT
COMMON/OBJ OBJ,OBJ NSAMP2
COMMON/SYST/TRAN/TRAN/TRAN/CLUT/CLUT/CLUT/CLUT/FSTART,FEND,NPOINT
INTEGER OBJ(512),OBJ-P(512),TRAN-A(512),TRAN-B(512)
BYTE A

TYPE 905
CALL SYSNP
STEP=FEND-FSTART/NCPOINT)
CALL SPDAT
TYPE 903
ACCEPT 1000.A
IF (A EQ 'N') GO TO 220
WRITE(UNIT,504)
WRITE(UNIT,905)/FSTART,FEND,STEP,NPOINT
WRITE(UNIT,906)
DO 210 K=1,NCPOINT
AMPLIF=FLOAT(OBJ,OBJK),K,5
PHASE=FLOAT(OBJ,OBJK),K,25
FRESH=FSTART+FLOAT(K-1)+STEP
WRITE(UNIT,907),FRESH,AMPLIF,PHASE
210 CONTINUE
220 CALL CORREC
HERE LIST THE CORRECTED SPHERE DATA

COMMON/UNIT

WRITE(UNIT,906)
DO 277 K=1,NCPOINT
INDK=K
AMPLIF=FLOAT(OBJ,OBJK),K,05
PHASE=FLOAT(OBJ,OBJK),K,25
FRESH=FSTART+FLOAT(K-1)+STEP
WRITE(UNIT,907),K,FRESH,AMPLIF,PHASE
277 CONTINUE

WRITE(UNIT,906)
DO 277 K=1,NCPOINT
INDK=K
AMPLIF=FLOAT(OBJ,OBJK),K,05
PHASE=FLOAT(OBJ,OBJK),K,25
FRESH=FSTART+FLOAT(K-1)+STEP
WRITE(UNIT,907),K,FRESH,AMPLIF,PHASE
277 CONTINUE

THIS SECTION WILL STORE THE CORRECTED DATA FOR SYSTEM RESPONSE

TYPE 802
ACCEPT 1000.A
IF (A EQ 'N') GO TO 400

CALL ASSIGN(20,-1,'NEW','NC')
WRITE(20,*,FSTART)
WRITE(20,*),FEND
WRITE(20,*,NPOINT)
DO 510 K=1,NPOINT
WRITE(20,OBJK)
WRITE(20,OBJK)
510 CONTINUE
CALL CLOSE(20)

THIS SECTION WILL CORRECT FOR RANGE

CALL RANGE
TYPE 914
ACCEPT 1,IRFLAG
CALL RANGE
COMMON/UNIT

WRITE(UNIT,914)
DO 400 K=1,NCPOINT
AMPLIF=FLOAT(OBJ,OBJK),K,05
PHASE=FLOAT(OBJ,OBJK),K,25
FRESH=FSTART+FLOAT(K-1)+STEP
WRITE(UNIT,907),K,FRESH,AMPLIF,PHASE
400 CONTINUE

WRITE(UNIT,907)
FRESH=FSTART+FLOAT(K-1)+STEP
WRITE(UNIT,907),K,FRESH,AMPLIF,PHASE
400 CONTINUE

THIS SECTION WILL STORE THE RANGE CORRECTED DATA

CALL ASSIGN(20,-1,'NEW','NC')
WRITE(20,*,FSTART)
SUBROUTINE SYSIMP

THIS SUBROUTINE WILL READ IN THE SYSTEM RESPONSE FILES AND PLACE THEM IN A COMMON BLOCK TO BE PASSED TO OTHER ROUTINES.

COMMON/SYSTA/TRN1A, TRNPA, CLUTA, CLUTP, FSTART, FEND, NPOINT

INTEGER TRN1A(512), TRNPA(512), CLUTA(512), CLUTP(512), NPOINT

TYPE 900

CALL ASSGN(12,-1,'OLD','NC',1)

READ(12,*) FSTART
READ(12,*) FEND
READ(12,*) NPOINT
DO 100 K=1,NPOINT
READ(12,*) TRANS(K)
READ(12,*) TRNP(K)
CONTINUE
CALL CLOSE(12)

RETURN

COMMON BLOCK /SYSTA/ SIZE = 010012 (2053 WORDS)

NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
TRANA 1=2 000000 TRNPA 1=2 000200 CLUTA 1=2 004000
CLUTP 1=2 000000 FSTART R=4 010000 FEND R=4 010004
NPOINT 1=2 010010

LOCAL AND COMMON ARRAYS:

NAME TYPE SECTION OFFSET ---- SIZE ---- DIMENSIONS
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END

FORTAN IV  STORAGE MAP FOR PROGRAM UNIT SPHAT
LOCAL VARIABLES:  PSTATE, PTYPE, DATA, SIZE =  000022 (9  WORDS)
NAME  TYPE  OFFSET  NAME  TYPE  OFFSET  NAME  TYPE  OFFSET
A  L+1  000012  K  I+2  000014

COMMON BLOCK /OBJ/, / SIZE =  004002 (1025 WORDS)
NAME  TYPE  OFFSET  NAME  TYPE  OFFSET  NAME  TYPE  OFFSET
OBJA  I+2  000000  OBJP  I+2  002000  NSAMP2  I+2  004000

COMMON BLOCK /SYSTA/, / SIZE =  010012 (2053 WORDS)
NAME  TYPE  OFFSET  NAME  TYPE  OFFSET  NAME  TYPE  OFFSET
TRANA  I+2  000000  TRAMP  I+2  002000  CLUTP  I+2  004000

NAME  TYPE  SECTION  OFFSET  ------ SIZE ------ DIMENSIONS
CLUTA  I+2  SYSTA  004000  002000  (512) (512)
CLUTP  I+2  SYSTA  004000  002000  (512) (512)
OBJA  I+2  OBJP  000000  002000  (512) (512)
OBJP  I+2  OBJP  002000  002000  (512) (512)
TRANA  I+2  SYSTA  000000  002000  (512) (512)
TRAMP  I+2  SYSTA  000000  002000  (512) (512)

SUBRoutines, Functions, Statement and Processor-Defined Functions.
NAME  TYPE  NAME  TYPE  NAME  TYPE  NAME  TYPE  NAME  TYPE
ASSIGN  R+4  CLOSE  R+4  OBJDAT  R+4

LOCAL AND COMMON ARRAYS:

1  POINT: (*)

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SUBROUTINE SPHAT
C
C THIS SUBROUTINE WILL CALL OBJDAT AND OBTAIN ONE LINE OF
C DATA FOR THE SPHERE IF NEW DATA IS SPECIFIED OTHERWISE
C AN OLD SPHERE DATA FILE WILL BE READ. IN THE CASE OF NEW DATA
C THIS ROUTINE WILL WRITE THE NEW FILE WITH THE DESIRED NAME
C
COMMON/OBJ/OBJA, OBJP, NSAMP2
C
INTEGER OBJA(SI2), OBJP(SI2)
INTEGER TRANA(SI2), TRANP(SI2), CLUTA(SI2), CLUTP(SI2), FIPOINT
BYTE A

0001 TYPE 900
0002 TYPE 901
0003 ACCEPT 700, A
0004 IF IA EQ "N" GO TO 300
0005 TYPE 902
0006 ACCEPT *, NSAMP2
0007 Pulse
0008 CALL OBJDAT
0009 TYPE 903
0010 CALL ASSIGN(12,-1,'NEW', 'NC', 1.)
0011 WRITE(12,*) FIPOINT
0012 WRITE(12,*) FSTART
0013 WRITE(12,*) FEND
0014 DO 200 K+1, FIPOINT
0015 WRITE(12,*) OBJA(K)
0016 WRITE(12,*) OBJP(K)
0017 CONTINUE
0018 CALL CLOSE(12)
0019 300 GO TO 500
0020 CALL ASSIGN(12,-1,'OLD', 'NC', 1.)
0021 READ(12,*) FIPOINT
0022 READ(12,*) FSTART
0023 READ(12,*) FEND
0024 READ(12,*) FIPOINT
0025 READ(12,*) OBJA(K)
0026 READ(12,*) OBJP(K)
0027 CONTINUE
0028 CALL CLOSE(12)
0029 RETURN
0030 FORMAT(81)
0031 FORMAT(13,8X,'*** SUBROUTINE SPHAT OBTAINS SNEPT FREQUENCY
0032 DATA ****')
0033 FORMAT(*8*, 'TAKE NEW DATA (Y OR N) ?')
0034 FORMAT(*8*, 'SET UP THE SPHERE, HIT RETURN TO CONTINUE')

FORTRAN IV

0020 CLSIN=CLMP+5IN(CLPH)

0021 TEMPS=REAL PART OF OBJECT-CLUTTER

0022 TEMINS=IMAGINARY PART OF OBJECT-CLUTTER

0023 ATEMP=MAGNITUDE OF OBJECT-CLUTTER

0024 ABSTEM=MAGNITUDE IN DBM OF (OBJECT-CLUTTER)

0025 PTEMP=PHASE OF OBJECT-CLUTTER

0026 ADDRESS=MAGNITUDE OF RESULT(A TEMP/TRANP) DIVIDE BY TRANSFER CHARACTERISTIC IN DBM

0027 PHASE=PHASE OF RESULT(OBJECT-CLUTTER)/TRANSFER

0028 ******** SUBTRACT CLUTTER FROM OBJECT DATA ********

0029 TECOS=OBCOS-CLCOS

0030 TEMIS=OBSIN-CLISIN

0031 ******** CONVERT BACK TO PHASOR FORM ********

0032 PTEMP=ATAN2(TEMIS,TECOS)

0033 ATEMP=SQRT(TEMIS**2+TECOS**2)

0034 ******** DIVIDE BY TRANSFER CHARACTERISTIC ********

0035 ADDTEM=10**ALOG10(ATEMP)

0036 ADDRESS=ADDTEM*200MP

0037 PRES=(PTEMP-TRAMP)

0038 IF(PRES GT 0)PRES=-PRES-2.IP1

0039 IF(PRES LT -P1)PRES=-PRES+2.IP1

0040 ******** REPLACE DATA INTO INTEGER ARRAY ********

0041 OBJJX=IFIX(20 ADDRESS)

0042 OBPK=IFIX(PRES/DEO*4+1)

0043 100 CONTINUE

0044 RETUN

0045 END

FORTRAN IV

00001 

00002 SUBROUTINE RANGE

00003 VERSION 1.1

00004 THIS SUBROUTINE WILL CALCULATE THE DISTANCE TO THE OBJECT

00005 AND RETURN THAT VALUE. DEPENDING ON THE FLAG PASSED IT WILL

00006 QUERY WHAT TECHNIQUE TO BE USED IN THE RANGE CALCULATION

00007 COMMON/RANGE1/DIST,IRFLAG,UNIT

00008 COMMON/OBJ-OBJA,OBJP,MSAMP

00009 COMMON/DYSTA,TRANP,CLUTP,FSTART,FEND,NPOINT

00010 COMMON/OBJA(15),OBJP(15),TRANP(15),TRANP(15),TRANP(15)

00011 COMMON/CLUTP(15),NPOINT,MSAMP,IRFLAG

00012 COMMON/REALMSAMP,C,PI

00013 COMMON/DATA.C(2)997925E+08/F,L1/1.1415926/

00014 COMMON/IFLAG NE 1 GO TO 200

00015 COMMON/**** THIS SECTION FOR DIRECT RANGE INPUT ********

00016 COMMON/TYPE,900

00017 COMMON/ACCEPT,DIST

00018 COMMON/DO TO 1000

00019 COMMON/IF(IRFLAG NE 2) GO TO 1000

00020 COMMON/**** THIS SECTION FOR FOURIER TRANSFORM METHOD FOR RANGE ********

00021 COMMON/AMULT,ALOG(10000000000),ALOG012.)

00022 COMMON/IF(ALS(AMULT-10000000000.-100000000000.)GO TO 1000

00023 COMMON/N2=IFIX(AMULT+01)

00024 COMMON/N2=IFIX(AMULT+1)

00025 COMMON/TN=N2,THE NUMBER OF POINTS IN TRANSFORM

00026 COMMON/**** ZERO OUT CLUTA AND CLUTP ARRAYS FOR LATER USE ********

00027 COMMON/DO 510 K=1,512

00028 COMMON/CLUTA(K)=0

00029 COMMON/CLUTP(K)=0

00030 COMMON/CONTINUE

00031 COMMON/**** FIND SCALE FACTOR ********

00032 COMMON/AMNY=0

00033 COMMON/DO 590 K=1,NPOINT

00034 COMMON/AMNP=10**(FLOAT(OBJA(K))*05)/10.

00035 COMMON/AMNY=AMNP

00036 COMMON/CONTINUE

00037 COMMON/AMNY *(AMX*(FLOAT(NPOINT))

00038 COMMON/SCALE=52676/015

00039 COMMON/TYPE=1.

00040 COMMON/TYPE=S SCALE

00041 COMMON/DO 600 K=1,NPOINT

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00056 PHASE=FLOAT(OBJA(K)) * 256/F,180.

00057 AMBD=FLOAT(OBJA(K)) * 05.
*** REUSE CLUTA AND CLUTP ARRAYS FOR FOURIER TRANSFORM ***

```
0045 CLUTR(A)=IFIX(AM)
0046 CLUTP(A)=IFIX(AM)
0047 600 CONTINUE
0048 CALL PRT(TMPN,CLUTA,CLUTP,1,ISCALE)
0049 CALL PRTP(TMPN,CLUTA,CLUTP,PUP)
0050 ALIAS(C/(A+((FEND-FSTART)/FLOAT(N)+1),EP)
0051 RES=C/((FEND-FSTART)/2 + 1)/EP)
0052 WRITE(IUNIT,90)ALIAS,RES
```

*** FIND MAXIMUM ENERGY POINT AND RANGE ***

```
0053 AMMAX=AM
0054 DO 900 K=1,N/2
0055 IF (AMMAX=AM(K)) 750,750,800
0056 750 AMMAX=AM(K)
0057 PHAX=PH
0058 800 CONTINUE
0059 DISTP=PHAX
0060 1000 RETURN
0061 900 FORMAT(**** ENTER THE DISTANCE TO THE OBJECT IN METERS. ****)
0062 901 FORMAT(**** ALIASING RANGE (METERS): 1/IP015 7)
0063 END
```

**FORTRAN IV STORAGE MAP FOR PROGRAM UNIT RANGE**

LOCAL VARIABLES. PSECT DATA. SIZE = 004156 ( 1079 WORDS)

<table>
<thead>
<tr>
<th>NAME</th>
<th>TYPE</th>
<th>OFFSET</th>
<th>NAME</th>
<th>TYPE</th>
<th>OFFSET</th>
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<tbody>
<tr>
<td>ALIAS</td>
<td>R4</td>
<td>00410A</td>
<td>AM</td>
<td>R4</td>
<td>004064</td>
<td>AMDB</td>
<td>R4</td>
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<td>AM</td>
<td>R4</td>
<td>004074</td>
<td>AMP</td>
<td>R4</td>
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<td>AMAX</td>
<td>R4</td>
<td>004114</td>
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<td>AMP</td>
<td>R4</td>
<td>004070</td>
<td>AMUL</td>
<td>R4</td>
<td>004030</td>
<td>AMI</td>
<td>R4</td>
<td>004040</td>
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<tr>
<td>C</td>
<td>R4</td>
<td>004090</td>
<td>IERROR</td>
<td>I+2</td>
<td>004100</td>
<td>ISCALE</td>
<td>I+2</td>
<td>004102</td>
</tr>
<tr>
<td>I</td>
<td>1+2</td>
<td>004036</td>
<td>PHMAX</td>
<td>I+2</td>
<td>004120</td>
<td>N</td>
<td>I+2</td>
<td>004034</td>
</tr>
<tr>
<td>PHASE</td>
<td>R4</td>
<td>004054</td>
<td>PI</td>
<td>R4</td>
<td>004004</td>
<td>RES</td>
<td>R4</td>
<td>004110</td>
</tr>
<tr>
<td>SCALE</td>
<td>R4</td>
<td>004050</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

**COMMON BLOCK /RANGE1/. SIZE = 000010 ( 4 WORDS)**

<table>
<thead>
<tr>
<th>NAME</th>
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<th>OFFSET</th>
<th>NAME</th>
<th>TYPE</th>
<th>OFFSET</th>
</tr>
</thead>
</table>

**COMMON BLOCK /OBJ/. SIZE = 004002 (1025 WORDS)**

<table>
<thead>
<tr>
<th>NAME</th>
<th>TYPE</th>
<th>OFFSET</th>
<th>NAME</th>
<th>TYPE</th>
<th>OFFSET</th>
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</thead>
</table>

**COMMON BLOCK /RANGE1/. SIZE = 000010 ( 4 WORDS)**

<table>
<thead>
<tr>
<th>NAME</th>
<th>TYPE</th>
<th>OFFSET</th>
<th>NAME</th>
<th>TYPE</th>
<th>OFFSET</th>
</tr>
</thead>
</table>

**COMMON BLOCK /OBJ/. SIZE = 004002 (1025 WORDS)**

| NAME | TYPE | OFFSET | NAME | TYPE | OFFSET |
0099 WRITE(UNIT=96)
0100 DO 410 I=1,NPOINT
0101 IND+1
0102 AMPLI=FLOAT(OBJ.VK(I))*0.05
0103 PHASE=FLOAT(OBJ.WK(I))/25
0104 FREQ=START+FLOAT(IND-1)*STEP
0105 WRITE(UNIT=97,96) FREQ,AMPLI,PHASE
0106 CONTINUE
0107 CONTINUE

THIS SECTION WILL STORE THE RANGE CORRECTED DATA

0111 TYPE 991
0112 ACCEPT 1000.A
0113 IF (A.EQ. 'N') GO TO 500
0114 TYPE 990
0115 CALL ASSST(I20,-1,'NEW', 'NC')
0116 WRITE(20,4)START
0117 WRITE(20,5)END
0118 WRITE(20,6)NPOINT
0119 DO 460 I=1,NPOINT
0120 WRITE(20,7)OBJ.VK(I),OBJ.WK(I)
0121 CONTINUE
0122 CALL CLOSE(20)

THIS SECTION WILL DISPLAY THE DATA

0131 500 CONTINUE
0132 CONTINUE

FORMAT STATEMENTS

0133 900 FORMAT('ENTER THE FILE NAME FOR THE RANGE

[CORRECTED DATA]')
0134 901 FORMAT('ENTER THE FILE NAME FOR THE CORRECTED DATA')
0135 902 FORMAT('DO YOU WANT TO STORE THE CORRECTED DATA (Y OR N)')
0136 903 FORMAT('DO YOU WANT TO STORE THE RANGE CORRECTED DATA (Y OR N)')
0137 904 FORMAT('THIS SECTION WILL GENERATE CORRECTED SPHERE DATA

FROM EXPERIMENTAL DATA')
0138 905 FORMAT('PRINT THE UNCORRECTED DATA (Y OR N)')

SOFTWARE

0139 914 FORMAT('ENTER THE RANGE CORRECTION FLAG')
0140 915 FORMAT('DIRECT THREE MEASUREMENTS')
0141 916 FORMAT('PRINT SPHERE CORRECTED FOR SYSTEM RESPONSE

FOR 1 OR N')
0142 917 FORMAT('TRANSFER CHARACTERISTIC OF SYSTEM **

**********')
0143 918 FORMAT('********** SYSTEM ATTITUDE **********')
0144 919 FORMAT('********** END OF PROGRAM **********')
0145 END

LOCAL VARIABLES. PSET DATA. SIZE = 00010 ( 33 WORDS)

NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
A 14* 000036 AMPLI R4 1 000046 FREQ R4 2 000056
IND 18 000062 K 18 000044 PHASE R4 1 000052
STEP R4 1 000040

COMMON BLOCK/RANGE1/. SIZE = 000010 ( 4 WORDS)

NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
D15T R4 1 000000 IRFLAG 18 1 000004 UNIT 18 1 000006

COMMON BLOCK/OBJ/. SIZE = 000102 ( 1025 WORDS)

NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
OBJ.A 18 1 000000 OBJ.P 18 1 002000 NSAMP 1 18 1 004000

COMMON BLOCK/SYSTA/. SIZE = 000102 ( 1025 WORDS)

NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
TRAN 18 1 000000 TRANP 18 1 002000 CLU1A 1 18 1 004000
CLU1P 18 1 004000 FSTART R4 1 001000 FEND R4 1 001000

LOCAL AND COMMON ARRAYS

NAME TYPE SECTION OFFSET SIZE DIMENSIONS
CLU1A 1 18 004000 002000 ( 512 ) ( 512 )
CLU1P 1 18 004000 002000 ( 512 ) ( 512 )
OBJ.A 1 18 000000 002000 ( 512 ) ( 512 )
OBJ.P 1 18 000000 002000 ( 512 ) ( 512 )
CLU1A 1 18 000000 002000 ( 512 ) ( 512 )
CLU1P 1 18 002000 002000 ( 512 ) ( 512 )

SUBROUTINES, FUNCTIONS, STATEMENT AND PROCESSOR-DEFINED FUNCTIONS

NAME TYPE NAME TYPE NAME TYPE NAME TYPE NAME TYPE
ASSIGN R4 CLOSE R4 CORREC R4 FLOAT R4 RANCOR R4
RANG 19 R4 SPMAT R4 SNEEP R4 SYS1 R4
FORTRAN IV 2-1

SUBROUTINE SYS1

VERSION 1.0 29-NOV-79

THIS SUBROUTINE WILL READ IN THE SYSTEM RESPONSE
FILES AND PLACE THEM IN A COMMON BLOCK TO BE PASSED TO OTHER
Routines

COMMON SYSTA, TRANP, CLUTA, CLUTP, FSTART, FEND, NPPOINT

BYTE C

INTEGER TRANP(512), CLUTP(512), CLUTA(512), NPPOINT

TYPE 900

TYPE *, 'OLD OR NEW DATA (Y=NEW, 0=OLD)'

ACCEPT +, FLAG

IF (FLAG) 50, 10

TYPE *, 'ENTER THE STARTING FREQ IN GHI:

ACCEPT +, FSTART

TYPE *, 'ENTER THE ENDING FREQ IN GHI:

ACCEPT +, FEND

TYPE *, 'ENTER THE NUMBER OF FREQ. POINTS:

ACCEPT +, NPPOINT

TYPE *, 'ENTER THE NUMBER OF SAMPLES AT EACH FREQ.:

ACCEPT +, NSAMP2

TYPE *, 'SET UP REFLICTING PLANE FOR TRANSFER FUNCTION MEASUREMENT

PAUSE '***** HIT RETURN TO PROCEED *****'

CALL SWAT(ITRANP, TRANP, FSTART, FEND, NPPOINT, NSAMP2)

TYPE *, 'SET UP FOR CLUTTER MEASUREMENT

PAUSE '***** HIT RETURN TO PROCEED *****'

CALL SWAT(CLUTA, CLUTP, FSTART, FEND, NPPOINT)

TYPE *, 'STOWE DATA ON DISC ? Y OR N`

ACCEPT 900, C

IF (C EQ 'Y') GOTO 300

TYPE 901

CALL ASSN(I2, =), 'NEW', 'NC', 1, 1)

WRITE(I2, =), FSTART

WRITE(I2, =), FEND

WRITE(I2, =), NPPOINT

DO 20 P = 1, NPPOINT

WRITE(I2, =), TRANP(K)

WRITE(I2, =), CLUTP(K)

CONTINUE

CALL CLOSE(I2)

TYPE 902

CALL ASSN(I2, =), 'NEW', 'NC', 1, 1)

WRITE(I2, =), FSTART

WRITE(I2, =), FEND

WRITE(I2, =), NPPOINT

DO 40 P = 1, NPPOINT

WRITE(I2, =), CLUTA(K)

WRITE(I2, =), CLUTP(K)

CONTINUE

CALL CLOSE(I2)

DO TO 200

0049 CALL ASSIGN(I2, =), 'OLD', 'NC', 1, 1)

0050 READ(I2, =), FSTART

0051 READ(I2, =), FEND

0052 READ(I2, =), NPPOINT

0053 DO 100 K = 1, NPPOINT

0054 READ(I2, =), TRANP(K)

0055 READ(I2, =), TRANP(K)

0056 CONTINUE

0057 CALL CLOSE(I2)

0058 TYPE 902

0059 CALL ASSIGN(I2, =), 'OLD', 'NC', 1, 1)

0060 READ(I2, =), FSTART

0061 READ(I2, =), FEND

0062 READ(I2, =), NPPOINT

0063 DO 100 K = 1, NPPOINT

0064 READ(I2, =), CLUTA(K)

0065 READ(I2, =), CLUTP(K)

0066 CONTINUE

0067 CALL CLOSE(I2)

0068 RETURN

0069 FORMAT (A1)

0070 FORMAT (A1, '**** SUBROUTINE SYSNP OBTAINS THE SYSTEM RESPONSE

FILES *****

0071 901 FORMAT (A1, 'ENTER THE TRANSFER FUNCTION FILE NAME: '),

0072 902 FORMAT (A1, 'ENTER THE ANTENNA SYSTEM FUNCTION FILE NAME: '),

0073 END

LOCAL VARIABLES: PSECT $DATA, SIZE = 000044 ( 1024 WORDS)

NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET

C L=0 000022 FLAG R=4 000004 K I=2 000032

NSAMP2 I=2 000030

COMMON BLOCK /SYSTA / SIZE = 010012 ( 2053 WORDS)

NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET

TRANP I=2 000000 TRAP I=2 000000 CLUTA I=2 000000

CLUTP I=2 000000 FSTART R=4 010000 FEND R=4 010004

NPPOINT I=2 010010

LOCAL AND COMMON ARRAYS

NAME TYPE SECTION OFFSET ----- SIZE ----- DIMENSIONS

CLUTA I=2 SYSTA 000000 002000 ( 512 ) (512)

CLUTP I=2 SYSTA 000000 002000 ( 512 ) (512)

TRANP I=2 SYSTA 002000 002000 ( 512 ) (512)

TRAP I=2 SYSTA 002000 002000 ( 512 ) (512)

SUBROUTINES, FUNCTIONS, STATEMENT AND PROCESSOR-DEFINED FUNCTIONS.

NAME TYPE NAME TYPE NAME TYPE NAME TYPE NAME TYPE

ASSGN R=4 CLOSE R=4 , SWAT R=4
0090 WRITE(UNIT,907),X,FREQ,AMPL,PHASE

0091 CONTINUE

C C C

THIS SECTION WILL STORE THE RANGE CORRECTED DATA

C C C

0092 470 TYPE '01'

0093 ACCEPT 10000.A

0094 IF (A.EQ. 'N') GO TO 500

0095 TYPE 'R4'

0096 CALL ASSIGN(20,..,NEW,'NC')

0097 WRITE(20,*)FSTART

0098 WRITE(20,*)FEND

0099 WRITE(20,*)IP

0100 NO 400=1,1.POINT

0101 WRITE(20,*OBJ,W(K)

0102 CONTINUE

0103 CALL CLOSE(20)

C C C

THIS SECTION WILL DISPLAY THE DATA

C C C

0104 500 CONTINUE

C C C

FORMAT STATEMENTS

C C C

0107 900 FORMAT('ENTER THE FILE NAME FOR THE RANGE

0108 9-1 FORMATS FOR THE FILE NAME FOR THE CORRECTED DATA.','

0109 902 FORMAT('DO YOU WANT TO STORE THE CORRECTED DATA? Y OR N)

0110 900 FORMAT('**** PROGRAM SPHERE ****')

0111 901 FORMAT('DO YOU WANT TO STORE THE CORRECTED DATA

0112 902 FORMAT(**** THIS SECTION WILL GENERATE CORRECTED SPHERE DATA

0113 903 FORMAT('PRINT THE UNCORRECTED DATA (Y OR N)')

0114 904 FORMAT(**** UNCORRECTED SPHERE DATA ****)

0115 905 FORMAT('STARTING FREQUENCY GHz',1P015.7/15X,FREQUENCY STEP GHz,

0116 906 FORMAT('ENDING FREQUENCY GHz',1P015.7/15X,FREQUENCY STEP GHz,

0117 907 FORMAT(7.5X,1P015.7,3D15.7,1P015.7)

0118 909 FORMAT(**** CORRECTED SPHERE DATA

0119 911 FORMAT(**** CORRECTED SPHERE DATA CORRECTED

0120 912 FORMAT(*LATE RANGE ****)

0121 913 FORMAT(*ENTER LOGICAL UNIT NUMBER FOR OUTPUT (7-)

0122 914 FORMAT(*CALCULATED RANGE TO THE TARGET*1P015.7,

0123 915 FORMAT(*PRINT SPHERE DATA CORRECTED FOR SYSTEM RESPONSE

0124 916 FORMAT(*PRINT SPHERE DATA CORRECTED FOR RANGE (Y OR N)

0125 917 FORMAT(**** TRANSFER CHARACTERISTIC OF SYSTEM ****)

0126 918 FORMAT(**** SYSTEM CLUTTER *********)

0127 1000 FORMAT(****

0128 STOP '****** END OF PROGRAM ******'

0129 END

LOCAL VARIABLES, PSECT DATA, SIZE = 000074 ( 30 WORDS)

NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET

A L41 000032 AMPLIT R44 000042 FREQ R44 000052

IND1 I=2 000006 K I=2 000040 PHASE R44 000066

STEP R44 000034

COMMON BLOCK /RANGE1/, SIZE = 000010 ( 5 WORDS)

NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET

DIST R44 000000 IFLAG I=2 000004 INI3T I=2 000056

COMMON BLOCK /OBJ / SIZE = 004002 ( 1025 WORDS)

NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET

OBJA I=2 000000 OBJ B I=2 002000 NSAMP2 I=2 004000

COMMON BLOCK /SYS/T1, SIZE = 010012 ( 2053 WORDS)

NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET

TRANS I=2 000000 TRAMP I=2 002000 CLUTA I=2 1=000000

CLUTP I=2 006000 FSTART R44 010000 FEND R44 010004

NPOINT I=2 010010

LOCAL AND COMMON ARRAYS:

NAME TYPE SECTION OFFSET SIZE DIMENSIONS

CLUTA I=2 SYS T 000000 002000 I=2 000000 ( 512 ) (512)

CLUTP I=2 SYS T 000000 002000 I=2 000000 ( 512 ) (512)

OBJA I=2 OBJ 000000 002000 I=2 000000 ( 512 ) (512)

OBJ B I=2 OBJ 002000 002000 I=2 000000 ( 512 ) (512)

TRANS I=2 SYS T 000000 002000 I=2 000000 ( 512 ) (512)

TRAMP I=2 SYS T 000000 002000 I=2 000000 ( 512 ) (512)

SUBROUTINES, FUNCTIONS, STATEMENT AND PROCESSOR-DEFINED FUNCTIONS

NAME TYPE NAME TYPE NAME TYPE NAME TYPE

ASSIGN R44 CLOSE R44 CORDET R44 FLOAT R44 RANCOR R44

RANGE R44 SPHAT R44 SLEEP R44 SYS2 R44
FORTRAN IV/VS 1-1 FRI 30-NOV-79 00 20 30 PAGE 001
0001 SUBROUTINE SYS2
0002 VERSION 1 0 29-NOV-79
0003
0004 THIS SUBROUTINE WILL READ IN THE SYSTEM RESPONSE FILES
0005 AND PLACE THEM IN A COMMON BLOCK TO BE PASSED TO OTHER
0006 ROUTINES
0007
0008 COMMON/SYST/TRAN, TRNP, CLUTA, CLUTB, FSTART, FEND, NPOINT
0009
0010 TYPE 900
0011 TYPE = 'OLD OR NEW DATA (1=NEW,0=OLD)'
0012 ACCEPT *FLAG
0013 IF (FLAG) S= 50, 10
0014 10 TYPE = 'ENTER THE STARTING FREQ IN GHZ: '
0015 ACCEPT *FSTART
0016 TYPE = 'ENTER THE ENDING FREQ IN GHZ: '
0017 ACCEPT *FEND
0018 TYPE = 'ENTER THE NUMBER OF FREQ. POINTS: '
0019 ACCEPT *NPOINT
0020 TYPE = 'ENTER THE NUMBER OF SAMPLES AT EACH FREQ: '
0021 ACCEPT *NSAMP2
0022 TYPE = 'SET UP REFLECTING PLANE FOR TRANSFER FUNCTION MEASUREMENT'
0023 PAUSE **** HIT RETURN TO PROCEED *****
0024 CALL SNDAT(TRAN, TRNP, FSTART, FEND, NPOINT, NSAMP2)
0025 TYPE = 'STORE DATA ON DISC (Y OR N)'
0026 ACCEPT 800, C
0027 IF (C .EQ. 'N') GO TO 300
0028 TYPE 901
0029 CALL ASSIGN(12, 1, 'NEW', 'NC', 1, 1)
0030 WRITE(12, 20) FSTART
0031 WRITE(12, 20) FEND
0032 DO 30 N=1,NPOINT
0033 WRITE(12, 20) TRAN(N)
0034 WRITE(12, 20) TRNP(N)
0035 CONTINUE
0036 CALL CLOSE(12)
0037 GO TO 500
0038 TYPE 901
0039 CALL ASSIGN(12, 1, 'OLD', 'NC', 1, 1)
0040 READ(12, 20) FSTART
0041 READ(12, 20) FEND
0042 READ(12, 20) NPOINT
0043 DO 50 N=1,NPOINT
0044 READ(12, 20) TRAN(N)
0045 READ(12, 20) TRNP(N)
0046 CONTINUE
0047 CALL CLOSE(12)
0048 RETURN
0049 END

LOCAL VARIABLES
NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
C L=1 000012 FLAG R=4 000014 K I=2 000022
NSAMP2 I=2 000020

COMMON BLOCK /SYST/, SIZE = 010012 (2053 WORDS)
NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
TRAN I=2 000000 TRNP I=2 000000 CLUTA I=2 000000
CLUTB I=2 000000 FSTART R=4 010000 FEND R=4 010000
NPOINT I=2 010010

LOCAL AND COMMON ARRAYS:
NAME TYPE SECTION OFFSET ----- SIZE----- DIMENSIONS
CLUTA I=2 SYSTA 004000 002000 ( 512 ) ( 512 )
CLUTB I=2 SYSTA 006000 002000 ( 512 ) ( 512 )
TRAN I=2 SYSTA 000000 002000 ( 512 ) ( 512 )
TRNP I=2 SYSTA 002000 002000 ( 512 ) ( 512 )

SUBROUTINES: FUNCTIONS, STATEMENT AND PROCESSOR-DEFINED FUNCTIONS
NAME TYPE NAME TYPE NAME TYPE NAME TYPE
ASSIGN R=4 CLOSE R=4 SNDAT R=4

0049 901 FORMAT(//"", 'ENTER THE TRANSFER FUNCTION FILE NAME. '"
0050 901

THIS SUBROUTINE WILL TAKE THE DATA THAT WAS TAKEN FROM
SPINDAY AND CORRECT IT WITH THE DATA FROM SUBROUTINE
SYSSINP. WHICH IS THE SYSTEM RESPONSE.

VERSION 1.0 30-NOV-79
COMM!/OBJ/OBJA, OBJP, NSAMP2
COMM!/SYSSYSA,TRAN, AFP, CLUTA, CLUTP, FSTART, FEND, NPOINT

*** SUBTRACT ANTENNA CLUTTER FROM OBJECT DATA. THIS CLUTTER DATA
MUST NOT!!! BE CORRECTED FOR THE SYSTEM TRANSFER FUNCTION
*** THE NEXT STEP IS TO DIVIDE BY THE TRANSFER CHARACTERISTIC
OF THE SYSTEM IN ARRAYS TRAN(AMPITUDE) AND TRAPH(PHASE).

PI=3.1415926
DEO=P1/180
DO 100 K=1,NPOINT
TDBAMP=FLOAT(TRAN(K))*05
TPHAMP=FLOAT(TRAPH(K))*254E0
ODBAMP=FLOAT(OBJP(K))*05
0BPH=FLOAT(OBJP(K))*254E0

*** TRANSFER CHARACTERISTIC IN DB:
TRAPH-PHASE OF TRANSFER CHARACTERISTIC IN RADIANS

*** DIVIDE BY TRANSFER CHARACTERISTIC

ADDRESS=OBBAMP-TDBAMP
014 IF(PRES=10) PRES=RES-2+PI
017 IF(PRES LT -PI) PRES=PRES+2+PI

*** REPLACE DATA INTO INTEGER ARRAY

OBJA(K)=IFIX(20+ADDRESS)
OBJP(K)=IFIX(ADDRESS/DEO+40)
100 CONTINUE
RETURN

LOCAL VARIABLES: PSECT #DATA. SIZE = 010040 ( 2064. WORDS)

NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
FEND R4 000006 FREQ R4 010020 FSTART R4 0 000004
IA 1+2 010032 IP 1+2 010034 K 1+2 010024
NPOINT 1+2 000010 NSAMP2 1+2 & 000012 STEP R4 0 010020

LOCAL AND COMMON ARRAYS:

NAME TYPE SECTION OFFSET ---- SIZE ----- DIMENSIONS
CLUTA 1+2 & DATA 004014 002000 (512) (512)
CLUTP 1+2 & DATA 006014 002000 (512) (512)
OBJA 1+2 & DATA 000000 002000 (512) (512)
OBJP 1+2 & DATA 000000 002000 (512) (512)
TRAN 1+2 & DATA 000014 002000 (512) (512)
TRAPH 1+2 & DATA 002014 002000 (512) (512)

SUBROUTINES, FUNCTIONS, STATEMENT AND PROCESSOR-DEFINED FUNCTIONS.

NAME TYPE NAME TYPE NAME TYPE NAME TYPE
FLOAT R4 PHAMP2 R4 SHEEP R4
SUBROUTINE PHMNP2(INAMP, IAMPHASE, NUM)
C
THIS ROUTINE WILL TAKE NUM READINGS FROM A/D CHANNELS
C
0 AND 1 0<PHASE 1>AMPLITUDE

0002 AMP=0
0003 IFAMP=0
0004 DO 5 J=1,200
0005 9 CONTINUE
0006 DO 10 F=1,NUM
0007 IFAMP-1=10
0008 IFAMP-2=10
0009 IFAMP-2=10
0010 AMP=AMP+FLOAT(INAMP)
0011 IAMP=IAMP+FLOAT(INAMP)
0012 DO 20 J=1,20
0013 20 CONTINUE
0014 10 CONTINUE
0015 AMP=AMP+FLOAT(FLOAT(NUM))
0016 RETURN
0017 END

FORTRAN IV STORAGE MAP FOR PROGRAM UNIT PHMNP2
LOCAL VARIABLES. . .PESCT #DATA. SIZE = 000050 ( 20 WORDS)
NAME TYPE NAME TYPE OFFSET NAME TYPE NAME TYPE OFFSET
AMP R4 000006 IAMP I+2 @ 000000 IAMP I+2 000022
IAMPHASE I+2 000002 IAMPHAS I+2 000024 J I+2 000016
K I+2 000020 NUM I+2 @ 000004 PHASH R4 000012

SUBROUTINES, FUNCTIONS, STATEMENT AND PROCESSOR-DEFINED FUNCTIONS.
NAME TYPE NAME TYPE NAME TYPE NAME TYPE
FLOAT R4 IADIMP I+2 IFIX I+2

FORTRAN IV VO2 1-1 FRI 24-AUG-79 00:19:16 PAGE 001
0001 SUBROUTINE SHEEP(MODE,FREQ, IBAND, IEEE0)
C
MODE IS THE SHEEPER MODE 1-9. MODE 1 IS DESELECT MODE FOR SETI
C
THE CHEM FREQUENCY. OTHER MODES ARE OUTLINED IN THE SHEEPER IEEE
C
MANUAL.
C
C IF MODE=10 THEN THE PROGRAM WILL RESET THE INTERFACE
C
C IBAND IF IBAND=4 THEN FULL SHEEP 2-16 OR OTHERWISE THE
C PROGRAM WILL COMPUTE THE NECESSARY BAND
C
C INITIALIZE IBAND2 AND MODE2 TO ZERO IN THE MAIN LINE

0002 BYTE CMD(7),MD(3),BD(3)
0003 DATA CMD(7)/15/,MD(3)/15/,BD(3)/15/
0004 DATA CMD(1)/'V'/,MD(1)/'M'/,BD(1)/'B'/
0005 IF (MODE=10) 3,2,3
0006 2 CALL IBIPFC
0007 3 IF (MODE-MODE1) 5,10,5
0008 5 ENCODE(1,1000,MD(2)) MODE
0010 CALL IBIFPC
0011 CALL IBSEN
0012 CALL IBSEND(MD, IEEE0)
0013 DO 9 Iter=1,1500 TIME DELAYS TO CHARGE MD 13 3 MS
0014 9 CONTINUE
0015 10 MODE1=MODE
0016 IF (IBAND=14) 25,20,25 IF IBAND IS EQUAL TO 4 THEN TRANS
0017 20 IBAND=4
0018 25 GO TO 35
0019 35 IF (FREQ GT 2.00) AND (FREQ LT 6.051) IBAND=1
0021 IF (FREQ GT 6.051) AND (FREQ LT 12.41) IBAND=2
0023 IF (FREQ GT 12.41) AND (FREQ LT 18.01) IBAND=3
0025 35 IF (IBAND2-IBAND1) 36,38,36
0026 36 ENCODE(1,1000,MD(2)) IBAND1
0027 CALL IBSEND(MD, IEEE0)
0028 IBAND2=IBAND1
0029 30 GOTO 46,50,60,70IBAND1
0030 40 BL2=00022
0031 BL1=4 19734E-04
0032 BL1=4 27261E-10
0033 00 TO 80
0034 50 BL1=5 99786
0035 005 38039E-04
0036 BL2=2 03999E-10
0037 007 GO TO 80
0038 60 BL4=12 0018
0039 BL1=5 98325E-04
0040 BL2=4 48486E-11
0041 00 TO 80
0042 70 BL1=1 99686
0043 0021 99999E-03
0044 004 B2=4 01267E-11

FORTRAN IV VO2 1-1 FRI 24-AUG-79 00:19:52 PAGE 002
C
C THESE CONSTANTS WERE DERIVED USING PROGRAM CALAB BAS ON
C AIC-24-1979
FORTRAN IV STORAGE MAP FOR PROGRAM UNIT 309

<table>
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<th>NAME</th>
<th>TYPE</th>
<th>OFFSET</th>
<th>NAME</th>
<th>TYPE</th>
<th>OFFSET</th>
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<tr>
<td>BO</td>
<td>R*4</td>
<td>000036</td>
<td>B1</td>
<td>R*4</td>
<td>000042</td>
<td>B2</td>
<td>R*4</td>
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<td>FRED</td>
<td>R*4</td>
<td>000002</td>
<td>IBAND</td>
<td>I*2</td>
<td>000004</td>
<td>IBAND1</td>
<td>I*2</td>
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<tr>
<td>IBEH</td>
<td>I*2</td>
<td>000034</td>
<td>IEEEND</td>
<td>I*2</td>
<td>000006</td>
<td>ITER</td>
<td>I*2</td>
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<td>I*2</td>
<td>000052</td>
<td>MODE</td>
<td>I*2</td>
<td>000000</td>
<td>MODE1</td>
<td>I*2</td>
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LOCAL AND COMMON ARRAYS:

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<tr>
<th>NAME</th>
<th>TYPE</th>
<th>SECTION OFFSET</th>
<th>SIZE</th>
<th>DIMENSIONS</th>
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<tbody>
<tr>
<td>END</td>
<td>L+1</td>
<td>8DATA</td>
<td>000022</td>
<td>(2) (3)</td>
</tr>
<tr>
<td>CMD</td>
<td>L+1</td>
<td>8DATA</td>
<td>000010</td>
<td>(4) (7)</td>
</tr>
<tr>
<td>MD</td>
<td>L+1</td>
<td>8DATA</td>
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<td>(2) (3)</td>
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SUBROUTINES, FUNCTIONS, STATEMENT AND PROCESSOR-DEFINED FUNCTIONS:

<table>
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<tr>
<th>NAME</th>
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<th>NAME</th>
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<tr>
<td>IBIFF</td>
<td>I*2</td>
<td>IMEN</td>
<td>I*2</td>
<td>IBEND</td>
<td>I*2</td>
<td>IFIX</td>
<td>I*2</td>
</tr>
</tbody>
</table>
PROGRAM BISCAT

COMMON /SCT/THETA, FPSI, PSI
COMMON SO1, SO2, SC1, SC2, KAS, KAE, KPI, PSI, THETA
COMMON SO1, SO2, SC1, SC2, KA, THETA
REAL KA, MAGSO, S12, KAS, KAE, PSI, THETA
BYTE ANSI
DATA C/299725E+10/

C

TYPE 0, 'ENTER SPHERE RADIUS (A) (CRL)'
ACCEPT 0, A
DATA 0, 'ENTER STARTING FREQ (GHz)'
ACCEPT 0, FSTART
DATA 0, 'ENTER ENDING FREQ (GHz)'
ACCEPT 0, FEND
DATA 0, 'SCT: H', 1/10E+9/C
KAS=KAS+KAS
KAE=KAE+KAE
THETA=THETA+THETA
DATA 0, 'ENTER SCATTERING ANGLE THETA (DEGREES)'
ACCEPT 0, THETA
DATA 0, 'SCT: H', 1/10E+22
PSI=PSI+SCT
DATA 0, 'ENTER POLARIZATION SCATTERING ANGLE PSI (DEGREES)'
ACCEPT 0, PSI
DATA 0, 'SCT: H', 1/10E+22
THETA=THETA+THETA
DATA 0, 'SCT: H', 1/10E+22
PSI=PSI+SCT
DATA 0, 'IN WHICH POLARIZATION CALCULATE FIELD (0=THETA, 1=PSI)'
ACCEPT 0, IPOL
DATA 0, 'ENTER NUMBER OF POINTS'
ACCEPT 0, NUMPTS
DATA 0, 'SCT: H', 1/10E+22
WRITE (UNIT: 8001, FSTART, KAS, KAE, NUMPTS, THETA=180/3.1415926)
DATA 0, 'SCT: H', 1/10E+22
IF (IPOL EQ 0) WRITE (UNIT: 810)
DATA 0, 'SCT: H', 1/10E+22
WRITE (UNIT: 811)
DATA 0, 'SCT: H', 1/10E+22

C

TYPE 0, 'BEGIN CALL TO BIFSLCA'
CALL BISCAT
DATA 0, 'SCT: H', 1/10E+22
IF (IPOL EQ 0) F=THETA
DATA 0, 'SCT: H', 1/10E+22
IF (IPOL EQ 1) F=PSI
DATA 0, 'SCT: H', 1/10E+22
RE=REAL(F)
DATA 0, 'SCT: H', 1/10E+22
CP=SIN(MAG)
DATA 0, 'SCT: H', 1/10E+22
AMP=AMPS
cREAL(MAG)+180/3.1415926)
DATA 0, 'SCT: H', 1/10E+22
MAGN=AMP
DATA 0, 'SCT: H', 1/10E+22
ANGLE=MAG
DATA 0, 'SCT: H', 1/10E+22
IF (AMP EQ 0 OR AMP EQ 1) AMPL=AMP
DATA 0, 'SCT: H', 1/10E+22
WRITE (UNIT: 801, FREQ, KA, A, 10+100010(MAGN), AND, FREQ=FRED+FRE)
DATA 0, 'SCT: H', 1/10E+22
P=AMP+FRE
DATA 0, 'SCT: H', 1/10E+22
CONTINUE
DATA 0, 'SCT: H', 1/10E+22

END

LOCAL VARIABLES: SIZE = 0.01034 (1024 WORDS)
NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
A R4 0.0026 AMP R4 0.0074 ANG R4 0.0110
ANS L4 0.0024 C R4 0.0000 CPUs R4 0.0120
F C 0.0004 FREQ R4 0.0026 FREDD R4 0.0150
FSTART R4 0.0032 I 1 2 0.0027 IPOL 1 2 0.0120
UNIT I 2 0.0052 KAE R4 0.0020 KAS R4 0.0140
N I 2 0.0072 NUMPTS 1 2 0.0050 REA R4 0.0160
STEPF R4 0.0064 STEP 1 R4 0.0054 WAV R4 0.0242
COMMON BLOCK / SIZE = 0.00050 (20 WORDS)
NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
SO1 C 0.0000 SO2 C 0.00010 SCI C 0.0000
SC2 C 0.00030 KA R4 0.00040 THERA R4 0.00040
COMMON BLOCK / SIZE = 0.00024 (10 WORDS)
NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
THETA C 0.0000 FPSI C 0.00010 PSI R4 0.0020
LOCAL AND COMMON ARRAYS:
SUBROUTINE BSCAT

THIS SUBROUTINE WILL CALL SUBROUTINES BSCAT1-BSCAT4 FOR THE CALCULATION OF THE BISTATIC SCATTERING OF A PERFECTLY CONDUCTING SPHERE. IT WILL RETURN THE SCATTERING COEFFICIENT F AS A FUNCTION OF SCATTERING ANGLE THETA AND ANGLE PSI.

THE SCATTERED FIELD AMPLITUDE IN THE THETA AND PSI POLARIZATIONS ARE FTHTETA AND FPSI.

COMMON/SCF/FTHTETA, FPSI, PSI

COMMON S01, S02, SC1, SC2, KA, THETA

COMPLEX S01, S02, SC1, SC2, KA, THETA

COMPLEX BI, B2, B3, B4

REAL # KA, THETA

0007 IF (IYA GT 4) GO TO 100

0008 CALL BSCAT1

0009 FTHTETA=CO(SI)1*SC1

0011 FPSI=SIN(SI)1*SC2

0012 GO TO 1000

0013 100 IF (IYA GT 1) GO TO 200

0015 CALL BSCAT2

0016 FTHTETA=CO(SI)1*SC1

0017 FPSI=SIN(SI)1*SC2

0018 GO TO 1000

0019 200 IF (IYA GT 200) GO TO 300

0021 CALL BSCAT3

0022 BI=01*SC1

0023 B2=002*SC2

0024 FTHTETA=CO(SI)1*B1

0025 FPSI=SIN(SI)1*B2

0026 GO TO 1000

0027 300 CONTINUE

CALL BSCAT4

FTHTETA=CO(SI)1*SC1

FPSI=SIN(SI)1*SC2

GO TO 1000

RETURN

END

LOCAL VARIABLES: PSCL & DATA, SIZE = 000040 (16 WORDS)

NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET

B1 C=8 000000 B2 C=8 000010 B3 C=8 000020

B4 C=8 000030

COMMON BLOCK / SIZE = 000050 (20 WORDS)

NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET

S01 C=8 000000 S02 C=8 000010 SC1 C=8 000020

SC2 C=8 000030 KA R=4 000040 THETA R=4 000044

SUBROUTINES, FUNCTIONS, STATEMENT AND PROCESSOR-DEFINED FUNCTIONS.

NAME TYPE NAME TYPE NAME TYPE NAME TYPE NAME TYPE

COS R=4
FORTRAN IV/V2 1-1
0001 SUBROUTINE BSCAT
0002 COMMON S01, S02, S1, C1, SC2, K, THETA
0003 REAL K, THETA
0004
0005 T1 = 5.0*COS(THETA)
0006 T2 = (3.0/45.0)*COS(THETA) + (1.0/12.0)*COS(2*THETA) + K*A
0007 T3 = (1.0/12.0)*((180.0/67.0 + 1253.0/105.0)*COS(THETA) + 1157.0/63.0)*COS(2*THETA) + (1.0/3.0)*COS(4*THETA) + K*A
0008 T4 = (1.0/12.0)*((44*COS(THETA) + 1.0/5.0)*((1 + 2*COS(THETA)) + 1.0/2.0))
0009 SC1R = (1.0/3.0)*SC2
0010 SC1I = 4.0
0011 SC1 = Cmplx(SC1R, SC1I)
0012 C1 = 5.0*COS(THETA) + 1
0013 C2 = (3.0/45.0)*COS(THETA) + (1.0/12.0)*COS(2*THETA) + K*A
0014 C3 = (1.0/12.0)*((180.0/67.0 + 1253.0/105.0)*COS(THETA) + 1157.0/63.0)*COS(2*THETA) + (1.0/3.0)*COS(4*THETA) + K*A
0015 C4 = (1.0/12.0)*((44*COS(THETA) + 1.0/5.0)*((1 + 2*COS(THETA)) + 1.0/2.0))
0016 SC2R = (1.0/3.0)*SC1 + C2
0017 SC2I = 4.0
0018 SC2 = Cmplx(SC2R, SC2I)
0019 RETURN
0020 END

LOCAL VARIABLES: P, V, E, DATA, SIZE = 00010 ( 26 WORDS)
NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
C1 R4 000030 C2 R4 000034 C3 R4 000040
C4 R4 000044 SC1 R4 000024 SC1R R4 000020

FORTRAN IV/V2 1-1
0001 SUBROUTINE BSCAT
0002 COMMON S01, S02, S1, C1, SC2, K, THETA
0003 REAL K, THETA
0004
0005 T1 = 5.0*COS(THETA)
0006 T2 = (3.0/45.0)*COS(THETA) + (1.0/12.0)*COS(2*THETA) + K*A
0007 T3 = (1.0/12.0)*((180.0/67.0 + 1253.0/105.0)*COS(THETA) + 1157.0/63.0)*COS(2*THETA) + (1.0/3.0)*COS(4*THETA) + K*A
0008 T4 = (1.0/12.0)*((44*COS(THETA) + 1.0/5.0)*((1 + 2*COS(THETA)) + 1.0/2.0))
0009 SC1R = (1.0/3.0)*SC2
0010 SC1I = 4.0
0011 SC1 = Cmplx(SC1R, SC1I)
0012 C1 = 5.0*COS(THETA) + 1
0013 C2 = (3.0/45.0)*COS(THETA) + (1.0/12.0)*COS(2*THETA) + K*A
0014 C3 = (1.0/12.0)*((180.0/67.0 + 1253.0/105.0)*COS(THETA) + 1157.0/63.0)*COS(2*THETA) + (1.0/3.0)*COS(4*THETA) + K*A
0015 C4 = (1.0/12.0)*((44*COS(THETA) + 1.0/5.0)*((1 + 2*COS(THETA)) + 1.0/2.0))
0016 SC2R = (1.0/3.0)*SC1 + C2
0017 SC2I = 4.0
0018 SC2 = Cmplx(SC2R, SC2I)
0019 RETURN
0020 END

LOCAL VARIABLES: P, V, E, DATA, SIZE = 00010 ( 26 WORDS)
NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
C1 R4 000030 C2 R4 000034 C3 R4 000040
C4 R4 000044 SC1 R4 000024 SC1R R4 000020
### Local Variables

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<th>Size</th>
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<td>000000</td>
<td>000070</td>
<td>000006</td>
</tr>
<tr>
<td>CON</td>
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<td>CON2</td>
<td>C</td>
<td>000120</td>
<td>000300</td>
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<td>000650</td>
<td>000050</td>
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<tr>
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<td>C</td>
<td>000650</td>
<td>000700</td>
<td>000050</td>
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<tr>
<td>T6</td>
<td>C</td>
<td>000700</td>
<td>000750</td>
<td>000050</td>
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<td>R</td>
<td>000420</td>
<td>000470</td>
<td>000050</td>
</tr>
<tr>
<td>XT</td>
<td>C</td>
<td>000470</td>
<td>000520</td>
<td>000050</td>
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### COMMON BLOCK

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<th>Offset</th>
<th>Offset</th>
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<tbody>
<tr>
<td>T4+P2+C4-C6</td>
<td>C</td>
<td>00076</td>
<td>00076</td>
<td>000080</td>
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<tr>
<td>P2=173966/(X+5INT)</td>
<td>C</td>
<td>00077</td>
<td>00076</td>
<td>000080</td>
</tr>
<tr>
<td>T3=P2*(C4-C6)</td>
<td>C</td>
<td>00078</td>
<td>00077</td>
<td>000080</td>
</tr>
<tr>
<td>CONP=194877.470070(di)</td>
<td>C</td>
<td>00079</td>
<td>00078</td>
<td>000080</td>
</tr>
<tr>
<td>C15=164200+X*23+CON9</td>
<td>C</td>
<td>00080</td>
<td>00079</td>
<td>000080</td>
</tr>
<tr>
<td>T6=C15+1(C3+C13)-(C5*C14)</td>
<td>C</td>
<td>00081</td>
<td>00080</td>
<td>000080</td>
</tr>
<tr>
<td>SC2=C11*(T4+T5+T6)</td>
<td>C</td>
<td>00082</td>
<td>00081</td>
<td>000080</td>
</tr>
<tr>
<td>RETURN</td>
<td>C</td>
<td>00083</td>
<td>00082</td>
<td>000080</td>
</tr>
</tbody>
</table>

**SUBROUTINES, FUNCTIONS, STATEMENT AND PROCESSOR-DEFINED FUNCTIONS**

---

************** CALCULATE SECOND CREEPING WAVE TERM ************

| C1=C1 | C | 00090 | 00090 | 000050 |
| P2=339997/(X+5INT) | C | 00099 | 00099 | 000050 |
SUBROUTINE BSCAT

COMMON SO1, SO2, SC1, SC2, KA, THETA
COMMON S01, S02, SC1, SC2, CI

REAL KA, THETA

PI = 2.0*ACOS(THETA/2)
CI = CMPLX(1.0, -PI)
SC1 = - 5.0*ACOS(CI)
SC2 = SC1

RETURN
END

LOCAL VARIABLES: P and DATA. SIZE = 000024 (10 WORDS)

TYPE NAME OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
C1 C# 000000 P1 R4 000000

COMMON BLOCK / SIZE = 000050 (20 WORDS)

TYPE NAME OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
SO1 C# 000000 S02 C# 000010 SC1 C# 000020
SC2 C# 000030 KA R4 000040 THETA R4 000044

SUBROUTINES, FUNCTIONS, STATEMENT AND PROCESSOR-DEFINED UTILITIES

NAME TYPE NAME NAME NAME NAME TYPE NAME TYPE TYPE
CEXP C# CMPLX C# COS R4

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0001 C

0002 COMMON KAF
0003 COMMON KAF
0004 REAL KA, THETA
0005 BYTE DATA C/2, 897975E+10/
0006 C

0007 TYPE *, 'ENTER SPHERE RADIUS (A) (CM):'
0008 ACCEPT A
0009 ACCEPT, FSTART
0010 ACCEPT, FEND
0011 TYPE *, 'ENTER ENDING FREQ (GHZ):'
0012 ACCEPT, FEND
0013 MAV = 2.0 [1.15526 + 1.0049/C]
0014 KAF = FSTART*40
0015 KAF = FEND*40
0016 TYPE *, 'ENTER NUMBER OF POINTS'
0017 ACCEPT, NUMPTS
0018 TYPE *, 'ENTER LOGIC UNIT NUMBER FOR OUTPUT'
0019 ACCEPT, IUNIT
0020 WRITE (IUNIT, 0001) A, FSTART, KA, FEND, KAF, NUMPTS
0021 WRITE (IUNIT, 0011)
0022 C

0023 STEP = (KAF-KAS)/NUMPTS
0024 FREQ = FSTART
0025 FREQ = FEND-FSTART/NUMPTS
0026 DO 100 I = 1, NUMPTS
0027 N = I
0028 CALL CAT
0029 AMP = A ABS(F)
0030 REAL = REAL(F)
0031 CMPLX = CMPLX(F)
0032 ANG = ATAN2(REAL, CMPLX)*180/3.1415926
0033 MAG = AMP
0034 ANGLE = ANG
0035 WRITE (IUNIT, 0001) AMP, FREQ, KA, 10, 100001, AND
0036 WRITE (IUNIT, 0011)
0037 CONTINUE
0038 TYPE *, 'STORE DATA FOR DISPLAY (Y OR N)?'
0039 ACCEPT Y, N
0040 IF (ANS EQ 'Y') GO TO 1000
0041 TYPE *, 'ENTER THE NAME FOR DATA FILE:'
0042 CALL ASSIGN(120, 'NEW', 'NC', 1)
0043 WRITE (20, +) NUMPTS
0044 WRITE (20, +) FSTART
0045 WRITE (20, +) FEND
0046 WRITE (20, +) A
0047 DO 200 I = 1, NUMPTS
0048 N = I
0049 WRITE (20, +) AMP
0050 WRITE (20, +) MAG
0051 WRITE (20, +) ANGLE
0034 200 CONTINUE
0035 800 FORMAT(///' RADIUS='F15.7/' 'FSTART='F15.7/'
0036 1' ' START K=4,'F15.7/' 'FEND='F15.7/' ' END K=4,'F15.7/'
0037 2' ' MURPTS=.'E15///)
0038 801 FORMAT(///' POINT 8', ' FREQUENCY', ' K=4',
0039 1' ' AMP DB', ' PHASE '//'S15 ///)
0047 700 FORMAT (A1)
0059 1000 STOP '***** END OF PROGRAM *****'
0059 END

LOCAL VARIABLES: PSECT DATA SIZE = 010112 (2035. WORDS)

NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
A P4 010014 AMP R4 010062 ANO R4 010076
AWS L=1 010014 C R4 010000 CPX R4 010072
FEND R4 010026 FREQ R4 010046 FSTART R4 010022
I I=2 010056 INIT I=2 010040 KAE R4 010010
KAT P4 010004 N I=2 010060 NURPTS I=2 010023
PEA R4 010066 STEPF R4 010052 STEPK R4 010042
NAV R4 010032

COMMON BLOCK / SIZE = 000014 (6 WORDS)

NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
F C=6 000000

LOCAL AND COMMON ARRAYS:

NAME TYPE SECTION OFFSET -------SIZE----- DIMENSIONS
CPLX R4 000000 000000 (1024) (512)
RGF R4 000000 000000 (1024) (512)

SUBROUTINES, FUNCTIONS, STATEMENT AND PROCESSOR-DEFINED FUNCTIONS

NAME TYPE NAME TYPE NAME TYPE NAME TYPE
AIMAG R4 ALDO10 R4 ASSIGN R4 ATAN2 R4 CABS R4
REAL R4 SCAT R4

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0001 SUBROUTINE SCAT
0002 COMMON KA,F
0003 COMPLEX C1,T2,T3,C1,C2,C4,C5,C6,C7
0004 COMPLEX CON.C1,CON2,CON4,B1,B2,FO1,FI1
0005 CONEX CON6,CON7,CON8,CON9
0006 REAL KA
0007 CON=0,0,1,00
0008 IF (KA GT 4) GO TO 100
0010 P=EX(0.2,0.2)*((KA)**3)
0011 F=EXLP1(P,L2)
0012 GO TO 1000
0013 IF (KA GT (B1) GO TO 200
0015 P=EX(0.2,0.2)*((KA)**3)*((5.0/54.0)*((KA**2)+17.0/100.)**2)
0016 F=EXLP1(P,L2)
0017 GO TO 1000
0019 IF (KA GT 20) GO TO 200
0020 ******** OPTICAL TERM C1 ********
0021 Y=KA
0022 BI=CONEX(1,0.2)
0023 B2=CONEX(0.2,0.2)
0024 FO1=(P/L2)*EXP(B2)*((1.0-B1)
0025 ******** CREEPING WAVE TERM FI1 ********
0027 F1=EXLP1(B1,B2)
0028 Y=EXLP1(B1,B2)
0029 Y=EXLP1(B1,B2)
0030 CON4=1.0151*EXP(B2)
0032 CON2=2.0*1.0*1.0151*EXP(B2)
0033 CON=1.0*1.0151*EXP(B2)
0034 CON=2.0*1.0*1.0151*EXP(B2)
0035 CON=1.0*1.0151*EXP(B2)
0036 CON=2.0*1.0*1.0151*EXP(B2)
0037 CON=1.0*1.0151*EXP(B2)
0038 CON=2.0*1.0*1.0151*EXP(B2)
0039 CON=1.0*1.0151*EXP(B2)
0040 CON=2.0*1.0*1.0151*EXP(B2)
0041 CON=1.0*1.0151*EXP(B2)
INTEGER REFA(128), REFP(128), TARA(128), TARP(128)

0004 TYPE *, '********** 2D FREQUENCY SWEPT HOLOGRAM ***********'
0005 TYPE *, 'ENTER STARTING FREQUENCY GHz:
0006 ACCEPT *, FREGIN
0007 TYPE *, 'ENTER ENDING FREQUENCY GHz:
0008 ACCEPT *, FSTOP
0009 TYPE *, 'ENTER THE NUMBER OF FREQUENCY POINTS (C128):
0010 ACCEPT *, NPTS
0011 TYPE *, 'ENTER ANGULAR SHEEP IN DEGREES:
0012 ACCEPT *, THETA
0013 TYPE *, 'ENTER THE NUMBER OF LINES:
0014 ACCEPT *, N LINES
0015 TYPE *, 'ENTER THE NUMBER OF SAMPLES/FREQUENCY POINT:
0016 ACCEPT *, NSAMP
0017 TYPE *, 'ENTER THE NAME OF THE FILE FOR DATA STORAGE:
0018 TYPE *
0019 CALL GLITIN, NAME, ?
0020 OPEN(UNIT=15, NAME=NAME, TYPE='NEW', ACCESS='SEQUENTIAL',
0021 FORM='UNFORMATTED')
0023 WRITE(15), FREGIN, FSTOP, N LINES, THETA, NPTS
0024 GET SYSTEM RESPONSE
0025 TYPE *, '**** PLACE REFERENCE TARGET IN THE FIELD ****
0026 PAUSE **** HIT RETURN TO CONTINUE ****
0027 CALL SWDAT, REFA, REFP, FREGIN, FSTOP, NPTS, NSAMP)
0028 GET SCALE FACTOR FOR DISPLAY
0029 TYPE *, '**** PLACE IMAGE TARGET IN THE FIELD ****
0030 (CALL SWDAT, TARA, TARP, FREGIN, FSTOP, NPTS, NSAMP)
0032 TARA(K) = TARP(K) - REFA(K)
0033 TARP(K) = TARP(K) - REFP(K)
0034 IF (TARP(K) .GT. 720) TARP(K) = TARP(K) - 1440
0035 IF (TARP(K) .LT. -720) TARP(K) = TARP(K) + 1440
0036 AMP = AMP + (TARA(K) * 05)
0039 CONTINUE
0040 AMP = AMP / NPTS
0041 TYPE *, 'AVERAGE AMPLITUDE IN DB: AMP
0042 TYPE *, 'ENTER DYNAMIC RANGE FOR DISPLAY IN DB:
0043 ACCEPT *, DBRNG
0044 AMIN = AMAX
0045 AMPIN = AMAX
0046 AMAX = 10 ** (AMAX / 10.0)
0047 AMIN = 10 ** (AMIN / 10.0)
0048 TYPE *, 'AMAX=', AMAX, AMIN=', AMIN
0049 SCALE = (200.0 * (2.0 ** 5)) / (AMAX - AMIN)
0050 TYPE *, 'SCALE FACTOR FOR DATA=', SCALE
0051 COLLECT HOLOGRAM DATA
0052 DO 500 J = 1, N LINES
0053 CALL SWDAT(TARA, TARP, FREGIN, FSTOP, NPTS, NSAMP)
0054 DO 100 K = 1, NPTS
0055 TARA(K) = TARP(K) - REFA(K)
0056 IF (TARP(K) .GT. 720) TARP(K) = TARP(K) - 1440
0057 IF (TARP(K) .LT. -720) TARP(K) = TARP(K) + 1440
0058 RNORM = 10 ** ((TARA(K) - 05) * AMP) / 1.0 + COS(TARP(K) * RAD)
0059 IX = IFIXNORM * SCALE
0060 TYPE *, IX
0061 WRITE(15) IX
0062 TYPE *, '**** END OF PROGRAM' ***
0063 DO 500
0064 CALL STEP2(DTHETA, 0)
0065 CONTINUE
0066 DO 500 CONTINUE
0067 DTHETA = DTHETA + 2
0068 STOP **** END OF PROGRAM ***
0069 DO 500

LOCAL VARIABLES: SPECTRUM SIZE = 002152 ( 566 WORDS)

NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET

AMAX R4 002110 AMIN R4 002114 AMPAY R4 +02100

AMIN R4 002104 AMP R4 002064 DBNORM R4 +02074

DTHETA R4 002056 FREGIN R4 002034 FSTOP R4 +02040

JZ 1+2 002132 J 1+2 002124 K 1+2 002072

NPTS R4 002052 NPTS R4 002044 NSAMP 1+2 002054

RADC R4 002062 RNORM R4 002126 SCALE R4 +02120

THETA R4 002046

LOCAL AND COMMON ARRAYS

NAME TYPE SECTION OFFSET ------SIZE------ DIMENSIONS

LOCAL R4+1 DATA 002099 000024 ( 10 ) (20)

COMMON R4+2 DATA 000000 000040 ( 128 ) (128)

THEA R4+2 DATA 001000 001000 ( 128 ) (128)

TARP R4+2 DATA 001400 000040 ( 128 ) (128)
SUBROUTINE LINDSP

THIS SUBROUTINE WILL DISPLAY A LINE OF DATA
UP TO 512 POINTS LONG.

COMMON/DisPL/12, IIINIT, NPTS, IxpbEd, IXBE0, ILEN, THETA
INTEGER 12(512)

COSV=COS(THETA)
SINV=SIN(THETA)
INT=ILEN+COSV+NPTS
TIME=ILEN+SINV+NPTS
IY=FLOAT(IYBE0)
IX=FLOAT(IxpbEd)
DO 100 IX=1, NPTS
100 CONTINUE
RETURN
END

SUBROUTINE STEP2(RADROT, NDIR)

AUTHOR C. WERNER 21-FEB-80

RADROT= ROTATION IN RADIANS
NDIR= DIRECTION FLAG. 0=CH 1=CCW

MCW=1024
MCCW=1536
ICM=1280
IWCCW=1792

STEPS/RAD=10000/PI

STRD=10000 0.3 14139
ISTEP=IF (STRD=RADROT)
IF (NDIR)= 10.10.20
IONMACW
IOFF+ICW
GO TO 22
ION+MCW
IOFF+ICW
CALL DOUT (...IERR, IOFF)
DO 25 IX=1, 200
CONTINUE
DO 30 DO 25 IX=1, 200
DO 25 CONTINUE
DO 25 CONTINUE
DO 25 CONTINUE
DO 25 CONTINUE
RETURN
END

LOCAL VARIABLES. PSECT #DATA. SIZE = 000056 (23 WORDS)

NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
COSV R=4 000004 DX R=4 000014 DY R=4 000020
IX I=2 000036 IV I=2 000040 IZVAL I=2 000042
X R=4 000034 SINV R=4 000010 X R=4 000024

COMMON BLOCK /DisPL/. SIZE = 002016 (519 WORDS)

NAME TYPE OFFSET NAME TYPE OFFSET NAME TYPE OFFSET
II I=2 000000 IXINIT I=2 002000 NPTS I=2 002002
IXBE0 I=2 002004 IXBE0 I=2 002006 ILEN I=2 002010
THETA R=4 002012

LOCAL AND COMMON ARRAYS:

NAME TYPE SECTION OFFSET ------SIZE------ DIMENSIONS
II I=2 000000 000000 062000 (512) (512)

SUBROUTINES, FUNCTIONS, STATEMENT AND PROCESSOR-DEFINED FUNCTIONS.