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AEGIS NEAR-FIELD ANTENNA TEST SYSTEM

AUTOMATED TEST SYSTEM FOR PHASED ARRAY ANTENNAS

A Project of the Manufacturing Technology Program
Naval Sea Systems Command

FINAL REPORT
June 1980



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ADMINISTRATION INFORMATION

The work in this report was sponsored by the Naval Sea Systems Command as part of the Manufacturing Technology Program. The data discussed in this document was prepared by RCA Corporation, Government Systems Division, Moorestown, N. J., under contract N00123-77-1091.

ACKNOWLEDGEMENTS

The project would never have reached the high level of professionalism that it achieved without the concerted efforts of Levi L. Coulter, Jr., James C. Kulp, and Wayne A. Harmaning, all of RCA, and special acknowledgement must be given to Mr. Allen Newell of the National Bureau of Standards who functioned as a consultant to the project. Mr. Newell is recognized as a leader in near-field measurement technology.

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MT-S-475-77

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS
BEFORE COMPLETING FORM

1. REPORT NUMBER NAVSEA/MTS-475-77	2. GOVT ACCESSION NO. AD-A091697	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) AEGIS NEAR-FIELD ANTENNA TEST SYSTEM Automated Test System for Phased Array Antennas		5. TYPE OF REPORT & PERIOD COVERED Final Report 3 Oct 77-30 Dec 78
6. AUTHOR(s) RL Mather, NOSC Code 821, RCA (Appendix A) Levi L. Coulter, Jr. Wayne A. Harmering James C. Kulp Robert L. Mather		7. PERFORMING ORGANIZATION REPORT NUMBER NOSC/TR-499
8. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Ocean Systems Center, San Diego, CA 92152		9. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
10. CONTROLLING OFFICE NAME AND ADDRESS Naval Sea Systems Command		11. REPORT DATE June 1980
12. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		13. NUMBER OF PAGES 118
14. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		15. SECURITY CLASS. (of this report) UNCLASSIFIED
16. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		17. DECLASSIFICATION/DOWNGRADING SCHEDULE
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Antennas Planar scanner Nearfield measurements		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) RCA has recently developed two major elements of an automated testing system for phased array antennas. The testing system applies the near-field technique for production acceptance test of the AEGIS AN/SPY-1A Phased Array Antenna. The two elements developed are 1) the programmed scanner and 2) the computer programs for real-time control, beamformer alignment, calibration, data reduction, and test results display. The programmed scanner scans the rf probe over an area 600 cm wide and 550 cm high in a raster fashion. Typical probe scanning velocities are: 15 cm/sec moving vertically upward during data collection, and 10 cm/sec moving horizontally (either step or continuous). Probe position accuracies achieved are 0.016 cm RMS (X) 0.019 cm RMS (Y), and 0.011 cm RMS (Z). (Continued)		

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20. ABSTRACT (Continued)

where (X,Y) is the plane of probe motion and (Z) is normal to that plane. Features of the computer programs are program-directed calibration routines interacting with the test conductor, test conductor selected test scenarios that are embedded in the control program, and automatic calculation and reporting of any needed antenna receive beamformer waveguide length corrections for antenna phase alignment.

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CONTENTS

SUMMARY . . .	page 1
INTRODUCTION . . .	3
BACKGROUND . . .	3
NEAR-FIELD VS FAR-FIELD . . .	4
DATA LOGIC . . .	5
AEGIS AN/SPY-1A . . .	5
PROJECT OVERVIEW . . .	6
ACKNOWLEDGEMENT OF PROJECT PARTICIPATION . . .	7
ECONOMIC ASPECTS . . .	8
Costs . . .	8
Benefits . . .	9
NOSC PARTICIPATION . . .	9
CONCLUSIONS AND RECOMMENDATIONS . . .	10
REFERENCES . . .	13
APPENDIX A	NAVSEA MANUFACTURING TECHNOLOGY PROGRAM DNS 00475 AUTOMATED TEST SYSTEM FOR PHASED ARRAY ANTENNAS . . .
APPENDIX B	ENGINEERING DRAWINGS AND COMPUTER PROGRAMS . . .

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OBJECTIVES

Develop a near-field phased array antenna test system for production test acceptance of Navy radar antenna systems, and provide industry with a new testing technology, as part of the Navy's Manufacturing Technology (MT) program.

RESULTS

1. RCA Corporation, partially supported by contract with the Naval Ocean Systems Center (NOSC), developed two major elements of a test acceptance test system: 1) a programmed scanner for scanning a waveguide probe over the radiating face of the antenna, and 2) requisite system computer programs.

2. At the time this report was written, the completed RCA-developed system was being used to test AN/SPY-1 antenna faces being manufactured for the AEGIS weapon system.

3. The near-field testing technique saves money over the traditional far-field technique, and the near-field approach provides better data for acceptance or rejection decision making.

RECOMMENDATIONS

1. Future testing of AEGIS antenna assemblies be done by the near-field method.

2. Since the success of new near-field antenna testing systems depend on the quality of planning, it is recommended that planning problem areas be given specific attention.

SUMMARY

A unique near-field phased array antenna test system has been developed by RCA for acceptance testing of production AN/SPY-1 antenna faces for the AEGIS weapon system to go on Navy surface ships. Far-field testing techniques have traditionally been used to measure antenna performance.

Two major elements of the system developed by RCA are covered in detail in this report. These include the programmed scanner used for scanning a waveguide probe over the radiating face of the antenna, and the computer programs needed for control of the scanner and measurement equipment, for assisting test system calibration, for processing measured data, and for display of the antenna's measured performance.

The main body of this report contains an overview and analysis of the total automated test system, with details of the two RCA-developed system elements contained in Appendix A (RCA's final report). Appendix B contains lists of drawings and computer software available from Naval Ocean Systems Center (NOSC), San Diego.

This test system was supported partially by a Manufacturing Technology (MT) program contract with RCA by NOSC. The primary objectives of the MT program were to develop the near-field testing system for acceptance or rejection of production AEGIS radar antennas, and provide industry with a new testing technology.

For those planning similar systems, it may be of interest to note that the system under discussion cost approximately \$1.2M. Table 1 provides additional details.

The near-field technique and equipment described in this report provides an improved method of antenna testing uniquely suited to array antennas. In an industrial production/engineering environment a significant savings can be demonstrated. It can also be demonstrated that use of the near-field technology will provide the Navy (and other customers) with a greater product reliability in their acceptance/rejection process.

INTRODUCTION

A new type of measurement technique for production acceptance test of the microwave antenna face of the AEGIS radar system is receiving its first major industrial application at RCA, Moorestown, N.J. The nearfield measurement technique being used has been given extensive laboratory investigation at the National Bureau of Standards in Boulder, Colo, at the Georgia Institute of Technology, and at other laboratories. There is an extensive list of public literature on these laboratory investigations.

The shift of a laboratory technique to an industrial setting entails some risks; but, in this application one can show benefits of reduced costs and increased production which justify support from the NAVSEA Manufacturing Technology (MT) program. The total project has three-way support from MT, AEGIS, and RCA.

The major portion of the technical work was performed by RCA. Their final report is attached as Appendix A. The bulk of the RCA reporting is of less general interest and is described in Appendix B. The availability of this material is also discussed in Appendix B.

BACKGROUND

Antenna testing is broadly separable into two types of tests: near-field and far-field. Each has certain features of superiority but there can be a large region of equivalency. The limitations have been well delineated in laboratory investigations although an antenna of the AEGIS type has not been previously tested by near-field methods. The usual application of far-field data requires no phase information from the antenna probe and indeed it is usually impossible to measure phase well on a far-field range. In near-field testing, phase information is required in the transform data processing.

As important as the acquisition of the measurement data is the handling of the data after acquisition. In large measure, it is efficient data handling that makes the near-field tests competitive in practical application.

The system was designed around a first version of an official acceptance test procedure for the AEGIS antenna. The system hardware is very flexible in allowing other versions of test procedure to be used.* Any version can be put under rigid quality control procedures that will assure consistent testing and the first version is under such control. The system software documentation which makes such control effective has been developed for the first version.

The first version of an official acceptance test procedure is described with its data reduction and presentation. The reduced data will be examined by a Navy representative and he will make a decision to accept or reject the face. The customer, in this case AEGIS, specifies the pertinent available information to be reduced and presented in an easily reviewable form from the official tests.

At present the antenna acceptance criteria are in terms of far-field parameters, requiring a transformation of near-field data to the far-field format. Far-field criteria are used

*The system is under software control and can be directed to do a wide variety of procedures (within its mechanical limitations), data reduction and data presentation. Tests, other than acceptance tests, can be carried out for the AEGIS program without degrading the acceptance test capability. The quality control program (and its attendant expenses) for these other tests may or may not be implemented.

primarily because antenna designers and testers are most comfortable and familiar with far-field descriptors such as gain, beamwidth, sidelobe levels, etc. In addition the antenna performance is specified in terms of far-field parameters.

As experience and confidence with near-field testing of AN/SPY-1 arrays increases, it may be desirable to specify antenna acceptance on the basis of near-field criteria directly, without the need of an extra data reduction step to derive far-field patterns.

NEAR-FIELD VS FAR-FIELD

An antenna is a component which launches electromagnetic waves into free space from confined waves inside the equipment. For many applications, such as radar, the region of importance of these launched waves is far from the antenna; and, the antenna, with reasonable approximation, can be considered a point source of radiation. The far-field characteristics of antenna gain, beamwidth, and sidelobe structure hold true only at distances from the antenna greater than $2D^2/\lambda$; where, D is the mean diameter of the antenna and λ is the wavelength of the radiation. For the AEGIS antenna, the minimum far-field distance is approximately 1000 feet.

Far-field antenna characteristics are usually measured by placing a probe antenna in the far-field of the antenna under test and measuring the signal coupling between the two antennas as a function of direction by turning the antenna under test.

Since the radiation energy which reaches the far-field has to have passed through the antenna structure, an alternate measurement method should be possible by which the fields in a small region close to the antenna are probed. A theoretical expression relating near-field measurements to far-field measurements can be derived. For instance, Ernst Abbe in 1873 developed a theory of the microscope in which he showed that radiation fields at large distances are related to field in the aperture by a mathematical Fourier transform. Recent developments in microwave instrumentation and computers have now made it possible to utilize this transform relationship in what is called a near-field antenna measurement method.

The typical near-field data set has more measurement information in it than does the typical far-field data set. Because the near-field measurements are made close to the antenna (about 1 foot distance for the AEGIS antenna) the data can be used for more purposes than just verifying array performance. The present application makes good use of the technique for beamformer alignment and diagnostics.

The near-field method has two big advantages: 1) the measurements may be made indoors, and 2) the antenna need not be turned (the transform does the equivalent). For a large heavy antenna which requires special handling equipment, the savings can be substantial.

Electronically-steered phased-array antennas consist of an array of small radiating elements each phased relative to the others by electronic control. Although these arrays may have mechanical symmetry, this symmetry does not necessarily appear on the far-field characteristics of the beam because of the electronic phasing properties. Consequently a full plane of data must be measured for each phasing setting in order to describe the function of the antenna. Fortunately this type of antenna can electrically reconfigure itself in a matter of microseconds and many sets (about 100) of measurements can be made in a small period (about a fifth of a second - a period during which the near-field probe moves about 3 cm) if there are computer techniques to sort and store the measurements. Thus, there is need for a very large amount of data combined with a capability of supplying the data if modern instrumentation and data handling is used. The cost per data unit is very low once the system is set up.

DATA LOGIC

The Fourier transform utilized here requires the near-field probe to be located at a regularly spaced array (say 3-cm spacing) of points on a mathematical plane. Other transforms for cylindrical surfaces and spherical surfaces exist, but the planar surface is particularly appropriate for the AEGIS antenna. The array of measurement points needs to be relatively exact (about 0.030 inch) to avoid errors in the transformed observations. It is less costly to provide this exactness in the mechanical scanner than to correct for such imperfections in the data processing.

The measurements are made in a time sequence which presumes a constant mechanical scan velocity. Any deviations from constant scan velocity are immediately corrected by the servo loop. Velocity transients would introduce the same sort of errors into the data set as would a mechanical distortion of the scanner. The servo loop was custom tuned to cope with the mechanical resonances of the scanner structure and this, combined with software programming which avoids introduction of resonant-frequency components into the servo loop, results in a very smoothly operating constant-velocity motion of the near-field probe.

The appropriate scan velocity is computed in the PLAN subprogram of the computer software according to the amount and type of data requested and the various transient switching times of the RF measurement system. Up to a certain amount of data the velocity is limited by the maximum velocity of the scanner. Beyond that amount, the more data requested, the slower the scan velocity and the longer the time required to complete the scan. The system is planned to be capable of measuring the required data for the final acceptance test within one working day.*

The basic data array for the Fourier transform is 256 X 256 data points. However, there are not this many measured points. The remaining points are filled with a suitable value (such as zero). For some purposes the transform ambiguity (similar to grating lobes) resulting from a data array with twice the spacing would be satisfactory and the software permits a 256 X 256 array of measured data points to be replaced with four 128 X 128 independent data arrays. Data reduction for these 128 X 128 arrays is appropriately modified.

AEGIS AN/SPY-1A

AEGIS is a new generation fleet air defense system presently in production for deployment in CG-47 class ships beginning in 1983. When deployed, AEGIS is expected to contribute significantly to fleet air defense capabilities in the heavy threat environment projected for the 80's and 90's.

One of the key elements of AEGIS is the S-band AN/SPY-1 radar system designed and built by RCA. This radar uses an electronically-steered phased-array antenna system which gives the radar the capability of tracking many rapidly-moving targets simultaneously primarily because the radar beam can be electronically steered. The antenna system consists of four antenna faces each directed in a quadrant of azimuth. The AEGIS Near-field Antenna Test System (ANFATS) under discussion was built primarily to test these antenna faces at the RCA production facility in Moorestown, New Jersey.

*In the final stages of production the antenna face will, however, remain on the near-field test system for several weeks while a number of preliminary tests and adjustments are made prior to final acceptance testing.

Each of the four AN/SPY-1 antenna faces is approximately 12 feet in diameter and contains 4096 radiating elements. It is steered by row-column steering commands from the antenna position programmer.

The antenna is organized into 128 array modules having 32 elements each. During production, tests are conducted at the element, array module, and the beamformer level to assure that antenna components and subsystems are functioning properly before assembly. The purpose of acceptance testing is to assure that the antenna has been assembled properly and that no components have failed or been damaged during assembly.

Typically, a representative set of antenna measurements are conducted to satisfy the acceptance test requirements. Acceptance testing can be performed by either a far-field or a near-field range. A significant bonus for near-field testing is that the near-field data can be used directly to assist in identifying failed elements, beamformer misalignment, etc. while the antenna is still in the factory, so that system check out and debugging may be more easily accomplished.

PROJECT OVERVIEW

The first engineering development models of the AEGIS antenna face were tested by traditional methods on a far-field antenna range at RCA (circa 1972 and later). The testing proved burdensome and alternative methods of test were investigated. Investigative reports exist from this era (References 1, 2) and the consensus of them was that the near-field test method was both technically and economically feasible and would offer some clear advantages.

The Navy Manufacturing Technology (MT) program was forming at that time with the aim of helping to finance the introduction of new technology into defense industries in return for open availability of the details of that technology. RCA submitted an unsolicited proposal to NOSC 1 March 1977, which was accepted and eventually resulted in contract N00123-77-C-1091, which started 30 September 1977.

The proposal was titled "Automated Test System for Phased Array Antennas" and outlined a three-way support for the total system. MT, AEGIS, RCA capital. The MT portion was to supply the programmed scanner hardware and the computer software, RCA capital was to supply the shelter for the facility at its plant in Moorestown, N.J., the computer, the RF hardware, the RF measuring equipment, etc. AEGIS was to support the integration of the test system and the AEGIS antenna system. Thus the MT contract was for two major pieces of the system but with a commitment from RCA to supply the remaining pieces.

The MT portion was essentially completed Dec 1978. The current status (Oct 79) is that the RCA portion has been completed and the first AEGIS production antenna face is in place in the tester and has started tests. This is essentially according to schedule. It is planned that comparative far-field data be taken on this face. It may be assumed that in the comparison some things will become better understood about both the near-field and the far-field data. Present indications are that no modifications to the scanner hardware or the data-taking process will be needed.

The test system design makes full use of computer versatility. All antenna tests are done under computer control and with computer participation (the facility has a dedicated computer). This is in addition to the dedicated beam-steering computer within the AN/SPY-1 system. The entire functioning of the combined antenna and test system is governed

by the computer software loaded into the test system computer. For accountability purposes a version of this software is documented and under full AEGIS quality-control practices. This version will be used for official testing.

This report addresses the technical side of the project. However, it must be acknowledged that the MT contract budget and schedule were met. RCA should be given much credit for this.

It should be noted that the programmed scanner exceeded the required mechanical precision by a substantial amount. Practically every function is under computer software control so that measurements and data reduction of almost infinite variety can be programmed by modifying the software. This gives the test system an unusual degree of adaptability to new tasks. For a comparatively small additional cost, the test system could be adapted for other RF frequency ranges, and other types of antennas might be tested. For the present, the test system will be devoted to AEGIS purposes.

ACKNOWLEDGEMENT OF PROJECT PARTICIPATION

The vital interest which AEGIS had in this program led to active participation of AEGIS technical staff in all the MT review meetings. Among the technical staff for the Navy, R. Marcus of NAVSEA 65232C, E. Irzinski of Johns Hopkins APL, J. Frank of Technology Service Corp. deserve special mention. The technical staff of RCA that was involved was larger in number and more varied in their contribution to the project. The authors of the RCA final report (Appendix A) are L. L. Coulter, W. A. Harmoning, and J. C. Kulp. Some clue to names of other RCA contributors may be found in the list of End-of-Contract Review Attendees on page x of the RCA final report (Appendix A).

Special mention should be made of the staff of the National Bureau of Standards, Boulder, Colo. in particular Mr. Allen Nowell. NBS has pioneered much of the experimental and theoretical work on near-field antenna measurement systems and has served as a consultant to NOSC on this contract. He has also served as consultant to AEGIS and to RCA, and has supervised the near-field probe antenna calibration for the RCA portion of this project.

There are also near-field projects in the Army and the Air Force. These projects do not duplicate each other and there is communication between all projects. In particular, J. Borowick of ERADCOM, U.S. Army, Ft. Monmouth, N.J., attended a number of review meetings on the MT contract (note page x of Appendix A). He currently monitors a contract for a near-field test system placed with Hughes, Fullerton, Calif.

The obligation for technology dissemination included in the MT contract will be completed by the availability of this report,* copies of hardware drawings and computer software documentation (see Appendix B), and the open house presentation and demonstration which occurred near the end of the MT contract (see pages viii, ix, and x of Appendix A). The hardware and software produced under the MT contract has been turned over as government furnished equipment to the AEGIS production contract with RCA, contract N00024-78-C-5188. This does not preclude further technology dissemination (witness: W. A. Harmoning, "Instrumenting a Near-Field Antenna Test Facility" *Microwave Journal*, Sept. 1979, pp 44-55, plus addendum p. 88 Oct 79) if AEGIS and RCA management concur.

*henceforth to be available from Defense Technical Information Center, formerly known as the Defense Documentation Center.

ECONOMIC ASPECTS

Costs

A table of costs for the present system is given in table I. The table is itemized at a major module level.

ITEMS	K \$
<u>MT Portion</u>	
Scanner	343
Software	263
Sub-Total (MT contract Price)	606
<u>RCA Portion</u>	
Shelter	150
RF System	250
Computer	200
Sub-Total	600
Total	1206

Table I. ANFATS costs.

The cost given is for the system as it was designed and built. No attempt is made to explain the many decisions by which this design was chosen over alternatives. The most critical requirements appeared to be: 1) a Navy supplied list of antenna measurements to be made for acceptance test purposes (a fairly extensive list but still only a spot check of antenna properties), and 2) a requirement that an AEGIS production rate of three ships per year be maintainable. AEGIS production readiness costs, relevant to utilization of the test fixture, are not included. The subdivision within the MT and RCA totals are estimated cost divisions. There are questions about apportionment of overhead costs and other questions which leads one to ascribe a $\pm 20\%$ accuracy to these numbers.

It is thought that a failure to anticipate costs properly would keep others from adapting this technology to their needs. Otherwise one might be tempted not to include table I. Actually the experience with this project indicates that costs can be predicted well with appropriate effort.

Costs of future ANFATS-like systems should be less, because of the technology and experience which will be available from this system. This is one of the justifications for MT support of this project.

Benefits

Near-field production testing of phased arrays has demonstrated, at this early stage of AEGIS production, that a thorough test planning program does provide the appropriate combination of low expenditures and maximum data to satisfy Navy acceptance procedures.

The AEGIS AN/SPY-1 antenna face was qualified during the EDM-1 and EDM-3 design phases. In the present production phase there is a sequence of component and sub-assembly tests which precede the testing of the final complete package (a combination of the AN/SPY-1 antenna face and its beam-steering computer). The primary purpose of the array production acceptance testing is to check for assembly errors. Far-field tests, which have been customary, are not very sensitive to small assembly errors; and, when something wrong is indicated, the indication of what is wrong is ambiguous. The near-field data is much more sensitive to small assembly defects and, moreover, often tells what is wrong so specifically that it can be remedied efficiently. There is not yet enough experience to specify the optimal data reduction techniques for the near-field data. The data reduction subprogram BFAL in the present system is a start. It should be noted that there is no far-field counterpart of this subprogram.

In the initial RCA proposal (1976), the cost savings per ship was estimated at \$100,000 if near-field acceptance testing was used. For a production run of 24 ships this would produce savings beyond the cost of the near-field facility. Of greater importance than the cost savings is the potential that far-field testing would become a bottleneck in achieving a production rate of three to four ships per year. Near-field testing can easily handle the projected production rate.

The reader's attention should be drawn to the existence of two earlier economic analysis studies (References 1, 2). Both references have drawn on some of the same sources of information but the treatment is sufficiently different that a comparative summary will not be attempted here. Both reports give a moderate edge to the near-field method. The TS study assumes a prior far-field range which has to be improved with greater automation, etc. The Georgia Tech study assumes that both the far-field and the near-field systems are built from scratch.

By March 1980 there were good comparative costs and times available from RCA experience for near-field vs. far-field testing. The near-field costs were lower by \$400,000 per ship. The saving in total test times was 6 months per ship. A portion of these additional savings over the 1976 estimate is due to incremental improvements of the initial proposal.

Several qualifications to the benefits analysis must be noted. Over the period 1976-80 there was significant general inflation of costs. There were also significant fluctuations in best estimates of the final number of AEGIS ships. There are also several opinions on the proper method of benefits analysis. However, the conclusion that the ANFATS will more than pay for itself in savings appears to be "robust".

NOSC PARTICIPATION

NOSC coordinated the government side of evaluating the RCA proposal and preparing the MT contract. Contract monitoring was primarily by Dr. R. L. Mather of Code 8211 (microwave antennas are a major topic in this code). Mr. Allen Newell of NBS was supported as an advisor on this contract.

It was thought that the role of a Navy laboratory should be to offer guidance and judgment to the Navy in taking technical risks. Fortunately, the direst risks (risks to the AEGIS program) did not materialize.* The technical priorities (the primacy of an excellent programmed scanner, for example) were set early in the project. On some mechanical details there seemed to be as many opinions as there were advisors, whereas on computer software there seemed to be little available advice. A course of action on these details was chosen after review of the information and opinions available.

CONCLUSIONS AND RECOMMENDATIONS

The AEGIS Near Field Antenna Test System (ANFATS) has been completed and is in active use for acceptance testing of the AEGIS AN/SPY-1 radar antenna faces. A substantial increase in the productivity of the antenna test process has been achieved. The best use of this productivity is intimately involved with the specifics of the AEGIS program but it is obvious that it can be used in several ways, for short term or long term goals and the optimum usage is still being worked out. The ANFATS will more than repay its cost (\$1.2M) over the planned AEGIS program.

It is recommended that future acceptance testing of the AEGIS antenna assembly be done by near-field methods. It should be noted that this is a decision for AEGIS. This recommendation includes testing after acceptance of the antenna assembly, however a discussion of post-acceptance testing plans is not appropriate here.

From a broader point of view (and of more importance for the purposes of this report) the ANFATS has worked out pretty much as planned. This means that the laboratory work which has been done on near-field antenna testing is adequate to support initial industrial applications. The ANFATS experience supplies some cost figures and detailed description of supporting techniques which will make planning of future near-field test systems much more certain.

In evaluating the proposal for ANFATS, it was apparent that the application to the AN/SPY-1 antenna was an especially favorable case for the planar near-field technique. The two main favorable items are 1) the very large program (AEGIS), and 2) the very complex electrical properties of the antenna.

In a general way the choice between near-field and far-field techniques rests on real estate costs, equipment costs, staffing costs, versatility of the facility, and the differing advantages of the techniques. The last two depend on the mix of antennas and the nature of the measurements required. The costs for the two test methods differ in their distribution between first costs and continuing costs. Increasingly, suitable real estate for a far-field range is not reasonably available which favors the near-field method. The near-field method, however, requires a relatively heavy investment in instrumentation and highly technical staff. The instrumentation and staff is affordable if the amount of measurement information being handled is large. With the trend toward urbanization of industrial land and the trend to more technically sophisticated antennas an increasing number of near-field test systems will be built.

The success of new near-field antenna testing systems will depend on the quality of the planning which goes into them. There is a good deal of experience being accumulated on the use of such systems. Worldwide, there are a number of systems under construction

*In retrospect, the AEGIS program has remained on schedule within normal limits.

which are trying interesting new techniques. No commercial systems have been available but this is expected to change. The reader who contemplates acquiring a near-field system will have a number of system choices and it is recommended that he assess his needs and devise proper methods of making the choice, using estimates based on the available experience from existing systems. Sufficient experience exists that a reasonable quality of planning is possible.

It is recommended that some planning problem areas be given specific attention. It is mentioned above that the potential near-field user should carefully assess his needs. Very likely his needs are multiple and disparate. In a typical situation of an industrial contractor, a military service, and the nation (government) each of these will have different perceptions of purpose based on the nature of their contractual relations and it is a management art to achieve a unity of purpose. Given a purpose, the needs can be given a priority, a proper method of making choices between alternatives can be devised and the needed technical estimates be specified. Dollar cost is the usual common estimate unit. There seems to be a tendency to underestimate the cost of precision measurement and adjustment. There also seems to be a tendency to underestimate the cost of computer software. Both tendencies may have a common source in that the necessary details for itemized estimation are hard to work out in advance of the effort.

In spite of the propensity of underestimating costs, the near-field technology is a very practical and effective technique and it is anticipated that its usage will grow considerably in the near future.

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"A Study of Comparative Costs for Far-Field Antenna Patterns Determined by Near-Field Measurements and by Far-Field Measurements," 31 Jan 1974, 78 pp, prepared for U.S. Army Missile Command, Redstone Arsenal Alabama, and available as AD 775 472 from National Technical Information Service, U.S. Department of Commerce.
2. J. Frank and G. C. Rose (Technology Service Corporation, Silver Spring, MD)
"Comparison of Near-Field and Far-Field Techniques for Acceptance Testing of SPY-1 Antennas," July 1975, 64 pp, prepared for Naval Ship Engineering Center, Code 6175, Hyattsville, MD.

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APPENDIX A

Report Number ANFATS-SP-025

NAVSEA MANUFACTURING TECHNOLOGY PROGRAM DNS 00475
AUTOMATED TEST SYSTEM FOR PHASED ARRAY ANTENNAS

Programmed Scanner and Computer Programs for an
Automated Test System for Phased Array Antennas

Prepared for:

NAVAL OCEAN SYSTEMS CENTER
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Contract Number N00123-77-C-1091

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) NAVSEA MANUFACTURING TECHNOLOGY PROGRAM DNS-00475 AUTOMATED TEST SYSTEM FOR PHASED ARRAY ANTENNAS		5. TYPE OF REPORT & PERIOD COVERED Final Report 3 Oct. 77 to 30 Dec. 78
7. AUTHOR(s) Levi L. Coulter, Jr. James C. Kulp Wayne A. Harmening		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS RCA Corp., Government Systems Division Missile and Surface Radar Moorestown, N.J. 08057		8. CONTRACT OR GRANT NUMBER(s) N00123-77-C-1091
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Sea System Command Washington, D.C. 20360		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
13. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Naval Ocean Systems Center San Diego, California 92152		12. REPORT DATE 29 December 1978
		13. NUMBER OF PAGES 99
		14. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approval for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Antennas; planar scanning; near-field measurements		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) RCA has recently developed two major elements of an automated testing system for phased array antennas. The testing system applies the near-field technique for production acceptance test of the AEGIS AN/SPY-1A Phased Array Antenna. The two elements developed are 1) the programmed scanner and 2) the computer programs for real-time control, beamformer alignment, calibration, data reduction, and test results display. The programmed scanner scans the rf probe over an area 600 cm wide and 550 cm high in a		

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raster fashion. Typical probe scanning velocities are: 15 cm/sec moving vertically upward during data collection, 50 cm/sec moving vertically downward during retrace, and 10 cm/sec moving horizontally (either step or continuous). Probe position accuracies achieved are 0.016 cm RMS (X) 0.019 cm RMS (Y), and 0.011 cm RMS (Z), where (X, Y) is the plane of probe motion and (Z) is normal to that plane. Features of the computer programs are program-directed calibration routines interacting with the test conductor, test conductor selected test scenarios that are embedded in the control program, and automatic calculation and reporting of any needed antenna receive beamformer waveguide length corrections for antenna phase alignment.

PREFACE

This report is submitted as Contract Data Requirements List Item A006 under Contract N00123-77-C-1091. It describes the work done under NAVSEA Manufacturing Technology Program DNS-00475 for elements of an automated test system for phased array antennas using the near-field measurement technique.

This contract was issued on 3 October 1977 by Naval Regional Procurement Office, Long Beach, California. Technical direction for the contract was provided by Naval Oceans System Center, San Diego, California. Dr. Robert L. Mather, NOSC, Code 8211, was the assigned technical representative.

The work was done by RCA Corporation, Government Systems Division, Moorestown, NJ 08057.

SUMMARY

RCA has recently developed two major elements of an automated testing system for phased array antennas. The testing system applies the near-field technique for production acceptance test of the AEGIS AN/SPY-1A Phased Array Antenna.

These two major elements are the programmed scanner that is used for scanning a waveguide probe over the radiating face of the antenna and the computer programs needed for control of the scanner and measurement equipment, for assisting test system calibration, for processing of the measured data, and for display of the antenna's measured performance.

The Antenna Near-Field Test System being developed by RCA is illustrated in Figure 1. A block diagram is shown in Figure 2.

Programmed Scanner - The programmed scanner, shown as Figure 3, was accepted in November 1978 and has the following characteristics:

	<u>X Axis</u> <u>Horizontal</u>	<u>Y Axis</u> <u>Vertical</u>	<u>Z Axis</u> <u>⊥ to X-Y</u>
Coverage	600 cm	550 cm	Fixed
Scan Velocity	10 cm/sec	15 cm/sec	Fixed
Slew Velocity	10 cm/sec	50 cm/sec	Fixed
Probe Position Error			
RMS	0.016 cm	0.019 cm	0.011 cm
Periodic	0.007 cm	0.007 cm	0.003 cm

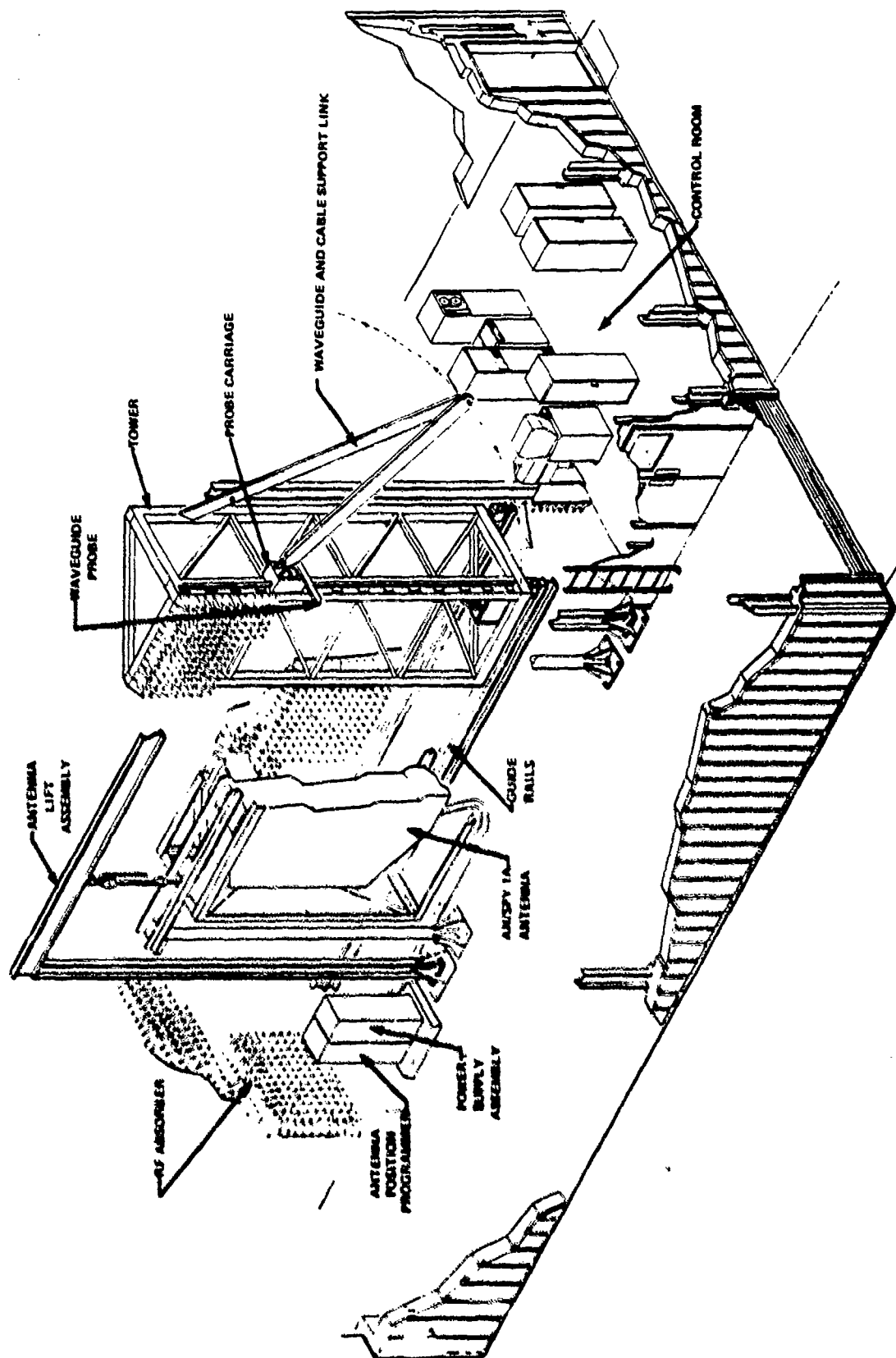


Figure 1. AEGIS Near-Field Antenna Test System.

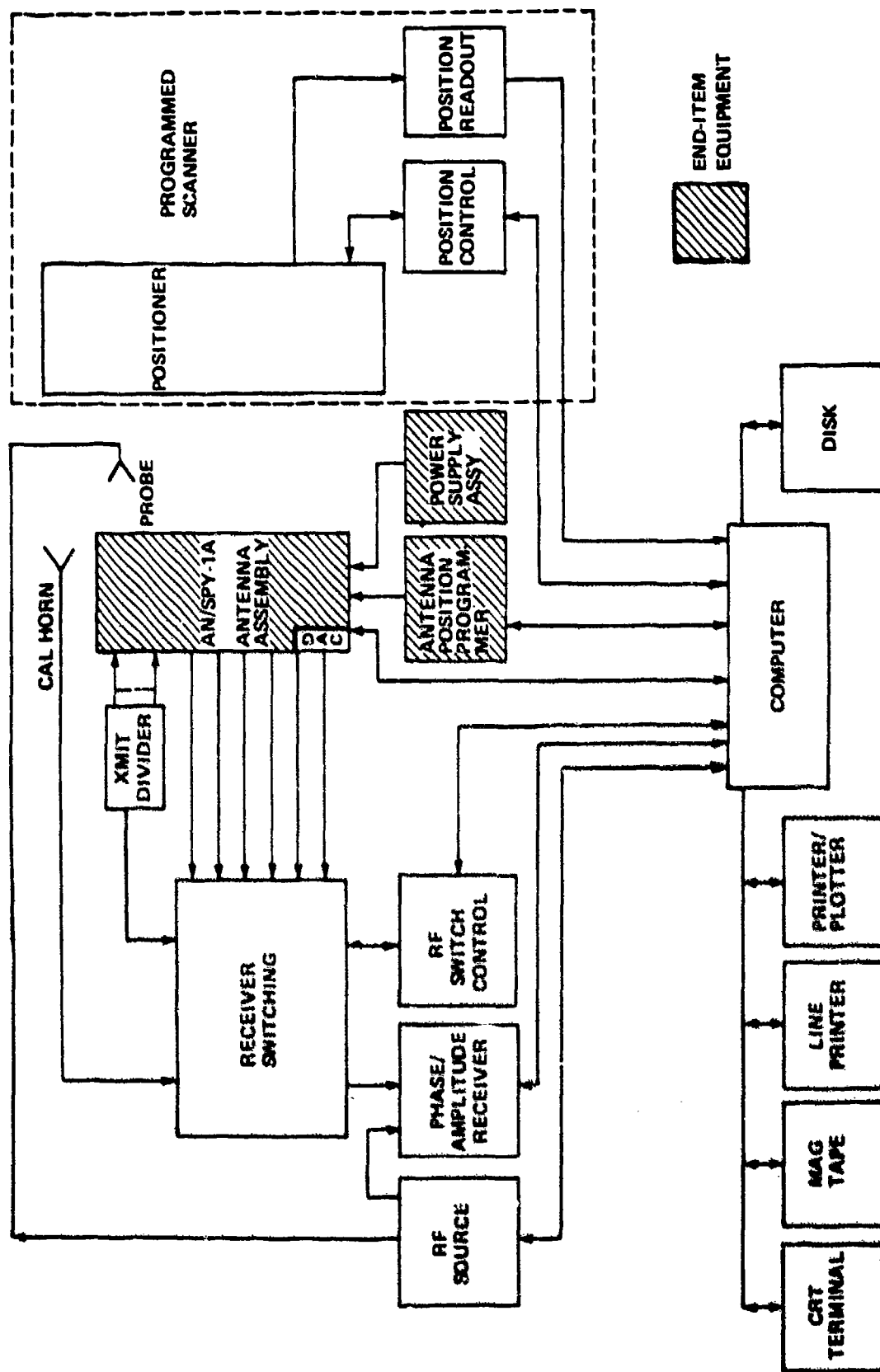


Figure 2. Block Design - AEGIS Near-Field Antenna Test System.

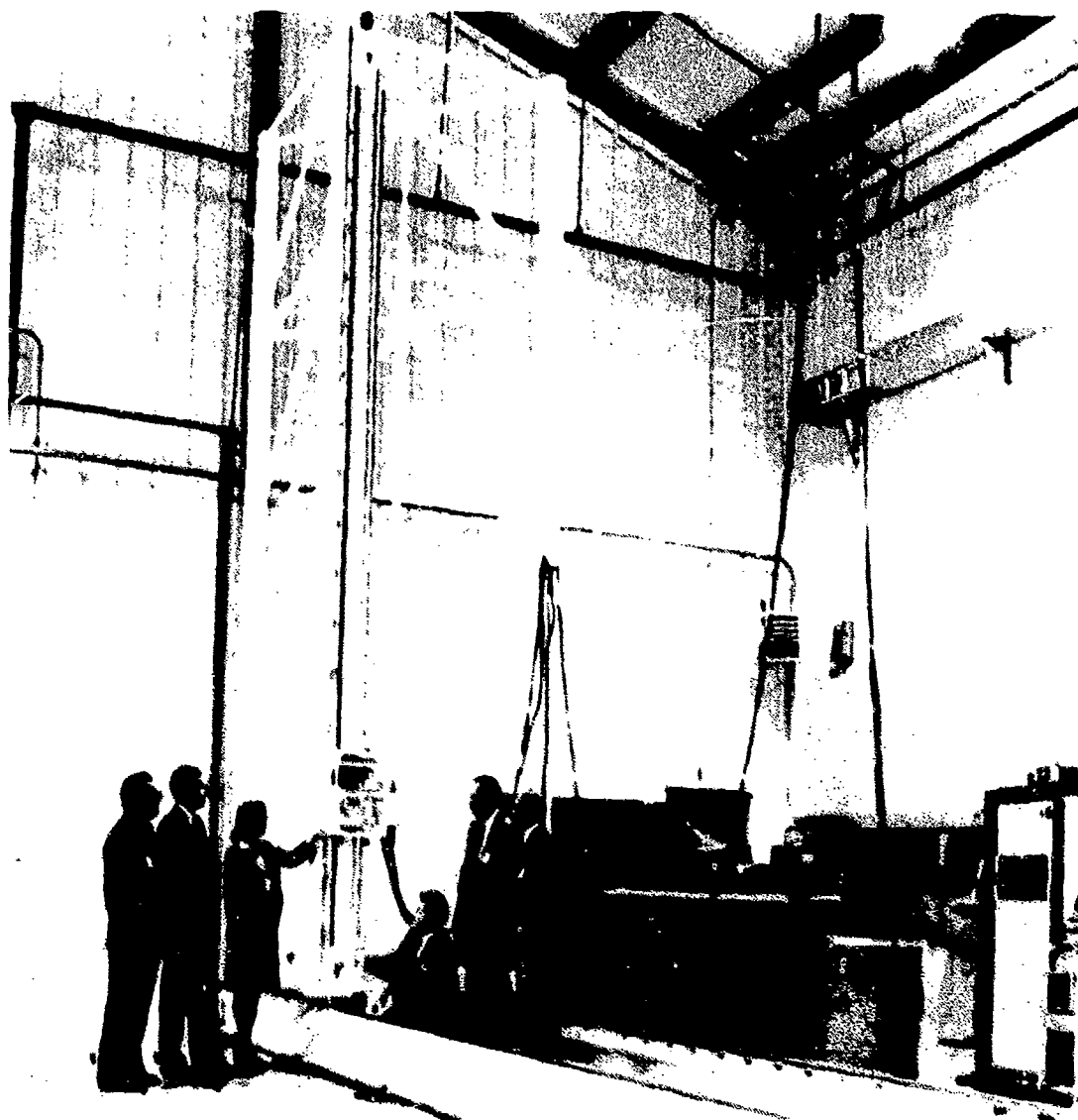


Figure 3. Programmed scanner: E. T. Hurfurth describes the carriage assembly of the programmed scanner to (Left to Right) Dr. R. L. Mather, NOSC; and L. L. Coulter, W. A. Harmening, D. H. Mercer, L. A. Caplan, all RCA.

Probe position error performance was four to five times better than the specified 0.08 cm and exceeds the needs of the AN/SPY-1A Antenna.

Computer Program - The block diagram of the computer programs developed for the test system are shown in Figure 4. These computer programs were developed on the RCA Interdata 8/32 computer (see Figure 5).

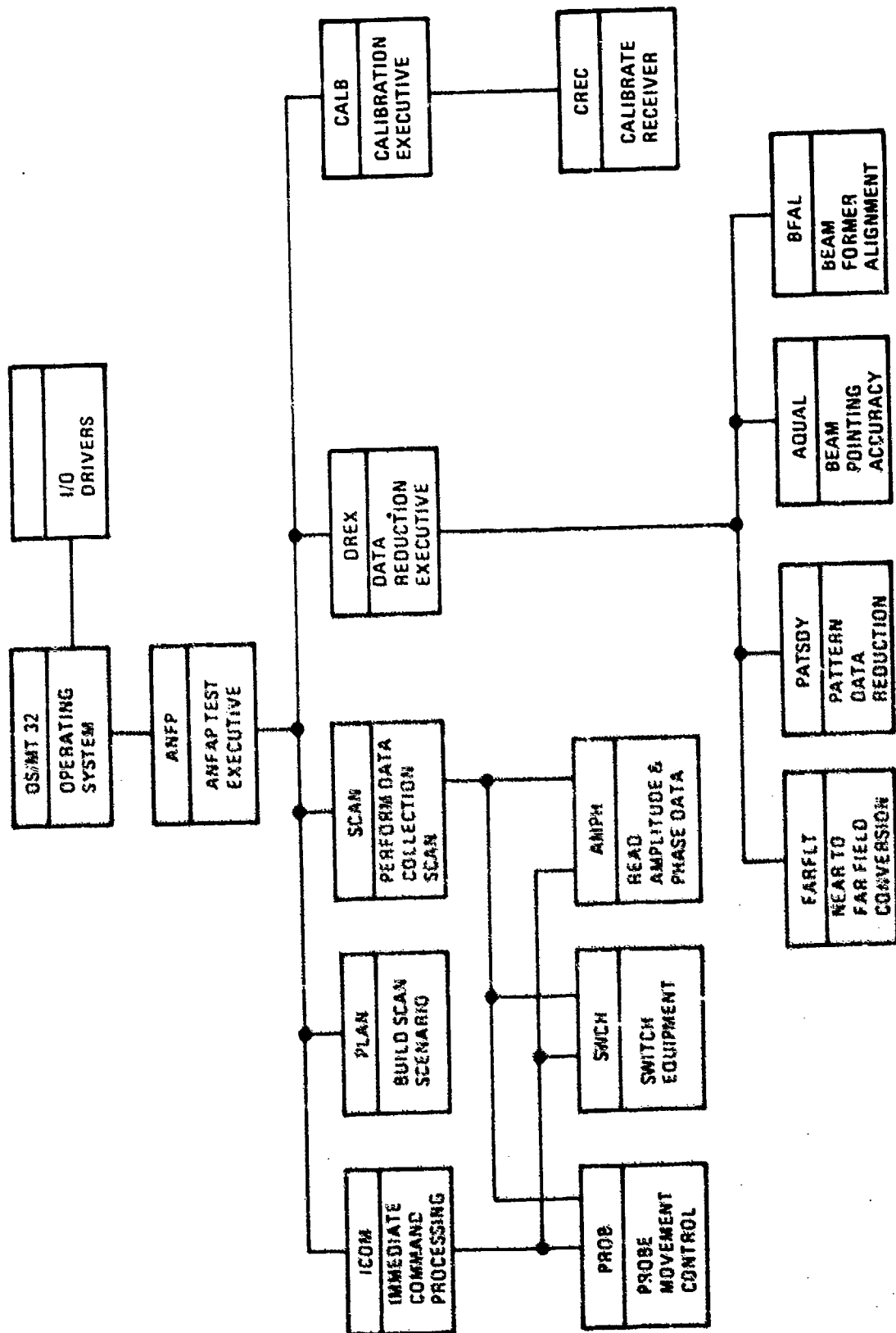


Figure 4. Computer Program Architecture.

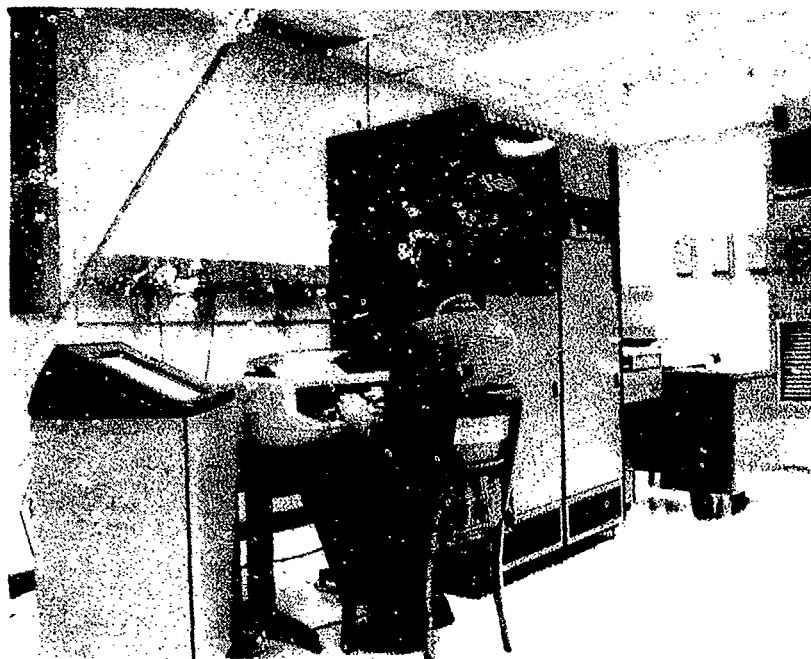


Figure 5. Computer programs were developed on the Interdata 8/32 computer system which is located in the control room shown in Figure 1.

In addition to the antenna acceptance computer programs, a program was developed to provide computer assistance during alignment of the antenna receive beam-former. This program processes the measured near-field data back to the antenna's aperture plane to identify which of the 68 receive subarrays is misaligned. From this measurement data a waveguide length correction report is generated to direct which of the 88 waveguide runs must be adjusted and the amount of the adjustment. These computer programs were accepted in December 1978.

Test System Housing - Housing the test system is an RCA supplied pre-engineered insulated steel building with 40 by 50 ft floor area and 30 ft interior height (see Figure 6).

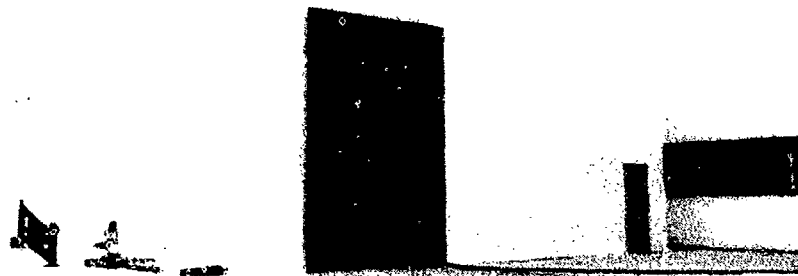


Figure 6. Test System Enclosure.

Engineering Data - Engineering drawings of the programmed scanner and its servo cabinet and extensive computer program documents were prepared on this program. The computer program documents include a performance specification, a design specification, a program description document for each subprogram, a data base document, and Fortran IV listings for each program. This data is available from NOSC, Code 8211.

End-of-Contract Review - A program review and end-of-contract demonstration were conducted for representatives of government and industry in December 1978. The results of the scanner performance measurements were shown as well as actual performance. Computer program architecture was discussed and selected computer printouts were shown. Figures 7 and 8 show the participants of this meeting during the formal presentations and during the scanner demonstrations.



Figure 7. Scanner Performance Demonstration: W. A. Harmening (right) demonstrates the scanner assembly during the end-of-contract review.



Figure 8. End-of-Contract Program Review: The participants of the end-of-contract presentations are listed in Table 1.

Table 1. Attendees - End-of-Contract Review, 7 December 1978

Name	Organization
W. A. Harmening	RCA
J. Bloomer	NAVSEC, Philadelphia, PA
L. L. Coulter	RCA
D. A. Palmer	Raytheon, MSO
J. C. Kuip	RCA
N. E. Artuso	RCA
R. M. Scudder	RCA
K. Egan	NSWC
R. B. Marcus	NAVSEA
J. J. Augustyn	NAVSEA Tech Rep
P. J. Dacri	NAVSEA Tech Rep
J. Tweedie	DCAS-Residency
J. Bordwick	ERADCOM U.S. Army - Ft. Monmouth
T. W. Morris	Martin Marietta
C. E. Kirchhoff	Martin Marietta
R. E. Morath	NSWC
D. Wilsker	NAVMIRO, Philadelphia, PA
L. J. Clayton	RC.
E. Schwartz	RCA
E. Stagnitti	Scientific Atlanta
D. Hess	Scientific Atlanta
D. S. Henderson	NWESA
D. Gamble	NOSC
D. H. Mercer	RCA
R. L. Mather	NOSC

TABLE OF CONTENTS

<u>SECTION</u>	<u>PAGE</u>
1 INTRODUCTION	1
1.1 Background	1
1.2 Project Objectives	2
1.3 Critical Requirements	3
2 PROGRAMMED SCANNER	5
2.1 General Description	5
2.2 Configuration Features	7
2.3 Operational Description	9
2.4 Error Allocation	12
2.5 Mechanical Design	20
2.6 Mechanical Alignment	27
2.7 Scanner Calibration	38
2.8 Servo Control System	47
3 COMPUTER PROGRAMS	59
3.1 Computer System	59
3.2 Computer Program Architecture	62
3.3 Typical Mode Scenario	67
3.4 Data Reduction Outputs	70
3.5 Computer Program Documentation	75
4 CONCLUSIONS AND RECOMMENDATIONS	76
APPENDIX A - Computer Program Documents	78

LIST OF ILLUSTRATIONS

<u>Figure Numbers</u>	<u>Title</u>	<u>Page</u>
2.1-1	Tower Mounted Drive Components for X-Axis	5
2.1-2	Tower Mounted Encoder Assembly for X-Axis	6
2.1-3	Carriage Mounted Buffers	7
2.4-1	Scanner Geometry and Coordinates	14
2.4-2	Error Derivation - Primary X Rail, X-Y Plane	17
2.5-1	X Shaft Assembly	21
2.6-1	Coordinate System Designations	28
2.6-2	X Rail Alignment Tool	32
2.6-3	A Clinometer is used to measure tower vertical angle deviations	32
2.6-4	Y-Axis Rail Straightness Measurements	35
2.6-5	Y-Axis Rail Clinometer Measurements	35
2.8-1	Block Diagram-Servo Control System	48
2.8-2	Servo Cabinet in Test	49
2.8-3	Block Diagram - Servo Rate Loop	50
3.1-1	Block Diagram - Computer System	60
3.1-2	Interdata 8/32 Computer System	61
3.2-1	Computer Program Architecture	63
3.2-2	Computer Program Memory Map	68
3.4-1	Principal Plane Line Cut	71
3.4-2	Monopulse Error Curve	72
3.4-3	Waveguide Correction Report	73

LIST OF TABLES

<u>Table Number</u>	<u>Title</u>	<u>Page</u>
2.4-1	Scanner Initial Error Budget Summary	13
2.4-2	Scanner Final Error Budget Summary	15
2.6-1	Alignment Requirements From Probe Position Error Budget	29
2.6-2	Other Alignment Requirements Imposed	30
2.6-3	Final Alignment Status	37
2.7-1	Calibration Results	44
2.7-2	Measured Values and Corrected Error Budget	46

Section 1

INTRODUCTION

1.1 Background

The present method of testing large phased array antennas uses a far-field test range to develop antenna patterns. This method is quite lengthy, requires hoisting a heavy antenna to an elevated pedestal, and has limited diagnostic capability. Near-field testing is relatively short, is performed inside the production plant, and has excellent diagnostic capability.

Studies authorized by the Naval Ship Engineering Center^{1,2}, US Army Missile Command³, and studies by RCA AEGIS Production Planning have shown the near-field method to have general application for production test of any antenna and to be particularly suitable for large planar phased array antennas. The laboratory work of the National Bureau of Standards and Georgia Institute of Technology confirms this.

RCA plans to apply the near-field method to production test of the AEGIS AN/SPY-1A Phased Array Antenna. Development of the test system is primarily under the AEGIS Production Program with two major elements provided under this Manufacturing Technology contract. RCA capital funds were used to provide the test system housing, computer equipment, and electronic measurement equipment.

1. Newell, Allen C., "Application of Planar Near-Field Antenna Measurement Techniques to Large Phased Arrays - Feasibility Study", NBS, Boulder, CO, August 1975.
2. Frank, J., and G. C. Rose, "Comparison of Near-Field and Far-Field Techniques for Acceptance Testing of SPY-1 Antennas," Technology Service Corporation, Silver Spring, Maryland, July 1975.
3. Burns, C. P., and G. D. Rodrigue, "A Study of Comparative Costs for Far-Field Antenna Patterns Determined by Near-Field Measurements and by Far-Field Measurements," Georgia Institute of Technology, Atlanta, Georgia, January 1974.

1.2 Project Objectives

The objectives of the Manufacturing Technology program were to develop a programmed scanner and computer programs to satisfy the requirements of AEGIS AN/SPY-1A antenna production test and to provide a technology directly useful to industry. Further, the test system must be amenable to operation by non-engineering production test personnel, be self-contained within the production plant independent of outside equipment and personnel, and produce test data in a form requiring minimal technical judgment for an accept-reject decision.

An objective of the programmed scanner design, in addition to meeting its technical requirements, was convenience in alignment adjustments and periodic re-calibration. It was recognized that the scanner needed for this application would be larger than any previously constructed and the height at the top of the probe support mechanism could be as high as thirty feet from the floor. This dictated a design that made the alignment features convenient to personnel without the need for elevated personnel platforms.

An objective of the computer program was to provide assistance in aligning the antenna's receive beamformer. The near-field technique appeared to be particularly suited to measure antenna phase variations for prediction of antenna beamformer waveguide length adjustments. Beamformer waveguide adjustments have been previously made only after extensive measurements of each antenna subarray in the far-field.

1.3 Critical Requirements

The overall near-field system specification requirements were defined to ensure a low probability of either acceptance of a defective array or rejection of an acceptable array. These requirements were:

- Reference pattern gain measurement within ± 0.3 dB
- At least 80% probability that errors in measurement of -30 dB sidelobes would be less than ± 2 dB
- Beam pointing errors less than 0.25 mrad RMS
- Accuracy of beamformer phase characteristics of $< 2^\circ$ RMS for array column correlated residual errors and $< 3^\circ$ RMS for subarray residual errors.

The above requirements were then allocated to the various near-field subsystems. The scanner subsystem requirements were thereby established as follows:

- a. Fourier components of position deviation from commanded linear paths or incremental positions in the X, Y, or Z coordinates were not to exceed ± 0.020 in (0.508 mm) in the X, Y, or Z directions.
- b. Total position deviation from commanded linear paths or incremented positions in the X, Y, or Z coordinates was not to exceed 0.030 in RMS (0.762 mm). This total error shall include the periodic errors of (a) above.
- c. The useful scan area was to be 6 m (X axis - horizontal) by 5.5 m (Y axis - vertical).

- d. The Y-axis rate capability was to be up to 50 cm/sec (data collection rate of ~15 cm/sec). The X-axis rate capability was to be up to 10 cm/sec (data collection rate of ~5 cm/sec).
- e. Appropriate self-protection features were to be incorporated. The design was to include a high degree of component interchangeability and ease of maintenance.

The critical requirements for the computer programs were established as follows:

- a. A real time controller was to:
 - Control probe scanning for various test scenarios
 - Collect measured phase/amplitude data during probe scan
 - Multiplex measured channel, beam position, and frequency.
- b. A calibration and pretest function was to provide the test conductor with computer directed assistance for measurement subsystem calibration and testing.
- c. A data reduction and display function was to perform a near-to-far field transformation, correct the measured data for probe characteristics, display pattern contours, line cuts, local minimums/maximums, and beam pointing error data.
- d. A report to the test conductor was to show the needed corrections to the antenna's receive beamformer to assure that antenna phase alignment was correct.

Section 2
PROGRAMMED SCANNER

2.1 General Description

The scanner mechanism (shown in Figure 1, page v) is a cantilevered tower supported by linear bearings on two horizontal floor mounted shafts which provide for a tower X travel of 6 m. A probe carriage is supported by linear bearings on two vertical tower-mounted shafts which provide for a carriage Y travel of 5.5 m.

A pair of pancake tachometers and a motor are housed together with a pair of bearings to create the drive motor package used for either scanner axis. The motor shaft drives a pinion gear (different size for each axis) which engages a fixed rack gear in each axis. Figure 2.1-1 illustrates the tower-mounted drive components for the X-axis.

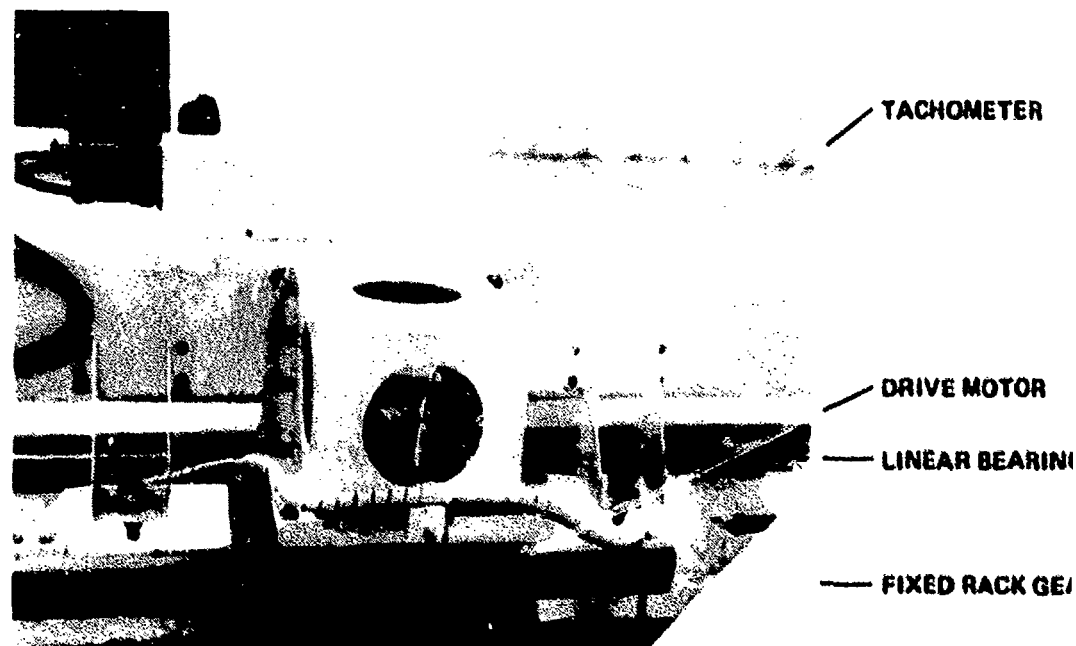


Figure 2.1-1. Tower-Mounted Drive Components for X-Axis.

Dual Digital (5 bit and 13 bit) encoders are driven from a separate fixed rack gear in each axis to report tower and carriage X and Y position to displays and to the computer. These units are identical for both axes. Figure 2.1-2 illustrates the tower-mounted encoder assembly for the X-axis.

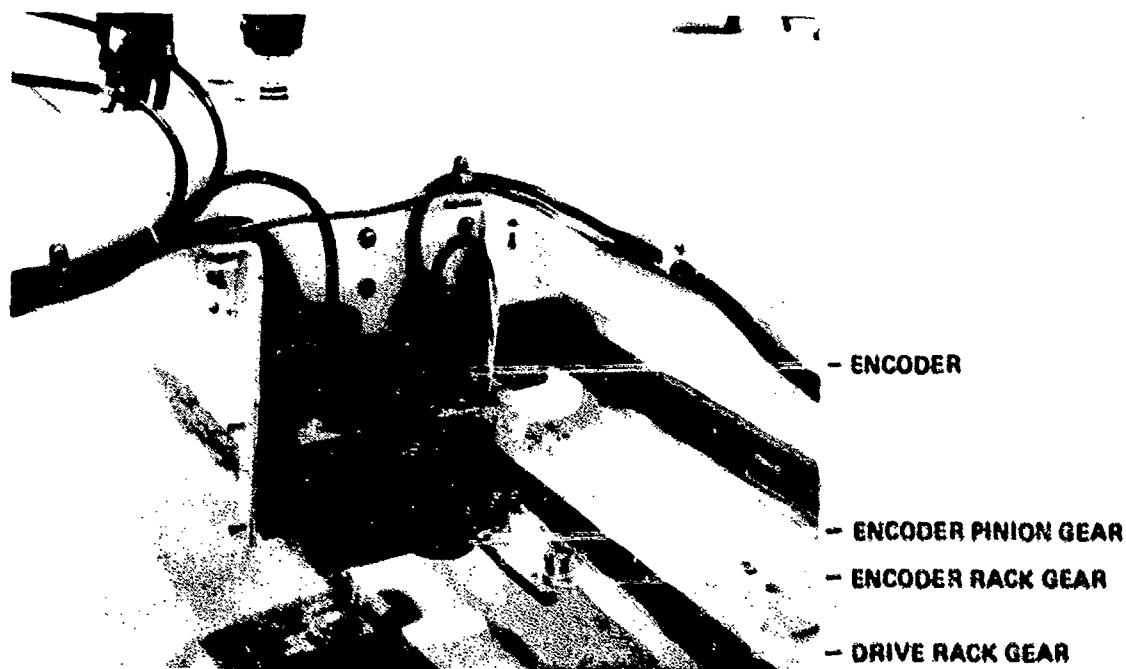


Figure 2.1-2. Tower-Mounted Encoder Assembly for X-Axis.

To minimize motor loads, the carriage is mass balanced by a counterweight and a pulley system. Redundant steel cables support the counterweight in the interior of a tower structural column.

Both axes utilize a total of four identical limit switches to control over-travel; in addition, six travel arresting buffers (four in X and two in Y) are used to decelerate safely tower or carriage motion in excess of the travel limits. Figure 2.1-3 illustrates carriage mounted buffers.

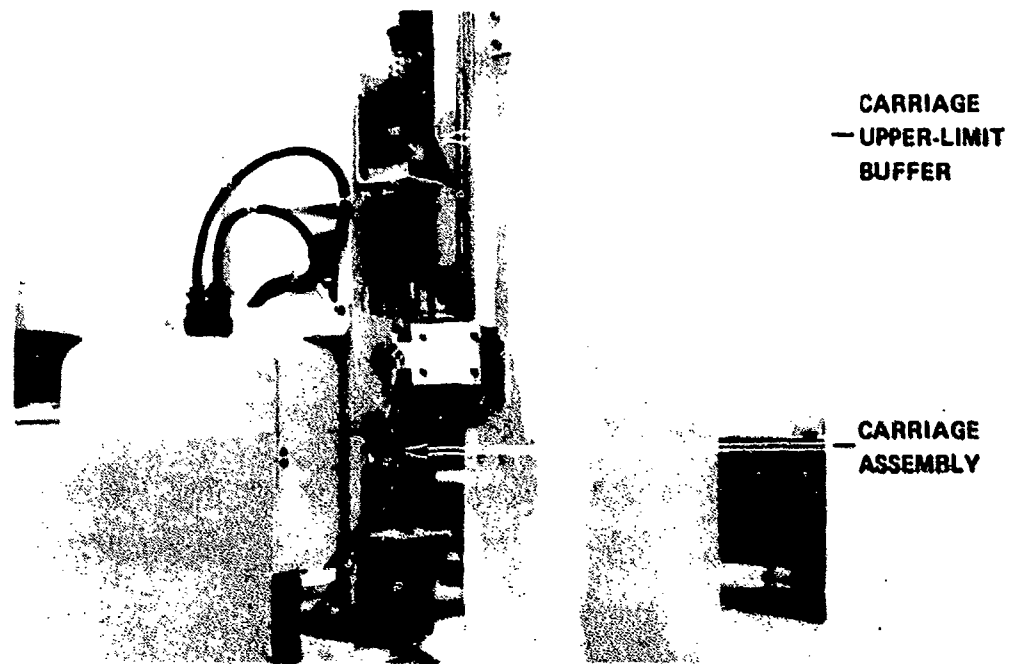


Figure 2.1-3. Carriage Mounted Buffers.

An RF probe will be mounted to the carriage and is capable of being driven by a closed digital control loop in a prescribed manner to collect RF phase and amplitude data of the antenna under test.

2.2 Configuration Features

The cantilevered tower scanner configuration is a departure from past practice and offers several features that are advantageous in a production test situation. First, the scanner is independent of the building wall and roof deflections caused by varying external wind, snow/ice, or thermal loads. This is critical since such deflections can perturb the RF probe's X, Y, and Z positions yielding erroneous test results. Second, the scanner tower and carriage can both be completely covered with RF absorber to minimize multiple reflections.

Third, the critical X axis rails are readily accessible for alignment checks and realignment if necessary. In addition, the linear bearings, motors, tachometers, pinion gears, encoders, limit switches, buffers and electrical junction boxes for both axes are accessible from floor level for maintenance, repair and replacement with or without the test antenna in place.

The RCA system resides in a temperature controlled environment. This and the all steel construction of the scanner, excluding the aluminum linear bearing pillow blocks, minimizes thermal deflections of the RF probe to improve measurement accuracy.

RCA recognized early in the program that the scanner/servo dynamic performance would play a major role in establishing the overall probe positioning accuracy. For this reason, considerable effort was expended in the detailed system configuration design to overcome recognized sources of dynamic error. The solution consisted first of minimizing external and self generated load disturbances and second of designing high stiffness structural elements in the critical load paths.

The external load disturbances were minimized by mounting the scanner and the test antenna on a 12 in-thick reinforced concrete pad isolated from the building.

The use of standard rack and pinion gearing to avoid flexible elements in the drive train partially resolved the self generated dynamic loads that can arise from drive motor forces. Further, the servo tachometer loops include electrical compensation networks to provide damping for the entire system. This is a fundamental improvement over other existing near-field scanners.

Self generated disturbances can also be created by the linear bearings used to restrain the tower or carriage statically. This configuration would normally require extremely tight tolerance control on shaft "gauge" (distance between shafts) to avoid stick-slip motion. These problems are partially overcome by articulating the single bearing on the shaft so that "gauge" variation effects are minimized. In addition, the drive motor is placed midway between the two bearings on the primary shaft with minimum offset between the shaft and drive rack gear to equalize bearing loads, to minimize lateral bearing forces, and to reduce the tendency for stick-slip motion.

2.3 Operational Description

The near field (X-Y) scanner employs a single RF probe antenna which is scanned over a planar surface parallel to and separated a few wavelengths from the aperture of the test antenna. A microwave receiver is connected to the test antenna port of interest and the amplitude and phase of the RF signal received at the probe antenna are recorded at intervals of typically 3 cm over the planar surface.

To obtain far-field test antenna parameters, the array of digitized disk recorded near-field data is transformed to the far-field via digital computation, and corrections are made for the characteristics of the probe to obtain the desired antenna gain and radiation patterns. For production acceptance testing, it is planned that acceptance criteria will be defined in terms directly related to far-field parameters and accept-reject decisions will be a software function.

A minicomputer is utilized to control the scanner, the test antenna beam position, the s-band test frequency, and the sampling of the near-field data.

2.3.1 Scan Definition

As defined previously, the near field RF amplitude and phase data are sampled at 3 cm intervals (X and Y) over the active scan area of 6 m (X) by 5.5 m (Y).

During a data collection scan, the probe carriage is driven at a constant velocity in the Y direction from the bottom to the top of the coverage area while the tower is maintained in a fixed X position. A slow speed return of the probe carriage is executed in the Y axis and simultaneously the X axis is incremented 3 cm in preparation for the next cycle of data collection. This process takes less than 1 min; however, the above cycle is repeated for 201 lines of data collection and therefore requires about 3 hr. All of the above actions are performed with digital position loops closed through the computer.

The slow speed Y axis return of the probe carriage is at a rate of 50 cm/sec and requires 11.7 sec. This time is utilized for equipment calibration, quick looks at the phase data collected, and for sorting and transfer of data from computer memory to the disk.

Although consideration was given to collection of data in both directions of carriage motion, it was concluded that the above features were necessary and that data reordering and sorting for the opposite scan direction was an unnecessary complication. Further, the acceptance tests to be performed on the test antenna require data from four antenna channels at three frequencies at a number of steered beam positions. Thus multiplexing of antenna channel, frequency, and beam position would further complicate

sorting of data collected in both directions.

A typical data collection scan speed is 15 cm/sec; this speed is controlled by the computer and is a function of the amount of data collected.

Multiplexing allows collection of as many as 100 data streams (product of the number of test antenna channels, frequencies, and beam positions) in one scan run. This capacity is limited by available disk space. The software control programs have been arranged for flexibility in selection of the actual data streams to be collected, the probe velocity, and the scanner tower positioning for data collection at this velocity.

In addition to the normal data collection during the Y scan with the X axis fixed, the scanner may be operated with the Y axis fixed and data collected in the X direction. This data collected is called a tie scan, and the data collected is utilized to normalize all scan data collected in the Y direction to account for time- or temperature-dependent drift in the electronic equipment.

2.3.2 Acceleration Control

It is expected that the tests of each antenna will require several 3-hr scans to perform all alignment work, to perform portions of the acceptance tests, and to perform the final acceptance tests. Since several antennas will be tested, each with several full scans and 201 axis scan lines per scan, the scanner wearout becomes significant. For this reason and to avoid dynamic excitation of the scanner, acceleration control has been given careful attention.

In starting the constant velocity data collection scan, it is possible to impose a step input of the commanded scan rate instantaneously. However, this tends to excite dynamic modes and is abusive of drive train gears and bearings.

For this reason, the acceleration torque actually imposed is a half cycle sinusoid

This torque characteristic is obtained by imposing feed-forward signals in the scanner position loop during the acceleration/deceleration period. This in effect causes the scanner to reach data collection velocity smoothly. This feature, as compared to step commanded velocities, does require additional travel to accelerate to data collection speed. Approximately 3 cm of travel have been allocated at each end of each axis for this purpose. This travel is in addition to the 6 by 5.5 m active coverage area.

2.4 Error Allocation

An early task, critical to scanner design, consisted of identifying RF probe position error sources and establishing values for each contributor. The initial design error budget is shown in Table 2.4-1. This tabulation is based on scanner geometry that has become obsolete due to probe relocation. However, it does point out the need for precise linear bearing shaft alignment as indicated by the large values for items 1 through 8 of Table 2.4-1.

The final scanner geometry is shown in Figure 2.4-1; a second, revised error budget (updated for final geometry only) is shown in Table 2.4-2. This error budget is based upon the selection of a particular method for obtaining scanner alignment. The method selected by RCA is predicated upon the use of a laser straightness interferometer as the basic alignment tool. Thus, the error budget is based upon the ability to measure straightness error of long linear bearing shafts.

Table 2.4-1. Scanner Initial Error Budget Summary.

ERROR SOURCE	AXIS - ERRORS IN MILS		
	X	Y	Z
(1) PRIMARY X RAIL VERTICAL PLANE, 0.002" STRAIGHTNESS	14.6	2.0	0
(2) PRIMARY X RAIL HORIZONTAL PLANE, 0.005" STRAIGHTNESS	3.6	0	5.0
(3) SECONDARY X RAIL VERTICAL PLANE, 0.003" PARALLEL TO 1 ABOVE	0	0	11.10
(4) PRIMARY Y RAIL X-Y PLANE, 0.004" STRAIGHTNESS	4.0	0	0
(5) PRIMARY Y RAIL Y-Z PLANE, 0.004" STRAIGHTNESS	0	10.2	0
(6) SECONDARY Y RAIL X-Y PLANE, 0.004" PARALLEL TO 4 ABOVE	8.3	0	0
(7) LINEAR BEARING CLEARANCE (0.0005" ADJUSTED)	1.5	1.3	0
(8) X TO Y ORTHOGONALITY ERROR	8.0	0	0
(9) ENCODER LSB ERROR	0.3	0.3	0
(10) ENCODER ACCURACY	0.3	0.3	0
(11) ENCODER PINION TOTAL COMPOSITE ERROR	0.6	0.6	0
(12) RACK GEAR TOTAL COMPOSITE ERROR	2.8	2.8	0
(13) RACK GEAR RUNOUT ERROR (0.005" PARALLELISM)	1.8	1.8	0
(14) THERMAL ERRORS (+5°F)	3.5	3.2	0.7
(15) THERMAL GRADIENT ERRORS (10°F)	0	6.5	0
(16) DYNAMIC ERRORS - Y DRIVE ONLY	1.2	0.5	5.4
(17) SERVO POSITION ERROR (STARTING TRANSIENT)	3.0	3.0	0
ROOT SUM SQUARE (RSS) VALUE			
	20.3	13.5	13.3
SPECIFICATION ALLOWABLE RMS			
	30	30	30
WORST CASE SUM			
	53.5	32.5	22.2

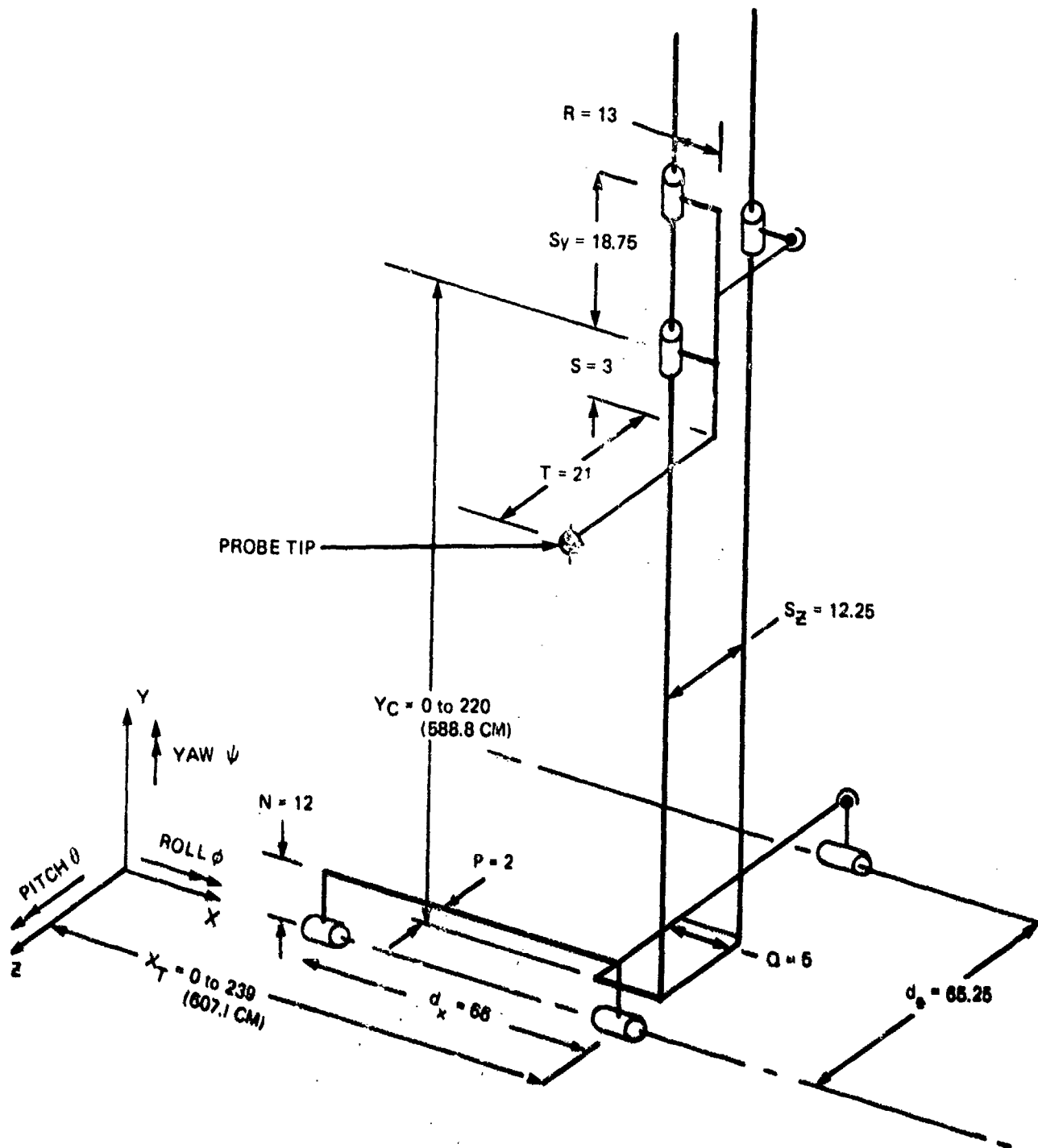


Figure 2.4-1. Scanner Geometry and Coordinates.

Table 2.4-2. Scanner Final Error Budget Summary.

ERROR SOURCE	AXIS - ERRORS IN MILS		
	X	Y	Z
(1) PRIMARY X RAIL VERTICAL PLANE, 0.002" STRAIGHTNESS	13.9	3.1	0
(2) PRIMARY X RAIL HORIZONTAL PLANE, 0.005" STRAIGHTNESS	3.5	0	7.7
(3) SECONDARY X RAIL VERTICAL PLANE, 0.003" PARALLEL TO 1 ABOVE	0	2.1	10.5
(4) PRIMARY Y RAIL X-Y PLANE, 0.004" STRAIGHTNESS	5.3	5.5	0
(5) PRIMARY Y RAIL Y-Z PLANE, 0.004" STRAIGHTNESS	0	9.0	5.3
(6) SECONDARY Y RAIL X-Y PLANE, 0.004" PARALLEL TO 4 ABOVE	6.9	0	4.2
(7) LINEAR BEARING CLEARANCE (0.0005" ADJUSTED)	1.5	1.3	0
(8) X TO Y ORTHOGONALITY ERROR	8.0	0	0
(9) ENCODER LSB ERROR	0.3	0.3	0
(10) ENCODER ACCURACY	0.3	0.3	0
(11) ENCODER PINION TOTAL COMPOSITE ERROR	0.6	0.6	0
(12) RACK GEAR TOTAL COMPOSITE ERROR	2.8	2.8	0
(13) RACK GEAR RUNOUT ERROR (0.005" PARALLELISM)	1.8	1.8	0
(14) THERMAL ERRORS (+5°F)	3.5	3.2	0.7
(15) THERMAL GRADIENT ERRORS (10°F)	0	6.5	0
(16) DYNAMIC ERRORS - Y DRIVE ONLY	1.2	0.5	5.4
(17) SERVO POSITION ERROR (STARTING TRANSIENT)	3.0	3.0	0
ROOT SUM SQUARE (RSS) VALUE	19.5	14.2	15.6
SPECIFICATION ALLOWABLE RMS	30	30	30
WORST CASE SUM	52.6	40	33.8
RMS VALUE	5.2	3.8	5.8

In establishing the error budget, the scanner tower and carriage are each viewed as bodies with 6 degrees of freedom. For each body one of the three translations (X, Y, Z) is the desired scanning motion and two constitute errors. All three angular motions (pitch about Z, roll about X, and yaw about Y) are error sources.

In assessing RF probe position errors due to tower or carriage motion, one of the three bearings is selected and considered to undergo pure (three axis) translational motion only. The remaining two bearings are then viewed as imparting the three rotational motions of the tower or carriage. These rotational motions are generated by linear displacement of the remaining two bearings with respect to the single translating bearing but displaced from this bearing by fixed distances yielding rotational angles.

For example, item 1 of the error budget (Table 2.4-1 or 2.4-2) refers to the vertical plane of the primary bearing shaft for the X axis and is associated with an alignment straightness tolerance of 0.002 in.

Figure 2.4-2 illustrates the derivation of the probe position errors ($\Delta X = 13.9$ mil and $\Delta Y = 3.1$ mil) for this case. The worst-case phasing of the rail straightness error curve is assumed to avoid imposing a phasing tolerance on the alignment process. This assumption permits alignment flexibility since trade-offs between measured angle and straightness errors are permissible.

The following equations define the error values associated with line items 1 through 6 of the error budget (Table 2.4-2) and are based on the geometry shown in Figure 2.4-1 and the straightness/parallelism tolerances used for alignment:

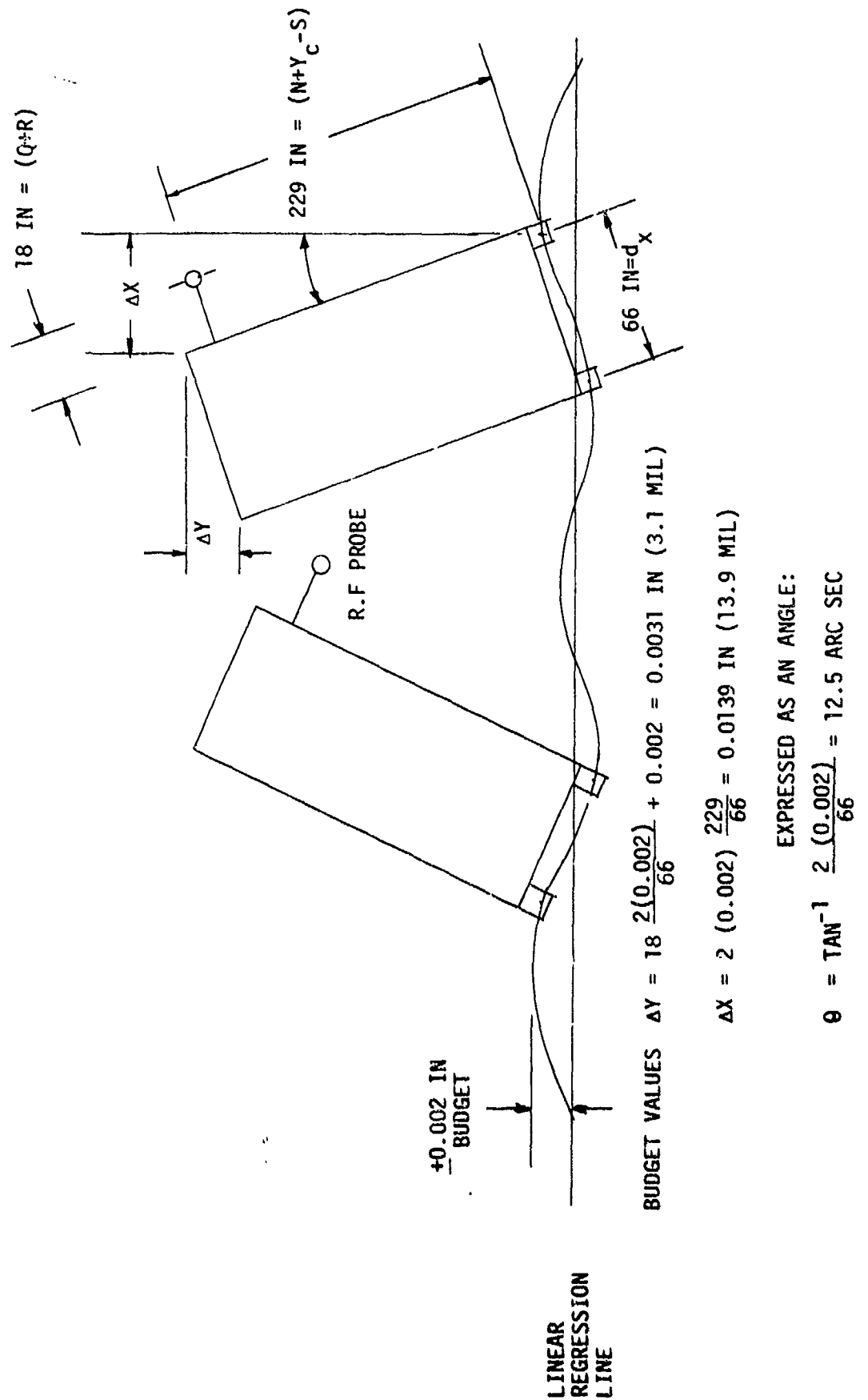


Figure 2.4-2. Error Derivation - Primary X Rail, X-Y Plane.

Budget Line 1 - Primary X Rail, X-Y Plane

(0.002 in straightness, tower pitch angle = ± 12.5 arc sec max.)

$$\Delta X = (N + Y_C - S) \frac{2 (0.002)}{d_x} = (912 + 220 - 3) \frac{0.004}{66} = 0.0139 \text{ in} \quad (13.9 \text{ mil})$$

$$\Delta Y = (Q + R) \frac{2 (0.002)}{d_x} + 0.002 = (5 + 13) \frac{0.004}{66} + 0.002 = 0.0031 \text{ in} \quad (3.1 \text{ mil})$$

Budget Line 2 - Primary X Rail, X-Z Plane

(0.005 in straightness, tower yaw angle = ± 31.25 arc sec max.)

$$\Delta X = (T + P) \frac{2 (0.005)}{d_x} = (21 + 2) \left(\frac{0.010}{66} \right) = 0.0035 \text{ in} \quad (3.5 \text{ mil})$$

$$\Delta Z = (Q + R) \frac{2 (0.005)}{d_x} + 0.005 = (5 + 13) \left(\frac{0.010}{66} \right) + 0.005 = 0.0077 \text{ in} \quad (7.7 \text{ mil})$$

Budget Line 3 - Secondary X Rail, X-Y Plane

(0.003 in parallel to line 1, tower roll angle ± 9.5 arc sec max.)

$$\Delta Y = (T + P) \frac{0.003}{d_z} = (21 + 2) \left(\frac{0.003}{65.25} \right) = 0.0021 \text{ in} \quad (2.1 \text{ mil})$$

$$\Delta Z = (N + Y_C - S) \left(\frac{0.003}{d_z} \right) = (12 + 220 - 3) \left(\frac{0.003}{65.25} \right) = 0.0105 \text{ in} \quad (10.5 \text{ mil})$$

Budget Line 4 - Primary Y Rail, X-Y Plane

(0.004 in straightness, carriage pitch angle = 88 arc sec max.)

$$\Delta X = (S) \frac{2 (.004)}{S_y} = 3 \left(\frac{0.008}{18.75} \right) = 0.0053 \text{ in} \quad (5.3 \text{ mil})$$

$$\Delta Y = (R) \frac{2 (.004)}{S_y} = 13 \left(\frac{0.008}{18.75} \right) = 0.0055 \text{ in} \quad (5.5 \text{ mil})$$

Budget Line 5 - Primary Y Rail, Y-Z Plane

(0.004 in straightness, carriage roll angle = ± 88 arc sec max.)

$$\Delta Y = T \frac{2 (0.004)}{S_y} = 21 \left(\frac{0.008}{18.75} \right) = 0.0090 \text{ in} \quad (9.0 \text{ mil})$$

$$\Delta Z = S \frac{2 (0.004)}{S_y} + 0.004 = 3 \left(\frac{0.008}{18.75} \right) + 0.004 = 0.0053 \text{ in} \quad (5.3 \text{ mil})$$

Budget Line 6 - Secondary Y Rail, X-Y Plane

(0.004 in parallel to Line 4, carriage yaw angle = ± 67.35 arc sec max.)

$$\Delta X = (T) \frac{0.004}{S_z} = 21 \frac{0.004}{12.25} = 0.0069 \text{ in} \quad (6.9 \text{ mil})$$

$$\Delta Z = R \left(\frac{0.004}{S_z} \right) = 13 \left(\frac{0.004}{12.25} \right) = 0.0042 \text{ in} \quad (4.2 \text{ mil})$$

The values for budget line items 7, 9, 10, and 11 are defined by vendor-supplied data for the components selected.

The X to Y orthogonality error of 0.008 in (line 8 of the budget) is a tolerance selected for alignment of the primary X and Y bearing rails in the X-Y plane. The X rail is set vertical in the Y-Z plane to approximately one arc min and does not appear as an error because the test antenna is aligned to a best fit X-Y plane defined by scanner calibration.

The data rack gear total composite error (line 12 of budget) is based on the use in each axis of 22 11-in sections of a PIC precision three rack. Each section has a total composite error of 0.0006 in. The alignment tolerance value entered in the error budget is $0.0006 \sqrt{22}$ or 0.0028 in (2.8 mil). The rack gear runout alignment value of 0.005 in yields an error of 0.0018 in (1.8 mil) based on a tooth pressure angle of 20° . The runout tolerance of 0.005 in

refers to lack of parallelism between the data rack pitchline and the primary rail alignment in one plane (X-Z plane of primary X rail and Y-Z plane of primary Y rail).

The remaining budget values (items 14 through 17) have been generated by analysis.

The error budget as shown in Table 2.4-2 has served the intended purpose of defining alignment requirements. Measured scanner errors show that all significant error sources have been identified.

It is noted that the RSS values of Table 2.4-2 are statistical representations of the worst-case errors expected, whereas the RMS values listed represent the specification for expected probe tip RMS errors; thus the error budget is very conservative.

2.5 Mechanical Design

The following material presents the details of the major scanner mechanical elements. The scanner assembly and details are defined by RCA drawing number 8364786.

2.5.1 Linear Bearings and Shafts

The scanner tower horizontal motion is achieved by mounting a Thomson linear ball bushing (Thomson Part SUPER-32-OPN) at each corner of the tower base. These bearings have a 2 in bore selected for conservative load-life ratings. The three linear bearings are supported on two, 2-in OD, steel shafts: two on the front (primary) X rail and one on the rear (secondary) rail. Both rails are supported by heavy floor mounted "I" beams.

The Y axis rail configuration is identical, except the basic bearings have a 3/4 in bore (Thomson Part SUPER-12-OPN) and the rails of course are mounted vertically on the tower structure.

The shafts for both axes are fabricated of 1060 steel by Thomson and are case hardened to RC60. Because the required shaft lengths are not obtainable as a single piece, they are butt joined with an axial dowel pin press fitted at one end and slip fitted at the other end. Figure 2.5-1 shows the X shaft during assembly.



Figure 2.5-1. X-Axis Shaft During Assembly: The X Shaft Segments are Joined with an Axial Dowel Run.

The bearings are housed in aluminum pillow blocks obtained from Thomson (Part Numbers SPB-32-OPN and SPB-12-OPN). Except for these pillow blocks, the entire scanner is constructed of steel.

The single bearing on the secondary shaft, in each axis, is connected to the tower or carriage using Fafnir rod end bearings. This rod end articulation

(ball and socket joint) permits $\pm 1/32$ in variation between rails in the plane of both. This variation is of no significance in defining or controlling scanner accuracy and avoids tight tolerance control as well as preventing significant lateral forces from developing on the bearings.

Preventing lateral force buildup decreases tendency for stick-slip motion when driven by a motor and permits achievement of smooth scan motions.

2.5.2 Drive Motors, Tachometers, and Gears

The motor and dual tachometer assembly is interchangeable between the X and Y axis except for the output pinion gear. The drive gear rack for each axis is a standard, 12 pitch, 20° pressure angle steel gear (Boston Gear Part Number L2012-6) with a 1 in square section, built up with 6 ft-long sections.

The drive pinions are also 12 pitch, 20° pressure angle gears with a 1 in facewidth. The gear for the X axis has a 1.8333 in pitch diameter (22 tooth), and the gear for the Y axis has a 4 in pitch diameter (48 tooth). These gears are custom made of SAE 4340 steel heat treated to RC 38.

The drive motor is an Inland pancake, brush type DC torque (Part Number QT6202) with a samarium cobalt magnet field assembly. This motor is 1.24 in long, has an OD of 7.20 in and an ID of 3.94 in, and is rated at 11 ft-lb peak (stall) torque. The power amplifier output, however, is current limited so that the maximum torque developed in this application is 7 ft-lb.

Dual tachometers are housed with the above motor. The tachometers are Inland (Part TG2936C) pancake units, 3.730 in OD, 1.640 in ID, and 1.240 in long.

The motor and both tachometers are placed in a built up housing and supported with Kaydon ball bearings at one end and a matched preloaded set at the pinion gear end of the housing.

2.5.3 Position Encoders and Gearing

Scanner position information is required from both axes to communicate with the minicomputer, to drive servo cabinet readout displays, and to close a manual position loop on the servo cabinet. The encoding system used is identical for each axis and is a two-speed, 18-bit, electro-optical system.

The 13-bit fine encoder and the 5 bit coarse encoder are obtained from Itek (Part Numbers RA13/23CMX and RA5/23CMX, respectively). The coarse encoder is coupled to the fine encoder shaft by a 32:1 ratio (2^5) gearbox; the fine encoder will then rotate 32 revolutions for one revolution of the coarse encoder (turns counter for fine encoder). The shaft of the fine encoder is in turn driven by an antibacklash, 24 pitch, 20° pressure angle, 60-tooth (2.5 in) stainless steel gear obtained from PIC (Part Number P7-2-60), as were all encoder gears and gear boxes.

This gear engages a 24 pitch, 20° pressure angle, precision three rack gear obtained from PIC (Part Number AG-31-P3) in 10.9956 in lengths.

With the above gears, the encoders are capable of uniquely encoding over a lineal distance of 638.7 cm, which is in excess of the required X- or Y-axis travel.

2.5.4 Buffers and Limit Switches

Travel-arresting buffers were obtained from Ace Controls (Part Number SAHS-3/4 in bore, 1 in stroke). Two buffers are mounted on the carriage arranged to arrest carriage motion at both travel extremes. Four buffers are mounted in pairs at the base of the tower, one pair is arranged to arrest tower motion at one travel limit and the second pair at the other travel limit.

Four microswitches (Micro Switch Part Number 23EN9-G) are mounted on the scanner, two on the carriage and two on the tower. These switches have gold plated contacts to prevent welding. The switches are located and adjusted to open just prior to contact with the travel limiting buffers to prevent application of drive torque in the direction of the violated travel limit. The motor can be driven away from this limit.

2.5.5 Counterweight System

The carriage is mass balanced using a dual cable system over two pulleys at the top of the tower and a counterweight interior to the 6 in by 12 in tower box beam. Mass balance of the carriage thereby reduces drive motor torque requirements. The cable compliance determines the carriage dynamic resonance frequency which is of concern for the Y-axis rate loop.

In addition, the counterbalance mass swings as a pendulum for X-axis accelerations; thus the counterweight has been protected with sponge rubber to minimize dynamic perturbations caused by X-axis acceleration.

2.5.6 Structural Arrangement

The scanner is structurally very simple, consisting of a carriage, the tower and the foundation. (See Figure 3, page v.)

The carriage is weldment fabricated from ASTM-A36 steel tubing, 3/4 in square by 0.060 in wall thickness. The carriage has provisions for mounting the RF probe, the RF linkage, and RF absorber on the front face.

The tower is also a weldment with the vertical columns fabricated from ASTM A50

GRB steel. Two of the columns are 6 in square with a 0.18 in wall, and the third is a 6 in by 12 in by 0.25 in wall. All bracing struts are of ASTM A36 steel, 1.75 in square with a 0.12 in wall.

The 6 in by 12 in by 0.25 in wall column dimensions were selected for size compatibility with the Y-axis linear bearings and the drive rack and data rack gears.

This column provides a stiff load path for the Y-axis and is a key element in the tower bending stiffness. The remaining tower columns were selected to equalize as much as possible the tower section inertia about orthogonal axes as defined by the tower sectional geometry and the sectional properties of the three columns.

The X-axis primary bearing shafts are supported on standard wide flange steel beams, WF 10 X 112 for the primary rail and WF 8 X 48 per ASTM A36 for the secondary rail. These beams are permanently clamped and grouted to the concrete base. The base is a 12 in-thick reinforced concrete slab (15 ft by 31 ft) isolated from the floor of the building.

The tower face will be covered with RF absorber to minimize RF reflections.

2.5.7 Bearing Shaft Supports

The X-axis and Y-axis linear bearing shaft supports are similar for both axes. The support consists of a steel tee section with a single bolt through the tee leg to a hole tapped into the linear bearing shaft at each support point. The support vertical and lateral adjustment is obtained using a six-bolt pattern on the tee crossbar; three of the bolts are jacking

screws and three are holddown bolts. Lateral motion is achieved by differential operation of the jacking screws; thus vertical and lateral adjustments are not independent.

It is desirable to have independent support adjustment capability, and such supports are available from Thomson. However, the low stiffness for the available X-axis supports could have resulted in a low frequency tower rocking mode. A low-frequency rocking mode will impact the Z-direction accuracy as well as the X-axis servo rate loop capability, and is therefore not acceptable.

The Y-axis shaft supports are not critical dynamically, and the standard Thomson independently adjustable supports could be used. This would undoubtedly decrease the time spent in aligning the Y axis rails and would be cost effective.

The X-axis rails were easier to align than the Y-axis rails because of the greater stiffness of the shaft, the "I" beam base, and the reduced support spacing. Although the independent adjustment feature is not as necessary in X, it is possible that the standard Thomson support could also be used here by increasing the bearing shaft diameter and/or reducing support spacing to obtain sufficient stiffness to control the tower rocking modes.

2.6 Mechanical Alignment

The Scanner Assembly requires careful alignment to fulfill the probe position tolerances specified in Section 2.4. Other alignment constraints were imposed to assure proper system operation in addition to the alignment parameters defining probe errors above.

The total scanner alignment problem is thus a sizeable task requiring considerable skill, time, and patience to achieve an acceptable system.

2.6.1 Alignment Criteria and Considerations

Table 2.6-1 repeats alignment tolerances impacting probe position errors; this data is extracted from Section 2.4. Table 2.6-2 defines additional alignment tolerances required to meet other system functional parameters.

Both tables are based on the scanner coordinate system defined in Figure 2.6-1.

As defined in Section 2.4, the linear bearing shaft straightness and parallelism requirements are entered in the error budget as translations plus worst-case angle rotations. This is done to simplify the alignment criteria and is predicated on the use of a laser straightness interferometer as the primary alignment tool.

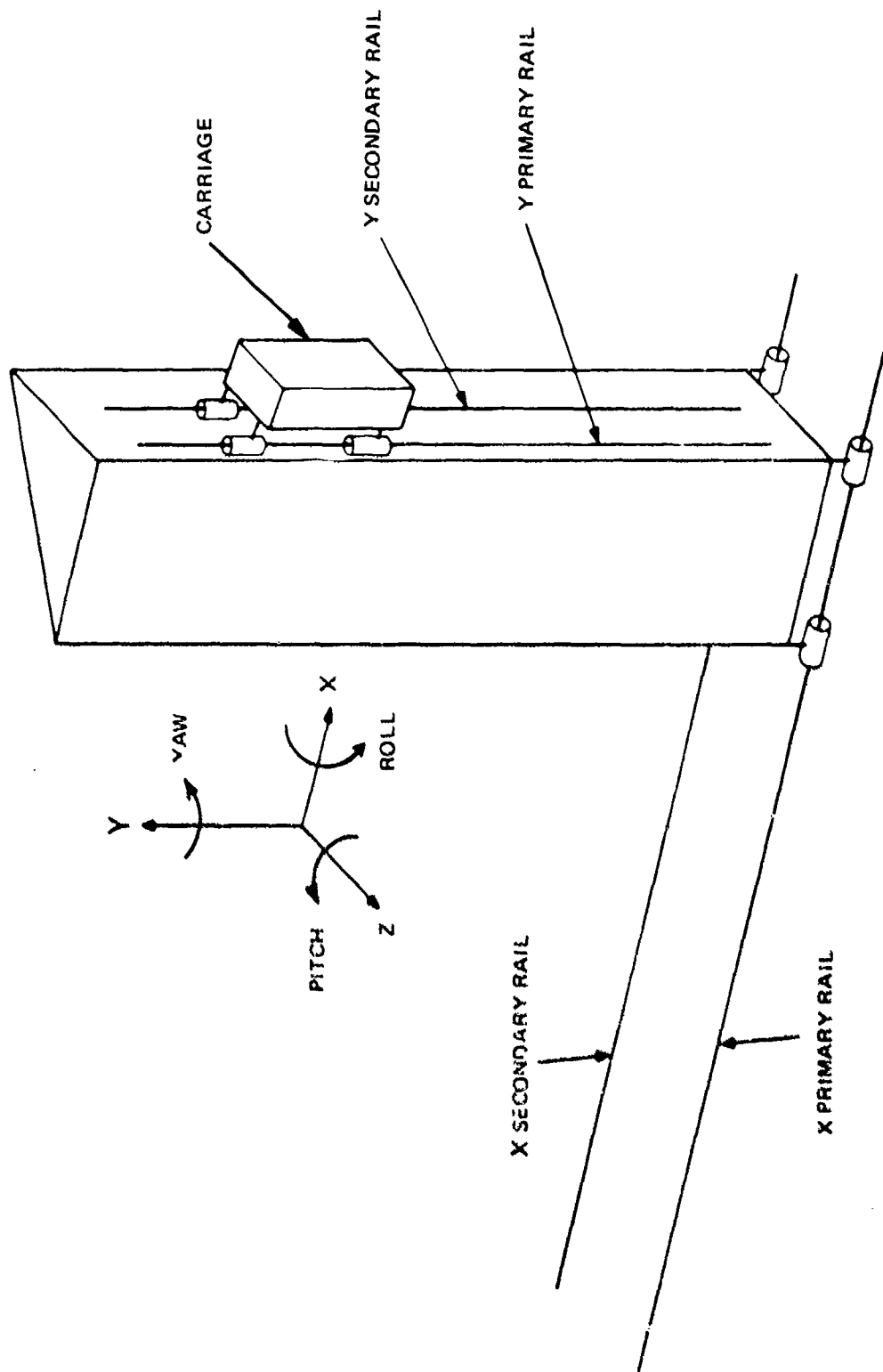


Figure 2.6-1. Coordinate System Designations.

TABLE 2.6-1. ALIGNMENT REQUIREMENTS FROM PROBE POSITION ERROR BUDGET (TABLE 2.4-2).

ITEM	ELEMENT ALIGNED	ALIGNMENT TOLERANCE	ALIGNMENT EQUIPMENT
1	Primary X Rail, X-Y Plane	0.002" Straightness with ± 12.5 ARC Sec Max Tower Pitch Angle	Straightness Interferometer Angle with Clinometer
2	Primary X Rail, X-Z Plane	0.005" Straightness with ± 31.25 arc sec Max Tower YAW Angle	Straightness Interferometer Angle Calculated
3	Secondary X Rail, X-Y Plane	0.003" Parallel to 1 above with ± 9.5 arc sec Max Tower Roll Angles	Calculated Straightness Angle with Clinometer
4	Primary Y Rail, X-Y Plane	0.004" Straightness with ± 88 arc sec Max Carriage Pitch Angle	Straightness Interferometer Angle Calculated *
5	Primary Y Rail, Y-Z Plane	0.004" Straightness with ± 88 arc sec Max Carriage Roll Angle	Straightness Interferometer Angle with Clinometer *
6	Secondary Y Rail, X-Y Plane	0.004" Parallel to 4 above with ± 67.35 arc sec Max Carriage YAW Angles	Calculated Straightness Angle with Clinometer *
7	X to Y Orthogonality Error, X Y Plane	$\pm 0.008"$ at Max Carriage Height or ± 7 arc sec	Straightness Interferometer on Two Axes with Optical Square
8	X and Y Encoder Rack Runout	$\pm 0.005"$ Variation Normal to Pitch Plane	Dial Indicator

*Alignment Performed with Horizontal Tower and +Z-axis Toward Floor.

TABLE 2.6-2. OTHER ALIGNMENT REQUIREMENTS IMPOSED.

ITEM	ELEMENT ALIGNED	ALIGNMENT TOLERANCE	ALIGNMENT EQUIPMENT
1	Primary X Rail, X-Y Plane Level	$\pm 0.025^{\circ}$ Max Leveling Error	Clinometer
2	Primary Y Rail, Vertical In Y-Z Plane	$\pm 0.125"$ From Vertical Over Length of Y Rail	Plumb Bob
3	X and Y Encoder Rack Straightness	$\pm 0.005"$ Straightness Error in Pitch Plane	Dial Indicator
4	X and Y Drive Rack Runout	$\pm 0.003"$ Straightness Normal to Pitch Plane	Dial Indicator
5	X and Y Drive Rack Straightness	± 0.003 In. Straightness Error in Pitch Plane	Dial Indicator
6	Secondary X Rail X-Z Plane	$\pm 1/32"$	Dial Indicator
7	Secondary Y Rail Y-Z Plane	$\pm 1/32"$	Dial Indicator

Using the straightness interferometer, the bearing shafts are aligned until the straightness requirement has been met over a major portion of the shaft length. The actual angle variations are then measured directly or calculated based on the straightness data and known bearing separation. The angle and straightness data together then define the actual probe position error contribution and eliminate the worst case angle assumption. If the angle errors are appreciably less than the worst case angle assumed, then further reductions of the straightness errors are not required. In effect a tradeoff between contributions is performed to determine the need for additional straightness adjustments.

2.6.2 Alignment Method

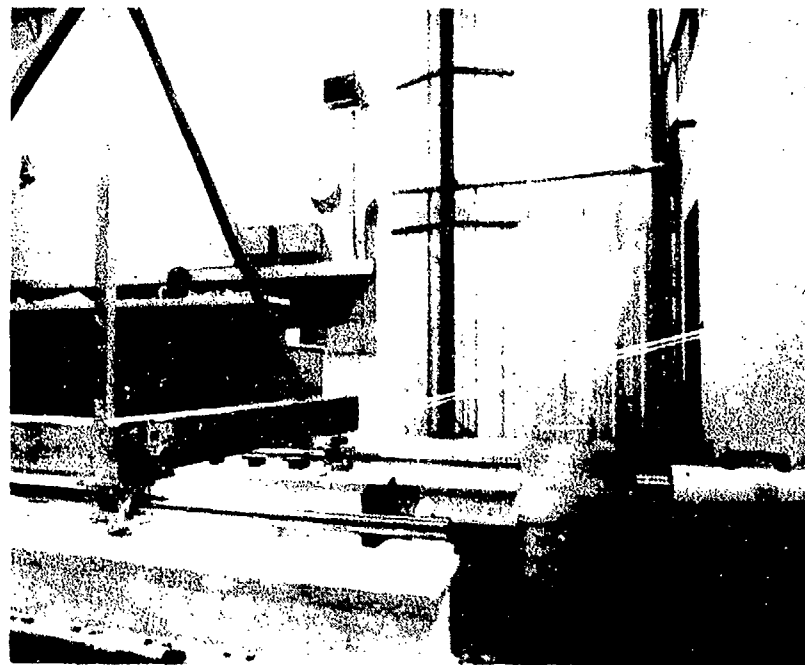
The laser straightness interferometer was the basic alignment tool; however, other equipment was also used as identified in Tables 2.6-1 and 2.6-2.

The straightness interferometer consisted of a Hewlett-Packard HP5500C Laser Head and HP5505A Laser Display with option HP031 Long Range Straightness Interferometer, HP10579A Resolution Extender and Adapter and HP10691A Straightness Interferometer and Reflector. For bearing rail alignment the straightness interferometer was placed as close to the rail centerline as possible to minimize the impact of other errors.

Tower vertical angle measurements were obtained with a Hilger-Watts clinometer.

2.6.2.1 X-Axis Alignment

The initial X-rail alignment was accomplished using a special tool which essentially replicated the tower base to permit X- and Y-rail alignment to proceed in parallel with a single laser system. Final X-axis alignment was performed with the actual tower in place. Figure 2.6-2 shows the special tool fitted to the X rails.



ALIGNMENT
TOOL

Figure 2.6-2. X-Axis Rail Alignment Tool.



CLINOMETER

Figure 2.6-3. A clinometer is used to measure tower vertical angle deviations.

The X-axis primary rail is a 2.00 in diameter shaft, 320 in in length, supported at 10 in intervals. The rail straightness in the Y and Z directions was measured at 5 in intervals along the length of the rail with the laser straightness system. There is an inherent slope to the straightness data with this measurement technique. Therefore, the data was reduced by the Least Square Fit method to obtain an error record at each measurement point. With the error record defined, the rail position was adjusted at each support to reduce the straightness error. The rail supports feature an adjustment capability of a three bolt jacking screw arrangement configured about a three bolt clamping pattern. The jacking screws were manipulated to lift or rotate each support into the required position. This process was reiterated until the straightness tolerance was essentially achieved. As this laser system is capable of measuring only one plane of straightness at a time, adjustments were alternated between the orthogonal planes. Dial indicators were used to monitor the second plane during adjustments.

Clinometer readings or calculated angle variations were then obtained to determine the need for further straightness adjustment with respect to budgeted errors.

In addition, the clinometer was used to measure the level condition of the primary rail; out-of-level data was incorporated in the straightness adjustment procedure for the vertical plane of the X-axis primary rail. Figure 2.6-3 shows the tower clinometer measurements.

The secondary rail horizontal plane was first adjusted by the dial indicator to $\pm 1/32$ in of parallelism of the primary rail horizontal plane.

The secondary rail parallelism to the primary rail in the vertical plane was assessed by direct clinometer measurement of tower roll angle at intervals of one-half the rail support spacing. The angle measurement was then converted to vertical plane straightness errors of the secondary rail and adjustments made to correct tower roll angle errors.

2.6.2.2 Y-Axis Alignment

The straightness for the Y-axis primary rail in the X and Z directions was measured at 6.5 in intervals along the 247 in long, 0.75 in diameter, Y shaft which is supported on 13.00 in centers. The straightness data was reduced as described for the X rail and adjusted in the same manner with the rail supports. No leveling condition had to be considered in the Y axis.

The Y-axis rail alignment was accomplished with the tower placed horizontally and with the Z axis perpendicular to the floor. Thus, clinometer readings were obtained as indicated in Table 2.6-1, and tradeoffs between straightness and angle variations were considered, as before, to determine acceptability of the straightness adjustments. Figure 2.6-4 shows the laser equipment measuring rail straightness. Figure 2.6-5 shows the Y-axis rail clinometer measurements.

2.6.2.3 X to Y Orthogonality

The X-axis to Y-axis rail orthogonality in the Y-Z plane was measured with a plumb bob. The X-axis secondary rail rod end bearing length was adjusted to suit the requirement. Determination of the orthogonality in the X-Y plane (item 8 of error budget) necessitated use of the HP Option 031 system in conjunction with the HP10693A Vertical Straightness Adapter, HP10692B Optical Square, and HP10558A Beam Bender. The measuring configuration required optical setup compatibility of

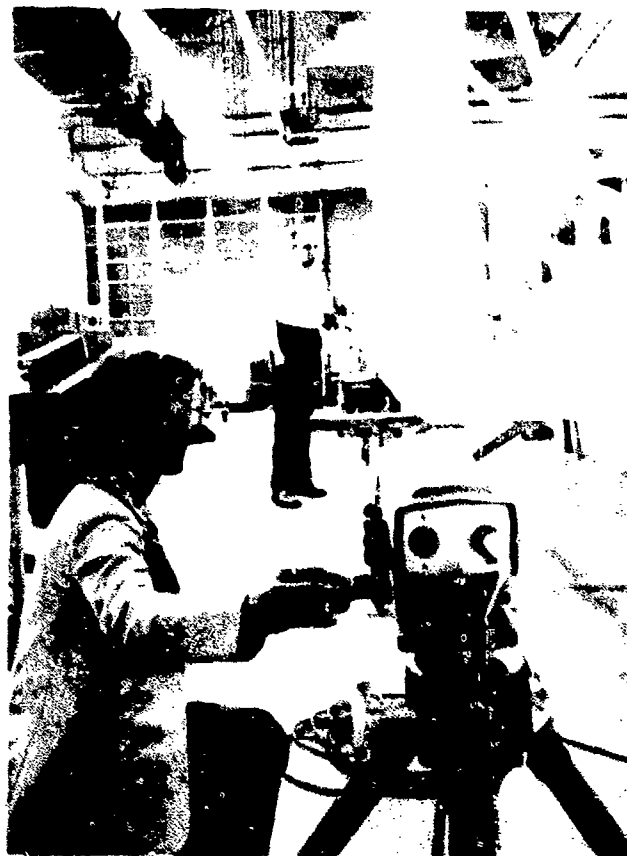
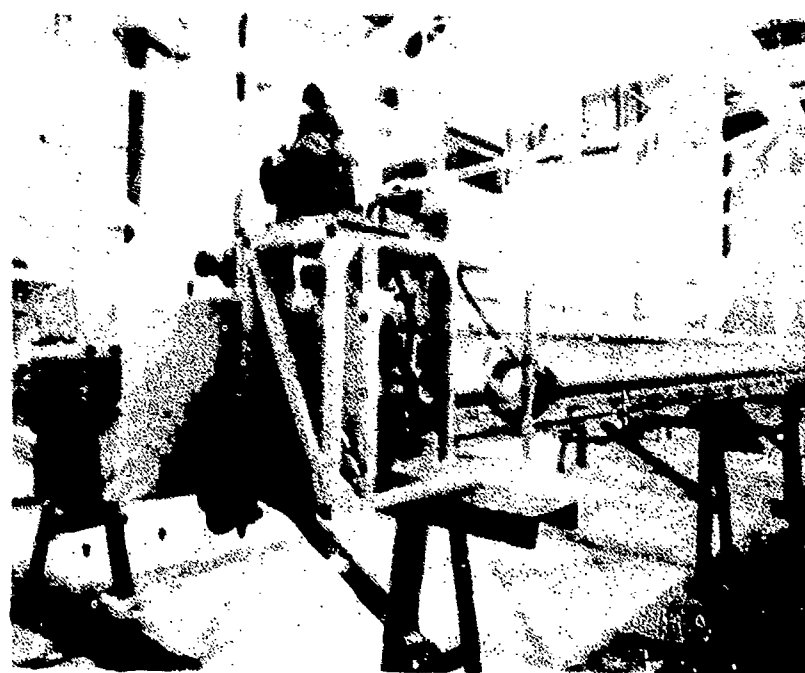


Figure 2.6-4. HP Laser System is used to align the Y-axis rails.



CLINOMETER
MOUNTED
TO THE
CARRIAGE

Figure 2.6-5. Y-Axis Rail Clinometer Measurements.

Y-direction straightness on the X-axis with X direction straightness on the Y axis. The inherent slope in straightness data for both measurements together with the known calibration of the optical square is utilized to determine the orthogonality value between the two axes at a particular tower X location. One pillow block of the tower on the X-axis primary rail was shimmed until the required orthogonality was obtained.

2.6.2.4 Gear Alignment

The drive and data rack alignments for both X and Y axes were measured with a dial indicator located at the motor or encoder pinion position, accordingly. The individual racks and/or rack supports were shimmed to meet the specified tolerances normal to and parallel to the pitch plane.

2.6.3 Alignment Results

2.6.3.1 Rail Assembly Goals

The rail straightness requirements budgeted in Table 2.4-2 served as the assembly goal for rail alignment. In addition, they are important to the final scanner accuracy calibration discussed in Section 2.7. Therefore, the final straightness alignment measurements are summarized in Table 2.6-3.

2.6.3.2 Alignment Acceptance

The final scanner alignment status is summarized in Table 2.6-3. It is noted that the straightness tolerance is not achieved in all cases; however, the measured angles were less than the worst case values assumed thereby achieving an acceptable error contribution.

TABLE 2.6-3. FINAL ALIGNMENT STATUS.

ITEM	ELEMENT ALIGNED	ALIGNMENT TOLERANCE	MEASURED ERROR
1	Primary X Rail X-Y Plane	0.002" Straightness ± 12.5 arc sec Max Tower Pitch	+0.0024" to -0.0019" +11.5 to -8.5 arc sec
2	Primary X Rail X-Z Plane	0.005" Straightness ± 31.25 arc sec Max Tower Yaw	+0.0043" to -0.0033" +20.5 to -19.5 arc sec
3	Sec. X Rail X-Y Plane	0.003" Parallelism to 1 above ± 9.5 arc sec Max Tower Roll	+0.0018" to -0.002" +5.6 to -65 arc sec
4	Primary Y Rail X-Y Plane	0.004" Straightness ± 88 arc sec Max Carriage Pitch	+0.0041" to -0.0029" +28.2 to -46.8 arc sec
5	Primary Y Rail Y-Z Plane	0.004" Straightness ± 88 arc sec Max Carriage Roll	+0.0045" to -0.0048" +66.4 to -52.7 arc sec
6	Sec Y Rail X-Y Plane	0.004" Parallelism to 4 above ± 67.35 arc sec Max Carriage Yaw	+0.0017" to -0.0022" +29.4 to -38.6 arc sec
7	X to Y Orthogonality X Y Plane	$\pm 0.008"$ (± 7 ARC Sec)	+5 arc sec
8	X and Y Encoder Rack Runout	$\pm 0.005"$ Variation Normal to Pitch Plane	$\pm 0.005"$ (X) $\pm 0.004"$ (Y)
9	Primary X Rail Level	$\pm 0.025^0$ Max	0.013 ⁰
10	Primary Y Rail Vertical	$\pm 0.125"$	0.09"
11	X and Y Encoder Rack Straightness	$\pm 0.005"$ Straightness in Pitch Plane	$\pm 0.005"$ (X) $\pm 0.002"$ (Y)
12	X and Y Drive Rack Runout	$\pm 0.003"$ Variation Normal to Pitch Plane	$\pm 0.003"$ X and Y
13	X and Y Drive Rack Straightness	$\pm 0.003"$ Straightness in Pitch Plane	$\pm 0.003"$ X and Y
14	Sec. X Rail X-Z Plane	$\pm 1/32"$	$\pm 1/32"$
15	Sec. Y Rail Y-Z Plane	$\pm 1/32"$	$\pm 1/32"$

2.7 Scanner Calibration

2.7.1 Calibration Error Model

The scanner probe tip positional errors ΔX , ΔY and ΔZ are described as a function of the probe X and Y encoder readout positions (X_{en} , Y_{en}) by the following three equations:

$$\Delta X (X_{en}, Y_{en}) = \Delta X (X_{en}, Y_{init}) + \Delta X (X_{init}, Y_{en}) - Y [\theta (X_{en}, Y_{init})] \quad (2.7-1)$$

$$\Delta Y (X_{en}, Y_{en}) = \Delta Y (X_{init}, Y_{en}) + \Delta Y (X_{en}, Y_{init}) \quad (2.7-2)$$

$$\Delta Z (X_{en}, Y_{en}) = \Delta Z (X_{en}, Y_{init}) + \Delta Z (X_{init}, Y_{en}) + Y [\phi (X_{en}, Y_{init})] \quad (2.7-3)$$

where: X_{en} = X encoder readout position, cm
 Y_{en} = Y encoder readout position, cm
 X_{init} = X encoder readout position for X-mechanical zero, stow position, cm
 Y_{init} = Y encoder readout position for Y-mechanical zero, stow position, cm
 Y = $Y_{en} - Y_{init}$, cm
 θ = tower pitch angle, radians
 ϕ = tower roll angle, radians

In order to assess fully the scanner accuracy, each of the eight variables comprising the three equations above was measured at $3 \text{ cm} \pm 0.01 \text{ cm}$ intervals. Those variables dependent upon X_{en} required 203 data points; those dependent upon Y_{en} required 187 data points. The computation of the three error equations for all X_{en} , Y_{en} describe ΔX , ΔY , and ΔZ with 37,961 data points each, on a 3 cm by 3 cm grid over the scanner coverage of 6 m along X by 5.5 m along Y.

2.7.2 Calibration Method

The data collection for the eight variables is divided into three types (linear, straightness, angular), each requiring a particular instrumentation combination.

2.7.2.1 Instrumentation

Basic Hewlett Packard Laser System:

HP5500C Laser Head

HP5505A Display Meter

Hewlett Packard Option 010, Linear Interferometer:

HP10565B Remote Interferometer

HP10550B Reflector

Hewlett Packard Option 031, Long Range Straightness

Interferometer:

HP10579A Resolution Extender and Adapter

HP10691A Straightness Interferometer and Reflector

Hewlett Packard Accessories:

HP10558A Beam Bender

HP10692B Optical Square

HP10693A Vertical Straightness Adapter

Hilger-Watts Clinometer

2.7.2.2 Linear Interferometer Measurements

The two encoder calibration measurements, $\Delta X (X_{en}, Y_{init})$ and $\Delta Y (X_{init}, Y_{en})$, were each obtained using the basic HP laser system with Option 010. The tower was stowed at X_{init} for the $\Delta Y (X_{init}, Y_{en})$ measurement. The carriage was stowed at Y_{init} for the $\Delta X (X_{en}, Y_{init})$ measurement. The

reflector was fixed at the probe tip location in both cases. Data from both the encoder readout and the laser display was recorded in pairs at 3 cm intervals of the encoder readout for full travel in both X and Y.

The error record input to the calibration reduction routine was derived from these data pairs. For $\Delta X (X_{en}, Y_{init})$ the difference between the laser and encoder readouts was determined. Because the error was unidirectional, an average error was computed. The final error record, $\Delta X (X_{en}, Y_{init})$, was then the difference between the direct error and the average error. For $\Delta Y (X_{init}, Y_{en})$ the difference between the two readouts was determined. As this error was not unidirectional, no averaging was desired and this remained the final error record for the calibration reduction.

2.7.2.3 Straightness Interferometer Measurements

The four straightness calibration measurements, $\Delta Z (X_{en}, Y_{init})$, $\Delta Z (X_{init}, Y_{en})$, $\Delta X (X_{init}, Y_{en})$ and $\Delta Y (X_{en}, Y_{init})$, were obtained using the basic HP laser system with Option 031. The tower was stowed at X_{init} for the two measurements dependent on Y_{en} and the carriage was stowed at Y_{init} for the two measurements dependent on X_{en} . The interferometer was fixed at the probe tip position. For $\Delta Z (X_{init}, Y_{en})$ and $\Delta X (X_{init}, Y_{en})$ the vertical adapter, optical square, and beam bender were incorporated in the optical path for ease of handling and aligning the other optical elements.

Data for both $\Delta Z (X_{en}, Y_{init})$ and $\Delta Z (X_{init}, Y_{en})$ was recorded from the laser display and encoder readout in pairs at 3 cm intervals for full travel in X or Y, accordingly. A linear regression analysis was used to describe a Least squares fitted straight line and to determine the error from that line at each measurement point. Thus, these two error records were compiled for the calibration reduction.

The elements $\Delta X (X_{init}, Y_{en})$ and $\Delta Y (X_{en}, Y_{init})$ are related by the orthogonality between the X and Y axes in the initial stow position of the tower. The orthogonality measurement is described in Section 2.6. As before, the laser display and encoder readouts were recorded in pairs at 3 cm intervals for each measurement. The individual data sets were reduced for ΔX and ΔY errors with the linear regression analysis. In addition, the orthogonality between the two axes was determined mathematically from the slopes of the two data sets (with respect to the optical square and reflector reference) and the known optical square calibration factor. Because this is the measurement of orthogonality at the tower stow position, the value determined is the initial pitch angle value.

2.7.2.4 Angular Measurement

The two angular data sets, $\theta (X_{en}, Y_{init})$ and $\phi (X_{en}, Y_{init})$, for tower pitch and roll angle excursions were obtained with the clinometer. The clinometer was clamped to the tower base in one of two orthogonal locations. Data was recorded in pairs from the clinometer and encoder readout at 3 cm intervals. The absolute values of the clinometer readings were of no significance, but the relative values create the desired error information.

For the pitch angle error record, an intermediary record for each measurement point was created of the average of all the measured values subtracted from each measurement. Then, an adjustment value, equal to the difference between the orthogonality value and the measured pitch angle in the tower stow position, was subtracted from each of the data points of the intermediary record.

This initialized the tower pitch angle to the orthogonality value and described the deviations from that initial value over full tower travel.

The roll data is not associated with an initializing value, and therefore the average of all the measured angles was subtracted from the measured data to describe the error at each point.

2.7.3 Calibration Data Reduction

The calibration measurements and their individual reductions described above develop five two-dimensional fields of 203 error measurements distributed on the X axis and three two-dimensional fields of 187 measurements distributed on the Y axis.

Equations 2.7-1, 2.7-2, and 2.7-3 were used to generate the ΔX , ΔY , and ΔZ values over the entire X-Y coverage area of the scanner. Each of these three fields then contains 37,961 error values.

For the ΔX and ΔY error fields, the RMS values and the 20 worst-case error values with their associated X_{en} and Y_{en} coordinates were identified. The ΔZ values were subject to a multiple linear regression analysis to determine the least square error fitted plane. The three coefficients defining the plane were identified. The error between that plane and the ΔZ error field was determined as well as the RMS value of all those errors. The 20 errors of greatest magnitude were identified with their associated X_{en} and Y_{en} coordinates.

The harmonic or spectral content of the probe tip ΔX , ΔY and ΔZ errors was next assessed by use of a two-dimensional Fast Fourier Transform (FFT). The two-dimensional discrete Fourier transform, $A(m, n)$, is a mapping into the two-dimensional sequence of Fourier coefficients, $A(K, l)$, defined by:

$$A(K, l) = \frac{1}{N_x N_y} \sum_{m=1}^{N_x} \sum_{n=1}^{N_y} A(m, n) \exp \left[-j \left\{ \frac{2\pi}{N_x} (m-1)(K-1) + \frac{2\pi}{N_y} (n-1)(l-1) \right\} \right],$$

where $K = 1, \dots, N_x$

$l = 1, \dots, N_y$

and N_x = the total number of points on X

N_y = the total number of points on Y

ΔX and ΔY are evaluated as the complex pair

$\Delta X + j\Delta Y$ for all m and n

Z is evaluated as the complex number

$\Delta Z + j0$ for all m and n

The calibration data evaluation computer program identifies any components $A(K, l)$ greater than any value arbitrarily specified by the program user.

2.7.4 Calibration Results and Discussion

The near-field scanner calibration data was recorded, reduced, and analyzed as described in the preceding sections.

It is observed that the calibration measurements performed are for a static situation and do not include thermal effects. Errors due to thermal variations, thermal gradients, dynamics, and servo transient errors (lines 14 through 17 of Table 2.4-2) are not assessed with this calibration method.

The comparison of errors obtained from calibration measurements and specification requirements is presented in Table 2.7-1. The RMS values of the position errors at the probe tip are significantly better than the requirement. This improves the accuracy of the antenna measurements. In addition to the specification requirements, mean and maxima error data is presented to offer a more complete representation of scanner accuracy.

Table 2.7-1 Calibration Results

AXIS	RMS PROBE ERROR, cm (in)		MAXIMUM HARMONIC COMPONENT ERROR, cm (in)	
	MEASURED	SPECIFIED	MEASURED	SPECIFIED
X	0.0159 (0.0063)	0.0762 (0.030) All Three Axes	X + jY 0.0072 (0.0028)	0.0508 (0.020) All Three Axes
Y	0.0190 (0.0075)			
Z	0.0109 (0.0043)		0.0032 (0.0013)	

AXIS	MEAN ERROR, cm (in)	MAX ERROR, cm (in)	X, Y LOCATION OF MAX ERROR, ENCODER READOUTS, cm	
			X	Y
X	0.0020 (0.0008)	0.0745 (0.0293)	16.318	505.382
Y	-0.0007 (-0.0003)	0.0518 (0.0204)	289.318	145.382
Z	7.964×10^{-8} (3.135×10^{-8})	-0.0411 (-0.0162)	328.318	427.382

As the test antennas will be aligned to the best fit plane developed by the multiple linear regression analysis, the plane equation and coefficients are offered here:

$$Z_p = M_x X_{en} + M_y Y_{en} + B_p,$$

where

M_x and M_y are slopes developed in the regression analysis
and B_p is the intercept coefficient

$$M_x = -2.312234 \times 10^{-5} \text{ cm}$$

$$M_y = 4.817124 \times 10^{-9} \text{ cm}$$

$$B_p = 7.384032 \times 10^{-3} \text{ cm}$$

2.7.5 Adjusted Error Budget

Comparing Table 2.7-1 with Table 2.4-2 (revised error budget), it is noted that the peak and RMS measured errors agree rather well with the budgeted values for the Z axis.

The X-axis RMS errors are also in good agreement; however, the peak measured values differ from the budgeted RSS values. Both the peak and RMS measured errors differ from the RSS and RMS-budgeted values in the Y axis.

During calibration of the Y-axis encoder error versus Y position (see equation 2.7-2), rather large errors were observed that appear to be due to the total rack gear composite error (line 12 of Table 2.4-2). It is surmised that additional effort with these rack gears might have reduced this error to the budgeted value of 2.8 mil. It was obvious at this time, however, that the error budget would be met with such large margins that expenditure of additional effort was not justified.

Because the encoder error has been identified as more nearly directly related to the number of rack sections (rather than the square root of the number of sections), a better representation of the total rack gear composite error is $0.0006 (22) = 0.0132$ in (13.2 mil) rather than the value $0.0006 \sqrt{22} = 0.0028$ in (2.8 mil) assumed in line 17 of Table 2.4-2.

This correction should be applied to both the X and Y axes (no impact for the Z axis) of the error budget (line 12, Table 2.4-2).

Table 2.7-2 presents a comparison of the measured results versus the error budget with the above correction applied. From Table 2.7-2, it is seen that the apparent disparities between budgeted and measured values (for a corrected budget) are for all practical purposes eliminated.

Table 2.7-2. Measured Values and Corrected Error Budget.

Error Type	Probe Tip Errors, in/1000		
	X Axis	Y Axis	Z Axis
Corrected RSS Budget Value	23.4	19.2	15.6
Peak Measured Value	29.3	20.4	10.2
Corrected RMS Budget Value	6.3	5.1	5.8
RMS Measured Value	6.3	7.5	4.3

2.8 Servo Control System

2.8.1 General Description

The general configuration of the scanner servo control system is shown in Figure 2.8-1 in block diagram form. The servo cabinet is defined by RCA Drawing No. 8668170. Both the X and Y drives are defined by this diagram and the following discussion applies to both axes. The rate loop is the primary portion of the control system and is designed to accept commands either locally from the servo control unit or remotely from the computer to control DC torque motors. Two tachometers sense the motor velocity, and rate signals are fed back to close the rate loop. The rate loop consists of a summing and scaling amplifier, a compensation amplifier, and a power amplifier to provide the armature current to the motor. The rate loop also senses such conditions as overspeed, low voltages, and travel limits and conditions the loop to minimize the possibility of damage to the scanner motors.

Local signals to the rate loop originate either as a velocity control slew signal or a position control voltage generated by the voltage difference between a position reference voltage and the actual position as sensed by the encoder. The manual velocity control is simply an insertion of one of four available DC voltages which provide fast and slow slews in either direction. The manual position voltage generated by the encoder (through the digital to analog converter - DAC) is compared to a potentiometer-controlled voltage reference signal, and the difference in amplitude between these two voltages causes the carriage to move to a position at which the voltage difference between the reference and DAC output is zero.

Positional information is provided by a two speed 18 bit encoder system located on the carriage (or tower). These 18 parallel bits are converted to a serial

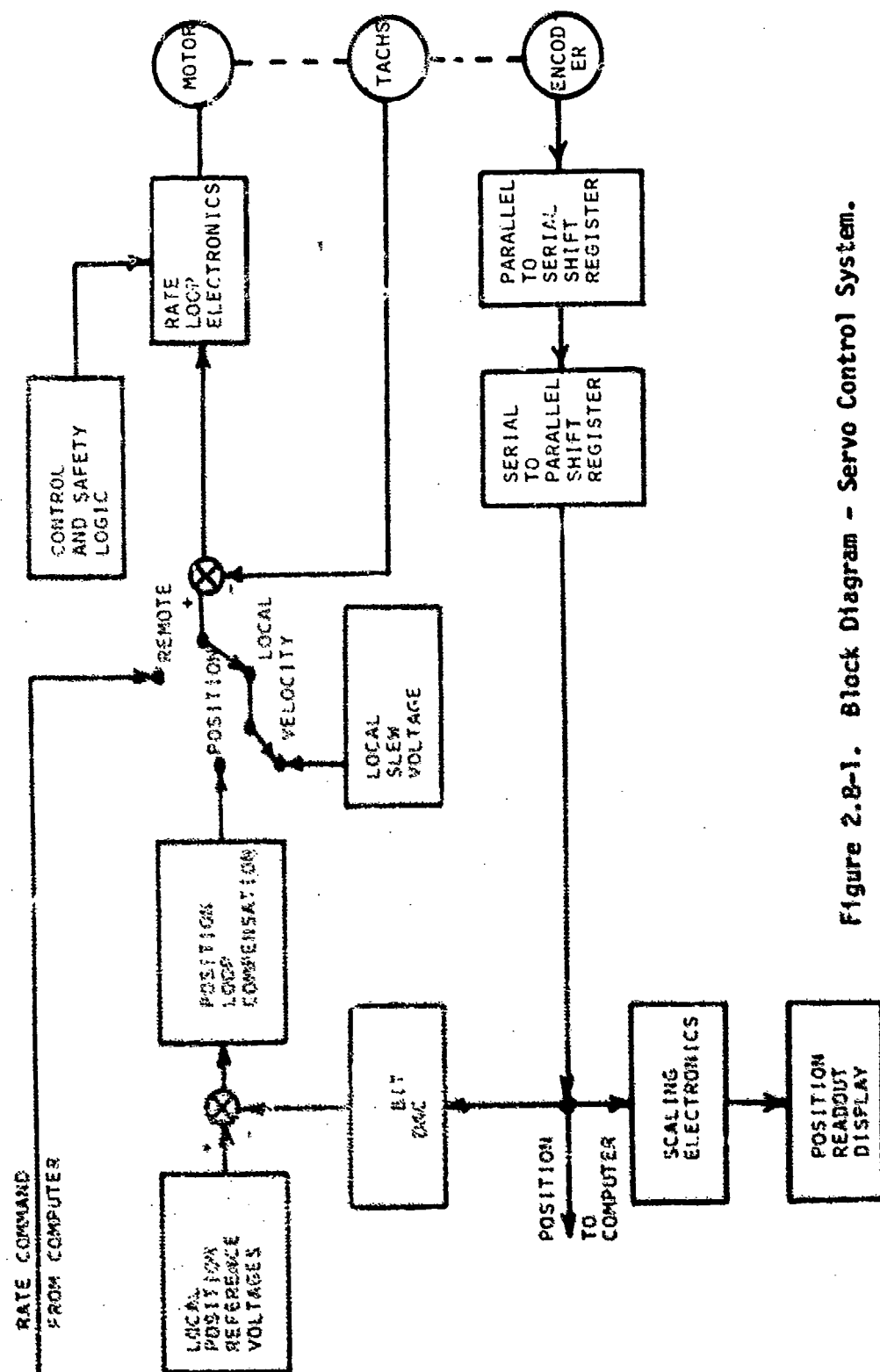


Figure 2.B-1. Block Diagram - Servo Control System.

train of pulses for transmission to the servo control unit. Here they are reconverted to a parallel form and transmitted to the computer as well as being converted to an analog signal for manual position loop closure and to drive the readout displays scaled to indicate carriage (tower) position in centimeters from an arbitrary reference point. Figure 2.8-2 shows the servo cabinet in test.

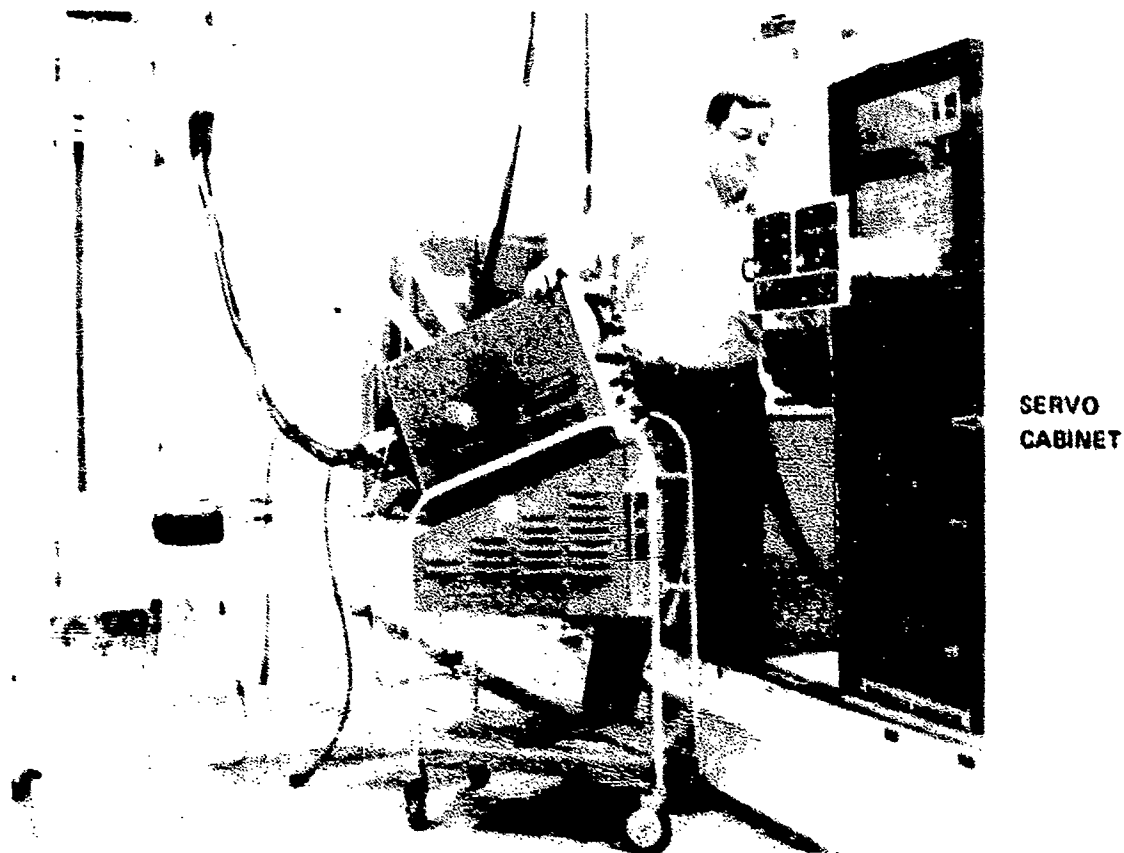


Figure 2.8-2. Servo Cabinet in Test.

2.8.2 Rate Loop

Details of the rate loop are shown in Figure 2.8-3. This rate loop is used to ensure smooth, even motion of the RF probe over a large range of velocities. An electronic integrator is used in the loop as a part of the compensation circuitry. The values of compensation differ for the two axes. For the X axis the

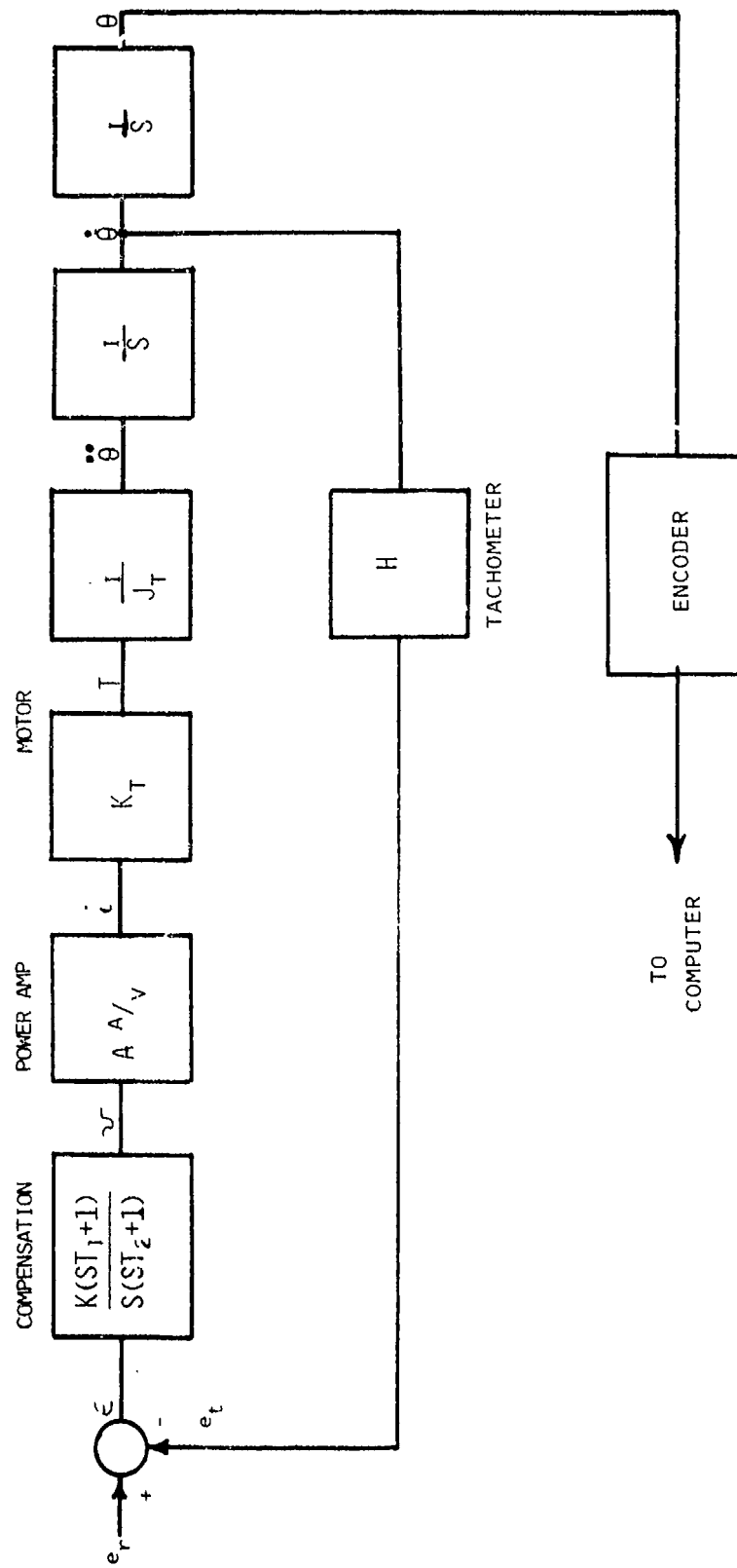


Figure 2.8-3. Block Diagram - Servo Rate Loop.

compensation value is

$$\frac{5.44}{S} \frac{\frac{S}{2\pi(.5)} + 1}{\frac{S}{2\pi(5)} + 1}$$

which configures the X-axis rate loop to a crossover frequency of 1.5 Hz. For the Y-axis the compensation value is

$$\frac{10.88}{S} \frac{\frac{S}{2\pi(1)} + 1}{\frac{S}{2\pi(10)} + 1}$$

which configures the Y-axis rate loop to a crossover frequency of 3.0 Hz.

The power amplifier for both axes is connected as a current source. Its nominal transfer function is

$$\frac{I_o}{e_{in}} = 1.0 \text{ amps/volt}$$

with a current limit set at 6.0 A maximum. This limits the torque that can be applied to either axis to 6.9 ft-lb, a value selected to obtain specified performance without applying excess torque or producing excessive heat in the motor.

The drive motors and tachometers are identical in both the X and Y axes. The motors are permanent magnet DC torque motors having a nominal armature resistance of 3.6 ohms and a nominal torque constant of 1.15 ft-lb/A. The tachometers are also permanent magnet devices having a nominal gradient of 1.1 V/rad/sec with an output resistance of approximately 300 ohms.

The nominal closed rate loop gradients are 1.0 cm/sec/V in the X axis and

5.0 cm/sec/V in the Y axis. Carriage rate control in the range of 0.025 cm/sec to 50 cm/sec and tower rate control in the range of 0.125 cm/sec to 10 cm/sec have been successfully demonstrated.

2.8.3 Position Loop

The local position loop is a convenience mode for positioning the scanner carriage in the absence of a computer signal. The loop is a Type I configuration with the gain set to provide a single 20% overshoot to a large step displacement. The feedback position voltage produced by the DAC ranges from 0 to +10 VDC with 16-bit granularity which is equivalent to 0.15 mV/bit with one bit being nearly equal to 0.01 cm of tower or carriage travel. The reference position voltage used is the +15 VDC analog circuit power supply voltage. Because this power supply has random drift of up to 2.0 mV, the position loop drifts up to 0.13 cm. This is satisfactory for the manual positioning.

2.8.4 Encoder Signal and Readouts

Each axis uses two optical encoders to obtain 18 bits of positional information. The encoders are configured in a coarse-fine relationship with the coarse (5 bit) encoder being geared 32:1 with respect to the fine (13 bit) encoder. The encoders work in conjunction with a digital translator that receives the 18 bits of encoder parallel position data and converts them into a serial stream that is transmitted, along with a clock signal, to a receiving digital translator in the servo cabinet, where they are reconverted to parallel information. The encoder-translator combination is controlled by an external clock running at a 400 kHz rate. This allows the 18 bits of information present at the output of the receiving digital translator to be updated 4000 times/sec. This is approximately

10 times faster than the computer reads position data and assures that the information is no more than 0.25 msec old when sampled. This arrangement then provides position data at a relatively fast rate while requiring only 8 wires (4 pairs) between the carriage or tower and the servo control unit; a savings of cost, weight, and complexity.

In the servo control unit, three different functions are performed on the 18 parallel bits of position data available at the output of the digital translator.

- a. The entire 18 bits plus a data ready bit are sent, in parallel, to the computer by means of balanced line drivers.
- b. The most significant 16 bits are converted to an analog signal for closing the local position loop.
- c. The 18 bits are scaled through a combination of binary and decade counters working on a time interval basis to display the absolute carriage position in centimeters on LED readouts. Six digits are displayed in the readout with the least significant being equivalent to 0.001 cm.

2.8.5 Power Amplifiers

The power amplifier is a linear operational amplifier controlling a power bridge output circuit. The amplifier and bridge are encapsulated and mounted on an 11-in. heat sink. The current through the bridge (and therefore the motor armature) is limited to 6.0 A by means of an external resistor of 0.357 ohm. The amplifier is used in this application as a current source, its transfer function being in units of current out per volts in. This adds an integration to the rate loop since (once the friction level is surpassed)

a voltage into the power amplifier produces a current into the motor armature which has an equivalent torque value ($\text{torque} = K_T \times \text{current}$). This torque then causes the motor to accelerate the inertial load at a constant value.

The current output from the bridge goes through three closed relay contacts, connected serially, to the motor armature. The purpose of the relay contacts is to interrupt motor current and put a short across the armature in the event of an operational failure, such as power supply failures or overspeed. The configuration of the power amplifier permits a maximum of 55 V across the motor armature. The relay contacts are individually rated at 28 V maximum so that unless precautions are taken interruption of the motor could cause the relay contacts to weld. To prevent this from occurring, three contacts are connected in series and each contact has a bidirectional power zener diode connected in parallel with it. These diodes clamp at nominally 20 V and thus prevent the contact voltage maximum of 28 V from being attained when interrupting the armature, even at its maximum of 55 V.

2.8.6 Power Supplies

Four different DC voltages are required to operate the Scanner Servo. These voltages are:

- a. +5 VDC - for operating the digital logic chips, the readout display, the digital translators, and the encoders.
- b. +15 VDC - for operating the analog operational amplifiers.
- c. -15 VDC - for operating the analog operational amplifiers and biasing the power amplifier.

- d. +60 VDC - for operating the power amplifiers. Two 30 V supplies are connected in series to attain this magnitude of voltage.

Three +5 V supplies are used throughout the servo system. One is located within the servo cabinet and provides all +5 V requirements for the cabinet. This cabinet power supply is rated at 8.0 A. Each of the two encoder pairs and digital translators have dedicated +5 V power supplies on the scanner tower. This is necessitated by the encoders requiring 500 mA each plus 500 mA for the translator. To transport this power from the cabinet while keeping the voltage drop at less than 100 mV would not have been practical over the distances involved. These encoder power supplies are rated at 3.0 A.

The +15 VDC and -15 VDC supplies are part of a dual supply unit, each half of which is rated at 1 A. They are located within the servo cabinet and provide ± 15 VDC to circuits within the cabinet only.

The power amplifiers require a nominal supply voltage of 60 V which is provided by serially connected 30 VDC supplies. The peak current that could be required from this supply if both motors were accelerating simultaneously is 12 A. Each of the serially connected supplies is rated for 14 A and is adjustable from 24 to 36 V. In this application each supply is adjusted to +30 V with the overvoltage protection set to trip out at 32.5 V. This protects the power amplifier whose upper voltage limit is +65 V.

2.8.7 Protection Features

Several protection features were incorporated in the electronics design. Important among these features are the following:

- a. Travel Limits - Four distinct travel limits exist, namely in the +X, -Y, +Y, and -Y directions. The circuitry is configured so that upon actuating any one of the four limit switches, circuitry is activated to prevent input to the power amplifier of any signal that commands the scanner to continue in the direction it was traveling when the limit switch was actuated. The circuitry will, however, accept the reverse polarity so that it can drive the scanner away from the encroached upon travel limit. If the scanner were under computer control when it entered a travel limit, the servo system reverts to local control in the velocity mode. It will remain in the local mode until the travel limit reset switch is actuated. The object is that the computer, under a normal circumstance, should not drive the scanner into the limits and the reason that it did so should be evaluated prior to handing control back to the computer.

When the servo is driven to a limit, a signal is sent to the computer indicating which of the four limits is violated. Additionally, a lamp illuminates on the servo panel indicating that the scanner is in a limit and another lamp indicates the specific limit involved.

- b. Servo Ready - Comparator circuits monitor each of the four DC voltages used in the servo system. If any of the four voltages rises or falls outside a specific "window" of acceptable values, the Servo Ready Signal to the computer goes low and the servo is disabled.
- c. Remote Control - The computer can only obtain control of the servo if the following four conditions are met:
- 1) The Servo Ready Signal is high.
 - 2) The scanner is not at a Travel Limit.

- 3) The Servo Local/Remote switch is in the Remote Position.
 - 4) Remote Control is specifically requested by the continuous presence of a signal from the computer.
- d. Overspeed Protection - Failure modes can occur that cause uncontrolled runaway of the servo motor. Among these are power amplifier malfunctions, tachometer failure, electronic failures that cause open loop conditions, etc. Many of these failures cannot be sensed or controlled by the computer; therefore, it is necessary to employ another means of runaway protection. In this servo, the protection is provided by the armature relay circuits (discussed under the power amplifier paragraph) and comparator circuits to sense overspeed by monitoring the tachometer voltages. Two integral tachometers are employed on each drive motor and the rate electronics are scaled so that normal loop gradients occur only when both are functioning properly. If either (or both) tachometer senses overspeed (greater than 15 cm/sec in X, greater than 60 cm/sec in Y), the armature relay circuits are deactivated, interrupting motor current and placing a short circuit across the motor armature. This shutdown condition remains until the shutdown reset switch is activated. The use of two tachometers greatly reduces the possibility of a single tachometer failure causing a runaway mode with no capability for detecting the resulting overspeed condition.
- e. Shutdown - In addition to overspeed initiating the interruption of the armature circuit, the computer can command the shutdown action to be initiated. If any DC voltage goes out of its assigned "window" of values, the shutdown action also occurs. As in the case for overspeed, the shutdown reset switch must be activated to restore normal operation.

- f. Excess Error Indication - If the position of the scanner is different from the local command position by more than approximately 25 cm an appropriate lamp illuminates, indicating that either a positive or negative position error exists. If it is desired to go from Local Velocity to Local Position Control, the operator should turn the position control knob until the lamp is extinguished. At that time, Position Mode can be attained and the scanner will not make an excursion of more than 25 cm.

This feature reduces the possibility (when switching from Local Velocity to Local Position Control) of causing large position changes at high speed in either axis.

Section 3

COMPUTER PROGRAMS

3.1 Computer System

The computer system consists of an Interdata 8/32 computer with 768K bytes of memory, a magnetic tape, 76M byte disk storage, a hardcopy console (called a Carousal), a CRT console, and special-purpose hardware interfaces. Figure 3.1-1 shows the computer system block diagram and Figure 3.1-2 shows the physical arrangement.

Four of the six special-purpose hardware interfaces use the Interdata Universal Logical Interface (ULI) board. This board contains standard logic to communicate with the Interdata 8/32 computer and has an area where RCA incorporated the unique hardware logic to interface with the particular functional unit.

One of the ULI interfaces is used by the computer program to select the test frequency. Another ULI interface is used to switch the four channels. A third ULI interface is used to specify the beam position to the beam steering controller cabinet. The fourth ULI interface is used to read the probe position and status. By reading the probe's position at a specified rate, the computer program calculates the probe's velocity and can transmit a velocity correction to the servo control unit to control the probe's movement.

The other two interfaces are A/D and D/A standard Interdata hardware units. The A/D is used to read an amplitude and phase for each selected frequency, beam position, and channel.

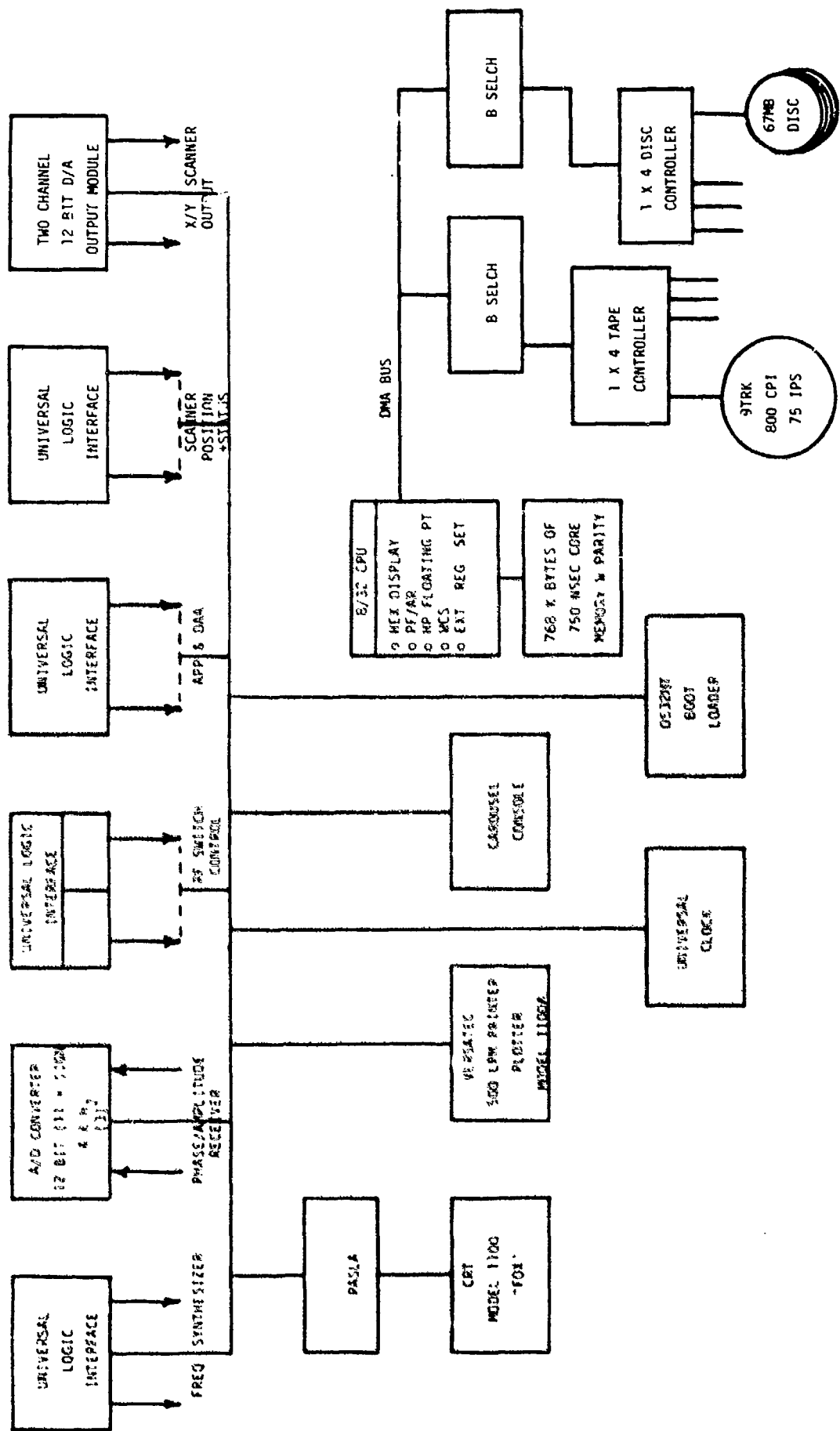


Figure 3.1-1. Block Diagram - Computer System.

PRINTER
PLOTTER



CENTRAL
PROCESSOR

DISC

CRT
TERMINAL

Figure 3.1-2. Interdata 8/32 Computer System.

3.2 Computer Program Architecture

The computer programs are structured into subprograms and implement the test system requirements by providing five modes of operation. Each mode provides a specific operational capability. The modes are

- a. Immediate Command Processing
- b. Plan
- c. Scan
- d. Data Reduction
- e. Calibration

Figure 3.2-1 shows the computer program architecture and subprograms.

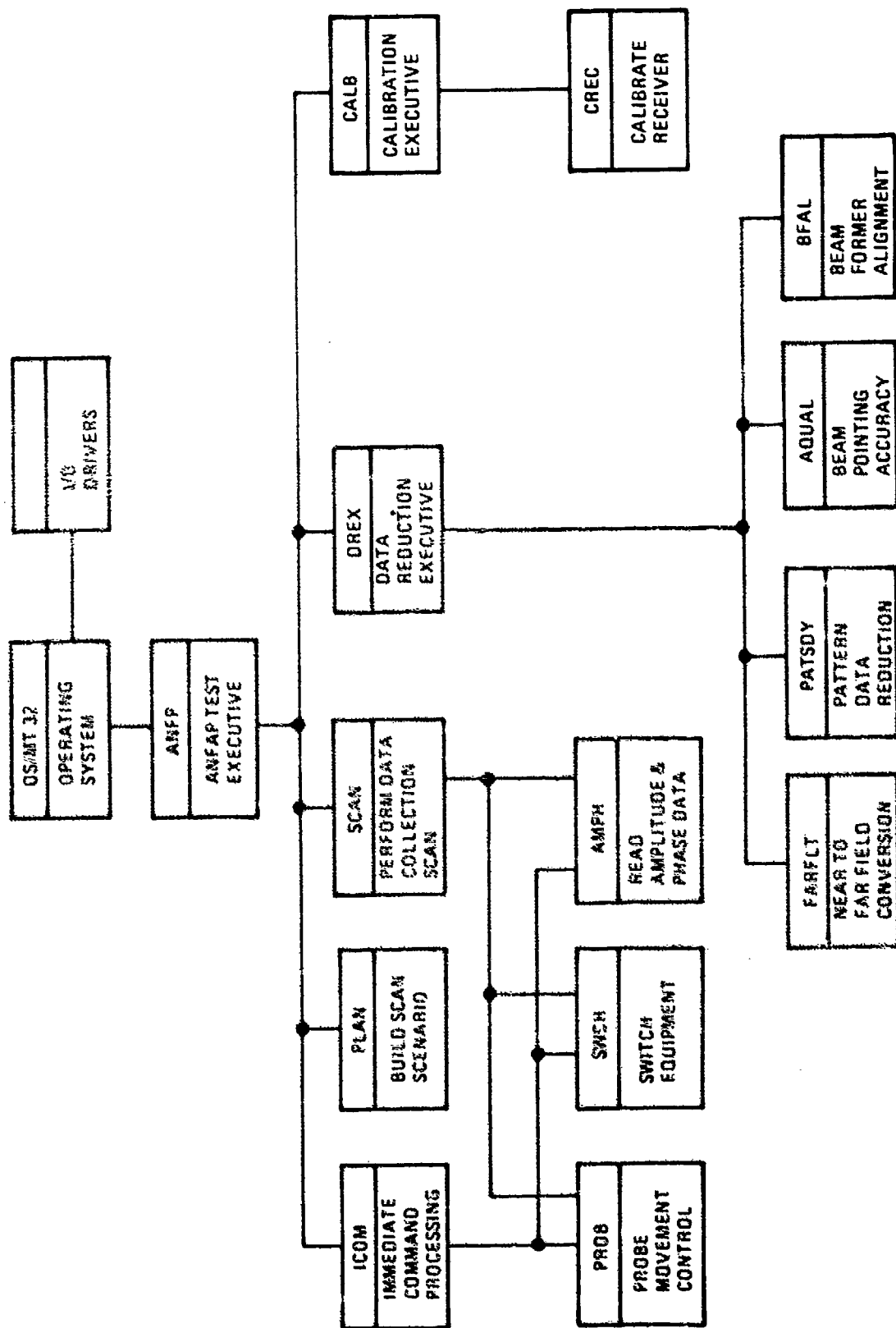
3.2.1 Immediate Command Processing (ICOM)

The Immediate Command Processing mode provides the test conductor with a manual control of the test system to perform the following functions:

- a. Move the probe to a specified position.
- b. Select a frequency.
- c. Select a beam position.
- d. Select a channel.
- e. Read amplitude and phase.
- f. Stop probe movement.

The test conductor is able to use these commands to assist in the antenna installation and checkout prior to the actual data scan and data processing.

The Immediate Command Processing (ICOM) subprogram interfaces with the operator. The PROB subprogram is called by ICOM to move or stop the probe. SWCH is called by ICOM to switch to a specified frequency, beam position, or



channel. AMPH is called by ICOM to read the amplitude and phase. These three subprograms are also used by the SCAN mode.

3.2.2 Plan

The Plan mode is used by the test conductor to define a complete scan scenario for later use. The parameters specified are

- a. Frequencies (specify up to 10).
- b. Scan Area (specify in terms of X and Y).
- c. Scan Spacing (specifies number of data points).
- d. Antenna Beam Positions (specify up to 10).
- e. Scan Type (two types of scan: (1) beamformer alignment or (2) pattern and/or beam-pointing accuracy).

The test conductor specifies these parameters and gives each scenario a name. The computer program will store the scan scenario on disk to be called up by its name. Many scan scenarios may be stored on disk. Plan also allows the test conductor to call up a previous scan scenario and make modification or delete the scenario from the system. This mode permits the test conductor to prepare for a scan anytime prior to its use.

3.2.3 Scan

The Scan mode performs an automatic scan as specified by a particular scan scenario. The computer program reads the scan scenario; calculates the scan rate; controls the probe movement; switches frequencies; beam position, and channels; and reads amplitude and phase data.

The Scan also parcels the data into unique data arrays; each array contains the amplitude and phase data of all data points for a frequency, beam

position, and channel. These data arrays are stored on disk ready for the Data Reduction mode to process them.

During a probe scan at each data point, the software automatically switches all channels for each beam position and for each frequency specified in the scan scenario. A maximum of 100 phase and amplitude data arrays (i.e., frequency i , beam position k , and channel j) can be read at each data point.

After a scan is completed, the operator is notified.

3.2.4 Data Reduction

The Data Reduction mode processes the data arrays collected by the Scan mode and produces antenna pattern data containing gain, sidelobe levels, and other parameters, beam pointing accuracy data, and beamformer alignment data. The Near-to-Far-Field transformation is the FARFLT program supplied by the National Bureau of Standards and adapted to the Interdata operating system.

The operator may request the following classes of outputs:

- | | |
|--|---|
| a. Pattern Data Amplitude
100° x 100° or
20° x 20° Field of View | - Contour
- Line cuts in α direction
- Line cuts in β direction
- Local maximums |
| b. Beam-Pointing Accuracy | - Accuracy data and error slopes |
| c. Beamformer Alignment | - Elevation waveguide correction
- Azimuth waveguide correction
- Transmit waveguide corrections
- Monopulse channel corrections |

Pattern data is processed one data array at a time. Beam-pointing accuracy data are processed using one frequency and one beam position at a time and

all three receive channels. Beamformer alignment processes all frequencies, beam positions, and channels for one waveguide correction output.

The test conductor may select either one data array at a time for pattern and beam pointing accuracy or select all data arrays. The Data Reduction Executive subprogram interfaces with the test conductor to receive the processing type, read the data array into memory, and call the appropriate subprogram to process the data. The first subprogram called by the Data Reduction Executive is the Near-to-Far-Field conversion (FARFLT) subprogram.

The test conductor also selects the type of processing to perform; these are PATTERN (Pattern Data Processing), AQUAL (Beam Pointing Accuracy Data Processing), or BFAL (Beamformer Alignment).

Each data processing type queries the test conductor asking for specific information to perform its particular data processing.

3.2.5 Calibration

The Calibration mode aids the test conductor in assessing the operational readiness of the antenna and directs the measurement system calibration. As the test conductor completes each instruction, he reports the task completed to the computer terminal, reads the resulting data, and instructs the computer to proceed. This continues until the calibration sequence is completed and all results are printed. Specific measurements include an overall measurement system integrity check, including dynamic range, amplitude linearity, and phase linearity.

In addition, calibration moves the probe in front of a standard calibration horn and reads the amplitude and phase. This data is used to calculate and store a calibration parameter of the probe using the standard calibration horn. This calibration data is used in subsequent data reduction.

The Calibration mode also accepts from the test conductor system parameters used by more than one mode. These are

- a. Identify a probe location by a name. This allows the test conductor to refer to the name at a later time and request the system to move the probe to that location.
- b. Identify the surface location of the antenna with respect to the scanner surface.
- c. Input the parameters that go into the equation to calculate gain, such as the probe reflection constant.

3.2.6 Software Memory Usage

Figure 3.2-2 shows the Interdata 8/32 memory usage for each mode of operation. Note that all modes have ample spare memory for future use. Of particular interest is the Data Reduction memory usage. The data array being processed is totally core resident which eliminates disk activity and increases computer efficiency. The four Data Reduction subprograms, FARFLT, PATDSY, AQUAL, and BFAL, are overlaid into the same memory area for execution.

3.3 Typical Mode Scenario

To help the reader in understanding the use of system modes, this section describes a typical operational scenario.

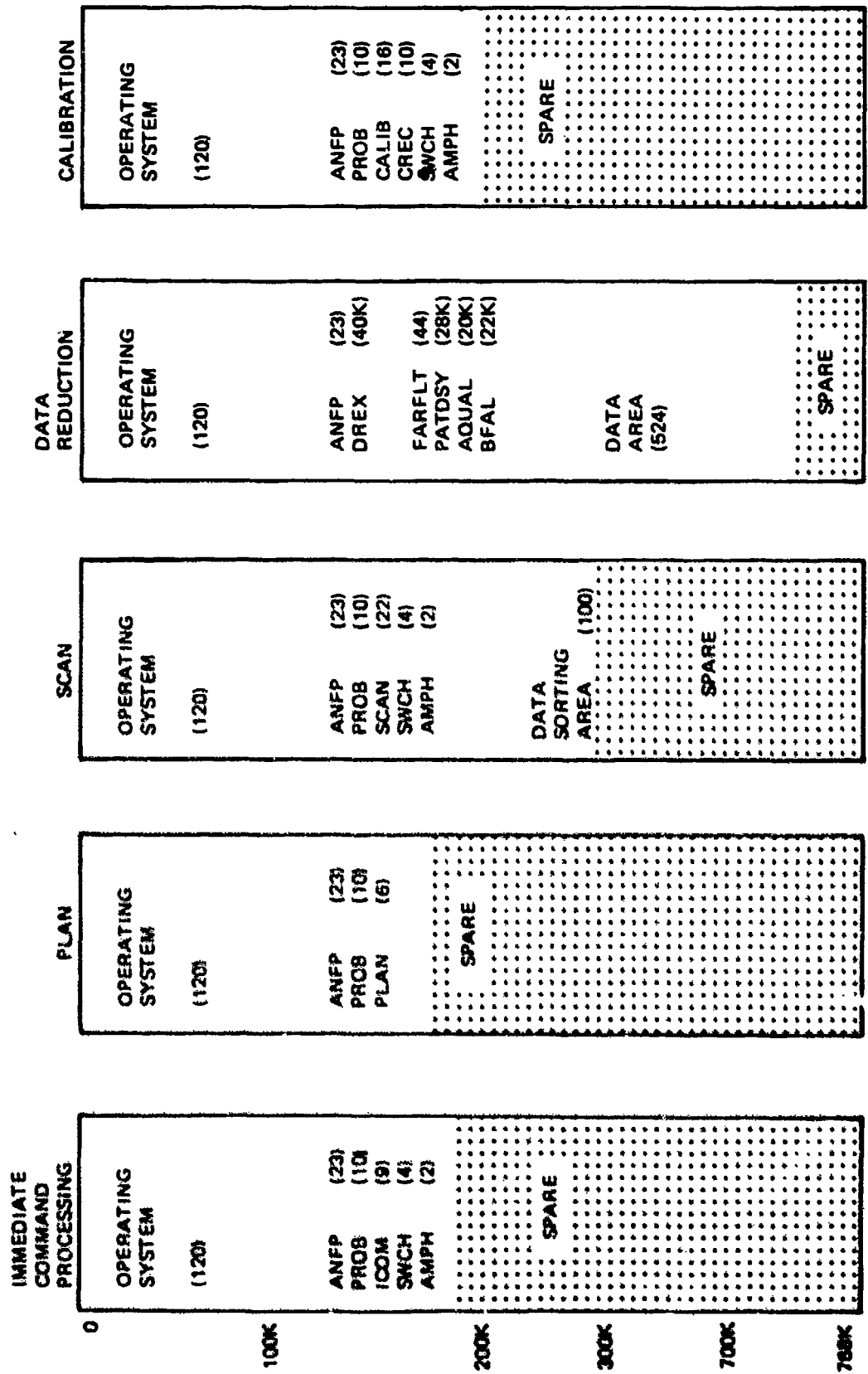


Figure 3.2-2. Computer Program Memory Map.

The test conductor supports the installation of the antenna into the test fixture by using the Immediate Command Processing mode to read amplitudes and phases at specific frequencies, beam positions, and channels. After installation, the Calibration mode is used to calibrate the measurement system.

Once the antenna is ready to be tested, the test conductor initializes the system using the Calibration mode. He inputs into the system the probe position where the standard calibration horn is located, defines the array location with respect to the scanner area, and requests the Calibration mode to take a reading of the standard calibration horn and store the respective calibration parameters for use during the scan.

Prior to running the actual scan, the test conductor selects or defines the scan scenario using the Plan mode. He may create a new scan scenario, review an existing scan scenario, and either modify it to fit his needs or decide it is correct as is.

The Scan mode then automatically performs the scan by calculating the scan rate; controls the probe movement; switches frequencies, beam positions, and channels; and reads the amplitudes and phases at each data point for each frequency, beam position, and channel. Scan organizes the amplitude and phase data into data arrays and stores them on disk. Each data contains the amplitude and phase of every data point for a frequency, beam position, and channel.

When the scan is completed, the test conductor is notified.

The test conductor next uses the Calibration mode and performs a postscan calibration reading of the standard calibration horn to confirm that the drift of the calibration parameters is within tolerance.

Data reduction is the final mode used. Appropriate commands are entered into the computer to perform Pattern and Beam Pointing Accuracy data reduction. The data is printed and plotted on hard copy, and is compared to preprogrammed acceptance criteria for the accept-reject decision.

3.4 Data Reduction Outputs

The Data Reduction programs for pattern and beam pointing accuracy came from the AAPDAS system used for the checkout and acceptance testing on the AEGIS EDM-1 and the EDM-3C arrays and were adapted to the Interdata 8/32 computer. This section identifies the type of data produced and shows some examples.

The Data Reduction outputs are

- a. Pattern Data - Amplitude contour plots, principle line cut plots in and directions, and local maximum printouts. Figure 3.4-1 shows a principle plane cut. (Note added in proof: This example of output has been deleted.)
- b. Beam-Pointing Accuracy - Monopulse curve with tabular data that contains: (1) the standard deviation of the beam position with respect to the commanded beam position, (2) the monopulse error slope, and (3) the total error which combines the error of the beam position and the variance of the error curve. Figure 3.4-2 shows the monopulse error curve. (Note added in proof: This example of output has been deleted.)
- c. Beamformer Alignment - The waveguide corrections for each subarray in elevation, the azimuth waveguide corrections, and the transmit beamformer waveguide. Figure 3.4-3 shows the waveguide correction report.

Figure 3.4-1 is an example of a line cut in the α direction. The operator selects a constant β direction and specifies the α window in degrees. The system prints each data point within the α window. Three windows are available: 2° , 20° , and 100° .

After looking at the line cut, the test conductor can request a local maximum chart which shows the local maximums starting at a test-conductor-specified decibel level. For example, the test conductor may look at the Figure 3.4-1 line cut and request a local maximum chart for all local maximums above -32 dB.

The local maximum will then print out an entire antenna scan and place an "X" at every location that is a local maximum above -32 dB. Along with the "X" the actual amplitude will be printed to an accuracy of .1 dB.

A test conductor request for a Beamformer Alignment data reduction run will result in an output as shown in Figure 3.4-3. If all waveguides are within tolerance, a printout of the words "Installation Report" will be produced.

In Figure 3.4-3, the elevation waveguide correction chart shows either a string of eight "*"s or a number. The eight "*"s indicate the subarray waveguide is within tolerance. The number indicates the elevation subarray must be adjusted by the value of the number in centimeters.

For more details concerning the data reduction outputs, the reader is referred to the computer programs documentation summarized in this report as Appendix A.

3.5 Computer Program Documentation

(Note added in proof: The computer program documentation is listed in Table B-2 p. 120.)

The Program Performance Specification (PPS) defines the system requirements the computer program is to perform. The Program Design Specification (PDS) defines the top level software design and defines the subprograms. A Program Design Description (PDD) defines the detailed design of each subprogram. It contains a design narrative, data description, and flow charts of the subprogram.

The Acceptance Test Plan describes the acceptance test requirements to demonstrate that the requirements contained in the PPS are met. Also, there is an Acceptance Test Procedure that is the step-by-step actions to execute the tests contained in the Acceptance Test Plan.

The Program Package is the delivered software and consists of a magnetic tape of the subprograms source code and a compiled source listing of each subprogram.

Section 4

CONCLUSIONS AND RECOMMENDATIONS

The scanner/servo as configured, fabricated, assembled, aligned, and calibrated has been demonstrated to satisfy all requirements imposed, and appears to be eminently suited to the intended task.

The scanner coverage area, velocities, and accelerations in conjunction with available overtravel are as specified. Scanner errors (per Table 2.7-1) are approximately one-quarter of the allowed errors; thus the existing scanner can be used to test higher RF frequency antennas with the X, Y, Z positional accuracy achieved.

The errors measured for the existing unit can be further reduced at the cost of additional time and effort for aligning the data rack gears as well as the X-axis linear bearing shafts.

One of the critical geometric properties of the scanner is the ratio of maximum scanner height to minimum distance between the X-axis bearings or tower aspect ratio. From Figure 2.4-1, the aspect ratio of the system is

$$\frac{N + Y_c + S_y}{d_z} = 3.8$$

It appears that the selected aspect ratio is somewhat conservative and could be increased to the range of 4.0 to 4.5 for a positional accuracy of 0.030 in.

The incorporation of the rate control servo loops offers significant advantages in ability to control system dynamic errors and operational smoothness. This feature, in conjunction with rack and pinion drive gearing and the use of one articulated linear bearing in each axis, results in a highly satisfactory scanner/servo system.

The rail support system as implemented has performed well. However, a considerable investment in bearing shaft alignment was required, thus investigation of support designs directed to reducing alignment time (without sacrificing X support stiffness) is warranted for future builds.

After alignment of the X axis bearings, the X axis was subjected to frequency response tests up to 200 Hz with a high amplitude resonance observed at 118 Hz. This resonance was sufficiently severe as to misalign the vertical plane of the primary X-axis bearing shaft; thus, frequency response tests should be limited to 15 Hz after X-axis bearing shaft alignment.

APPENDIX B ENGINEERING DRAWINGS AND COMPUTER PROGRAMS

This document, NAVSEA MT S-475-77 (NOSC TR 499) will be available from the Defense Technical Information Center.

RCA-developed engineering drawings and computer software documentation are listed in this appendix as tables B-1 and B-2. Copies may be obtained from NOSC (a reproduction charge may be assessed). Drawings are available from Code 9241, Electrical Design Branch; software from code 9122T, Customer Services & Administration Branch; Naval Ocean Systems Center, San Diego, CA 92152.

ENGINEERING DRAWINGS

The engineering drawing set obtained under the MT contract consists of some 175* sheets of drawings consisting of:

- 4 Page drawing list $8\frac{1}{2} \times 11$ inch.
- 101 Mechanical drawings of various sizes up to 30×42 inch.
- 12 Page workmanship specification, basic $8\frac{1}{2} \times 11$ inch.
- 58 Drawings servo system various sizes to 30×42 inch.

A detailed list of drawings is given in table B-1. The drawings are segregated into four hierarchical levels indicated by the number of triplet blanks ahead of the drawing number. Several of the drawings consist of more than one sheet and the number of extra sheets is listed. The number breakdown by hierarchy and extra sheets is:

Hierarchy	1	2	3	4	extra sheets
Number	1	2	71	25	60

The drawing titles are given. The drawing numbers are those of the RCA drawing library and serve only for identification purposes.

Except for those who may wish to make a complete duplicate of this system, many of the drawings need not be consulted. For the mechanical structure the second hierarchy assembly drawing 8364786-501 (the 501 indicates an assembly drawing) consisting of eight sheets is rather complete in itself and references most of the remaining drawings in its parts list. For the servo system the 35 sheets of logic diagrams probably describe most of the functional characteristics of the electrical servo system; however, in normal operation, the servo loop is closed through the computer so that the appropriate portions of the software package should be included also.

*The RCA drawing file is kept on aperture cards (basically a microfilm system). Reproduction of drawings at NOSC is by Ozalid machine so that the non-reproducible copy and the reproducible copy prepared by RCA differ in sizes and perhaps number of sheets. The NOSC review was made on the non-reproducible copy and numbers of sheets given apply to that copy.

Table B-1

DRAWING LIST: PROGRAMMED SCANNER

(SCANNER/SERVO)

HIERARCHICAL TOP DOWN - BREAK DOWN

<u>RCA Drawing No.</u>	<u>Title</u>	Page 1 of 5	<u>Extra Sheets</u>
8145596-501	Programmed Scanner (Scanner/Servo Subsystem)		2
---8364786-501	Near Field Scanner		7
-----8145388	Bracket		0
8145398	Cable Assembly		0
8145399	Shaft		0
8145584	Stow Pin Assy. - X-Axis		0
8145585	Stow Pin Assy. - Y-Axis		0
8145586	Nut Plate		0
8145587	Retainer		0
8364773	Beam		0
8364779	Tower Assembly		1
8364787	Frame Assembly		0
8364790-501	Motor Tachometer-Near Field Scanner		0
-----8145395	Retainer Bearing		0
8145396	Cover		0
8145397	Cover		0
8668030	Housing		0
8668031	Housing		0
8739648	Gear - 48 Teeth Pinion		0
8739649	Gear - 22 Teeth Pinion		0
8739660	Shaft		0
8739664	Spacer		0
8739665	Retainer - Motor		0
8739666	Extension Ring		0

Extra Sheets

---8364786-501	(Con't) Page 2 of 5	
-----8668003	Shaft	0
8668015	Support (Gear Rack)	0
8668016	Support (X-Axis Encoder Rack)	0
8668018	Plate Assembly	0
8668026	Stop	0
8668028	Mount Assembly	0
8668032-501	Encoder Assembly	0
-----8668023	Plate, Mounting	0
8739642	Hanger	0
-----8668046	Support, Shaft	0
8668172-501	"Y" Junction Box	2
-----8145512	Plate	0
8145513	Support	0
8364951	Logic Diagram "Y" Carriage Junction Box	2
8668050	Can	0
8739703	Bulkhead	0
8739704	Can	0
-----8668177-501	Junction Box X-Axis	1
-----8364953	Schematic Diagram - X-Axis Carriage Junction Box	1
8739702	Box, Terminal	0
-----8739627	Rack, Gear (Motor Drive)	0
8739643	Holer, Stop	0
8739644	Shield, Dust	0
8739646	Shield, Dust	0
8739650	Bushing (X Y Axis Rod Bearing)	0

---8364786-501

(Con't) Page 3 of 5

-----8739652	Bracket (Y-Axis Micro Switch MTG)	0
8739653	Bracket (Y-Axis Rod Bearing Support)	0
8679655	Yoke (Y-Axis Rod Bearing)	0
8739656	Yoke (Y-Axis Rod Bearing)	0
8739657	Screw, Shoulder (X Y Axis Rod Bearing)	0
8739659	Plate, Mounting Assembly	0
8739668	Support, Pulley	0
8739669	Retainer, Cable	0
8739670	Bracket	0
8739671	Guide	0
8739672	Counter Weight	0
8739673	Plate Assembly	0
8739674	Angle	0
8739675	Bracket Assembly	0
8739676	Bracket	0
8739677	Plate	0
8739678	Ramp	0
8739679	Support Assembly	0
8739680	Bracket	0
8739681	Bracket	0
8739682	Support	0
8739683	Bracket	0
8739684	Plate, Mount Assembly	0
8739701	Support, Cable	0
8739705	Cover, Terminal Box	0
8739783	Stow Bracket, Y-Axis	0
8739784	Stow Bracket, Y-Axis	0

---8364786-501	(Con't) Page 4 of 5	
-----8739785	Stow Bracket, Y-Axis	0
8739786	Stow Bracket, Y-Axis	0
8739787	Drip Pan	0
8739790-501	Junction Box, X-Axis	1
-----8364953	(REF)	M
8739697	Plate, Mounting	0
8739698	Bracket	0
8739699	Support	0
-----8739792	Near Field Scanner Cable Assy Definition	0

8145596-501	(Con't) Page 5 of 5	
---8668170-501	Cabinet Assy (Servo)	7
-----8278095	Near Field Scanner Cabinet "WIRE LIST" (connection)	2
8278096	Near Field Servo Control Unit "WIRE LIST" (connection)	5
8364788	Schematic-Near Field Scanner (Front Panel)	1
8364789	Logic Diagram - Servo Control Unit for Near Field Scanner (Platter)	9
8364908	Logic Diagram - Digital Translator and DAC (Platter 3)	2
8364950	Block Diagram - Cabinet Wiring	0
8364952	Logic Diagram - Power Amplifier Chassis	0
8364954	Logic Diagram - Near Field Scanner - (19 Sheets)	1
8668167	Panel, Servo Control Unit	0
8668168	Panel, Circuit Breaker	0
8668169	Panel, Front	0
8668171	Panel, Top	0
8668176	Panel, Servo Cont.	0

COMPUTER SOFTWARE

A block diagram of the hardware part of the "Automated Test System for Phased Array Antennas" is shown in figure B-1. The antenna under test is supplied by the AEGIS program. The programmed scanner is supplied by a portion of the Manufacturing Technology (MT) contract. The remaining hardware is supplied by RCA. This hardware does not function together without a set of computer programs (software) stored in the computer. Much of the software is supplied under the second portion of the MT contract. The required software is enumerated and discussed in the following.

Antenna Under Test

The antenna under test has three mechanical sections: 1) the antenna face array assembly, 2) the antenna position programmer (earlier called the beam steering computer), and 3) the array power supply and support system. Whether all three sections will be exchanged from one production unit test to the next is a matter of choice. If there is software within the antenna position programmer it is excluded from this discussion. There is however, a set of software, TABOR (Testing of the Array and Beam Steering Computer Operational Readiness), which is resident in the test system computer and is included as part of this discussion.

Provision is made for a set of test points in the hardware of both the array and the antenna position programmer which will indicate malfunctions of the equipment. In shipboard application these points are periodically monitored by the Data Acquisition Converter (DAC) for the Operational Readiness Test System (ORTS) and appropriate diagnostic messages generated if some of the readings are out of tolerance. TABOR is the test system substitute for ORTS. There is no sense in testing a malfunctioning antenna face so TABOR is consulted before testing is started.

TABOR is not part of the MT supplied software and is not included in the Program Package (PP) nor is there a Program Description Document (PDD) for it.

The Software System

The Interdata 8/32 computer comes with a basic package of software which includes an operating system (OS/MT 32), a FORTRAN VI compiler, and a library of standard functions. Almost any other make of equivalent computer would have an equivalent package supplied with it. Normally, this basic package may be assumed to be error free with no modifications to be expected. (There may be a few exceptions). No further mention of this basic software will be made and the following software will finish with the generation of a FORTRAN VI symbolic program which constitutes the Program Package (PP).

The software system to be described will automatically take a wide selection of data sets (various frequencies, beam directions, antenna ports, etc.) as instructed through the keyboard with the PLAN program. A given selection is retained under a name and can be recalled easily. Other selections with other names will normally also be resident in the computer memory. The complete definition of the action of the test system must include the name of the pertinent stored selection.

The remaining software system is block diagramed in figure B-2. Aside from TABOR and (OS/MT 32) there are 14 subprograms which constitute the Program Package (PP), version 0.1, supplied under the MT contract. Each of these subprograms has a

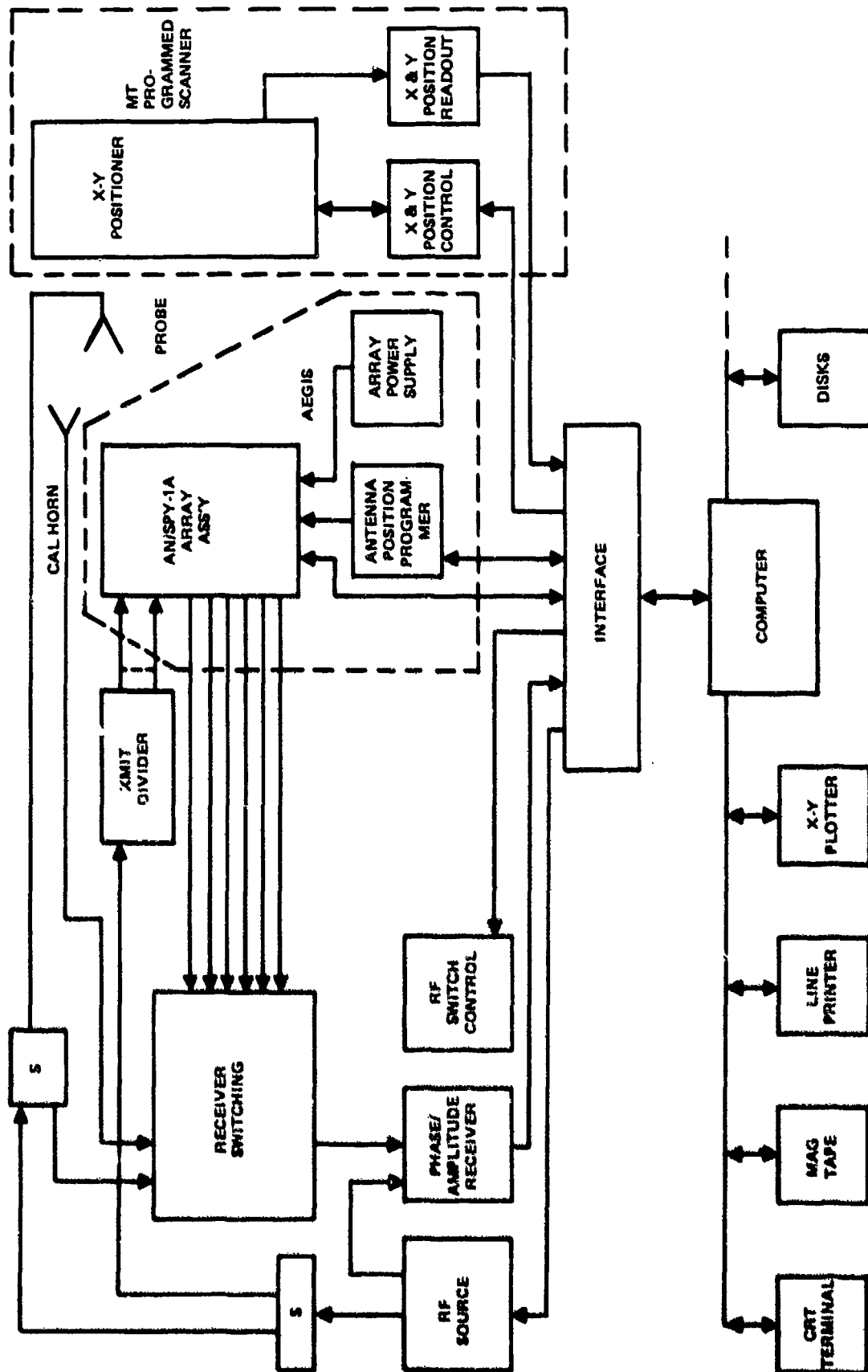


Figure B-1. (from PFS-4). Block diagram near-field test system hardware.

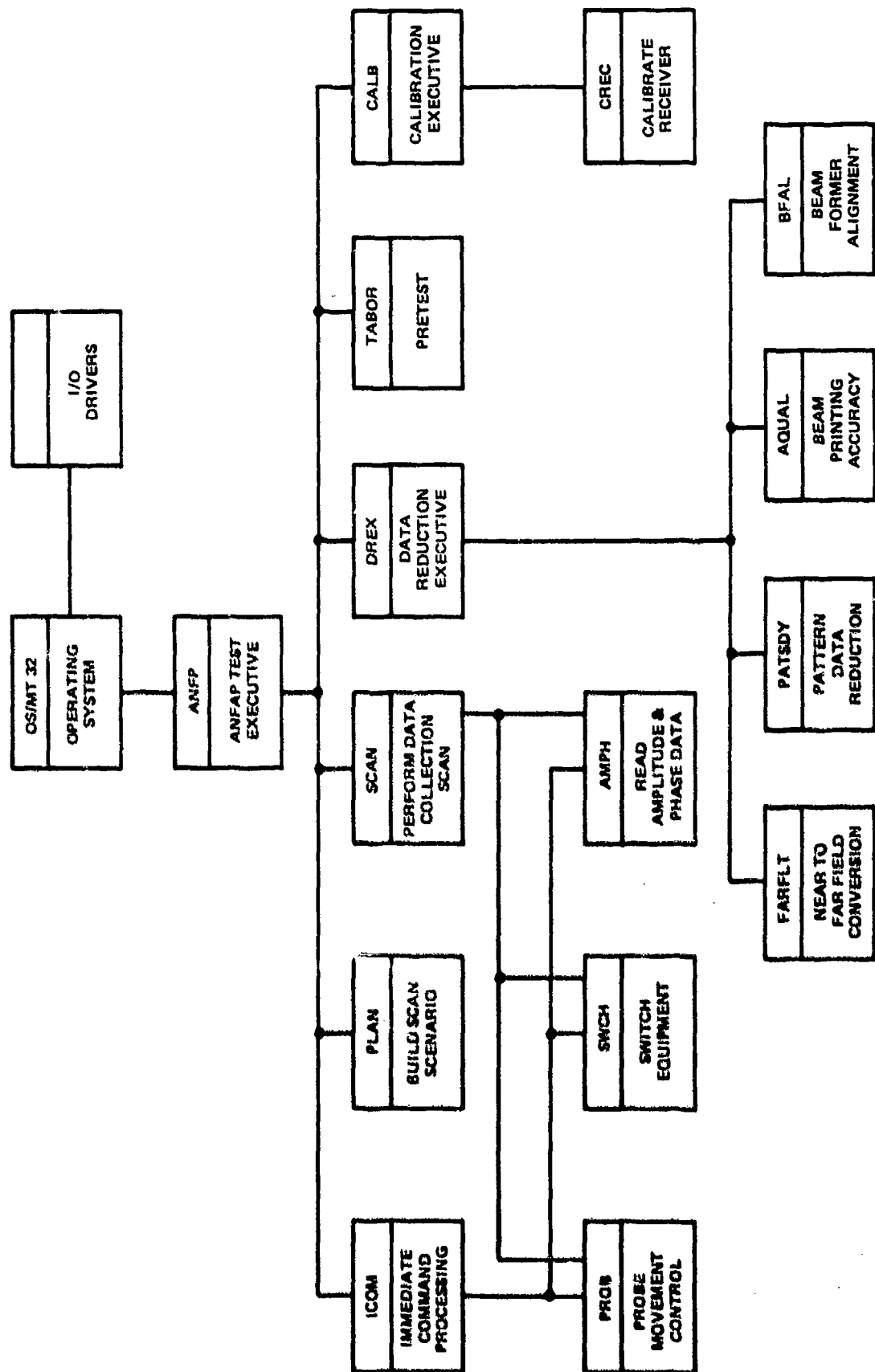


Figure B-2. ANFAP program structure (from PDS-11).

revision number appended to the listing. It is expected that there will be revisions of the various individual subprograms. When, for quality assurance reasons, the package is to be redocumented the updated package will be given a new version number and a copy will be preserved.

The MT supplied software documentation follows a "top-down" programming concept of four hierarchical levels: 1) Program Performance Specification (PPS), 2) Program Design Specification (PDS), 3) Program Description Document (PDD), and 4) Program Package (PP). The relationship between these documents are shown in figure B-3. The contract descriptions of these documents were taken from SECNAVINST 3560.1 "Tactical Digital Systems Documentation Standards" with minor modifications. The PPS covers the overall required functioning of the system in terms of the four main program functions: 1) Pretest, 2) Calibration, 3) Data Measurement, and 4) Data Reduction. The PDS breaks this down into 15 subprograms and an interface table, (see table 3.1-1 on pages PDS-7 to 10). The PDD has a section for each subprogram and goes into specifics (much of it has to do with specifying logical subprogram reaction to specific exceptional circumstances). The PP is a magnetic tape record of the FORTRAN symbolic code (including comment cards) accompanied by a printed listing of the code supplemented by a listing of variables used in each listed subprogram and subroutine. (The variable listing is for review convenience and is derived from the compile processing of the FORTRAN code and is not strictly a part of the PP).

There are some exclusions from this documentation. TABOR is not in the PP and there is no PDD for it. FARFLT, PATSDY, and AQUAL are adaptations of previously developed codes and no PDD was developed for them. FARFLT came from a program of A. Newell of the National Bureau of Standards, Boulder, Colo. PATSDY was developed for the presentation of far-field data from the earlier qualification tests of the SPY-1 antenna face. AQUAL computes the beam pointing accuracy from far-field data and was previously developed.

What has been available from NBS for example, is the equivalent to the PP only. Many of the technical community will not be familiar with a PPS, PDS, and PDD. SECNAVINST 3560.1 specifies a rather rigid format for these documents which results in each section numbered by a set of sometimes seven subscripts separated by periods. Generally the subscripts are single digit. These subscripts have to be watched very carefully in reading these documents as their importance is not equally distributed and a given subscript does not retain the same meaning throughout the document. For example, the bulk of the documents has the first subscript equal to three. The last subscript often refers to the subprogram and the preceding section subscript pertains to an aspect of that subprogram specified by the earlier subscripts. Since the ordering of the sections in the document is determined by the ordering of the subscripts as though the subscript string were a fancy digital number this results in a cycling through all the subprograms before the next aspect of the given subprogram is taken up. For the uninitiated a different ordering of the sections would make the documentation more readable.

The concept of "top down" programming is somewhat misleading in that the nature of the logic presented implies that programming can be a linear process. No one with experience seems to believe that programming can be a linear process. No one with experience seems to believe that programming is ever accomplished except by an iterative cyclic process and that after it is finished it can then be described in the documentation as though it had been done linearly. It is quite true that attempting to program linearly often

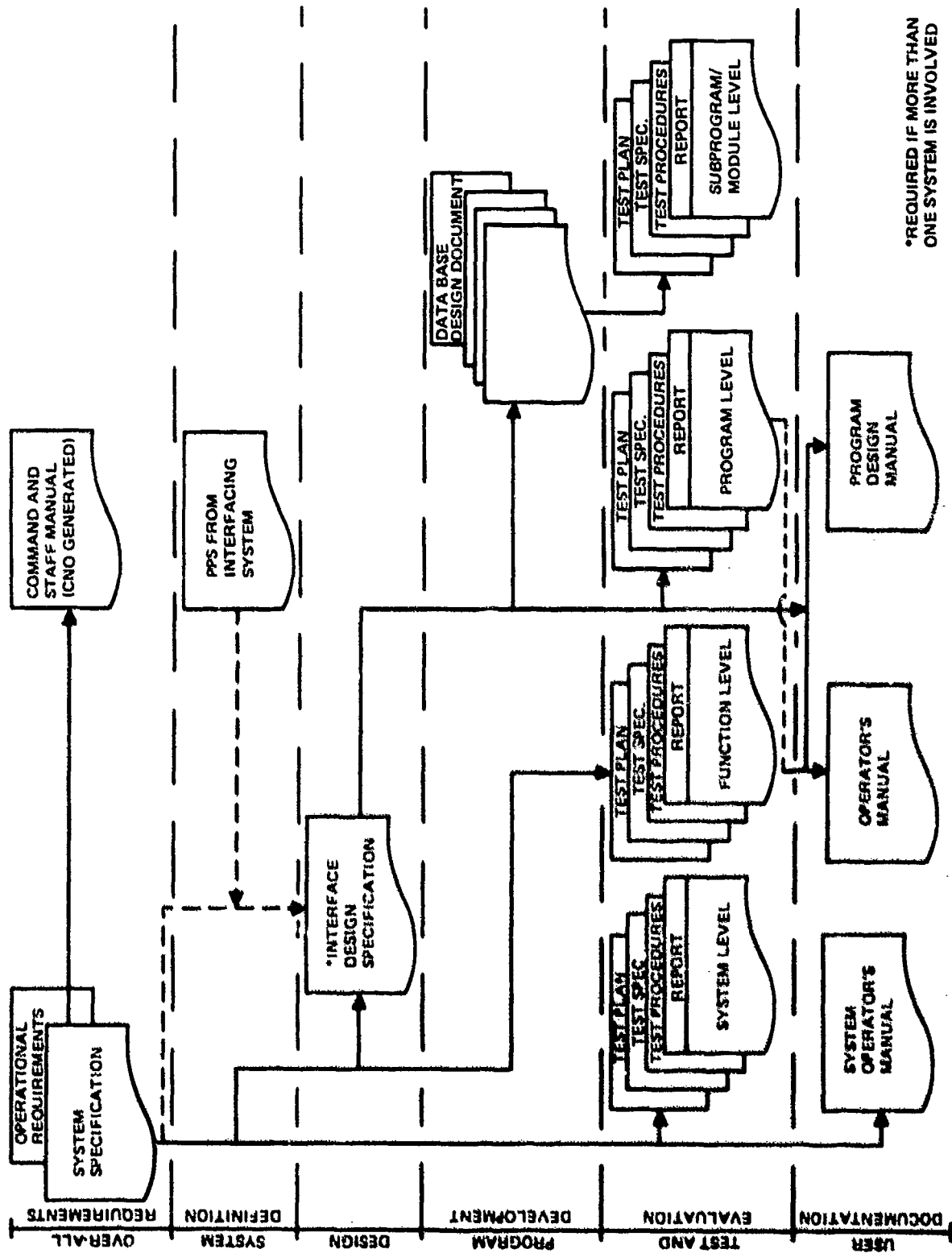


Figure B-3. SECNAVINST 3560.1 documentation relationships.

TABLE B-2
COMPUTER PROGRAM DOCUMENTS

Hierarchy, Sub-Program	Pages	RCA Document. Number
PPS	159	ANFATS-SP-0002
PDS	118	ANFATS-SP-0003
PDD		
Data Base Design	26	ANFATS-SP-0024
ANFP	42	ANFATS-SP-0006
ICOM	27	ANFATS-SP-0007
PLAN	37	ANFATS-SP-0008
SCAN	55	ANFATS-SP-0009
PROB	47	ANFATS-SP-0010
SWCH	30	ANFATS-SP-0011
AMPH	27	ANFATS-SP-0012
DREX	47	ANFATS-SP-0013
BFAL	72	ANFATS-SP-0017
CALB	84	ANFATS-SP-0018
CREC	50	ANFATS-SP-0019
FARFLT	--	
PATSDY	--	
AQUAL	--	
TABOR	--	

544

PP

Magnetic Tape.
Listing is about
800 pp

ANFATS-SP-0023

reduces the number of cycles of iteration needed. Another procedure which reduces iteration is to test the program with simulated input to see if it gives the expected output. The programs in version 0.1 have all been tested by simulation. Since these programs have not been tested with real-life inputs it may be wiser to think of version 0.1 as being in the first cycle of iteration rather than being the final product so that revisions (probably minor) are to be expected.

As part of the information dissemination aspect of the MT contract, copies of the software documentation will be made available from NOSC. All of the software documentation (with the exception of the PP magnetic tape) is on 8½ by 11 inch sheets. An index list of this documentation is given in table B-2 along with the number of pages.

Results of Documentation Quality Review

The NOSC software quality Control branch has given this software a partial but representative review* using the procedures of NOSC Technical Note 412 (C. O. Anderson 1 May 1978). These procedures essentially examine the documentation for internal consistency. Errors are referred to the software manager for analysis and remedy.

Roughly one such error was found for every 2-3 pages of documentation. Many of these errors do not imply that the PP software does not function properly but that there is misplaced or missing information in the documentation.

This review was made after the close of the MT contract so that the NOSC documentation does not have these errors remedied.

The number of pages of software documentation is much larger than would normally be prepared for laboratory software. For a trained engineer this could be very useful and this frequency of error would be of minor concern. For someone of lesser skill the total number of errors might prove a morass.

*Memorandum from NOSC Code 9133 (P. A. Rhodes, Software Quality Control) to NOSC Code 9254 (R. Gamble, Manufacturing Technology Office) March 1979.

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