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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A Transfer Alignment Feasibility System (TAFS) based on the SPASYN transducing and computing concept has been implemented and demonstrated under this contract. Ex- tensive tests have been performed with this system to: (1) determine the general feasibility of adapting the SPASYN concept to the problem of effecting accurate and		

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20. (cont'd) rapid airborne transfer alignments; (2) demonstrate the basic performance capabilities of the transfer alignment feasibility system; (3) investigate the effects of surrounding and intervening metallic structures on the performance capabilities of such a system; and (4) assess the general applicability and performance-growth potential of SPASYN transfer alignment systems. These system tests have demonstrated that: (a) it is feasible to develop a transfer alignment system based on the SPASYN concept, and (b) a transfer alignment rms accuracy of better than 0.1 degrees can be obtained over small ($<10^\circ$) attitude angle and translation angle excursions even in the presence of surrounding and intervening metallic structures.

The SPASYN concept is a transducing and computing scheme which provides a precise and continuous measure of the three relative attitude angles and the two (polar-coordinate) angles of relative translation between two independent rigid bodies. This concept utilizes a nutating electromagnetic field as the data link between the moving body and the reference body. The nutating field is generated, detected and controlled by a three-axis radiator, a three-axis sensor and appropriate electronic circuits operating in a closed-loop system arrangement. The closed-loop operation continuously forces an equilibrium condition between the sensor output signals and the radiator excitation signals. The desired orientation and translation angles are derived in the process of forcing this equilibrium.

The SPASYN concept was originated by PNSI and was initially adapted to an Advanced Helmet Mounted Sight application under the sponsorship of the Aerospace Medical Research Laboratory at Wright-Patterson AFB, Dayton, Ohio. The Transfer Alignment Feasibility System implemented under this contract represents a medium range, high accuracy extension of the previously-developed SPASYN technology.

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SUMMARY

One of many

The Air Force has many operational concepts for performing its various assigned missions. One of these many concepts requires that the physical alignment of separate system parts be aligned to each other so that the system will operate correctly. This method of alignment is termed transfer of alignment. This report deals with transfer of alignment by the use of radiated magnetic waves. This report details the design and laboratory testing of the Space Synchro (SPASYN) which is a five-degree-of-freedom transducing technique used to detect the orientation of one body with respect to another in measurements of pitch, roll and yaw angular displacements. The system consists of a Radiator, Sensor, Radiator Excitation Unit (REU), and System Control and Display Unit (SCDU).

PREFACE

The work described in this report was performed by Polhemus Navigation Sciences, Inc. (PNSI), in Burlington, Vermont for the Air Force Avionics Laboratory at Wright-Patterson Air Force Base, Dayton, Ohio, under Air Force Contract F33615-73-C-1027. Mr. Herbert P. Kohlmann of the Navigation Group, Navigation and Guidance Branch, Air Force Avionics Laboratory (NVN-2) was the technical monitor and cognizant project engineer for the Air Force under this contract and Lt. C. Schmader, 4950/PMEB, served as contract specialist for the Air Force.

The work described herein represents a high-accuracy, small-angle, medium-range application of the Space Synchro (SPASYN) concept originated by a PNSI scientist in June of 1971 as a promising new transducing technique for visually-coupled control systems.

Under the sponsorship of the Aerospace Medical Research Laboratory (AMRL) at Wright-Patterson Air Force Base, Dayton, Ohio, the SPASYN concept was first translated into a breadboard model of an Advanced Helmet-Mounted Sight system (AHMS) for airborne applications. This AHMS breadboard model system development was accomplished under Air Force Contract F33615-72-C-1482 during the period from November 1971 to July 1972. The requirements for this first military application of SPASYN were moderate accuracy ($\pm 2.0^\circ$) over relatively wide attitude-angle and pointing-angle excursions (up to $\pm 75^\circ$) and over very short distances (less than 3 feet) between radiator and sensor.

Then, under a follow-on contract awarded by AMRL (Air Force Contract F33615-73-C-0106), improved, high-powered transducing hardware was developed to operate in conjunction with the System Electronics Unit developed under the preceding contract. The purpose of this follow-on effort was to extend the transducing range of the AHMS breadboard model system to 100 feet or more with the emphasis put on range rather than accuracy. The accuracy requirements for this extended-range development effort were accordingly relaxed to $\pm 6.0^\circ$ for attitude and pointing angle excursions up to $\pm 30^\circ$.

The work described in this report was likewise concerned with developing practical hardware based on the SPASYN transducing concept, but the emphasis in this case was on medium range (up to 35 feet) with high resolution and high accuracy (better than 0.1°) for relatively small angular excursions (up to $\pm 10^\circ$). This work was performed during the period from 2 October 1972 through 31 May 1973 under Air Force Contract F33615-73-C-1027 and was sponsored by the Avionics Laboratory at WPAFB, Dayton, Ohio.

That this development effort was successful in accomplishing most of the original objectives of the work statement is testimony to the unstinting efforts of all of the individuals and organizations involved in this project, but the authors believe special acknowledgements are due the following individuals for their important contributions to the technical success of this program:

R. Pittman, Vice-President for Research and Development;
PNSI

E. B. Blood, Systems Engineer; PNSI

A. G. Rodgers, Engineering Technician; PNSI

M. F. Spears, President; Spears Associates, Inc.,
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SECTION I

INTRODUCTION

STATEMENT OF PROBLEM

A need exists in the Navigation, Guidance and Weapon Delivery field for the capability to simply, rapidly and accurately perform airborne transfer alignments between aircraft-mounted inertial navigation systems and weapons-mounted inertial guidance systems. The geometry of the transfer alignment problem is illustrated in Figure 1.

Past methods of performing transfer alignment tasks have been difficult, time-consuming, expensive, and of questionable accuracy. These methods have generally required considerable computer time and information storage capability. The results have sometimes been of questionable value in field operations because the quality of the master and remote inertial systems were greatly disparate in terms of performance capability. Furthermore, the ability to perform airborne transfer alignments has often been hampered by equipment malfunctions in the past.

It must therefore be concluded that the capability of the Air Force to perform airborne transfer alignments has been severely limited in the past by the state of the art. It follows that if a method of simply, rapidly and accurately determining the coordinates of one reference frame with respect to another reference frame were made readily available, it would greatly enhance the Air Force's ability to perform this transfer alignment function.

SPASYN DEVELOPMENT BACKGROUND

The Space Synchro (SPASYN) concept on which the development effort described in this report was based was originally proposed to the Air Force back in July of 1971 as a unique and promising electromagnetic transducing technique for application to visually-coupled control systems. As a result of that original proposal, Polhemus Navigation Sciences, Inc. (PNSI) was awarded a contract (F33615-72-C-1482) by the Aerospace Medical Research Laboratory (AMRL) at Wright Patterson Air Force Base, Dayton, Ohio, in November of 1971 to develop a breadboard model of an Advanced Helmet Mounted Sight (AHMS) system based on the SPASYN concept.

THE TRANSFER ALIGNMENT PROBLEM

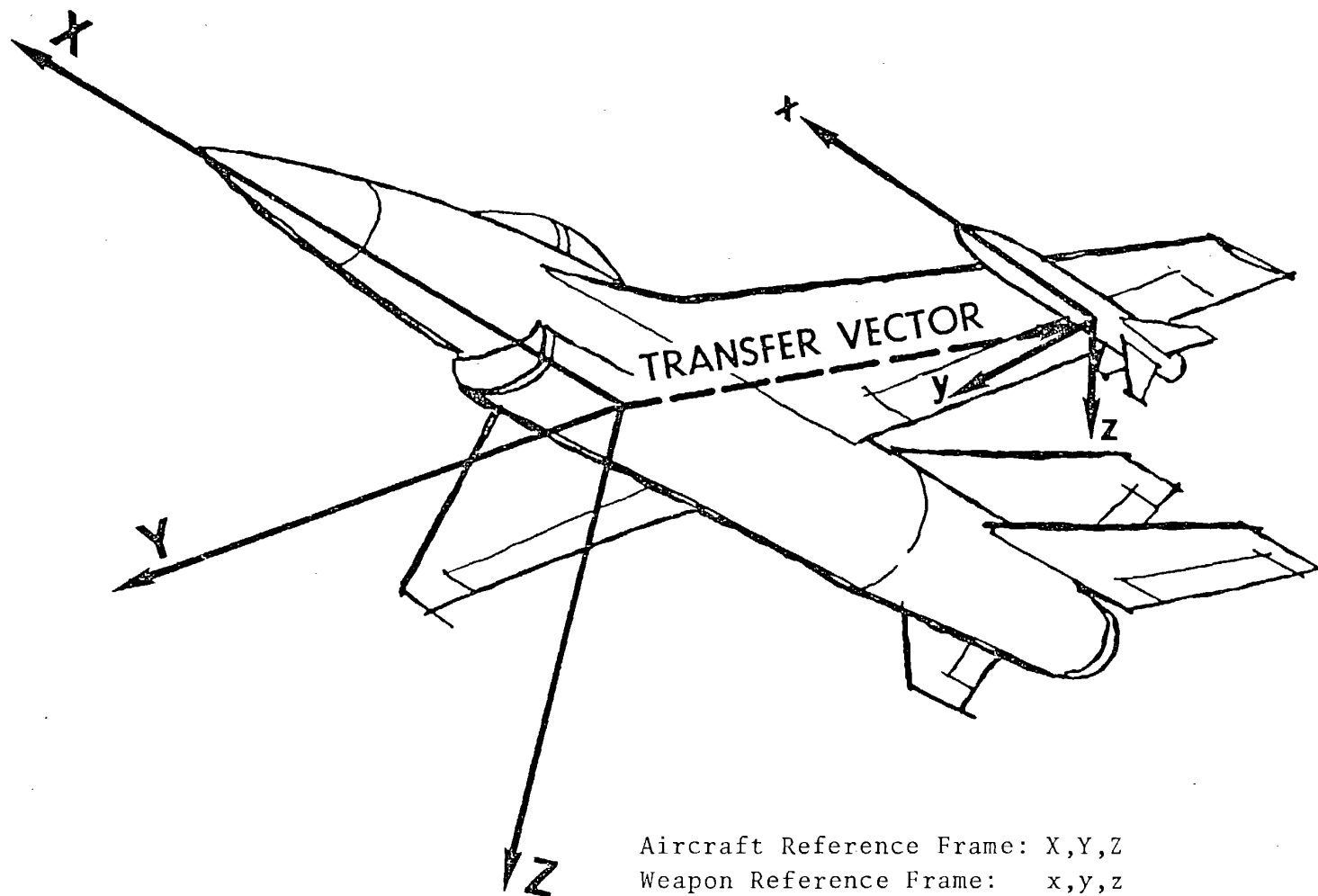


Figure 1. LOW COST AIRBORNE ALIGNMENT OF MISSILE SYSTEMS

The broad objective of the AHMS program was to demonstrate the feasibility of the SPASYN concept as a candidate solution to the AHMS problem, and the program was very successful in this respect. Although the breadboard model system did not meet all of the original performance goals (e.g., $\pm 2.5^\circ$ demonstrated accuracy versus a ± 1.0 accuracy goal), the feasibility of the concept was clearly demonstrated.

Then, in October of 1972, PNSI was awarded a follow-on contract (F33615-73-C-0106) by AMRL to develop additional hardware which would extend the transducing range of the original AHMS breadboard system to 100 feet. Since the emphasis for this follow-on effort was on range rather than accuracy, and feasibility demonstration rather than final design, the transducing accuracy requirement was relaxed to $\pm 6.0^\circ$. This program was also successful in demonstrating the feasibility of the SPASYN concept, particularly for long-range, closed-loop, control system applications that do not involve man in the closed-loop operation.

PROGRAM SCOPE AND OBJECTIVES

The broad objective of the development effort described in this report was to utilize the SPASYN technology developed under the AHMS program and determine its feasibility for performing the airborne transfer alignment task in a simple, rapid and accurate manner. Demonstration models of a radiator and sensor and their associated electronic units were to be designed, fabricated and then system tested while operating through, and in the vicinity of, various metallic structures. Finally, the test results were to be analyzed and a determination made as to the feasibility of exploring the SPASYN technique further as a candidate solution to the transfer alignment problem.

TECHNICAL REQUIREMENTS AND GOALS

The technical requirements and design goals established for this development program by the contractual work statement are outlined below:

Technical Requirements:

1. Design, fabricate and test a suitable three-axis electromagnetic radiator.
2. Design, fabricate and test a suitable three-axis electromagnetic sensor.

3. Design, fabricate and test a suitable radiator excitation unit.
4. Design, fabricate and test a suitable signal processing (and system control) unit.
5. Integrate and test the above components as a system.
6. Perform comprehensive structural interference tests with various types and configurations of peripheral or intervening metallic structures.
7. Reduce, analyze and evaluate all test results.
8. Make an assessment as to the practicality of using the SPASYN technology to perform the aircraft/missile transfer alignment function.
9. Make recommendations with regard to functional improvements and additions needed to convert the feasibility demonstration system into truly practical system for transfer alignment.
10. Make recommendations for a follow-on practical ground demonstration of a transfer alignment system mounted in a typical aircraft/missile environment.

Design Goals for the Transfer Alignment Feasibility System (TAFS)

1. Transducing range: 25 to 30 feet
2. Attitude-angle measurement accuracy about three orthogonal axes: 6 minutes of arc or better.
3. System power input: $\leq$ 35 watts.
4. Radiator power input: $\leq$ 8 watts.
5. Radiator size: $\leq$ 3 inches in diameter.
6. Sensor size: $\leq$ 3 inches in diameter.

SUMMARY OF PROGRAM RESULTS

The work accomplished under this contract, and the end results of that total effort, are summarized in Table I. Table I also

provides a comparison between the contractual requirements and goals outlined in the preceding paragraph and the results actually achieved by PNSI.

For a more detailed report on the various tasks performed under this contract, see APPENDIX A. This appendix outlines the complete progress history of the TAFS development effort. For a more detailed report on the results of all of the system testing performed under this contract, see Section 4 of this report.

Table I. Technical Accomplishments Under
Air Force Contract F33615-73-C-1027

Task/Result Accomplished	Contractual Requirements (or Design Goals)
<u>Design Tasks</u>	<u>Work Statement Paragraphs:</u>
1. System Implementation Scheme	
2. Radiator	4.1
3. Sensor	4.2
4. Radiator Excitation Unit (REU)	4.3
5. System Control and Display Unit (SCDU)	4.4
6. System Interconnect Cables	4.5
7. Radiator/Sensor Test Fixtures	4.6,4.7
<u>Fabrication and Assembly Tasks</u>	<u>Work Statement Paragraphs:</u>
1. Radiator	4.1
2. Sensor	4.2
3. REU	4.3
4. SCDU	4.4
5. Interconnect Cables	4.5
6. Radiator Test Fixture	
7. Sensor Test Fixture	
<u>Component/System Integration Tasks</u>	<u>Work Statement Paragraphs:</u>
1. REU checkout	4.3
2. REU/Radiator checkout and tailoring	4.1,4.3,4.5
3. SCDU checkout	4.4
4. SCDU/Sensor checkout and tailoring	4.2,4.4,4.5
5. SCDU/Sensor/Fixture alignment and calibration	4.5,4.6,4.7

Task/Result Accomplished	Contractual Requirements (or Design Goals)						
<u>Component/System Integration Tasks (Cont'd)</u>	<u>Work Statement Paragraphs:</u>						
6. Total system alignment and calibration (including fixtures)	4.5,4.6,4.7						
<u>System Testing Tasks</u>	<u>Work Statement Paragraphs:</u>						
1. Preparation of test plan	4.6*,4.7*						
2. Preparation of test set-up(s)	4.6*,4.7*						
3. Static accuracy tests in a structurally "clean" environment (Test Series A)							
4. Static accuracy tests with electrically conductive structures placed closeby, or between, the radiator and/or sensor (Test Series B)	4.6*,4.7*						
5. Static accuracy tests with the sensor enclosed in a conductive structure and another conductive structure placed between the radiator and sensor (Test Series D)	4.6*,4.7*						
*As amended by mutual agreement between the Air Force technical monitor and PNSI engineers.							
<u>Design/Performance Characteristics</u>							
1. Radiator volume: ≈ 30 cubic inches Size: 3.1" x 3.1" x 3.1"	(14 cu. in. max) (3 in. dia. sphere)						
2. Sensor volume: ≈ 12 cubic inches Size: 2.4" x 2.4" x 2.1"	(14 cu. in. max) (3 in. dia. sphere)						
3. Transducing range: 30 feet min.	(25 to 30 ft.)						
4. Angle measurement accuracy about 3 axes:	($\pm 0.1^\circ$)						
Standard Deviation for Small ($\pm 6.0^\circ$) Angles							
a. For Test Series A*:	<table><tr><th>ψ_e</th><th>θ_e</th><th>ϕ_e</th></tr><tr><td>0.05°</td><td>0.09°</td><td>0.11°</td></tr></table>	ψ_e	θ_e	ϕ_e	0.05 $^\circ$	0.09 $^\circ$	0.11 $^\circ$
ψ_e	θ_e	ϕ_e					
0.05 $^\circ$	0.09 $^\circ$	0.11 $^\circ$					
b. For Test Series B*:	<table><tr><th>ψ_e</th><th>θ_e</th><th>ϕ_e</th></tr><tr><td>0.11°</td><td>0.15°</td><td>0.17°</td></tr></table>	ψ_e	θ_e	ϕ_e	0.11 $^\circ$	0.15 $^\circ$	0.17 $^\circ$
ψ_e	θ_e	ϕ_e					
0.11 $^\circ$	0.15 $^\circ$	0.17 $^\circ$					
c. For Test Series D*:	<table><tr><th>ψ_e</th><th>θ_e</th><th>ϕ_e</th></tr><tr><td><0.18°</td><td><0.22°</td><td><0.24°</td></tr></table>	ψ_e	θ_e	ϕ_e	<0.18 $^\circ$	<0.22 $^\circ$	<0.24 $^\circ$
ψ_e	θ_e	ϕ_e					
<0.18 $^\circ$	<0.22 $^\circ$	<0.24 $^\circ$					
*See listing of system testing tasks above.							

Task/Result Accomplished	Contractual Requirements (or Design Goals)
<u>Design/Performance Characteristics</u> 5. System Input Power: $\approx$ 150 watts (excluding display requirements) Radiator Input Power: 5 to 8 watts	 ($\approx$ 35 watts) ($\approx$ 12 watts)

SECTION II

SYSTEM DESIGN

REVIEW OF SPASYN CONCEPT

The basic objective of the SPASYN concept is to provide a precise and continuous measure of the relative translation and rotation of one rigid body (the moving coordinate frame) with respect to a second, totally independent, rigid body (the reference coordinate frame). The problem to be solved therefore involves six degrees of freedom in the general case. The SPASYN concept can provide such a six-degree-of-freedom measurement capability with a two-radiator/one-sensor transducing configuration.

With a single-radiator/single-sensor transducing configuration, a SPASYN system can provide a five-degree-of-freedom solution. Such an implementation scheme is sufficient for applications where only measures of the attitude angles are required as output information. The transfer alignment application falls into this five-degree-of-freedom solution category.

Figure 2 illustrates the geometric relationships involved in the five-degree-of-freedom solution. The orthogonal X , Y and Z axes represent the reference coordinate frame, the orthogonal x , y , and z axes represent the moving coordinate frame, the ψ , θ , and ϕ angles represent the relative bearing, pitch, and roll angles of the moving body with respect to the reference body, and the α and β angles represent the angles of rotation of the magnetic field pointing frame with respect to the reference frame. The orthogonal axes X_p , Y_p and Z_p define the pointing frame and the angles α and β define successive rotations about the Z_p and Y_p axes respectively.

SPASYN is a closed-loop transducing/computing scheme which uses a dynamic magnetic field as the coupling, or data link, between the moving coordinate frame and the reference coordinate frame. This concept is depicted in Figure 3.

The functional entities, or components, which make up a five-degree-of-freedom SPASYN system are shown to be a three-axis electromagnetic Radiator which is rigidly fixed to the reference coordinate frame, a three-axis magnetic Sensor which is rigidly fixed to the moving coordinate frame, a System Electronics Unit (SEU) and a System Controller. Except for the incidental manual control and calibration functions provided on the SEU and/or System Controller, the only moving part in this system is the moving body to which the sensor is attached.

COMPOSITE POINTING/ORIENTATION GEOMETRY

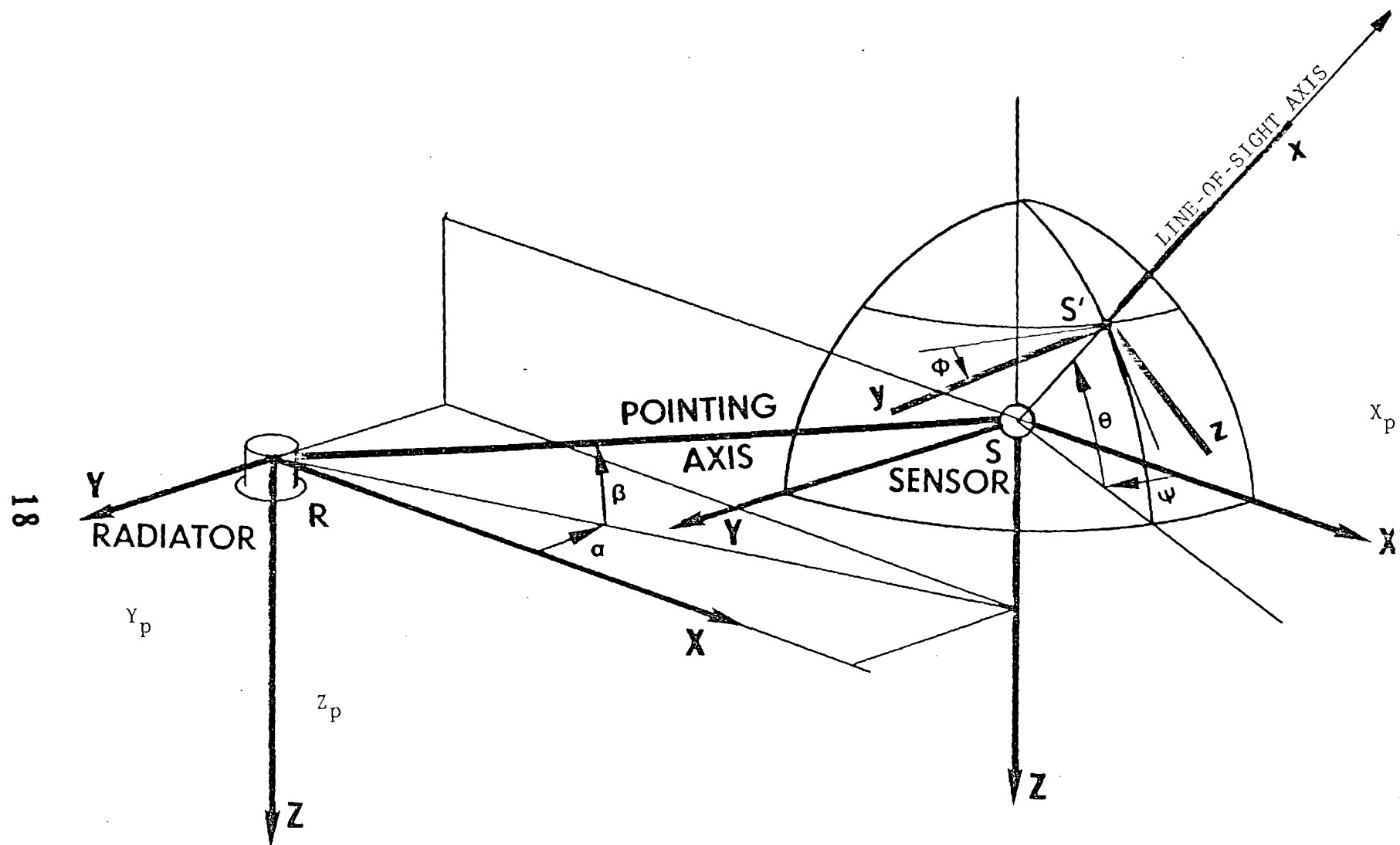


FIGURE 2. A FIVE DEGREE-OF-FREEDOM TRANSDUCING SCHEME

For any given application, it may be desirable to subdivide the SEU functions into more than one electronics unit or to combine the System Controller and SEU functions into one electronics unit. It may also be desirable to reverse the roles of the Radiator and Sensor for a particular application, i.e., the Radiator could be mounted on the moving body and the Sensor could be mounted on the fixed reference frame.

The conceptual system representation of Figure 3 serves to illustrate the basic SPASYN idea of using a conically nutating magnetic field as the data link between the rigid body to which the radiator is attached and the totally independent rigid body to which the sensor is attached. Figure 3 also illustrates the important fact that the SPASYN system is a closed-loop system in which the sensed information signals derived from the radiated magnetic field are in turn operated upon by the SEU to control the radiator excitation currents which produce the radiated field. To be more specific, the SEU operates so as to continuously force a null, or equilibrium, system condition whereby the bearing, pitch and roll angles of the moving body relative to the reference body are all explicitly and continuously derived as forced functions of this equilibrium-seeking mode of operation.

For a more detailed and complete explanation of the SPASYN concept, refer to APPENDIX B of this report. A more complete discussion and explanation of the nutating-magnetic-field and magnetic-field-pointing principles which are fundamental to the SPASYN concept can also be found in the report entitled An Advanced Helmet-Mounted Sight (AHMS) System. (See the BIBLIOGRAPHY included in this report.)

SYSTEM/COMPONENT DESIGN CONSIDERATIONS

As reported in the introductory paragraphs of this report, a great deal of SPASYN development work had already been accomplished under a previous Air Force contract at the time that work was started under this contract. However, most of this development work had been concentrated on the development of a short-range, moderate-accuracy system implementation whereas the transfer alignment application calls for much higher accuracy (for small-angle excursions) at much greater range. The development effort under this contract was therefore focused on those design considerations which have a direct bearing on the small-angle accuracy and effective range of the system. These considerations were:

1. Signal-to-noise requirements.
2. Choice of operating (carrier) frequency.

THE SPASYN FIVE-DEGREE-OF FREEDOM SYSTEM

A CLOSED LOOP TRANSDUCING/COMPUTING SCHEME USING A MAGNETIC FIELD COUPLING BETWEEN REFERENCE FRAME AND MOVING FRAME.

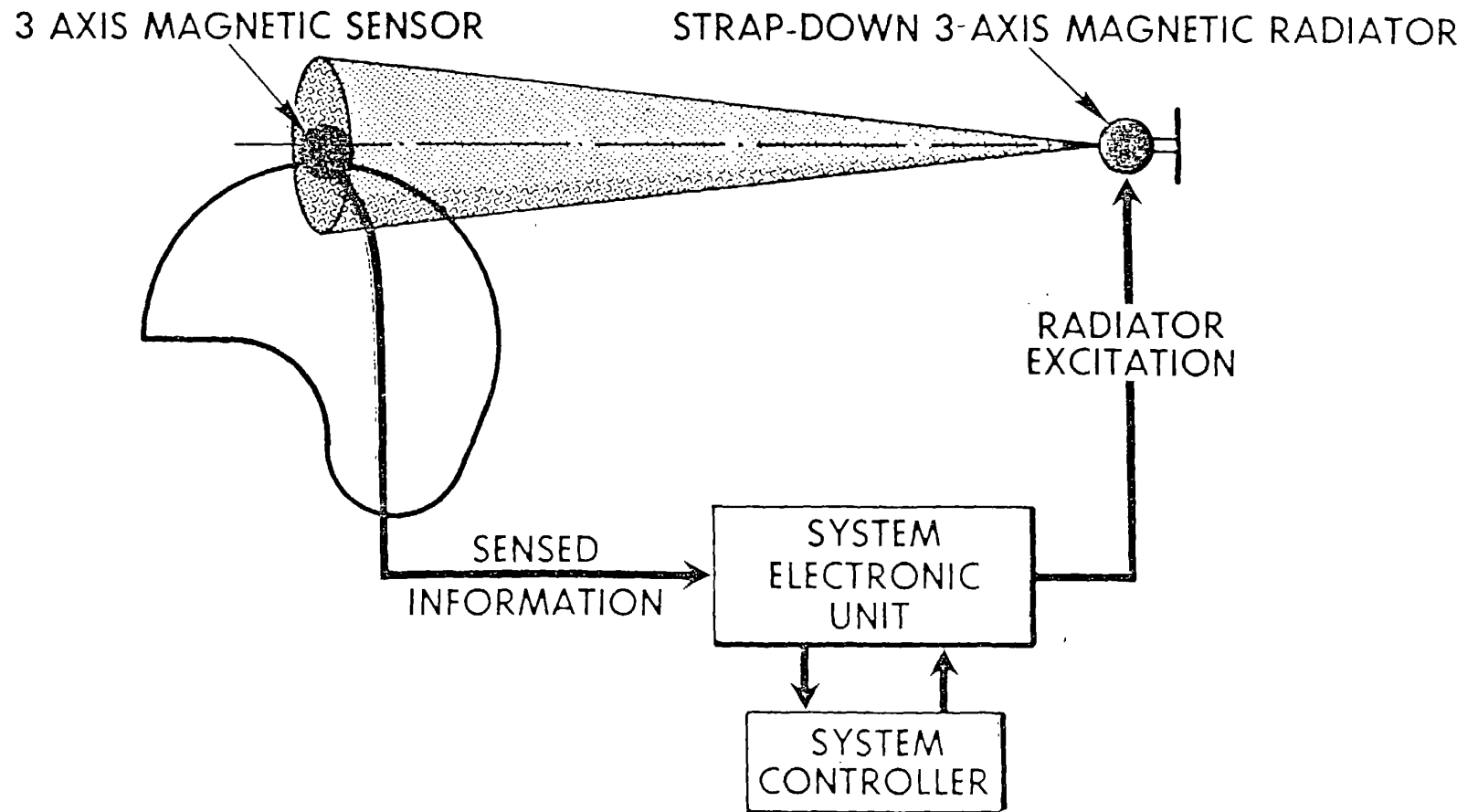


Figure 3. The SPASYN Five-Degree-of Freedom System

3. Radiator and sensor designs.
4. Design of the radiator excitation output stages.
5. Design of the sensor signal preamplifying input stages.
6. Design of the sensor signal bandpass filters.

All of the above considerations are, of course, highly inter-related.

Signal/Noise Considerations

To obtain a six-minute absolute angular accuracy at a range of twenty-five feet with a SPASYN transfer alignment system, it is necessary to give careful consideration to the disturbing effects of atmospheric noise picked up by the sensor. Assuming operation in the VLF electromagnetic spectrum, an atmospheric noise level of $20 \mu\text{v}/\text{m}/\sqrt{\text{Hz}}$ may be expected. Assuming a processing bandwidth of 100 Hz, a total noise level of $200 \mu\text{v}/\text{m}$ is indicated. Thus, to assure a root-mean-square angular uncertainty of less than 0.05 degree due to atmospheric noise effects within a 100 Hz bandwidth, a signal-to-noise-ratio of 810 to one, or 58dB, is required. This is obtainable with a signal level of 0.162 volts per meter at the sensor.

To obtain the required radiated field intensity level from a three-inch-cube radiator, 412 amp-turns of magnetic potential are required. A review of currently available voltage-to-current amplifiers capable of operating in this frequency range indicates that the practical design limit based on the current state of the art is about seven amperes peak output current. If an air-core radiator were used, about sixty turns of wire would be required. Such a design approach would result in an unacceptably high power dissipation level in the radiator windings and unacceptably high voltage levels across the windings; therefore, designs which employ a ferrite structure to enhance the effectiveness of the radiator windings were explored. Finally, from a series of measurements performed with various radiator core and winding geometries, an open-framed-cube configuration was selected for the transfer alignment application.

The design of the sensor was then modelled after the finalized radiator design. In the case of the sensor, however, the design was not limited by the acceptable voltage levels across the sensor windings. In this case, the number of turns per winding were increased to provide an optimum design in terms of noise figure versus source impedance, keeping in mind the possible effects of electrostatically-coupled signal pickup on the sensor windings.

Appendix C to this report provides further insight into the considerations which influenced the design of the radiator, sensor, preamplifying input stages, and radiator excitation output stages for the Transfer Alignment Feasibility System (TAFS).

Choice of Operating (Carrier) Frequency

The operating (carrier) frequency for the transfer alignment feasibility system was ultimately fixed at seven kilohertz (7 KHz) based on the following considerations:

1. Seven kilohertz is generally above the audio frequency pass band of the voice communication equipment used in modern aircraft.
2. Seven kilohertz is halfway between the seventeenth and eighteenth harmonics of 400 Hz which is the standard frequency for AC power systems in modern aircraft.
3. Seven kilohertz is within the full-power bandwidth capabilities of state-of-art high-current, wide-band, operational amplifiers (although very near the upper limit).
4. Generally speaking, the lower the carrier frequency, the less severe the magnetic interference effects should be due to eddy currents generated in nearby, electrically-conductive structures (although empirical test results have indicated that the improvement is hardly noticeable for a ten-to-one reduction in frequency (from 20 KHz to 2 KHz) with nearby aluminum structures typical of a modern aircraft cockpit environment.)
5. The lower the carrier frequency, the better the signal-to-noise ratio should be with respect to atmospheric noise effects for frequencies in the high audio (VLF) range.
6. The lower the carrier frequency, the easier it is to stabilize the closed-loop radiator excitation output stages when driving inductive loads.

The above-listed advantages of a 7 KHz operating frequency, as opposed to a substantially higher carrier frequency, are somewhat offset by the reduced "effective heights" of the radiator and sensor for the lower frequency case. This reduction in "effective height" necessitates a higher excitation level in the radiator in order to produce a particular signal level in the sensor.

System Power Requirements

The contractual work statement for the transfer alignment feasibility system specified a design goal of eight watts maximum power dissipation in the radiator. However, in the interest of maximizing the signal-to-noise ratio at the sensor, it was decided that the radiator windings should be excited at the maximum AC current level which state-of-the-art power operational amplifiers are capable of supplying at 7 KHz without excessive distortion or excessive power losses within the amplifiers themselves.

Thus, having finalized the winding parameters for the TAFS radiator (i.e., the wire size and number of turns per winding) and having set the low-frequency modulation level to provide a 90° enclosed nutation angle, the power dissipation in the radiator was empirally determined to be 12 watts at this maximum practical excitation level.

A reduction of the modulation amplitude so as to reduce the enclosed nutation angle to 45° would have reduced the radiator power dissipation to about 8 watts, and the "pointing" sensitivity of the transducing loop would have been somewhat degraded. Nevertheless, it is very likely that the system operation would still have been more than satisfactory for the intended application if the radiator excitation level had been reduced from 12 watts to 8 watts.

SYSTEM IMPLEMENTATION SCHEME

The limited implementation scheme finally decided upon for the transfer alignment feasibility system is depicted in the block diagram of Figure 4. This diagram does not include the digital measurement and display provisions which were built into the SCDU to facilitate system testing in accordance with the contractual work statement.

The four resolver functions required in the SCDU (see Figure 4) were implemented with analog multiplier circuits which are identical to those used to implement the multiplier functions in the REU. Two such multipliers are required per resolver; therefore, the total number of multipliers required for the transfer alignment feasibility system was eleven. The four SCDU resolver functions serve to implement the closed-loop radiator pointing scheme.

In the early planning stages of this program, the implementation of the five closed-loop, angle-computing functions was

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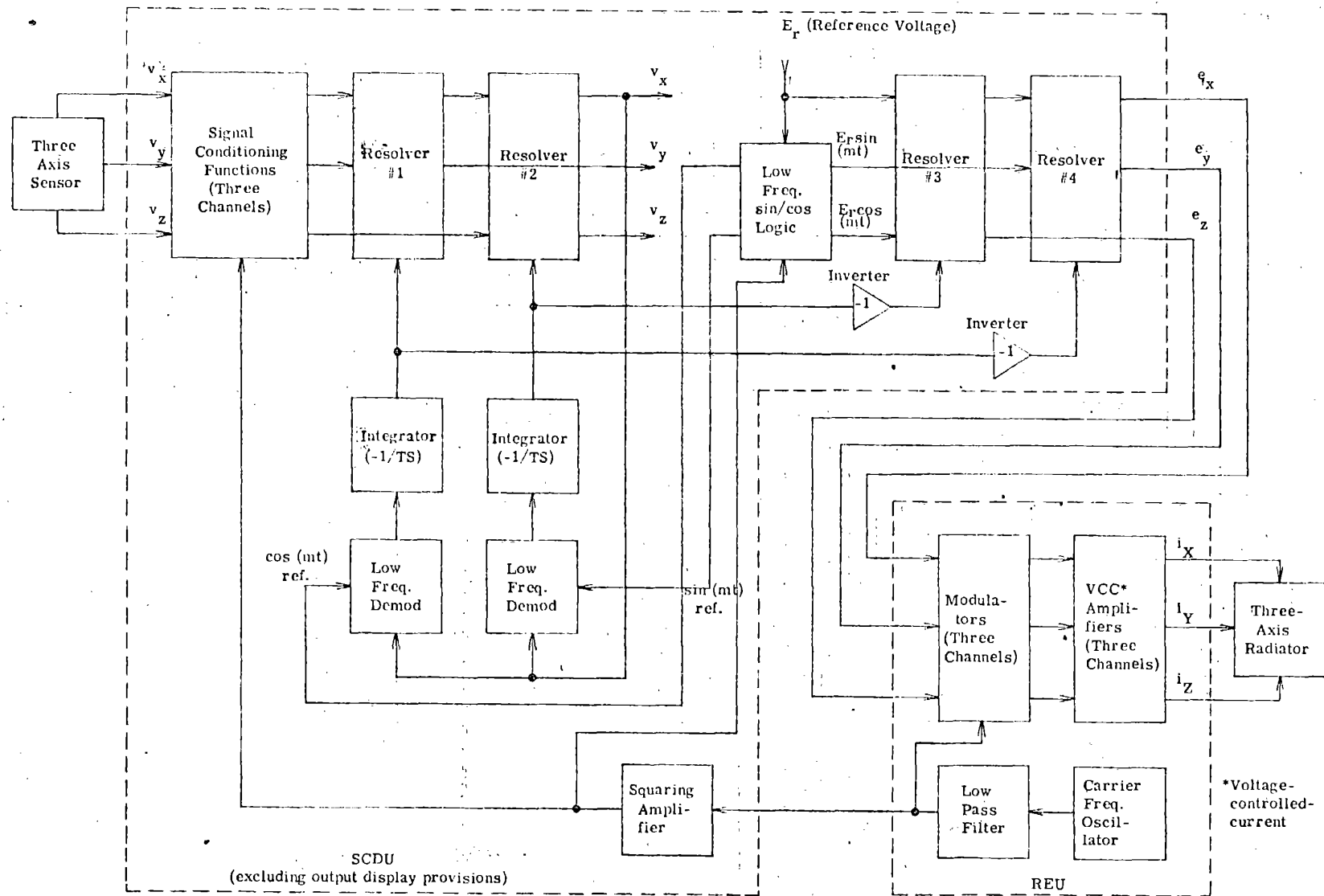


Figure 4. Functional Block Diagram of the Transfer Alignment Feasibility System

deemed unnecessary to the accomplishment of the contractual objectives. It was only after performing "structural effects tests" with the SPASYN/AHMS breadboard system, both in the laboratory and in actual cockpit installations, that the practical necessity for implementing at least the pointing-loop functions was established. In any complete, closed-loop SPASYN configuration, at least three additional resolver functions, or their time-shared equivalents, would be required to implement the attitude angle computing functions.

SECTION III

SYSTEM HARDWARE

RADIATOR AND SENSOR

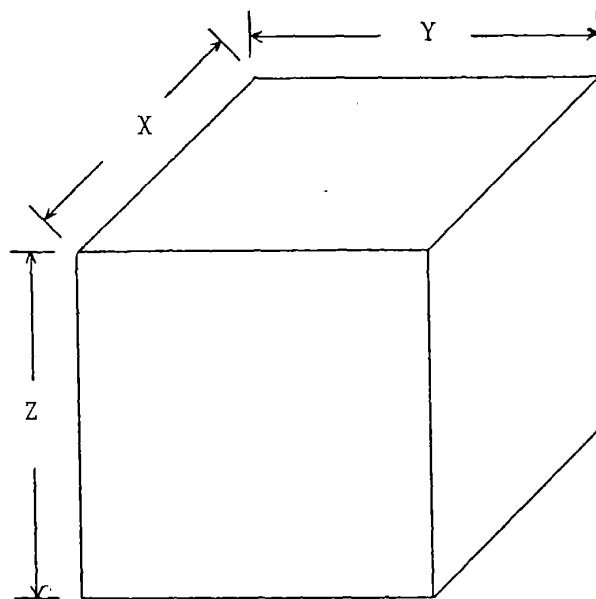
All of the pertinent physical and electrical characteristics of the Radiator and Sensor which were designed and fabricated under this contract are presented in Figure 5.

RADIATOR EXCITATION UNIT (REU)

All of the pertinent physical and electrical characteristics of the REU are presented in Figure 6. All externally accessible electrical adjustments, connectors, and controls are also identified as to location and function. A functional block diagram of this component is included in Figure 6.

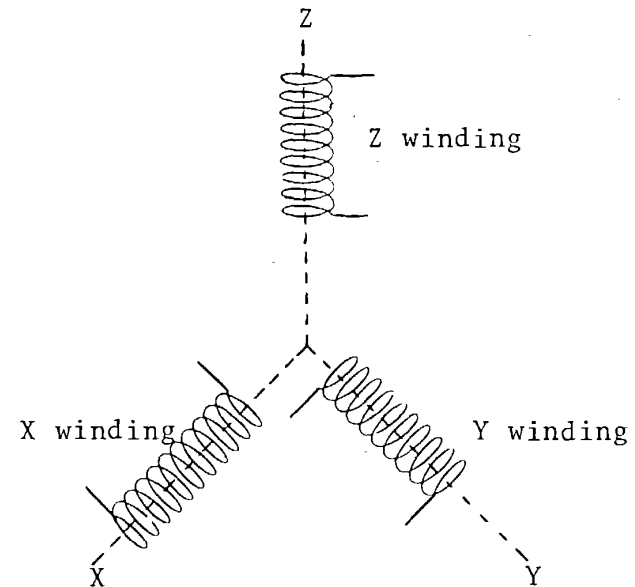
SYSTEM CONTROL UNIT (SCDU)

All of the pertinent physical and electrical characteristics of the SCDU are presented in Figure 7. All externally accessible electrical adjustments, connectors, and controls are also identified as to location and function. A functional block diagram of this component is shown in Figure 8.



Nominal Winding Impedances at 7KHz

Sensor:	$7 + j$	200 ohms	each winding
Radiator:	$0.6 + j$	6 ohms	each winding



	Dimensions (inches)		
	X	Y	Z
Sensor	2.7	2.8	2.8
Radiator	3.0	3.0	3.0

Figure 5. Radiator/Sensor

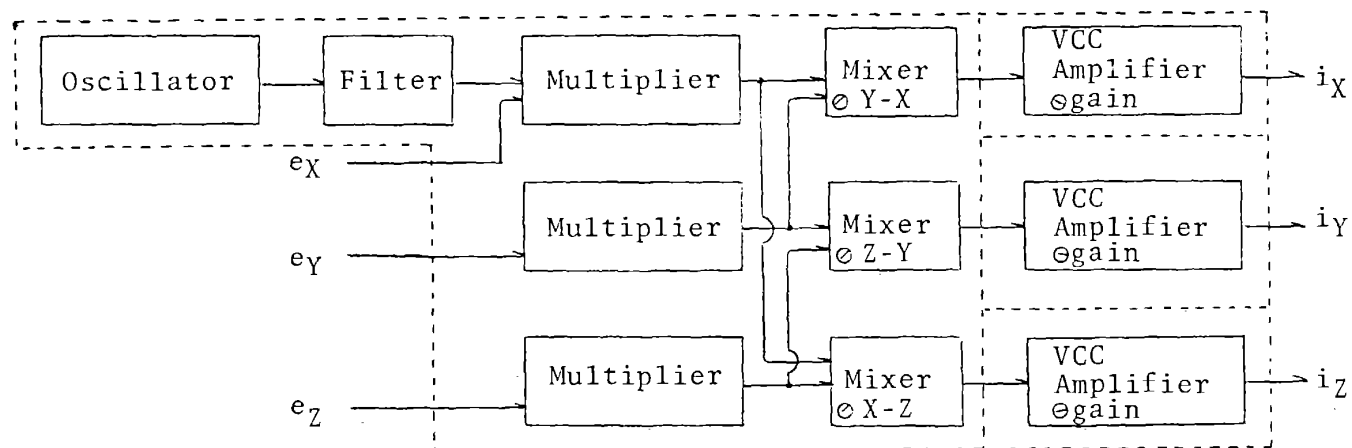
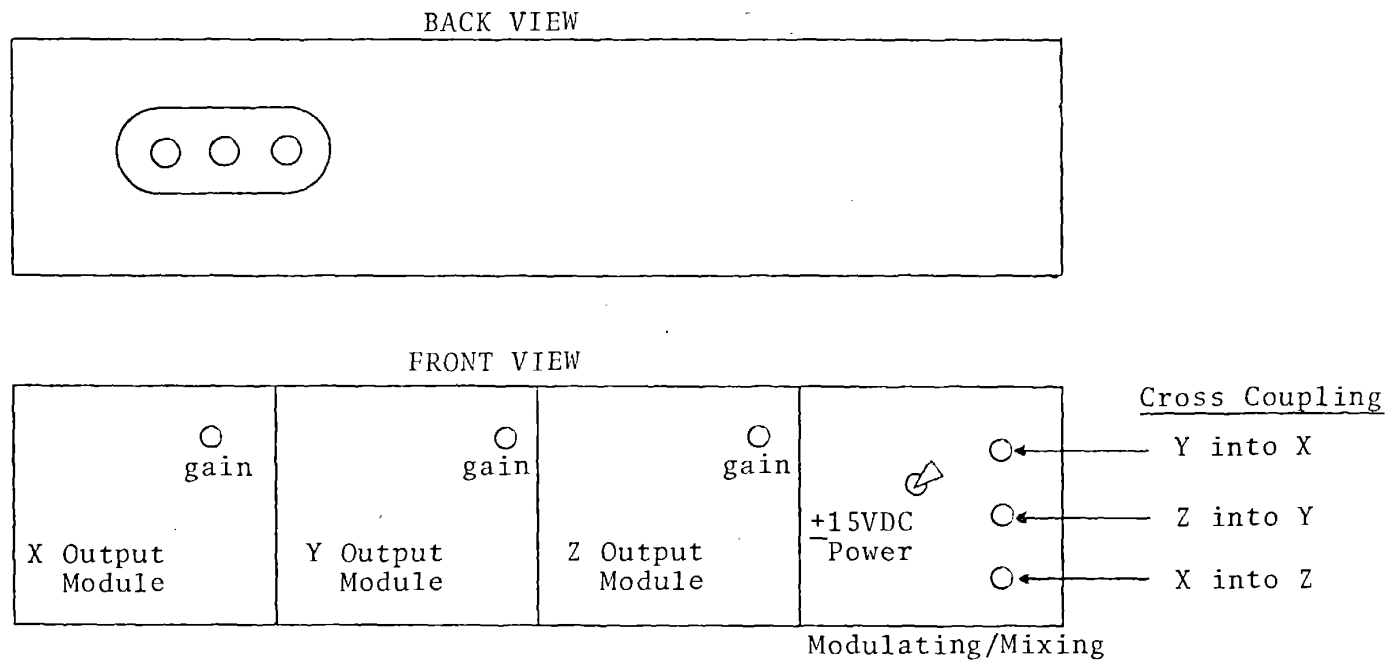


Figure 6. Radiator Excitation Unit

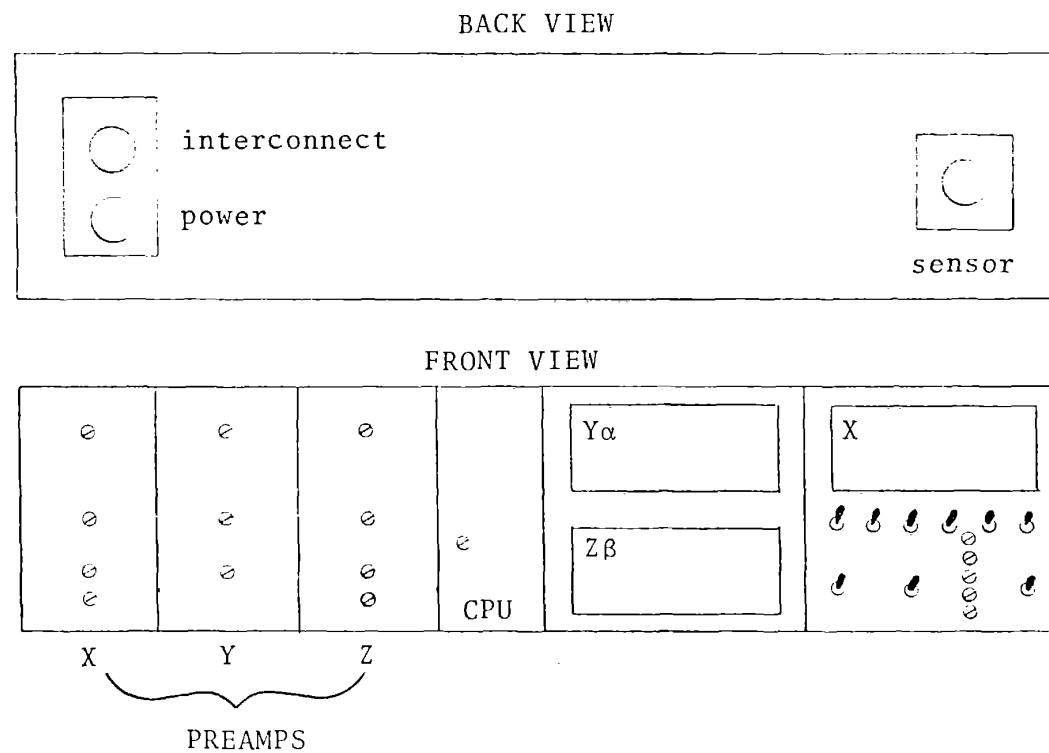


Figure 7. SCU

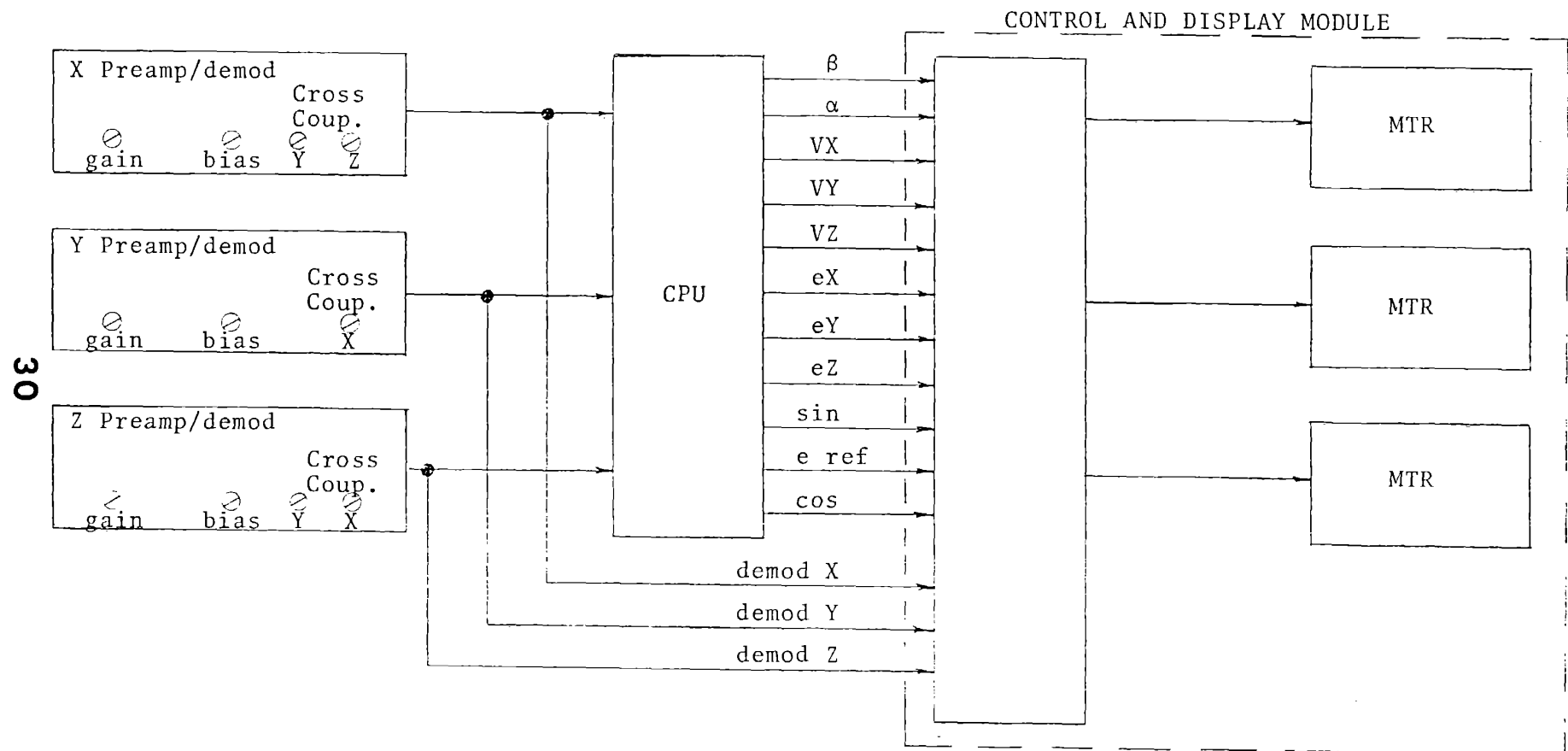


Figure 8. SCDU Functional Block Diagram

SECTION IV
SYSTEM TESTING

TEST PLAN

The statement of work applicable to the subject contract specified that system tests for static accuracy were to be conducted under certain environmental conditions with regard to the proximity of soft magnetic materials or electrically conductive materials to the transducing elements of the system. The intent was to determine the effects on system performance of magnetic and electrically conductive materials placed at various angles and locations with respect to the radiator and/or sensor.

It was determined early in the program, however, that the effects of eddy currents produced in nearby electrically conductive materials as a function of the alternating (7KH_z) magnetic field was potentially a much more serious problem for aircraft cockpit applications than the effects produced by soft magnetic materials. This fact was established as the result of tests conducted by PNSI engineers, both in the laboratory and in typical aircraft cockpits, shortly after the award of this contract.

Based on the fact that in an aircraft application, any nearby structure is much more apt to be made of aluminum than of soft magnetic material, it was decided that the TAFS testing should, for the most part, be concentrated on quantifying the effects of electrically conductive structures such as aluminum panels. This decision was arrived at by mutual agreement between the contractor and the Air Force project engineer.

To implement and facilitate the decision to concentrate on the effects of electrically-conductive structures, arrangements were made by the Air Force project engineer to have two typical aircraft/missile structures furnished to PNSI on a GFE or scrap basis for our test purposes under this contract. One structure was a typical aircraft fuselage panel. The other was a typical airborne missile nose cone.

At a subsequent meeting held at PNSI's facility in March, a general test plan based on the use of these two test structures was mutually agreed upon by PNSI engineers and the Air Force project engineer. It was further decided that all structural effects testing would be limited to working with these two typical structures. The detailed test plan outlined in Table 2 of this report was based on the agreements reached at that March meeting.

Table 2. TAFS Detailed Test Plan

Test Series	Description of Tests	Variable Test Conditions
A	Baseline static accuracy tests under "ideal" conditions (no electrically or magnetically conductive structures within 30 feet of the radiator or sensor in any direction; test to be conducted outdoors under mild to moderate atmospheric conditions. Test 1: Small-angle transducing tests using Input Condition Set #1. Test 2: Larger-angle transducing test using Input Condition Set #2.	Input Condition Set #1: All possible combinations of $+6^{\circ}$, $+3^{\circ}$ and 0° for the three (Ψ , θ and ϕ) attitude angle input gimbals; total combinations: 125 Input Condition Set #2: All possible combinations of $+12^{\circ}$ and $+6^{\circ}$ for the Ψ and θ input gimbals with -12° and -6° for the ϕ input gimbal; total combinations: 32
B	Static accuracy tests under various structural interference conditions and using Input Condition Set #3. Test 1: Small-angle tests with an electrically conductive panel placed between the radiator and sensor and close to the sensor. Test 2: Same as Test 1 except with the "interfering" panel placed directly above and close to the sensor. Test 3: Same as Test 1 except with the "interfering" panel placed directly in front of and close to the radiator.	Input Condition Set #3: All possible combinations of $+6^{\circ}$ and 0° for the Ψ , θ and ϕ input gimbals; total combinations: 27 Test 1: Symmetrically place the fuselage panel 10 to 20 inches in front of the sensor with the long axis of the panel parallel to the ground and at right angles to the radiator/sensor line, and the concave face of the panel toward the sensor. Test 2: Symmetrically place the fuselage panel 10 to 20 inches above the sensor with the long axis of the panel parallel to the ground and in line with the radiator/sensor line, and the concave face of the panel toward the sensor. Test 3: Symmetrically place the fuselage panel 10 to 20 inches in front of the radiator with the long axis of the panel parallel to the ground and at right angles to the radiator/sensor line, and the convex face of the panel toward the radiator.
C	Tests to quantitatively define the "interference" boundary, or perimeter, of the transducing components in relation to a particular separation distance between radiator and sensor and a particular "interference" test panel.	Conduct a series of test with the fuselage panel to define the "interference" perimeter for a 30 foot radiator to sensor spacing. The "interference boundary" criteria shall be for each different "approach" of the panel to either the radiator or sensor shall be: that maximum distance at which the SCDU readout indicate a field disturbance equivalent to $\pm 1^{\circ}$ of error for anyone of the three "sensed" attitude angles.
D	Static accuracy tests under the same conditions as for Test B3 except that the sensor shall be completely surrounded by a cylindrical "interfering" structure and Input Condition Set #4 shall apply.	Input Condition Set #4: The Ψ input gimbal shall be set at 0° , $+3^{\circ}$ and $+6^{\circ}$ (five different settings) with the ϕ and θ input gimbal initially set at or near zero and then held constant throughout the test.

TEST SET-UPS

The specific test set-ups which were employed in conducting the system tests are depicted in the line drawings of Figures 9, 10, 11 and 12. Test set-ups B3 and D1 are also shown in the photographs of Figures 13 and 14. Figure 15 shows a close up of the Sensor/Test-Fixture/SCDU set-up which was typical for all of the system tests except test D1. The system components and test structures are all clearly identified in Figures 13, 14 and 15, and the pertinent distances for the various test set-ups are specified in Figures 9 through 12. In the latter figures, the TAFS radiator and sensor and the two test structures are identified as follows:

<u>Symbol</u>	<u>Definition</u>
R	Radiator
S	Sensor
P	Fuselage Panel
C	Missile Nose Cone

No further explanation with regard to these test set-ups is deemed necessary for the purposes of this report except in the case of test set-up D1. For this set-up, the sensor had to be removed from the sensor test fixture and placed on a non-metallic rotatable platform which was large enough to support the missile cone so as to allow the missile nose cone to completely enclose the sensor. It is obvious from Figure 12 that this set-up permitted no access to the sensor within the missile nose cone during the test; therefore, this test was limited to rotations about the azimuth axis of the test fixture.

TEST RESULTS

The results of all of the system tests performed under this contract are summarized in Table 3. Both the standard deviations and "worst case" error results are listed for all of the tests performed. A complete listing of all system test results is included in this report as Appendix D. Appendix D also includes derivations and listings of the various mathematical relationships which were used to calculate the COMPUTED OUTPUT DATA listings from the INPUT DATA and MEASURED OUTPUT DATA listings.

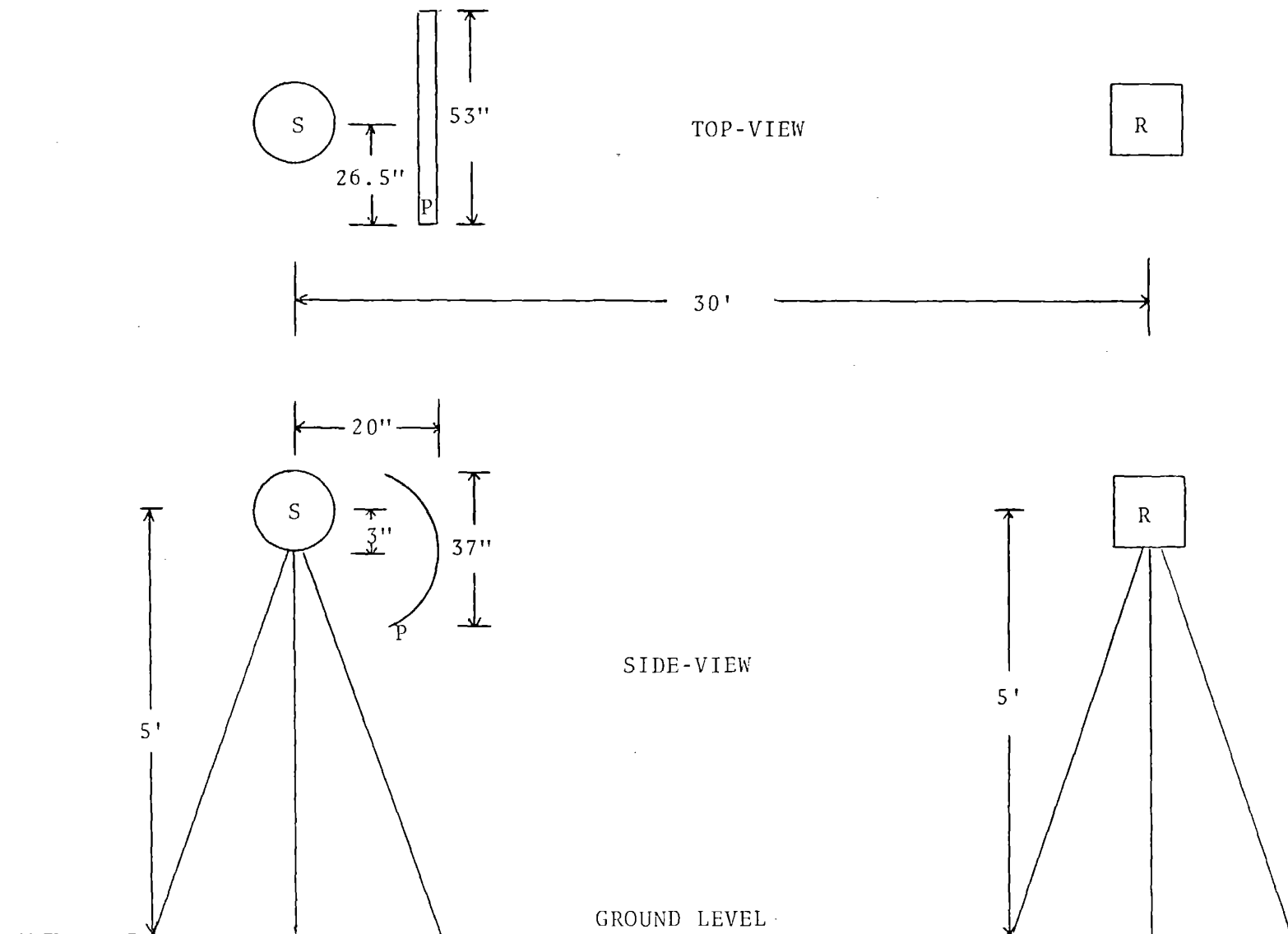


Figure 9. Radiator/Sensor/Structure Set-Up For Test B-1.

Figure 10. Radiator/Sensor/Structure Set-Up For Test B-2.

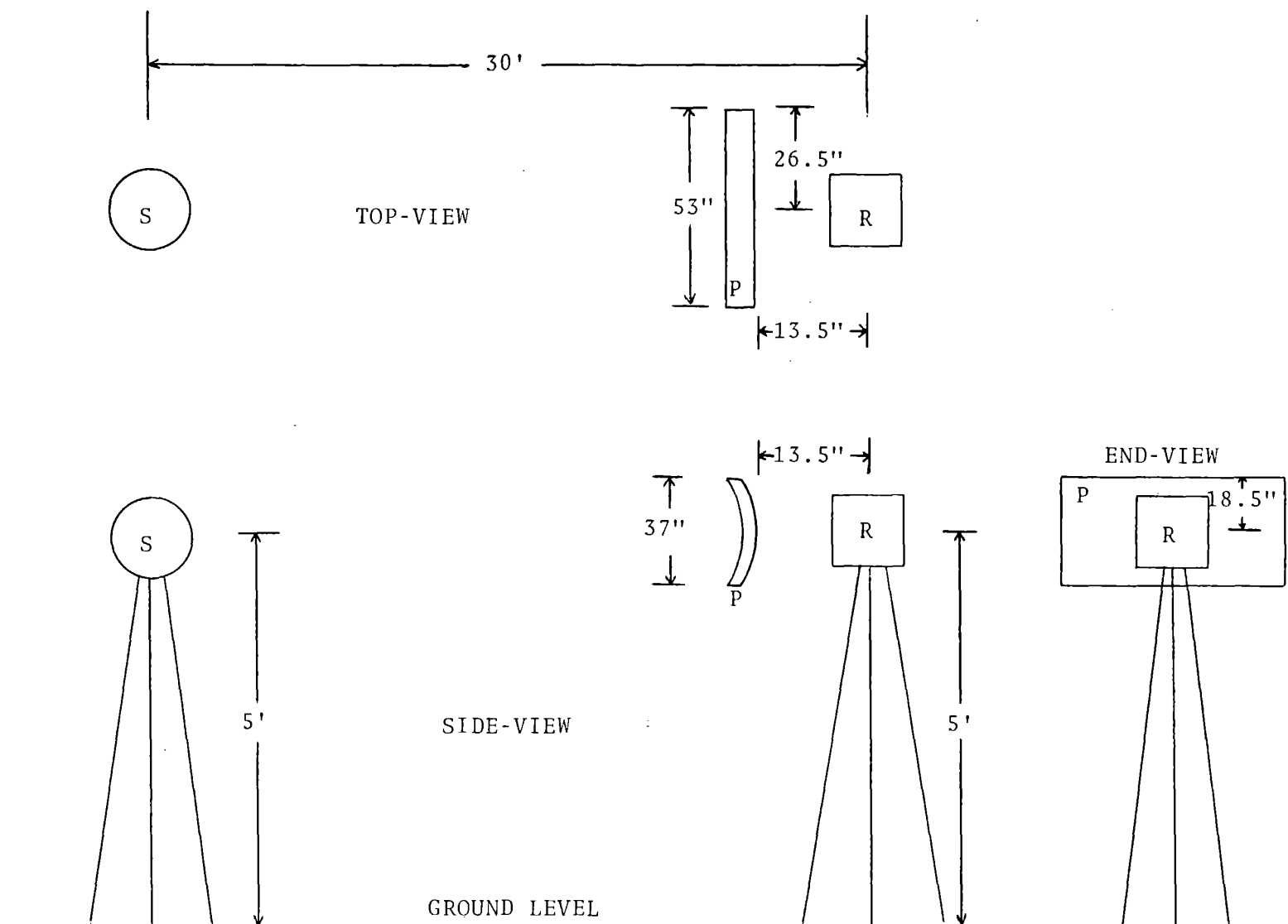


Figure 11. Radiator/Sensor/Structure Set-Up For Test B-3.

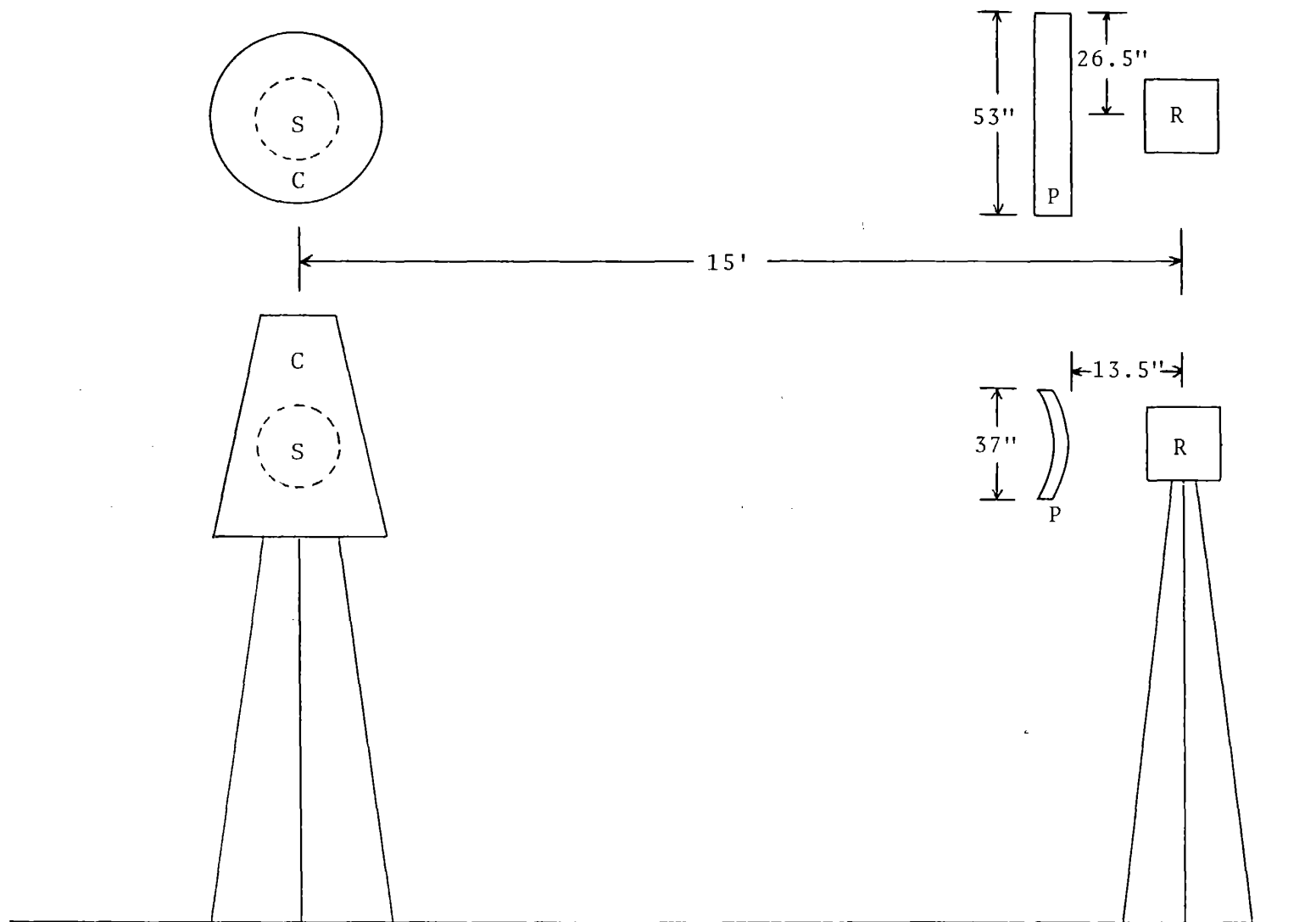


Figure 12. Radiator/Sensor/Structure Set-Up For Test D1.

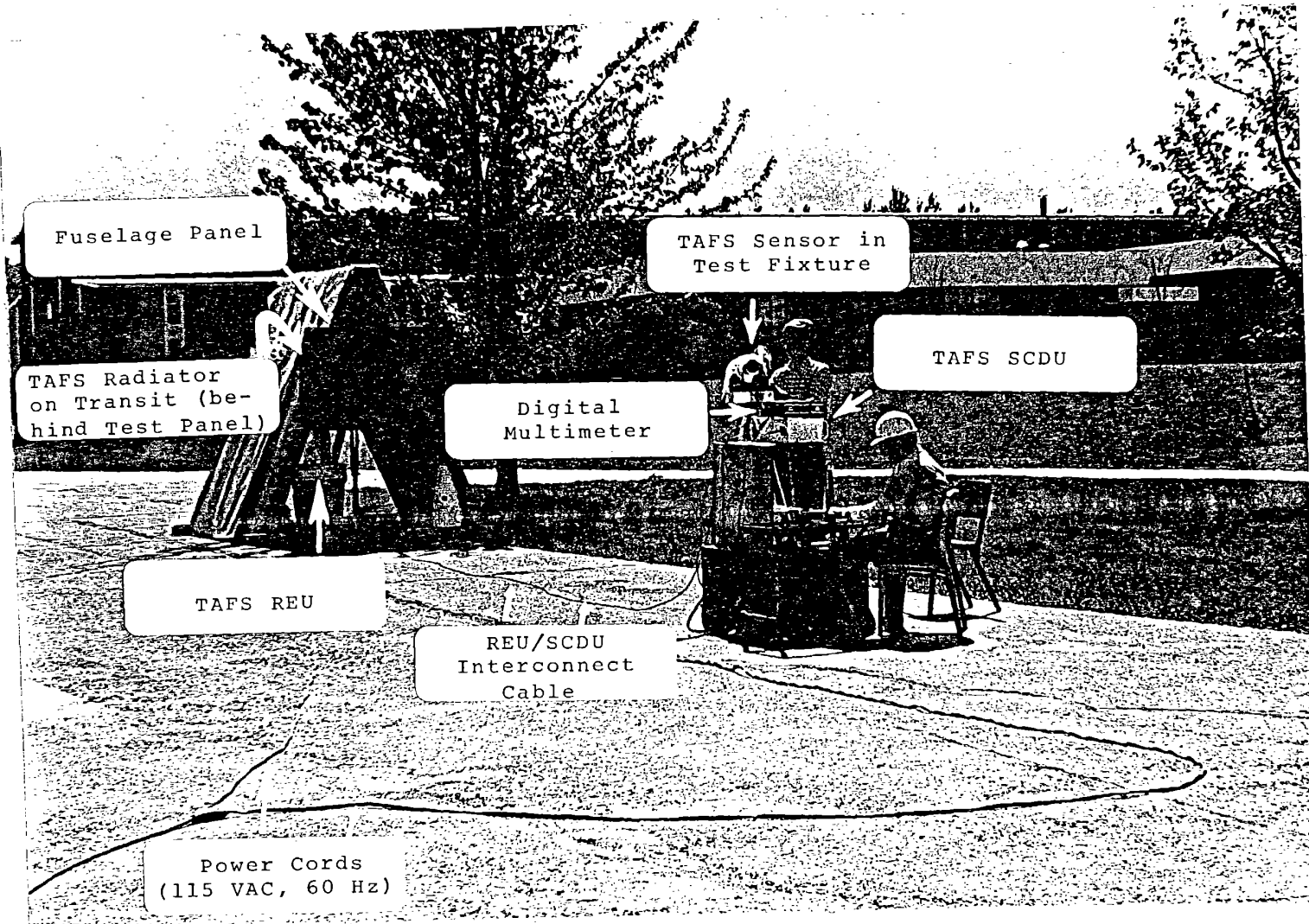


Figure 13. Test Set-Up For Test B3.

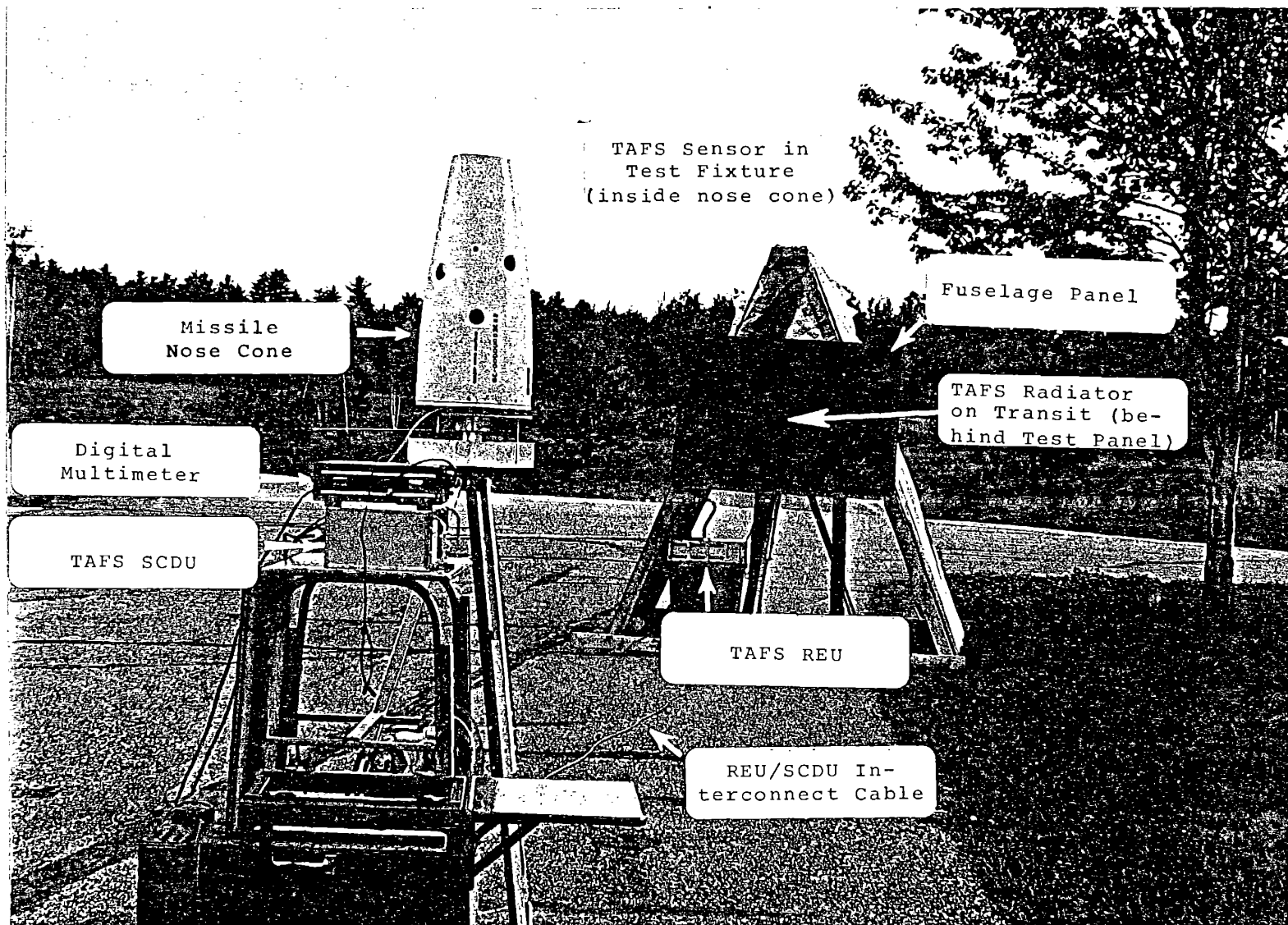


Figure 14. Test Set-Up For Test D1.

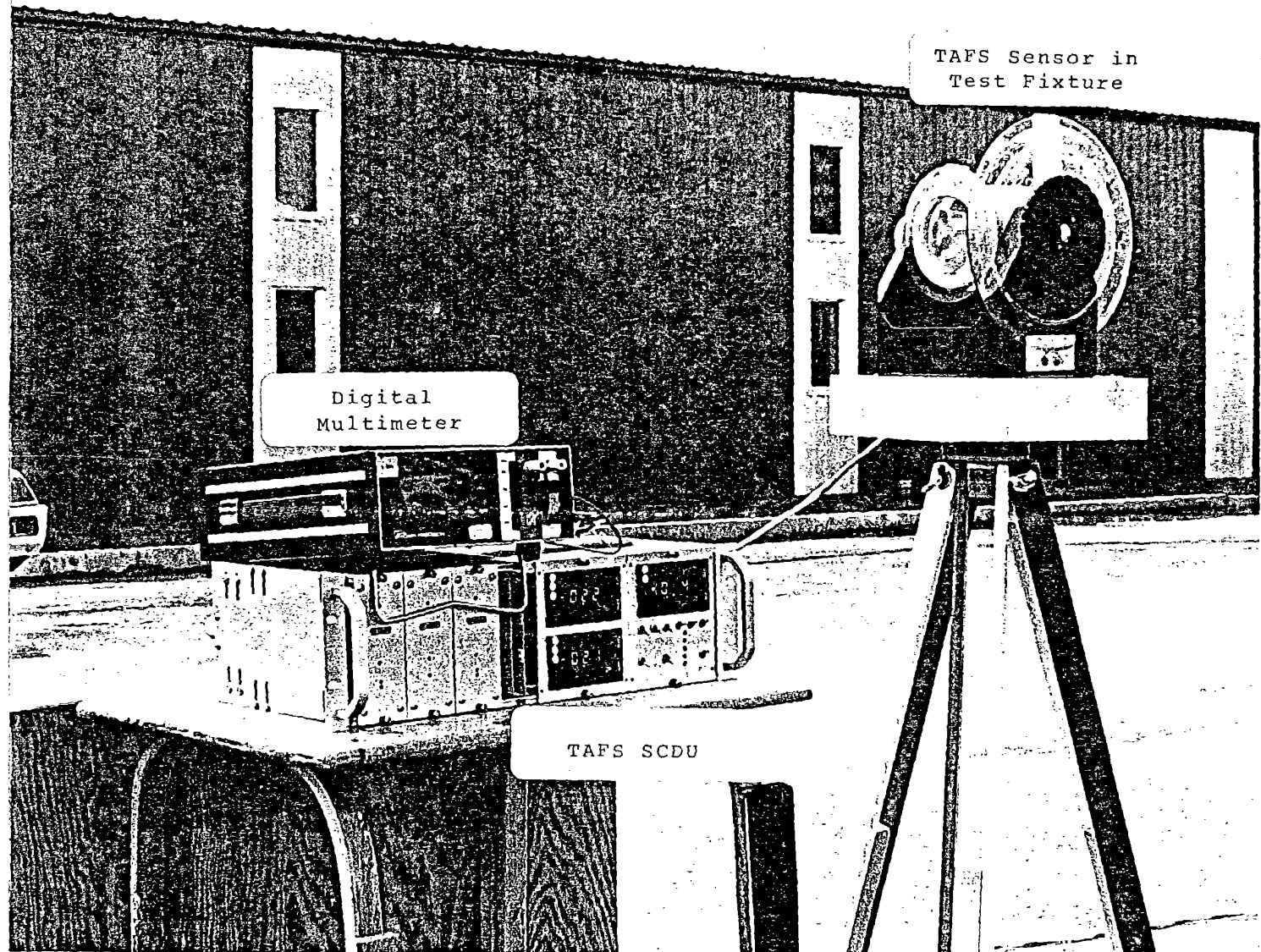


Table 3. Summary of TAFS Test Results

Test Series	Test No.	Characteristics Tested	Test Set-Up	Test Conditions (See Table 2)	TA Errors (In Degrees)					
					Std. Deviation*			Worst Case Errors		
					Ψ_e	θ_e	ϕ_e	Ψ_e	θ_e	ϕ_e
A	1	Static accuracy and resolution for angles $\leq +6^\circ$	Outdoors, no conductive structures	Input Condition Set I; 125 total combinations of attitude angles	0.05	0.09	0.11	0.15	0.19	0.25
	2	Static accuracy and resolution for angles $\leq +12^\circ$		Input Condition Set II; 32 total combinations of attitude angles	0.29	0.14	0.18	0.58	0.50	0.29
B	1	Static accuracy and resolution, for angles $\leq +6^\circ$, in the presence of an intervening or adjacent conductive structure	Fig. 9	Input condition Set III; 27 total combinations of attitude angles; with a single intervening structure near the sensor	0.10	0.17	0.10	0.28	0.35	0.23
	2		Fig. 10	Same input conditions as for test B-1; with a single structure closely adjacent to the sensor	0.17	0.11	0.07	0.42	0.22	0.14
	3		Fig. 11	Same input conditions as for test B-1; with a single intervening structure near the radiator	0.11	0.06	0.11	0.29	0.17	0.24

*Standard Deviation, as used here is defined as the root-mean-square error.

Table 3. Summary of TAFS Test Results (cont.)

Test Series	Test No.	Characteristics Tested	Test Set-Up	Test Conditions (See Table 2)	TA Errors (In Degrees)					
					Std. Deviation*			Worst Case Errors		
					ψ_e	θ_e	ϕ_e	ψ_e	θ_e	ϕ_e
C	1	Structural interference perimeter with radiator and sensor separated by a distance of 30'	See test conditions at right.		attitude angle disturbance is $<1^\circ$ when $d \geq 66''$					
	2				attitude angle disturbance is $<1^\circ$ when $d \geq 72''$					
	3				attitude angle disturbance is $<1^\circ$ when $d \geq 90''$					
	4				attitude angle disturbance is $<1^\circ$ when $d \geq 66''$					
	5				attitude angle disturbance is $<1^\circ$ when $d \geq 68''$					
D	1	Static accuracy and resolution for angles $\leq +6^\circ$	Fig. 12	Input Condition Set IV; 6 different values for ψ with ϕ and θ held constant at near-zero settings	0.17	0.21	0.23	0.50	0.57	0.48

*Standard Deviation, as used here is defined as the root-mean-square error.

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SECTION V

CONCLUSIONS AND RECOMMENDATIONS

The effort completed under this contract has clearly demonstrated the feasibility of utilizing the SPASYN concept to accurately transduce angular information over a substantial distance even when the transducing components must, of necessity, be placed in close proximity to, or within, electrically conductive structures. This, in the opinion of PNSI's engineering staff, is the general conclusion to be drawn from a critical review of the TAFS test results. The specific conclusions arrived at as a result of the total effort documented in this report are as follows:

- Based on the TAFS power requirements and statistical test results, it seems entirely feasible to utilize the SPASYN concept in airborne applications requiring the accurate sensing (within $\pm 0.2^\circ$ or better) of the relative motion, attitude and position of one rigid body with respect to a second rigid body at separation distances of 30 feet or more.
- Based on the statistical evidence from the static accuracy tests, it can be concluded that the set-ups, fixtures and instrumentation used in performing these tests were marginal at best (in terms of rigidity, gimbal orthogonality, input scale accuracy and setability, and readout resolution) relative to the accuracy goals of the contractual work statement and the capabilities of the system being tested. It is conservatively estimated that the cumulative errors introduced by the test fixtures and instrumentation, plus the unavoidable human errors introduced as an indirect result of the shortcomings of the test fixtures, were as high as $\pm 0.25^\circ$ in the "worst case" instances.
- Because of the inadequacies of the test fixtures and instrumentation, it seems valid to conclude that more weight should be given to the root-mean-square error values presented in Table 3 than to the corresponding "worst case" values. This is particularly true in view of the fact that in some of the data sets the "worst case" error is more than twice as high as the next highest error in that set thereby indicating that the data sample from which that "worst case" value was derived is suspect.
- Although the close proximity of electrically conductive structures does tend to significantly alter the characteristics of the pointable nutating field, which is the basis of the SPASYN concept, it seems that the effects produced

by such structures can be treated, for the most part, as psuedo-misalignment effects rather than random variables or non-linearities. As evidenced by the test results these psuedo misalignments can generally be eliminated, or at least greatly reduced, by making the necessary compensating (electrical) adjustments within the Radiator Excitation Unit during the initial alignment procedure. This approach is particularly applicable and appropriate when the interfering structure is rigidly fixed with respect to the radiator and/or sensor, both in rotation and translation. Such rigidly-fixed structures can generally be considered extensions of the radiator and/or sensor, as the case may be.

- From the results of Test D1 it can be concluded that the placement of either the radiator or sensor within an electrically conductive structure that completely surrounds the transducing component should be avoided, if at all possible, particularly in those cases where the clearance between the walls of the structure and the transducing component would be very short relative to the separation distance between radiator and sensor. In such cases the attenuation and distortion of the radiated field is apt to be so severe as to make the application of the SPASYN electromagnetic transducing technique impractical (unless the specified accuracy requirements are relatively modest).
- Bearing in mind the inadequacies of the present TAFS hardware and the test instrumentation used in conducting the TAFS tests, it is reasonable to conclude that an rms improvement of at least 2 to 1 could be realized from even a modest follow-on design and development effort.

Having successfully demonstrated the feasibility of a medium-range, SPASYN transfer alignment system in terms of a partially-implemented laboratory model, it would seem that the next logical step in the development of a practical system would be to design, fabricate and test a completely-implemented engineering model suitable for ground testing in a typical fighter aircraft. It is therefore recommended that such an engineering model be developed in accordance with the following guidelines:

- The system would be designed so as to incorporate all of the lessons learned up to that time with regard to the implementation of the SPASYN concept.
- If the contracting agency should so desire, the system would be designed to utilize as many of the TAFS components and parts as possible to minimize cost without sacrificing performance.

- The pointing angle and attitude angle computing loops would be implemented with a commercial grade digital processor to minimize cost.
- A more precise Sensor Test Fixture should be designed and fabricated to provide a means of adequately bench testing the deliverable hardware.
- The accuracy design goals would be $\pm 0.07^\circ$ CPE (Circular Probable Error) for azimuth and elevation angle outputs and ± 0.1 Standard Deviation (rms) for the roll angle output, for attitude and pointing angles up to 12° , and over a transducing range of at least 30 feet.

The proposed ground-test system should be installed in a typical fighter aircraft and then subjected to a series of static and simulated dynamic tests. These tests would aid in the selection of an output data scheme appropriate to the inertial platform alignment process. They would also aid in the preparation of a set of operational and technical requirements to be met in the development of a flight-worthy system.

A major problem with present airborne alignment systems is the validity of the filter program which defines the location and orientation of the missile system platform as the initial conditions are varied by the operating environment (for example, as weight and center of gravity change during a mission, or whenever the aircraft angle of attack is altered, or in the presence of turbulence).

One application of the SPASYN technique could be to monitor the position of a target datum located at some arbitrary point in or on the fuselage of the aircraft. As the pylon-mounted missile equipped with a SPASYN sensor moves with respect to the fuselage target (both in position and attitude) this movement would be explicitly and continuously measured and then input to the alignment system computer. With these inputs properly filtered the initial alignment process could be quickened and improved in accuracy.

An alternative approach would be to align the system to the heading and attitude data outputs from the aircraft master reference unit and thereby to communicate these data outputs as command information.

There are undoubtedly variations of these two approaches which will emerge with time and experience. In either case, the objective would be to provide a reference which is accurate to not worse than 0.1° , 2σ .

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APPENDIX A
TAFS DEVELOPMENT HISTORY

TRANSFER ALIGNMENT FEASIBILITY SYSTEM DEVELOPMENT HISTORY

The progress history of the Transfer Alignment Feasibility System development work performed under Air Force Contract F33615-73-C-1027 is outlined below. The total effort required eight months to complete, starting October 2, 1972 and ending June 1, 1973.

October 1972

- An analysis was performed to determine the radiated signal levels and receiver sensitivity required to obtain the stated accuracy objectives.
- Preliminary designs for the radiator and sensor were explored with the assistance of Spears Associates, Inc., Waltham, Mass.
- Various measurement models of radiator and sensor configurations were constructed and tested to measure inductance, Q and radiation efficiency.
- The driver amplifier requirements for the selected radiator design were defined.
- A radiator driver amplifier was ordered and a preliminary radiator excitation circuit design based on the use of this amplifier was completed.
- A search was conducted to find series-tuning capacitors capable of operating at the relatively high frequency and current levels required by the radiator design, and suitable capacitors were ordered.
- An input filter capable of providing the narrow noise bandwidth required by the system design analysis was designed, and suitable components were ordered.
- A preliminary conceptual design of the coordinate transformation scheme for the sensed-signal processor was accomplished.
- A gimballed sensor test stand was designed and constructed.
- A radiator test stand utilizing a conventional surveyor's transit as the gimballed mounting platform was designed and constructed.

November 1972

- The design of the radiator driver power amplifier circuits was completed, and the circuits were tested into a dummy load.
- The radiator driver amplifier was interfaced with the radiator.
- High current tests of the radiator were performed to determine heat rise, efficiency and electromagnetic radiation levels.
- The conceptual design of the sensed-signal processor was completed, and the necessary components were ordered.
- A temperature test of the tuning stability of the radiator was performed indicating a stability of one part in 10^3 over a 40°C temperature range.
- Preliminary structural interference tests were accomplished at relatively low power levels using measurement models of the radiator in conjunction with a single-axis sensing coil.
- Based on the results of preliminary interference tests, it was decided that the operating frequency should be made switch-selectable as either 14 or 7KHz.

December 1972

- The sensed-signal preamplifier circuitry was breadboarded and tested.
- Interconnecting system cables were specified and built.
- The preliminary structural interference studies were continued.

January 1973

- The high-current (15 amp, 24VDC) power supplies required to power the three-channel REU (Radiator Excitation Unit) and three-axis radiator were selected and ordered.
- The functional block diagram for the transfer alignment feasibility system was finalized.
- The radiator and sensor designs were finalized, and fabrication and assembly of these units was started; completion status was 20% at the end of the period.

January 1973 (Cont'd)

- The total circuit design effort for the feasibility demonstration system reached 90% completion with 70% of the required electronic parts on hand.
- Fabrication, assembly and wiring of the REU was started, and the status of completion was 30% at the end of the period.
- Fabrication, assembly and wiring of the Central Processing Unit (CPU) was started, and the status of completion was 10% at the end of the period.
- The system design documentation effort was 25% completed by the end of the period.
- Laboratory investigation of the effects of nearby metallic structures on the SPASYN system was continued throughout the period.

February 1973

- The high-current (15 amp, 24VDC) power supplies required to power the REU and Radiator were received and tested.
- The winding and assembly of the core structures for the deliverable Radiator and Sensor were completed. The completion status of these units was 80% as of February 28.
- The total circuit design effort reached 95% completion with only the Radiator and Sensor interaxis cross-coupling circuitry remaining to be finalized.
- 90% of the required electronic parts had been received as of 28 February.
- Fabrication, assembly and wiring of the Radiator Excitation Unit (REU) reached 45% completion.
- The preliminary laboratory investigation of the effects of nearby metallic structures on SPASYN system accuracy was completed.
- The task of formulating a comprehensive and detailed test plan for the final acceptance and structural effects testing of the deliverable system hardware was started during this period, and was 25% completed as of 28 February.

March 1973

<u>Task Description</u>	<u>Completion Status As Of</u>	
	<u>2/28</u>	<u>3/31</u>
- Fab, assembly and wiring of the REU (Radiator Excitation Unit)	45%	100%
- Initial electrical checkout and calibration adjustment of the REU	0%	100%
- Fab, assembly and wiring of the Radiator and Sensor	80%	100%
- Initial electrical checkout and tuning of the Radiator and Sensor	0%	100%
- Assembly, wiring and checkout of the PSU (Power Supply Unit)	0%	100%
- Fab, assembly, and wiring of the SCDU (System Control and Display Unit)	10%	80%
- Initial electrical checkout and calibration adjustment of the SCDU	0%	25%

April 1973

- Fab, assembly, and initial electrical checkout and calibration of the SCDU was completed.
- The system test plan was finalized.
- Initial checkout alignment and calibration of the total transfer alignment feasibility system was completed.
- A comprehensive series of system static accuracy tests in a structurally "clean" environment was started during this period, and the completion status of these baseline tests was 50% by the end of the period.

May 1973

- The baseline test series which was started in April was completed during this period, and all of the planned "structural effects" testing of the system was also completed during this period.

APPENDIX B
THE SPASYN

THE SPASYN

A New Transducing Technique
For Visually Coupled Control Systems

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(The material presented in this Appendix is a condensation of a paper presented by Mr. Kuipers at a symposium on Visually-Coupled Control Systems sponsored by the Aerospace Medical Research Laboratory, of the Aerospace Medical Division, Air Force Systems Command, Wright-Patterson Air Force Base, Dayton, Ohio. The symposium was held on November 8, 9, and 10 at Brooks Air Force Base, San Antonio, Texas.)

THE SPASYN
A New Transducing Technique
For Visually Coupled Control Systems

ABSTRACT

The SPASYN (Space Synchro) is a five degree-of-freedom transducing system which provides a precise and continuous measure of the three relative orientation angles and the two angles of relative translation (in polar coordinates), between two independent, rigid-body coordinate frames. The transducer consists of a Radiator fixed to one body frame and a Sensor fixed to the second body frame, both electrically connected to the System Electronics Unit (SEU). The signal generated in the Sensor as a result of the modulated vector field issuing from the Radiator, is operated upon by electronic coordinate transformation circuitry in the SEU thereby yielding a measure of the five angles. The nature of the radiated vector field structure is described and the various coordinate transformations involved in relating the two principle coordinate frames are discussed.

The SPASYN is presented as an elegant solution to the Advanced Helmet-Mounted Sight application for a Visually Coupled Control System. However, in addition to applications which interface man with machine, some multi-degree-of-freedom control problems which do not involve man directly in the loop are suggested as candidate applications for the SPASYN. Some of these are: inertial platform transfer alignment, automation of boom/receptacle coupling in Air-to-Air Refueling, stationkeeping for drones and RPV's, VTOL aircraft instrument landing aid, automatic docking of marine craft, at-sea replenishment navigational aid, etc.

THE SPASYN

A New Transducing Technique For Visually Coupled Control Systems

INTRODUCTION

The PNSI SPASYN (Space Synchro) is a transducing system for determining the relative orientation and "translation" between two independent rigid-body coordinate frames. More precisely, it is a five degree-of-freedom transducing system for measuring the three relative orientation angles and the two angles of the three polar coordinates of relative translation.

With a second transducer operating cooperatively with the first and sharing most of its components, a full six degree-of-freedom sensing system is achieved with some redundancy.

The SPASYN transducer is a closed-loop angle measuring technique which promises great flexibility in application, is relatively insensitive to intervening structure, and has wide-angle and long-range possibilities. In fact, in its most general two or three radiator configuration, there would be no restrictions on the observers freedom of movement insofar as angular orientation of the body and head are concerned, although the motion box in which the head is free to move may be limited in volume. The ultimate accuracy of the system is expected to be better than one-half degree.

The general physical characteristics of the SPASYN are simple and unencumbered, which makes it easily applied in systems employing the natural visual/motor skills of the operator to control sensors, weapons, and/or vehicles.

The SPASYN concept offers not only an elegant solution to the general problem of interfacing man with the machine in Visually-Coupled Control Systems, but is also uniquely suited to five or six degree-of-freedom guidance and control problems which do not necessarily involve the observer in the loop. A few examples of some likely applications of the SPASYN technique are: inertial platform transfer alignment, automation of boom/receptacle coupling in air-to-air refueling, station-keeping for drones and RPV's, VTOL aircraft instrument landing aid, automatic docking of marine craft, at-sea replenishment navigational aid, etc.

In order to facilitate the presentation and discussion of basic principles and performance, the SPASYN is described --where application orientation is necessary-- in the context of head-position sensing in a specific application of an airborne Visually-Coupled Control System.

DESCRIPTION OF A TYPICAL SPASYN SYSTEM

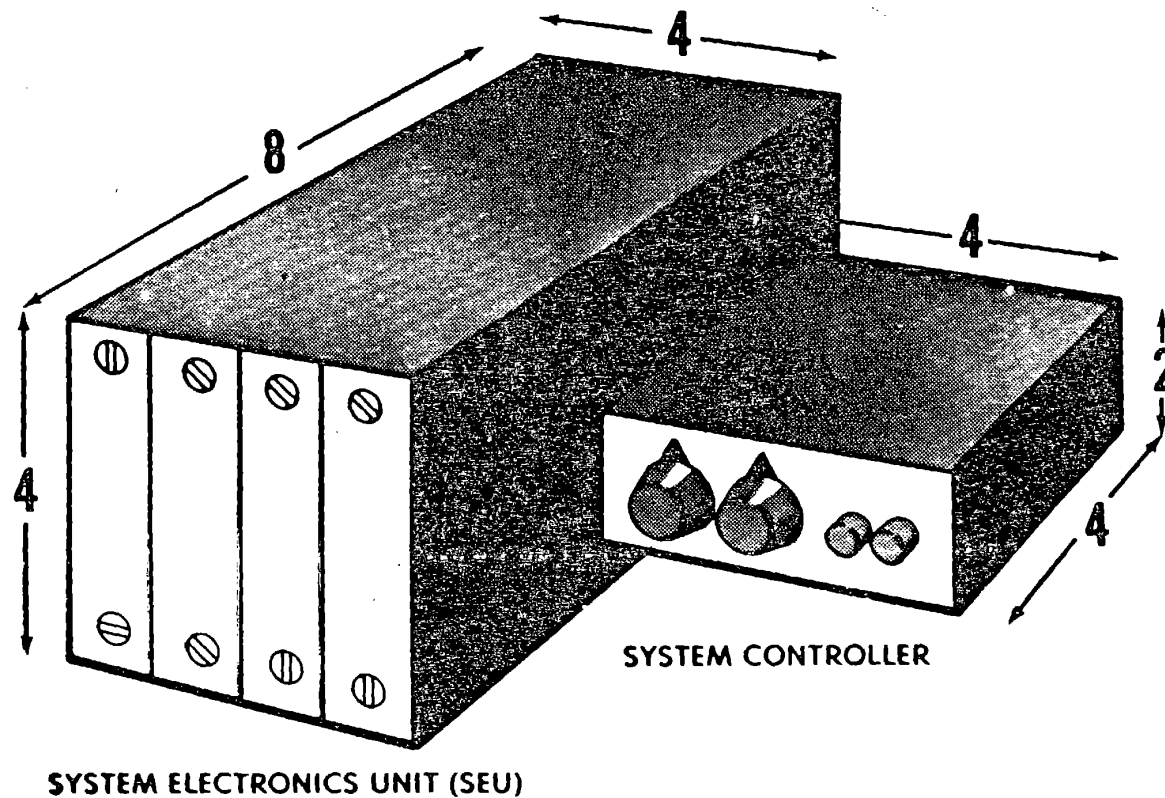
A typical SPASYN system for an airborne VCCS application would be comprised of four components as shown in Figure 1: a Radiator, a Sensor, a System Electronics Unit, and a System Controller.

The Radiator would be approximately two inches in diameter and be located at some convenient, but rather arbitrary, point in the cockpit and oriented precisely with respect to the aircraft body frame. It would be electrically connected to, and receives its excitation from, the System Electronics Unit (SEU).

The Sensor Unit would be approximately one inch in diameter and one ounce in weight. It would be precisely oriented with respect to the observers head gear. This head gear would include the necessary optical accountments for establishing the line-of-sight of the observer, since the optics and the sensor, which are both fixed to the helmet, must be boresighted. The sensor would be connected to the System Electronics Unit by means of a lightweight cable which can be conveniently attached to the head gear.

The Systems Electronics Unit (SEU) would contain all of the signal-processing and computational electronics as well as the power supply. As shown in Figure 1, we have reason to believe that a microminiaturized production version of the SEU could be enclosed in 160 cubic inches or less.

PRODUCTION HARDWARE CONCEPT



THREE-AXIS SENSOR



THREE-AXIS RADIATOR

WEIGHT: 8 LBS. MAX.
 VOLUME: 160 CU. IN. MAX.
 POWER REQUIREMENT: 40 WATTS MAX.

SPASYN SYSTEM

Figure 1
 B-5

SPASYN COORDINATE FRAME RELATIONSHIPS

The design objective of the SPASYN is that it provide a measure of sensor orientation (attitude and relative bearing) and sensor translation relative to a fixed coordinate frame centered in the radiator. This fixed frame with the radiator at its origin is boresighted to be coincident with the aircraft body axes and will be called the reference coordinate frame (designated XYZ). The degrees-of-freedom and the geometry relating the other pertinent coordinate frames of the problem are illustrated in Figure 2. The line segment RS (radiator to sensor) is shown directed in the reference coordinate frame XYZ. The direction of this line segment is completely determined in this frame by specifying the two angles α and β which, in this instance, are shown as successive rotations about the Z and Y' axes respectively.

The general orientation of the sensor is represented and defined in terms of the three conventional Euler angles ψ , θ , and ϕ , with the understanding that in this case the "attitude and relative bearing" angles are relative to the XYZ reference frame. The orientation of the sensor frame xyz is also illustrated in Figure 2. The point S' is shown displaced from the actual sensor point S for pedagogical reasons, i.e., merely to show clearly how the orientation angles are defined. In this case, following convention, the orientation angles ψ , θ , and ϕ are successive rotations about the z, y, and x axes respectively.

COMPOSITE POINTING/ORIENTATION GEOMETRY

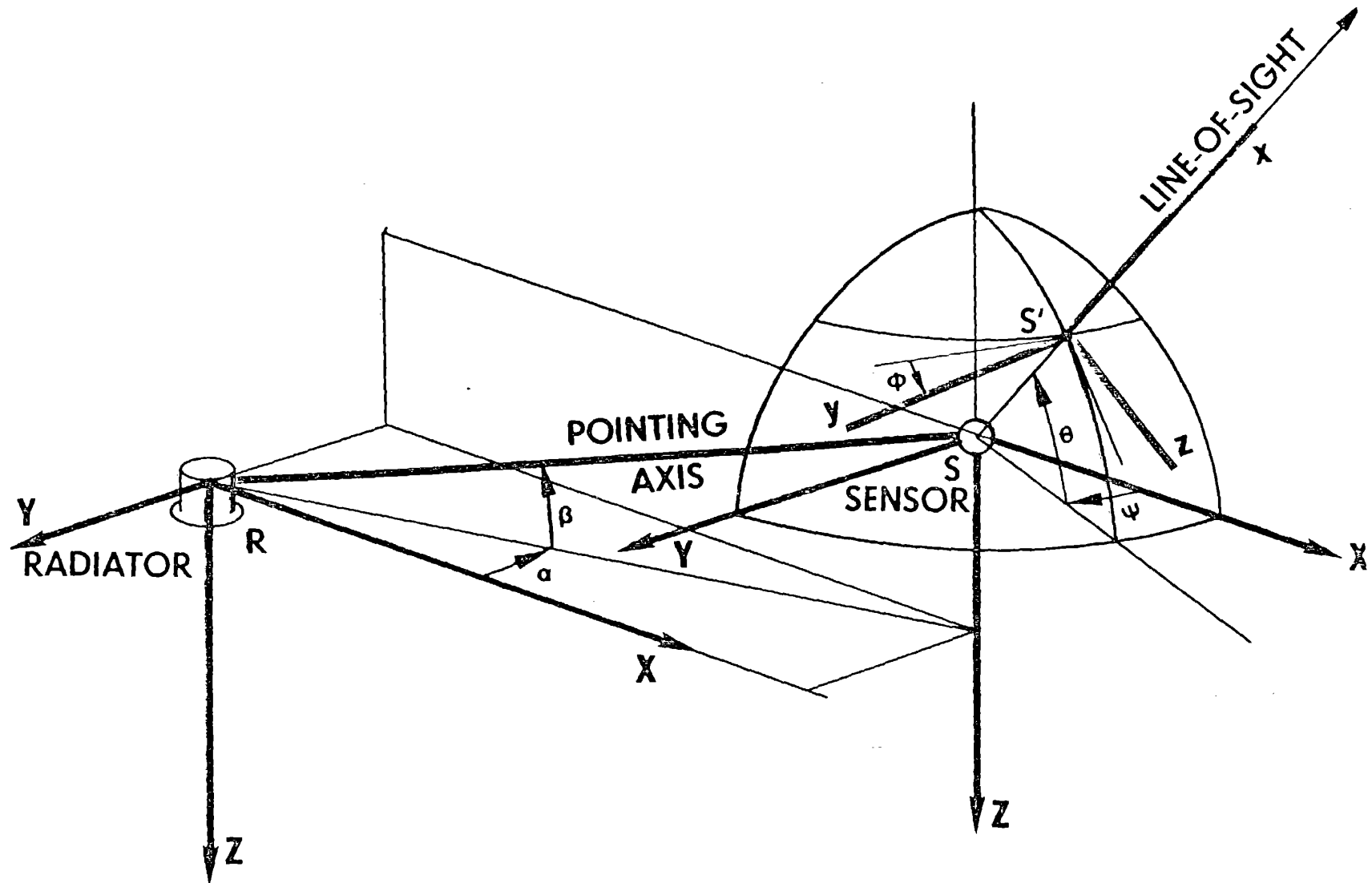


FIGURE 2. A FIVE DEGREE-OF-FREEDOM TRANSDUCER

It should be emphasized at this point that there is nothing unique about the particular selection of angles or successive axes of rotation; that is, there are many other angle/axis sequences equally manageable in principle. In fact, another arrangement could well be more appropriate to a different application.

One of the computational objectives of the SPASYN system is that the pointing axis of the vector field emanating from the radiator be made continuously and precisely coincident with the line segment RS.

A second computational objective is that the orientation of the xyz axes of the sensor be continuously and precisely determined with respect to the XYZ reference axes of the Radiator. Since the sensor is attached to an independent body, its orientation is clearly independent of the pointing angles.

RADIATOR/SENSOR UNITS

The Radiator and Sensor Units of the SPASYN are identical in principle, and in some applications may even be physically identical units. Each unit consists essentially of three identical orthogonal windings on some core structure which has radiating and sensing properties that are isotropic.

The Radiator Unit emanates a nutating vector field, as illustrated in Figure 3. With appropriate processing of the signals received by the Sensor Unit, the direction of the line containing the points representing the radiator and the sensor is continuously and precisely defined in the reference coordinate frame centered in the radiator. The two angles α and β completely define the direction of this "tracking" line to the sensor.

A reference excitation vector yielding a nutating field when applied component-wise to the respective xyz excitation windings of the Radiator, is defined by the vector f , where

$$f = \text{col}(E, N \cos mt, N \sin mt) \quad (1)$$

E = amplitude of the CW component

N = amplitude of nutation (modulation)

m = radian frequency of the nutation

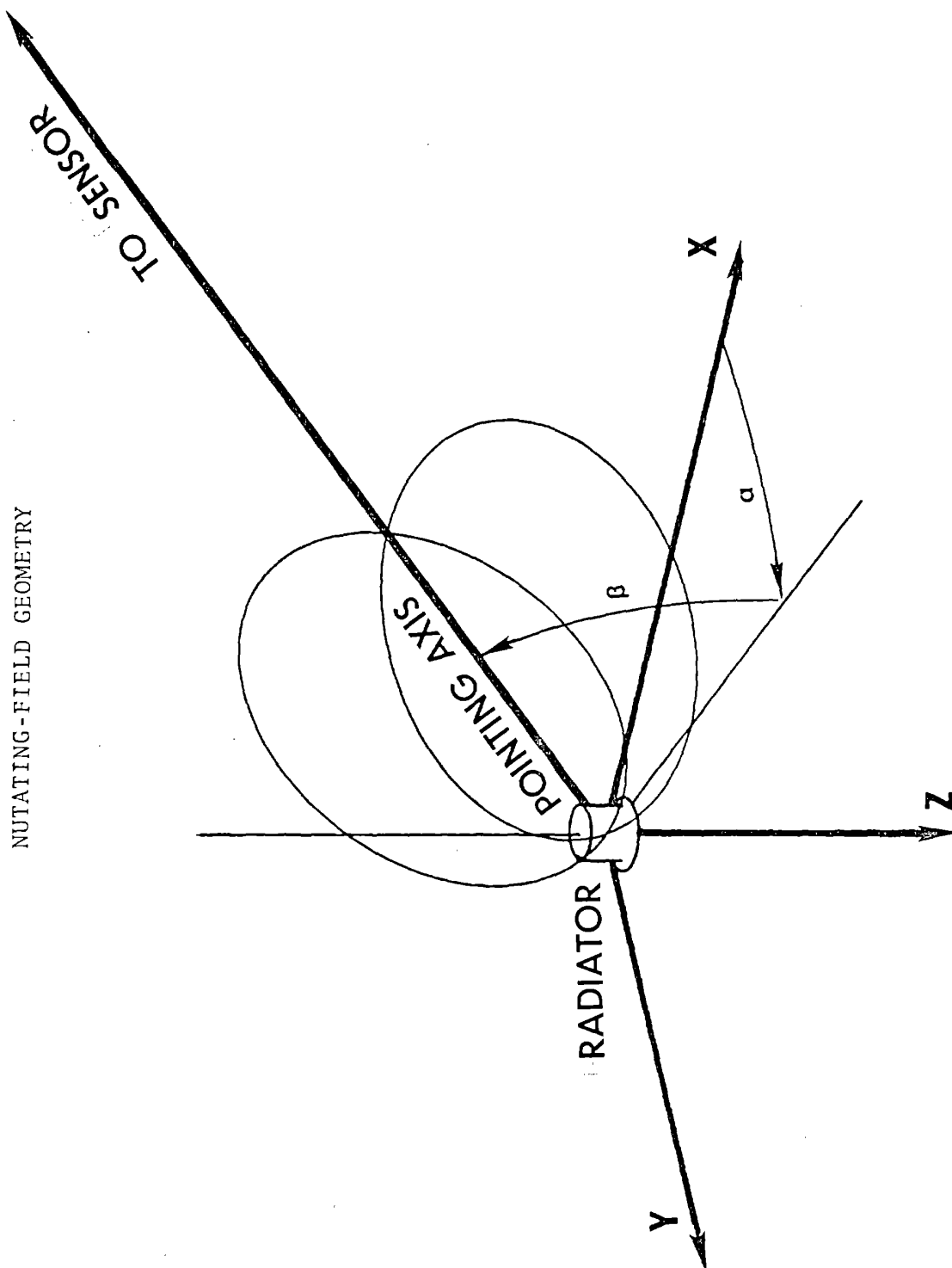


Figure 3

B-9

With the excitation represented by the vector f applied to the Radiator, a nutating field is generated whose nutation axis is coincident with the X-axis of the Radiator.

The SPASYN concept, in its present configuration, is based upon two fundamental notions:

1. A nutating vector field structure can be pointed electronically in any arbitrary direction on the unit ball. The terms "pointing" and "direction" in this case refer to the nutation axis of the field with respect to the reference frame.
2. Signals received from the radiator by the sensor, after being operated upon by suitable transformation and control circuitry, yield the two angles pointing to, and the three orientation angles of, the sensor.

Implicit in both of these notions is the imperative requirement that the windings of both the radiator and the sensor be mutually orthogonal and that their structures be isotropic.

Each of the lobes issuing from the Radiator (Figure 3) are to be interpreted as a typical dipole plot of the radial component of the field intensity. Rotation of this field intensity lobe is about the nutation or pointing axis and the two lobes shown correspond to the field intensity pattern at two different instants of time, one-half nutation period apart.

RADIATOR POINTING OR SENSOR TRACKING

The pointing or tracking capability of the SPASYN is achieved by electronically directing the radiated field structure such that the sensor lies on the nutation axis. The pointing circuitry has the characteristic small angle sinusoidal or proportional type sensitivity to off-axis errors which allows tight close-loop determination of the pointing angles. The discrimination circuitry which determines the closed-loop tracking strategy is discussed below in some further detail.

The pointing capability of the radiator is achieved electronically by operating upon the reference nutating field vector f in Equation (1), with an orthogonal coordinate transformation which consists essentially of two rotations. This has the effect of taking every point in the reference nutating field into a geometrically equiv-

alent point in the "pointed" nutating field, as shown in Figure 4.

The radiator operates at some nominal carrier frequency, each winding being appropriately modulated to achieve the properly pointed nutating field. The modulation signal applied to each of the three windings of the radiator is given by the respective component of the radiator modulation vector e_m , where

$$e_m = T_p^{-1} f \quad (2)$$

$$T_p^{-1} = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix} \quad (3)$$

The pointing angles α and β are determined in the System Electronics Unit by integrating the off-axis pointing error components detected against the logic of the quadrature reference components of the nutation.

SYSTEM ELECTRONICS UNIT

Proper relationships between the various coordinate frames is obviously important in the SPASYN system strategy, as manifested by the coordinate transformation circuitry in the System Electronics Unit. The block diagram of Figure 5 shows the computational sequence of the coordinate transformations required to obtain the correct solution for the radiator pointing angles and the orientation angles of the sensor. The order of the indicated transformations is important since matrices do not commute under multiplication.

The sensor orientation is represented by the three angles involved in the orthogonal transformation T_a which is defined as the indicated matrix product of the three matrices representing the three independent rotations:

$$T_a = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (4)$$

It is clear from the sequence of transformations shown in Figure 5, that the matrix product of the transformations

NUTATING FIELD POINTING CIRCUIT

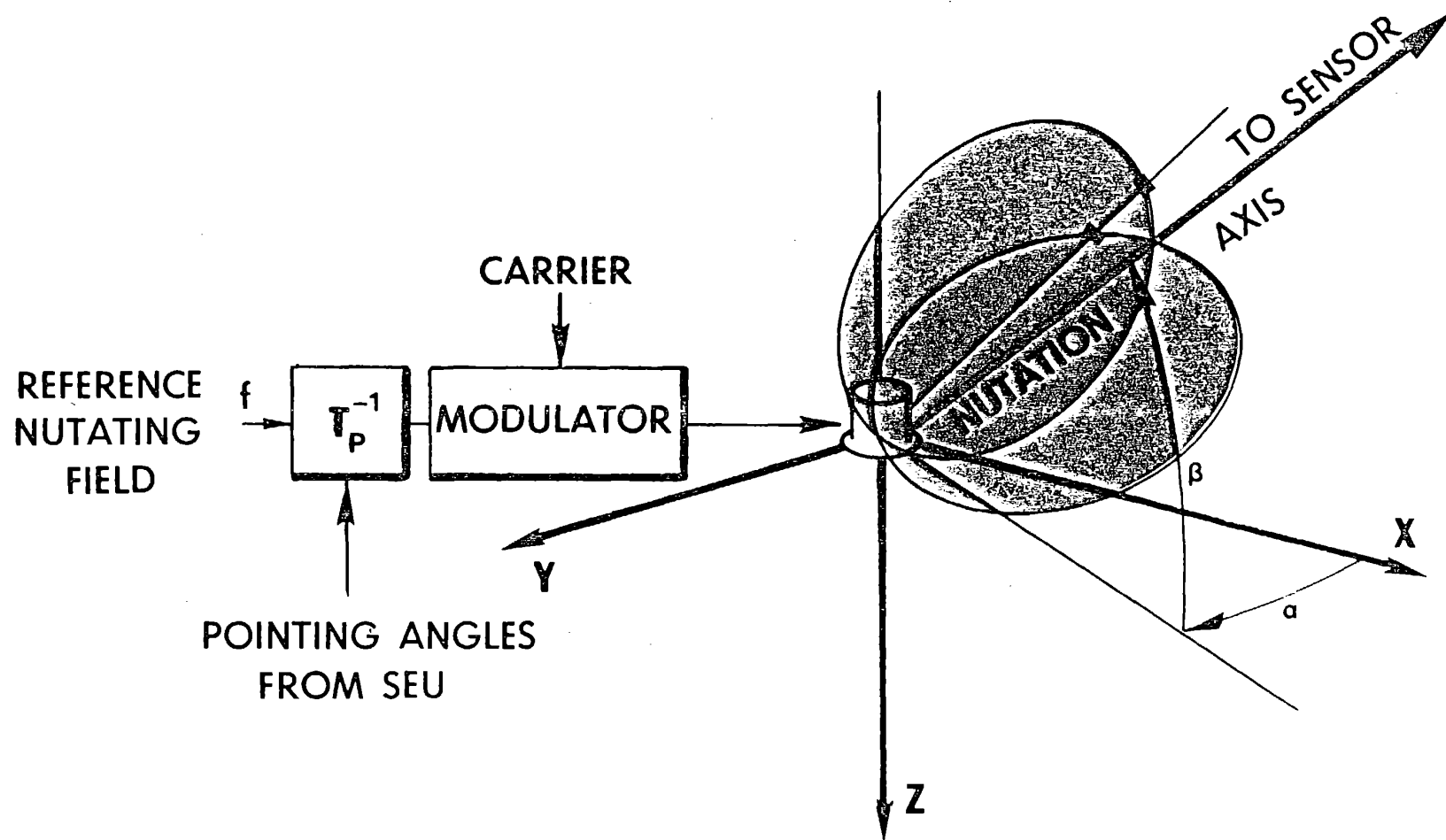


Figure 4
B-12

SPASYN

COORDINATE TRANSFORMATION BLOCK DIAGRAM

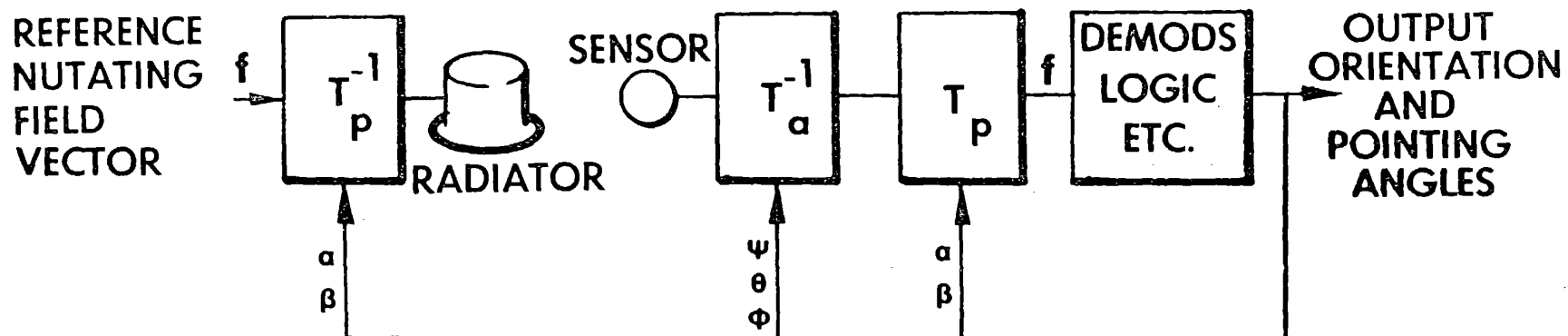


Figure 5
B-13

T_p = RADIATOR POINTING OR TRACKING TRANSFORMATION

T_a = "ATTITUDE AND HEADING" TRANSFORMATION

between the input reference nutating field vector f , and the output demods and decoding circuitry, is equal to the identity transformation. The demods and decoding circuits are, therefore, operating on perturbations about the nominal attitude and heading angles of the sensor and also about the nominal pointing angles to the sensor. This results in meaningful error signals appearing on the nominal signal components which comprise the nutating field vector f (see Equation 1).

The errors in the nominal relative bearing angle ψ and the elevation angle θ , appear as signals proportional to the E component and are detected on the f_y and f_z components, respectively.

The error in the nominal roll angle ϕ , is proportional to the phase error in the output nutation signals f_y and f_z measured with respect to the phase of the input reference f_y and f_z components.

SENSOR TRACKING

The sensor tracking capability of the SPASYN is achieved by nutating the entire vector field structure. This takes advantage of the dipole field strength characteristic of the radiator. The only field strength points that are invariant under nutation are those points on the nutation axis. It is this idea, illustrated in Figure 5, that is the basis of the SPASYN pointing strategy. The radial line which is shown off the nutation axis in Figure 5 indicates a variation in field strength over the half nutation period represented by the two field intensity lobes. From this illustration, it is clear that a modulation signal appears along the x-component of the modulation vector f , whenever the sensor does not lie on the nutation axis.

Discriminating between the errors on the two independent pointing angles α and β merely requires that the total error modulation appearing on f_x be demodulated against the quadrature components of the reference nutation vector f .

The resulting error signals are integrated in the usual closed-loop arrangement to effect the necessary corrections in the radiator pointing. In this case, the pointing transformation T_p^{-1} is included in the inner loop, as shown in Figure 4.

TRANSLATION COMPUTATION

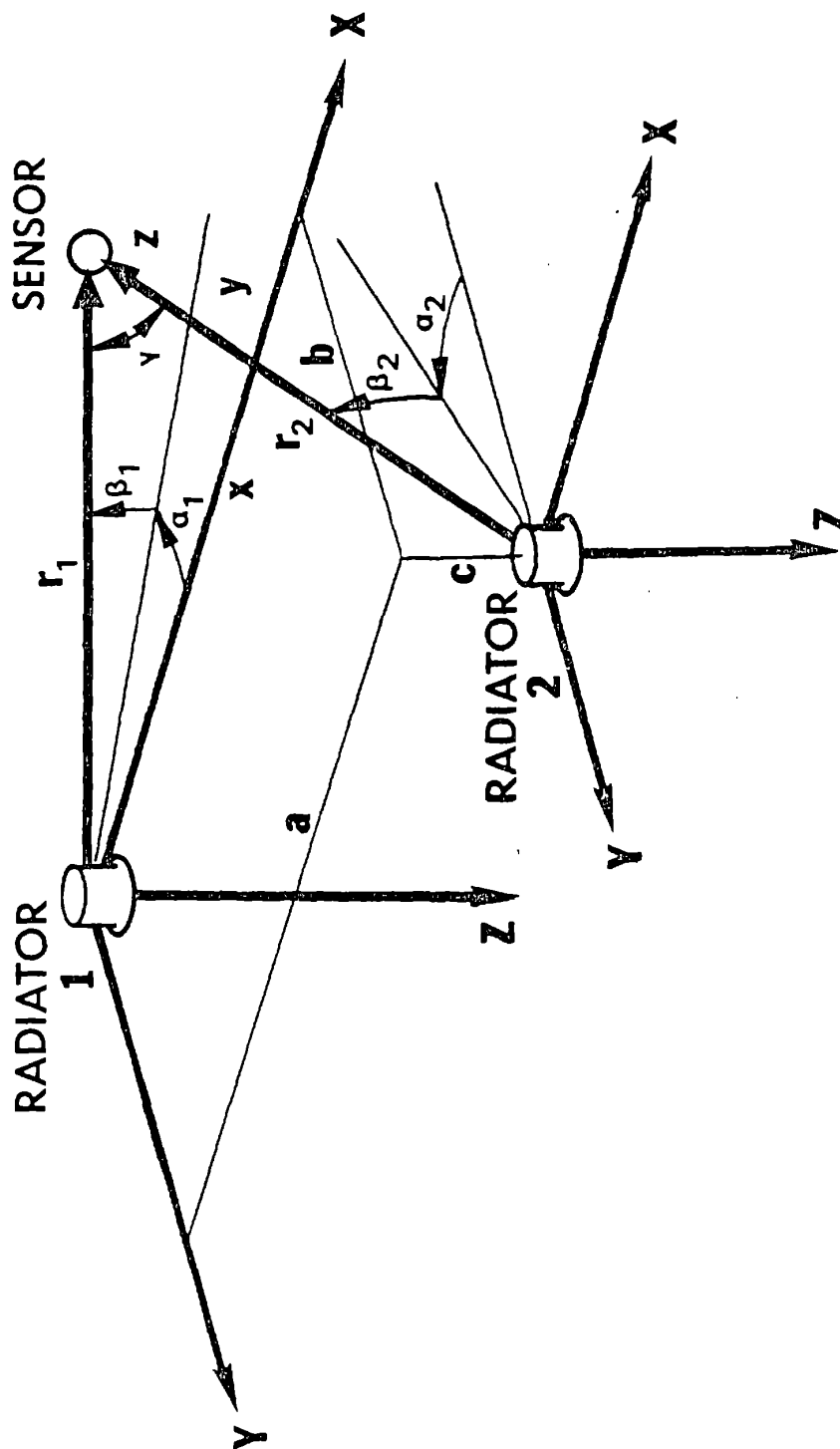
As mentioned above, a full six degree-of-freedom computation requires a second radiator positioned such that over the desired translational domain, the two pointing

axes cannot become colinear. In fact, in order to maintain a reasonable measure of error sensitivity in this computation, the two pointing axes which intersect at the sensor should be bounded such that the angle of intersection γ satisfies the criterium $|90^\circ - \gamma| < 30^\circ$. In other words, the best sensitivity in this computation occurs when the two pointing axes intersect at 90° . The sensitivity for the translation computation is zero when the two pointing axes are collinear. The two-radiator geometry is illustrated in Figure 6.

The computational scheme for each of the two radiators is in principle the same as discussed above and illustrated in Figure 5. Moreover, since there is only one sensor involved, the matrix T_a which defined the sensor orientation with respect to the reference frame must be the same for both computational loops. It is only the pointing loops and their transformations that are independent; in fact, it is this independence that makes it possible to determine r_1 and r_2 , the radial distance between the sensor and the two radiators by triangulation.

The computational strategy for determining r_1 and r_2 is illustrated in Figure 7, where the notation T_{p1} and T_{p2} refer now to the pointing transformations for radiator 1 and 2 respectively. The column vector $r = \text{col}(a, b, c)$ represents the location of the second radiator in the chosen reference frame, that is, with the reference frame taken to be centered in the first radiator.

The triple summation of vector quantities, component-wise, indicated in Figure 7 must result in nominal zeroes if the pointing angles and the values for r (which locates the second radiator in the reference frame centered in the first radiator), r_1 and r_2 are correct. Non-zero 'errors' on the x and y components are integrated in a closed-loop arrangement which yields the correct values for r_1 and r_2 consistent with the two sets of pointing angles.

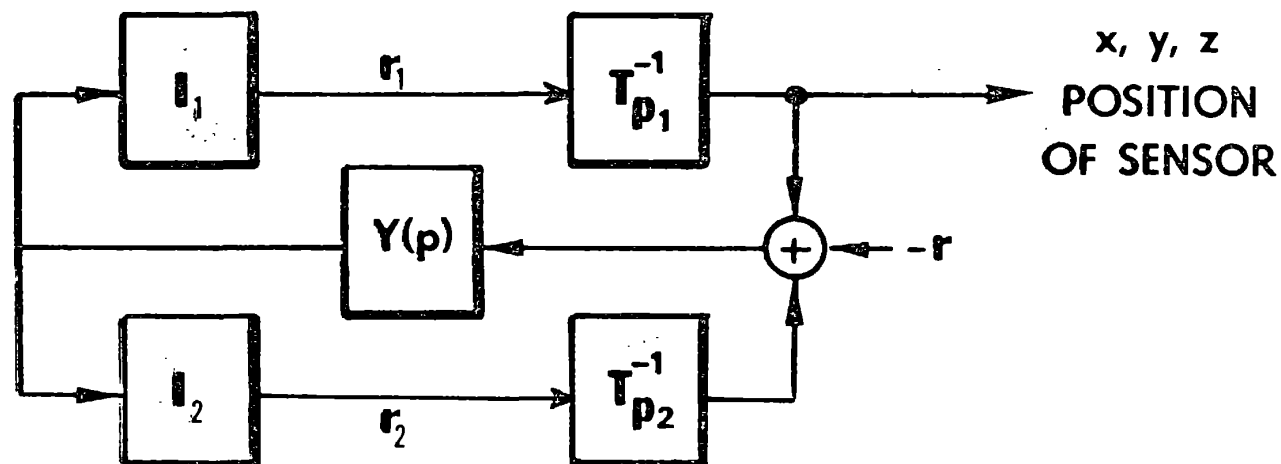


TRANSLATION GEOMETRY

Figure 6

B-16

TRANSLATION COMPUTATION



$$\mathbf{i}_k = (a_{ij}), \quad a_{ij} = 1 \text{ FOR } i = j = k \\ a_{ij} = 0 \text{ OTHERWISE}$$

$\mathbf{r} = \text{col}(a, b, c)$ = LOCATION OF THE SECOND RADIATOR IN THE REFERENCE COORDINATE FRAME OF THE FIRST RADIATOR

SUMMARY

This paper has described a five degree-of-freedom transducing scheme called the SPASYN, which can readily be arranged to give a measure of the full six degrees of freedom between two independent rigid bodies. In Aircraft or Aerospace parlance, the SPASYN can yield a measure of the three angles defining relative bearing and attitude (with all-attitude capability) in addition to the three translation coordinates (cartesian or polar), all relative to some established coordinate frame.

APPENDIX C
TAFS ANTENNA POWER REQUIREMENTS

Notes on Transfer Alignment Antenna Power Requirements

Jack Kuipers - August 29, 1972

These notes are based upon extrapolations from antenna design computations (by Morton Spears) dated 7-21-72 and upon a discussion of the Radiator/Sensor problem at Spears Associates on 8-28-72 (with Spears, Pittman, DeRuyck, and Kuipers in attendance).

1. In Spears computations (appended) an antenna was designed to the following specifications:

- a. Range: 600 ft.
- b. S/N at 600 ft. is 10 db
- c. Carrier frequency = 60 KHz
- d. Bandwidth = 1 Hz

This resulted in a requirement of 62 watts of power to excite a particular Spears antenna.

2. We at PNSI wish to extrapolate from the above results to a power requirement for a Radiator antenna designed to meet the following specifications imposed by the Transfer Alignment problem:

- a. Range = 25 ft.
- b. S/N at 25 ft. is at least 500 times better than 1.b. in order to achieve the required 0.1 degree accuracy.
- c. Carrier frequency = 10KHz
- d. Bandwidth = 20 Hz

3. The power budget is influenced by the specification changes from 1. to 2. in the following manner:

- a. Range: $\frac{600}{25} = 24$; 24^3 corresponds to +82.8 db
- b. Require 500 times better for 0.1 degree accuracy which correspond to -54.0 db
- c. Carrier frequency 60 KHz to 10 KHz increases noise (ITT Handbook pg 763) -12.0 db
- d. Bandwidth 1 Hz to 20 Hz costs $\frac{-13.0 \text{ db}}{+ 3.8 \text{ db}}$

This says that the power required by the Transfer Alignment application is reduced from 62 watts by 3.8 db: 25.8 watts

4. This 25.8 watt result for the 0.1 degree accuracy includes the original 10 db advantage in S/N specified in 1. which therefore corresponds to a S/N = 1500 or 64 db. For a perhaps more realistic S/N = 500 the required power is 2.58 watts. Therefore,

$$3 \text{ watts} < \left(\begin{array}{c} \text{Antenna Power Required} \\ \text{for} \\ \text{Transfer Alignment} \end{array} \right) < 25 \text{ watts}$$

ANALYSIS FOR POLHEMUS

By Morton Spears of
Spears Associates

July 21, 1972

Requirement: Receive at 600', 1Hz Bandwidth with 10 db
S+N/N ratio at 60 KHz

Signal/Noise: Noise = 4 μ v/meter; therefore, the signal
must be 12 μ v meter

Transmitter
loop: 4" x 4" x 4" - 10 turns - air loop
 $L = 9.6 \mu$ henrys $X_L = 3.62$ ohms
 $R_L = 0.015$ ohms (#10 wire air cooled)

Test: At 60KHz, the transmitter loop was energized
with 2.63 Amperes = 26.3 AT generated 61.8
mv/meter at 12'. Therefore,

$$\left(\frac{12'}{600'}\right)^3 \times 61.8 = 0.493 \mu\text{v/meter at } 600'$$

Transmitter
requirement: $\frac{12 \mu\text{v/meter (required)}}{.493 \mu\text{v/meter (obtained)}} = 24.3 \text{ AT Ratio}$

Amperes: $2.63 \times 24.3 = 64$ Amperes required

Volts: $3.62 \times 64 = 232$ volts required

Power: 62 watts required

Energy: $LI^2/2 = 0.02$ Joules

For 100 watts
power: $\left(\frac{100 \text{ watts}}{62 \text{ watts}}\right)^{1/2} \times \frac{12 \mu\text{v/m}}{4 \mu\text{v/m}} = 1.27 \times 3 = 3.81 \text{ ratio}$
 $\approx 12 \text{ db S/N Ratio}$

APPENDIX D
TAFS TEST RESULTS

TRANSFER ALIGNMENT FEASIBILITY SYSTEM TEST RESULTS

The measured and computed results of the various TAFS system tests performed under Contract F33615-73-C-1027 are presented in this appendix to the final report. The definitions and explanations needed to properly interpret and evaluate these results are given below.

Definitions and Explanations

- (1) In Tables 1-D through 9-D, the column headings XX, YX, ZX, XY, YY and ZY are defined as follows:

The first letter designates the measured signal output of a particular winding of the TAFS sensor and the second letter designates this measured output to be a function of the excitation input to a particular winding of the TAFS radiator. For example: XX denotes "the x signal output of the sensor as a function of the X excitation input to the radiator."

- (2) The designation "BAD DATA" is used in Table 2-D (and again in Table 7-D) to indicate that the computed test results for these so-called "BAD DATA" test increments were so grossly discrepant relative to the computed root-mean-square values for the entire test sequence that an obvious "human error" is indicated, either in setting up the sensor test gimbals (input data) or in recording of the sensor voltage readings (measured output data). The missing "BAD DATA" error values can be computed if desired from the corresponding measured output data by the use of the formulas presented below.
- (3) In Tables 5-D/7-D/9-D, an additional column of computed data labelled OFFSET ADJUSTED ROLL ERRORS is presented. These adjusted roll error values were obtained by calculating the algebraic mean of the corresponding unadjusted roll errors and then subtracting this algebraic mean from each of the unadjusted roll errors to obtain the adjusted error values.

This procedure removes the systematic offset (or bias) errors from the computed roll errors leaving only the random errors. These random errors are the errors of interest for the purposes of this report. In a general sense, one might expect that this offset canceling procedure should be applied to all of the computed attitude angle error data in Tables 1-D through 9-D to obtain the true random deviations from the mean, but a close examination of the data and a few trial calcu-

lations will quickly show that only in the two test cases mentioned above would this procedure significantly alter the test results. The implication is obvious: For some unknown reason, a systematic roll offset error was introduced into the data measurements in the process of performing tests B2 and B3 but not in performing tests A1, A2, B1 and D1.

Derivation of the Pertinent Mathematical Formulas

Attitude Angle Transducing Errors: The attitude angle transducing errors¹ are defined as the algebraic differences between the attitude angles calculated from the sensed information measurements² and the corresponding mechanical gimbal angles³ that were set into the sensor test fixture as the input conditions. Thus,

$$\psi_e = \psi_c - \psi_g$$

$$\theta_e = \theta_c - \theta_g$$

$$\text{and } \phi_e = \phi_c - \phi_g$$

where ψ , θ , and ϕ denote the azimuth, elevation and roll angles respectively and the subscripts e, c and g denote the error angle, the calculated angle and the gimbal angle respectively.

Calculated Attitude Angles: If the sensed information signals, which are measured in the orthogonal sensor reference frame, are mathematically "derotated" through the correct attitude angles and in the proper sequence to obtain the corresponding vector signals with respect to the orthogonal radiator reference frame, then the resulting "derotated" information signals should be directly proportional to the radiator excitation reference signals. Thus, if all of the sensed information signals and the corresponding radiator excitation reference signals are known, the sensed attitude angles can be calculated from the defining relationships derived below.

The block diagram of Figure 1-D depicts the three-angle orthogonal "derotation" operation using resolver notation.

¹Labelled SENSOR ANGLE ERRORS in the data tabulations.

²Labelled SENSOR VOLTAGE READINGS in the data tabulations.

³Labelled SENSOR GIMBAL ANGLES in the data tabulations.

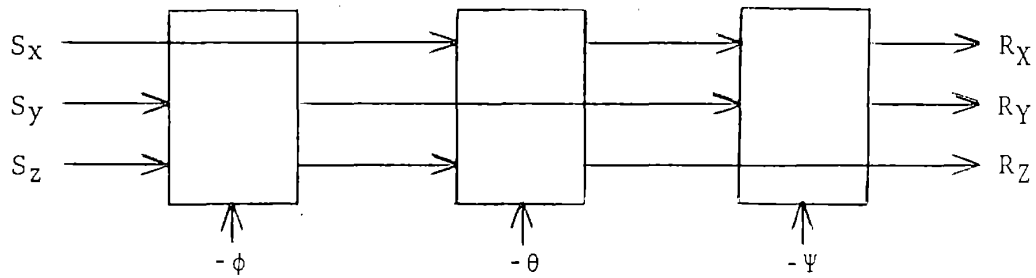


Figure 1-D

In this three-resolver block diagram, S_x , S_y and S_z represent the signal outputs from the x, y and z windings of the sensor, R_x , R_y and R_z represent the normalized excitation signals applied to the X, Y and Z windings of the radiator, and ϕ , θ and ψ represent the sensed attitude angles. With the resolver notation defined as indicated in Figure 2-D.

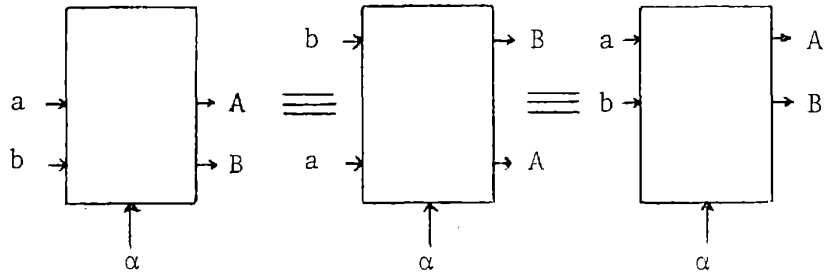


Figure 2-D

where $A = a(\cos\alpha) + b(\sin\alpha)$

and $B = b(\cos\alpha) - a(\sin\alpha)$,

it can be shown (using the inverse Euler transformations) that the general relationships between the sensor outputs and the radiator inputs can be expressed as follows:

$$\begin{aligned} \text{(Eq. 1)} \quad R_x = & S_x \cos\theta \cos\psi + S_y (\sin\phi \sin\theta \cos\psi - \cos\phi \sin\psi) \\ & + S_z (\cos\phi \sin\theta \cos\psi + \sin\phi \sin\psi) \end{aligned}$$

$$\begin{aligned} \text{(Eq. 2)} \quad R_y = & S_x \cos\theta \sin\psi + S_y (\sin\phi \sin\theta \sin\psi + \cos\phi \cos\psi) \\ & + S_z (\cos\phi \sin\theta \sin\psi - \sin\phi \cos\psi) \end{aligned}$$

$$\text{(Eq. 3)} \quad R_z = -S_x \sin\theta + S_y \sin\phi \cos\theta + S_z \cos\phi \cos\theta$$

Now, by defining two singular cases of radiator excitation conditions and the corresponding sensor signal outputs as indicated in the following table,

Case	Radiator Excit. Signals			Sensor Output Signals		
	X Axis	Y Axis	Z Axis	x Axis	y Axis	z Axis
A	E	O	O	XX	YX	ZX
B	O	E	O	XY	YY	ZY

it can be shown that:

for Case A, equation 2 reduces to

$$(Eq. 4) \quad 0 = XX \cos\theta \sin\psi + YX (\sin\phi \sin\theta \sin\psi + \cos\phi \cos\psi) \\ + ZX (\cos\phi \sin\theta \sin\psi - \sin\phi \cos\psi)$$

and equation 3 reduces to

$$(Eq. 5) \quad 0 = -XX \sin\theta + YX \sin\phi \cos\theta + ZX \cos\phi \cos\theta;$$

for Case B, equation 3 reduces to

$$(Eq. 6) \quad 0 = -XY \sin\theta + YY \sin\phi \cos\theta + ZY \cos\phi \cos\theta$$

Appropriate separation of variables between equations 5 and 6 yields the desired solutions for ϕ_c and θ_c as follows:

$$\phi_c = \arctan \left[\frac{XX \cdot ZY - XY \cdot ZX}{XY \cdot YX - XX \cdot YY} \right]$$

$$\theta_c = \arctan \left[\frac{\sin\phi_c (YX \cdot ZY - YY \cdot ZX)}{XX \cdot ZY - XY \cdot ZX} \right]$$

Finally, dividing equation 4 by $\cos\psi$ and rearranging terms yields the desired solution for ψ_c as follows:

$$\psi_c = \arctan \left[\frac{ZX \sin\phi - YX \cos\phi}{XX \cos\theta + YX \sin\phi \sin\theta + ZX \cos\phi \sin\theta} \right]$$

Many other expressions could have been derived as solutions for ϕ_c , θ_c and ψ_c , and they would have resulted in slightly different computed values for the error angles ϕ_e , θ_e , and ψ_e , but the expressions derived above were the ones that were used to obtain the computed error values listed in Tables 1-D through 9-D. The reasoning behind this choice of expressions is explained in the following paragraph.

The basic relationship, i.e., the one involving only the measured sensor voltages as independent variables, is the solution for ϕ_c . The solution for θ_c is then obtained as a function of the calculated value for ϕ_c . And finally, the solution for ψ_c is obtained as a function of the calculated values for ϕ_c and θ_c . Since the "derotation" sequence shown in Figure 1-D requires that the sensed information be operated upon first by ϕ , then by θ and finally by ψ , the expressions derived above seem to be particularly appropriate in terms of simulating the attitude angle solutions that would be obtained with a closed-loop implementation of the coordinate transformation scheme shown in Figure 1-D.

AN ELECTROMAGNETIC
POSITION SENSOR

30 Nov. 1973

ADDENDUM CHANGE

Reference: Appendix D. Remove pages
D-6 through D-18 and re-
place with the attached
corrected copies.

D-5a

In corrected Tables 2-D, 3-D, 5-D, 7-D and 9-D, the final, fully reduced, rms error values are encircled with a bold-faced rectangle to set them off for quick reference.

The rms error values designated "with bias" are the (corrected) rms errors as computed directly from the measured data through the use of the formulas presented in the introductory section of Appendix D. The error values designated "without bias" are the final values obtained by determining the algebraic mean of the computed error data and then extracting this systematic offset, or "bias" error from the rms error value according to the following formula:

$$S = \sqrt{\frac{\sum_{i=1}^N (X_i - \bar{X})^2}{N}}$$

where

S = the reduced ("without bias")
rms error value

X_i = the ith error data sample

$\bar{X}$ = the algebraic mean of the
error data = the bias

N = number of data samples

D-5-b

Table 1-D. Results of Test A1, Measured Data

INPUT DATA			MEASURED OUTPUT DATA					
SENSOR GIMBAL ANGLES (DEGREES)			SENSOR VOLTAGE READINGS (VOLTS)					
AZIMUTH	ELEVATION	ROLL	XX	YX	ZX	XY	YY	ZY
6.00	6.00	6.00	9.88	-0.93	1.12	-0.53	-4.93	0.46
3.00	6.00	6.00	9.93	-0.42	1.08	-0.27	-4.95	0.49
0.00	6.00	6.00	9.94	-0.10	1.03	-0.01	-4.96	0.52
-3.00	6.00	6.00	9.93	0.62	0.99	0.25	-4.95	0.55
-6.00	6.00	6.00	9.89	1.15	0.94	0.51	-4.93	0.59
6.00	3.00	6.00	9.92	-0.99	0.61	-0.52	-4.93	0.49
3.00	3.00	6.00	9.97	-0.48	0.57	-0.26	-4.95	0.51
0.00	3.00	6.00	9.98	0.05	0.52	0.00	-4.96	0.52
-3.00	3.00	6.00	9.97	0.57	0.48	0.26	-4.95	0.55
-6.00	3.00	6.00	9.93	1.10	0.43	0.52	-4.93	0.56
6.00	0.00	6.00	9.95	-1.04	0.08	-0.51	-4.93	0.51
3.00	0.00	6.00	9.99	-0.53	0.04	-0.26	-4.96	0.52
0.00	0.00	6.00	9.99	0.00	0.00	0.01	-4.96	0.53
-3.00	0.00	6.00	10.00	0.34	-0.03	0.18	-4.96	0.53
-6.00	0.00	6.00	9.96	1.03	-0.08	0.53	-4.94	0.54
6.00	-3.00	6.00	9.93	-1.09	-0.42	-0.50	-4.92	0.55
3.00	-3.00	6.00	9.97	-0.58	-0.47	-0.24	-4.95	0.54
0.00	-3.00	6.00	9.99	-0.05	-0.51	0.02	-4.96	0.53
-3.00	-3.00	6.00	9.97	0.45	-0.55	0.28	-4.95	0.52
-6.00	-3.00	6.00	9.94	0.98	-0.60	0.53	-4.94	0.51
6.00	-6.00	6.00	9.90	-1.15	-0.95	-0.49	-4.92	0.58
3.00	-6.00	6.00	9.94	-0.63	-1.00	-0.23	-4.95	0.56
0.00	-6.00	6.00	9.95	-0.11	-1.04	0.03	-4.96	0.53
-3.00	-6.00	6.00	9.94	0.41	-1.08	0.29	-4.96	0.51
-6.00	-6.00	6.00	9.90	0.93	-1.12	0.54	-4.94	0.49
6.00	6.00	3.00	9.88	-1.00	1.06	-0.53	-4.96	0.19
3.00	6.00	3.00	9.93	-0.48	1.05	-0.27	-4.98	0.22
0.00	6.00	3.00	9.95	0.04	1.05	-0.01	-5.00	0.25
-3.00	6.00	3.00	9.94	0.58	1.03	0.25	-4.99	0.30
-6.00	6.00	3.00	9.90	1.09	1.01	0.51	-4.97	0.33
6.00	3.00	3.00	9.92	-1.02	0.56	-0.53	-4.96	0.22
3.00	3.00	3.00	9.96	-0.49	0.54	-0.26	-4.99	0.24
0.00	3.00	3.00	9.98	0.02	0.53	0.00	-4.99	0.26
-3.00	3.00	3.00	9.97	-0.54	0.51	0.26	-4.99	0.28
-6.00	3.00	3.00	9.93	1.07	0.49	0.51	-4.97	0.30
6.00	0.00	3.00	9.94	-1.04	0.03	-0.52	-4.96	0.25
3.00	0.00	3.00	9.98	-0.53	0.01	-0.26	-4.98	0.26
0.00	0.00	3.00	10.00	0.00	0.00	0.00	-4.98	0.27
-3.00	0.00	3.00	9.99	0.52	-0.02	0.26	-4.99	0.27
-6.00	0.00	3.00	9.95	1.04	-0.04	0.53	-4.98	0.27
6.00	-3.00	3.00	9.92	-1.07	-0.49	-0.51	-4.96	0.25
3.00	-3.00	3.00	9.97	-0.55	-0.51	-0.25	-4.99	0.27
0.00	-3.00	3.00	9.98	-0.04	-0.52	0.01	-4.99	0.27
-3.00	-3.00	3.00	9.97	0.49	-0.54	0.27	-4.99	0.26
-6.00	-3.00	3.00	9.93	1.01	-0.55	0.53	-4.97	0.25
6.00	-6.00	3.00	9.88	-1.10	-1.01	-0.50	-4.96	0.31
3.00	-6.00	3.00	9.93	-0.58	-1.03	-0.24	-4.98	0.29
0.00	-6.00	3.00	9.94	-0.07	-1.05	0.02	-4.99	0.27
-3.00	-6.00	3.00	9.93	0.46	-1.06	0.28	-4.99	0.25
-6.00	-6.00	3.00	9.89	0.99	-1.07	0.54	-4.98	0.22

Table 1-D. (Continued)

INPUT DATA			MEASURED OUTPUT DATA					
SENSOR GIMBAL ANGLES (DEGREES)			SENSOR VOLTAGE READINGS (VOLTS)					
AZIMUTH	ELEVATION	ROLL	XX	YX	ZX	XY	YY	ZY
6.00	6.00	0.00	9.89	-1.04	1.01	-0.53	-4.97	-0.07
3.00	6.00	0.00	9.93	-0.52	1.03	-0.27	-5.00	-0.03
0.00	6.00	0.00	9.94	0.00	1.05	-0.01	-5.00	0.00
-3.00	6.00	0.00	9.93	0.52	1.05	0.25	-5.00	0.03
-6.00	6.00	0.00	9.98	1.04	1.06	0.50	-4.99	0.06
6.00	3.00	0.00	9.93	-1.05	0.50	-0.53	-4.98	-0.04
3.00	3.00	0.00	9.97	-0.52	0.51	-0.26	-5.00	-0.02
0.00	3.00	0.00	9.98	0.00	0.52	0.00	-5.00	0.01
-3.00	3.00	0.00	9.97	0.52	0.54	0.25	-5.01	0.02
-6.00	3.00	0.00	9.93	1.04	0.54	0.51	-4.99	0.04
6.00	0.00	0.00	9.94	-1.04	-0.02	-0.51	-4.97	0.00
3.00	0.00	0.00	9.98	-0.52	-0.01	-0.26	-4.99	0.00
0.00	0.00	0.00	10.00	0.00	0.00	0.00	-5.00	0.00
-3.00	0.00	0.00	9.98	0.52	0.01	0.26	-4.99	0.02
-6.00	0.00	0.00	9.94	1.05	0.02	0.52	-4.98	0.02
6.00	-3.00	0.00	9.92	-1.04	-0.53	-0.51	-4.98	0.03
3.00	-3.00	0.00	9.97	-0.53	-0.52	-0.25	-5.00	0.02
0.00	-3.00	0.00	9.98	0.00	-0.52	0.01	-5.00	0.01
-3.00	-3.00	0.00	9.97	0.52	-0.50	0.27	-5.01	0.00
-6.00	-3.00	0.00	9.93	1.05	-0.49	0.53	-4.99	-0.01
6.00	-6.00	0.00	9.88	-1.05	-1.06	-0.50	-4.98	0.06
3.00	-6.00	0.00	9.93	-0.52	-1.05	-0.24	-5.00	0.03
0.00	-6.00	0.00	9.94	0.00	-1.04	0.02	-5.00	0.02
-3.00	-6.00	0.00	9.93	0.52	-1.03	0.28	-5.00	-0.01
-6.00	-6.00	0.00	9.89	1.04	-1.02	0.54	-4.99	-0.03
6.00	6.00	-3.00	9.88	-1.09	0.96	-0.53	-4.97	-0.33
3.00	6.00	-3.00	9.92	-0.57	1.00	-0.27	-5.00	-0.30
0.00	6.00	-3.00	9.94	-0.06	1.04	-0.02	-5.01	-0.27
-3.00	6.00	-3.00	9.93	0.47	1.08	0.24	-5.01	-0.24
-6.00	6.00	-3.00	9.89	0.99	1.11	0.50	-4.99	-0.20
6.00	3.00	-3.00	9.94	-1.06	0.46	-0.53	-4.95	-0.26
3.00	3.00	-3.00	9.95	-0.55	0.49	-0.28	-4.98	-0.27
0.00	3.00	-3.00	10.00	-0.04	0.52	-0.02	-4.99	-0.26
-3.00	3.00	-3.00	10.00	0.49	0.54	0.24	-4.99	-0.25
-6.00	3.00	-3.00	9.95	1.01	0.57	0.50	-4.97	-0.23
6.00	0.00	-3.00	9.95	-1.03	-0.03	-0.53	-4.95	-0.26
3.00	0.00	-3.00	9.99	-0.52	-0.04	-0.28	-4.97	-0.26
0.00	0.00	-3.00	10.00	0.00	0.01	0.00	-5.00	-0.26
-3.00	0.00	-3.00	10.00	0.53	0.02	0.25	-4.97	-0.26
-6.00	0.00	-3.00	9.95	1.04	0.05	0.51	-4.96	-0.26
6.00	-3.00	-3.00	9.93	-0.99	-0.50	-0.53	-4.94	-0.22
3.00	-3.00	-3.00	9.97	-0.48	-0.56	-0.27	-4.97	-0.24
0.00	-3.00	-3.00	9.93	0.04	-0.53	-0.01	-4.97	-0.25
-3.00	-3.00	-3.00	9.97	0.55	-0.50	0.25	-4.97	-0.27
-6.00	-3.00	-3.00	9.94	1.07	-0.48	0.51	-4.95	-0.23
6.00	-6.00	-3.00	9.90	-0.97	-1.11	-0.52	-4.94	-0.21
3.00	-6.00	-3.00	9.95	-0.46	-1.09	-0.27	-4.96	-0.22
0.00	-6.00	-3.00	9.96	0.06	-1.06	-0.01	-4.97	-0.25
-3.00	-6.00	-3.00	9.95	0.57	-1.03	0.25	-4.96	-0.23
-6.00	-6.00	-3.00	9.91	1.10	-1.00	0.50	-4.95	-0.20

Table 1-D. (Continued)

INPUT DATA			MEASURED OUTPUT DATA					
SENSOR GIMBAL ANGLES (DEGREES)			SENSOR VOLTAGE READINGS (VOLTS)					
AZIMUTH	ELEVATION	ROLL	XX	YX	ZX	XY	YY	ZY
6.00	6.00	-6.00	9.87	-1.12	0.94	-0.53	-4.91	-0.58
3.00	6.00	-6.00	9.92	-0.62	0.99	-0.28	-4.93	-0.56
0.00	6.00	-6.00	9.93	-0.11	1.05	-0.02	-4.95	-0.53
-3.00	6.00	-6.00	9.92	0.40	1.10	0.24	-4.94	-0.50
-6.00	6.00	-6.00	9.93	0.92	1.15	0.49	-4.93	-0.47
6.00	3.00	-6.00	9.92	-1.08	0.42	-0.54	-4.91	-0.55
3.00	3.00	-6.00	9.96	-0.58	0.47	-0.28	-4.94	-0.54
0.00	3.00	-6.00	9.98	-0.06	0.52	-0.02	-4.94	-0.53
-3.00	3.00	-6.00	9.97	0.46	0.58	0.24	-4.94	-0.52
-6.00	3.00	-6.00	9.93	0.98	0.63	0.50	-4.92	-0.50
6.00	0.00	-6.00	9.94	-1.02	-0.11	-0.53	-4.91	-0.52
3.00	0.00	-6.00	9.98	-0.51	-0.05	-0.28	-4.94	-0.52
0.00	0.00	-6.00	9.99	0.00	0.01	0.00	-4.99	-0.52
-3.00	0.00	-6.00	9.99	0.51	0.06	0.24	-4.94	-0.52
-6.00	0.00	-6.00	9.95	1.03	0.12	0.50	-4.93	-0.52
6.00	-3.00	-6.00	9.93	-0.96	-0.64	-0.53	-4.92	-0.49
3.00	-3.00	-6.00	9.98	-0.46	-0.58	-0.27	-4.94	-0.51
0.00	-3.00	-6.00	9.99	0.06	-0.52	-0.02	-4.94	-0.52
-3.00	-3.00	-6.00	9.99	0.58	-0.47	0.24	-4.94	-0.53
-6.00	-3.00	-6.00	9.94	1.09	-0.41	0.50	-4.92	-0.55
6.00	-6.00	-6.00	9.90	-0.91	-1.16	-0.53	-4.92	-0.46
3.00	-6.00	-6.00	9.94	-0.41	-1.11	-0.27	-4.94	-0.49
0.00	-6.00	-6.00	9.96	0.11	-1.05	-0.02	-4.95	-0.52
-3.00	-6.00	-6.00	9.94	0.63	-0.99	0.24	-4.94	-0.54
-6.00	-6.00	-6.00	9.90	1.14	-0.94	0.50	-4.92	-0.57
END OF DATA								

Table 2-D. Results of Test A1, Computed Data

INPUT DATA			COMPUTED OUTPUT DATA		
SENSOR GIMBAL ANGLES			SENSOR ANGLE ERRORS		
(DEGREES)			(DEGREES)		
AZIMUTH	ELEVATION	ROLL	AZIMUTH ERROR	ELEVATION ERROR	ROLL ERROR
6.00	6.00	6.00	-0.01	-0.12	-0.04
3.00	6.00	6.00	0.04	-0.08	-0.02
B A D	D A T A				
-3.00	6.00	6.00	0.06	0.03	0.04
-6.00	6.00	6.00	0.02	0.11	0.19
6.00	3.00	6.00	0.02	-0.09	-0.02
3.00	3.00	6.00	0.08	-0.04	0.04
0.00	3.00	6.00	0.03	0.00	-0.02
-3.00	3.00	6.00	0.05	0.09	0.18
-6.00	3.00	6.00	-0.01	0.14	0.15
6.00	0.00	6.00	-0.02	-0.16	-0.11
3.00	0.00	6.00	0.04	-0.09	-0.02
0.00	0.00	6.00	0.00	0.00	0.10
B A D	D A T A				
-6.00	0.00	6.00	0.08	0.18	0.22
6.00	-3.00	6.00	-0.03	-0.07	0.07
3.00	-3.00	6.00	0.02	-0.04	0.08
0.00	-3.00	6.00	0.03	0.06	0.11
-3.00	-3.00	6.00	0.10	0.14	0.16
-6.00	-3.00	6.00	0.04	0.17	0.20
6.00	-6.00	6.00	-0.02	-0.15	0.11
3.00	-6.00	6.00	-0.03	-0.10	0.17
0.00	-6.00	6.00	-0.01	0.00	0.14
-3.00	-6.00	6.00	0.00	0.09	0.22
B A D	D A T A				
6.00	6.00	3.00	0.04	-0.17	-0.18
3.00	6.00	3.00	0.05	-0.11	-0.15
0.00	6.00	3.00	0.08	0.03	-0.01
-3.00	6.00	3.00	0.01	0.09	0.13
-6.00	6.00	3.00	0.08	0.16	0.17
6.00	3.00	3.00	0.01	-0.07	-0.15
3.00	3.00	3.00	-0.03	-0.04	-0.09
0.00	3.00	3.00	0.04	0.04	-0.02
-3.00	3.00	3.00	0.06	0.09	0.05
-6.00	3.00	3.00	0.02	0.16	0.13
6.00	0.00	3.00	-0.03	-0.14	-0.01
3.00	0.00	3.00	0.04	-0.10	-0.02
0.00	0.00	3.00	0.00	0.00	0.10
-3.00	0.00	3.00	0.02	0.05	0.09
-6.00	0.00	3.00	0.03	0.09	0.09
6.00	-3.00	3.00	0.00	-0.14	-0.09
3.00	-3.00	3.00	0.00	-0.09	-0.06
0.00	-3.00	3.00	0.07	0.01	0.10
-3.00	-3.00	3.00	0.02	0.06	0.14
-6.00	-3.00	3.00	0.03	0.16	0.18
6.00	-6.00	3.00	0.01	-0.15	-0.05
3.00	-6.00	3.00	0.01	-0.09	0.04
0.00	-6.00	3.00	0.07	-0.04	0.12
-3.00	-6.00	3.00	0.03	0.06	0.20

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CHANGE

Table 2-D. (Continued)

INPUT DATA			COMPUTED OUTPUT DATA		
SENSOR GIMBAL ANGLES			SENSOR ANGLE ERRORS		
(DEGREES)			(DEGREES)		
AZIMUTH	ELEVATION	ROLL	AZIMUTH ERROR	ELEVATION ERROR	ROLL ERROR
-6.00	-6.00	3.00	-0.02	0.15	0.17
6.00	6.00	0.00	-0.05	-0.15	-0.18
3.00	6.00	0.00	-0.02	-0.08	-0.02
0.00	6.00	0.00	0.00	0.03	0.01
-3.00	6.00	0.00	0.02	0.04	0.04
-6.00	6.00	0.00	0.09	0.07	0.08
6.00	3.00	0.00	0.02	-0.10	-0.15
3.00	3.00	0.00	-0.02	-0.07	-0.08
0.00	3.00	0.00	0.01	-0.02	0.11
-3.00	3.00	0.00	0.02	0.10	0.07
-6.00	3.00	0.00	0.04	0.13	0.14
6.00	0.00	0.00	-0.03	-0.11	-0.01
3.00	0.00	0.00	-0.02	-0.06	0.00
0.00	0.00	0.00	0.00	0.00	0.00
-3.00	0.00	0.00	0.02	0.07	0.23
-6.00	0.00	0.00	-0.03	0.14	0.22
6.00	-3.00	0.00	-0.03	-0.06	0.03
3.00	-3.00	0.00	0.03	0.01	0.08
0.00	-3.00	0.00	-0.01	0.02	0.12
-3.00	-3.00	0.00	0.01	0.14	0.15
-6.00	-3.00	0.00	-0.04	0.19	0.18
6.00	-6.00	0.00	0.02	-0.13	0.07
3.00	-6.00	0.00	-0.02	-0.04	0.05
0.00	-6.00	0.00	-0.03	0.03	0.25
-3.00	-6.00	0.00	0.00	0.09	0.22
B A D	D A T A				
6.00	6.00	-3.00	-0.05	-0.11	-0.17
3.00	6.00	-3.00	-0.04	-0.08	-0.11
0.00	6.00	-3.00	0.03	-0.02	-0.06
-3.00	6.00	-3.00	-0.02	0.06	-0.03
-6.00	6.00	-3.00	0.00	0.11	0.09
6.00	3.00	-3.00	-0.06	-0.04	0.08
3.00	3.00	-3.00	0.00	-0.03	0.06
0.00	3.00	-3.00	0.07	-0.02	0.03
-3.00	3.00	-3.00	0.04	-0.06	-0.01
-6.00	3.00	-3.00	0.06	-0.03	0.05
6.00	0.00	-3.00	-0.09	0.14	0.01
3.00	0.00	-3.00	-0.01	-0.07	0.00
0.00	0.00	-3.00	0.00	0.06	0.02
-3.00	0.00	-3.00	-0.04	-0.04	0.01
-6.00	0.00	-3.00	0.03	-0.03	0.00
B A D	D A T A				
3.00	-3.00	-3.00	-0.09	-0.07	0.07
0.00	-3.00	-3.00	-0.08	-0.05	0.11
-3.00	-3.00	-3.00	0.00	-0.03	0.04
-6.00	-3.00	-3.00	0.01	-0.07	0.08
6.00	-6.00	-3.00	-0.10	-0.09	-0.08
3.00	-6.00	-3.00	-0.06	-0.11	0.13
0.00	-6.00	-3.00	-0.04	-0.08	0.11

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Table 2-D. (Continued)

INPUT DATA			COMPUTED OUTPUT DATA		
SENSOR GIMBAL ANGLES			SENSOR ANGLE ERRORS		
(DEGREES)			(DEGREES)		
AZIMUTH	ELEVATION	ROLL	AZIMUTH ERROR	ELEVATION ERROR	ROLL ERROR
-3.00	-6.00	-3.00	0.04	-0.07	0.03
-6.00	-6.00	-3.00	-0.01	-0.07	0.15
6.00	6.00	-6.00	-0.17	0.09	-0.08
3.00	6.00	-6.00	-0.07	0.05	-0.14
0.00	6.00	-6.00	-0.01	0.07	-0.09
-3.00	6.00	-6.00	0.05	0.05	-0.07
-6.00	6.00	-6.00	0.11	-0.01	-0.04
6.00	3.00	-6.00	-0.08	0.07	-0.06
3.00	3.00	-6.00	0.02	0.04	-0.07
0.00	3.00	-6.00	0.02	0.00	-0.11
-3.00	3.00	-6.00	0.02	0.03	-0.16
-6.00	3.00	-6.00	0.02	0.01	-0.11
6.00	0.00	-6.00	-0.11	-0.01	-0.05
3.00	0.00	-6.00	-0.06	0.02	-0.01
0.00	0.00	-6.00	-0.01	0.06	0.05
-3.00	0.00	-6.00	0.06	0.04	-0.01
-6.00	0.00	-6.00	0.05	0.06	-0.03
6.00	-3.00	-6.00	-0.13	-0.09	-0.02
3.00	-3.00	-6.00	-0.03	-0.03	-0.06
0.00	-3.00	-6.00	-0.03	0.00	-0.02
-3.00	-3.00	-6.00	-0.02	-0.02	0.02
-6.00	-3.00	-6.00	0.03	-0.01	-0.07
6.00	-6.00	-6.00	-0.12	-0.10	0.00
3.00	-6.00	-6.00	0.00	-0.09	0.00
0.00	-6.00	-6.00	0.00	-0.05	-0.02
-3.00	-6.00	-6.00	0.00	-0.03	0.05
-6.00	-6.00	-6.00	0.06	-0.08	0.01

END OF DATA

STANDARD DEVIATIONS.

WITH BIAS	0.05	0.09	0.11
WITHOUT BIAS	0.05	0.09	0.10
BIAS	0.00	0.00	0.03

Table 3-D. Results of Test A2

INPUT DATA			MEASURED OUTPUT DATA					
SENSOR GIMBAL ANGLES (DEGREES)			SENSOR VOLTAGE READINGS (VOLTS)					
AZIMUTH	ELEVATION	ROLL	XX	YX	ZX	XY	YY	ZY
12.00	12.00	-6.00	9.45	-2.24	1.82	-1.00	-4.78	-0.74
6.00	12.00	-6.00	9.61	-1.24	1.96	-0.50	-4.87	-0.64
-6.00	12.00	-6.00	9.62	0.80	2.16	0.50	-4.89	-0.43
-12.00	12.00	-6.00	9.47	1.80	2.23	0.99	-4.83	-0.31
12.00	6.00	-6.00	9.63	-2.13	0.81	-1.01	-4.79	-0.63
6.00	6.00	-6.00	9.87	-1.12	0.94	-0.53	-4.91	-0.58
-6.00	6.00	-6.00	9.98	0.92	1.15	0.49	-4.93	-0.47
-12.00	6.00	-6.00	9.65	1.92	1.24	1.01	-4.82	-0.42
12.00	-6.00	-6.00	9.97	-1.92	-1.25	-1.01	-4.81	-0.40
6.00	-6.00	-6.00	9.90	-0.91	-1.16	-0.53	-4.92	-0.46
-6.00	-6.00	-6.00	9.90	1.14	-0.94	0.50	-4.92	-0.57
-12.00	-6.00	-6.00	9.59	2.13	-0.80	1.02	-4.80	-0.62
12.00	-12.00	-6.00	9.52	-1.81	-2.26	-0.98	-4.82	-0.29
6.00	-12.00	-6.00	9.69	-0.81	-2.19	-0.48	-4.89	-0.41
-6.00	-12.00	-6.00	9.70	1.23	-1.97	0.52	-4.82	-0.63
-12.00	-12.00	-6.00	9.55	2.24	-1.82	1.01	-4.79	-0.73
12.00	12.00	-12.00	9.42	-2.41	1.55	-1.00	-4.68	-1.24
6.00	12.00	-12.00	9.62	-1.44	1.81	-0.50	-4.78	-1.15
-6.00	12.00	-12.00	9.63	0.56	2.24	0.50	-4.83	-0.94
-12.00	12.00	-12.00	9.47	1.56	2.41	0.99	-4.78	-0.82
12.00	6.00	-12.00	9.53	-2.21	0.58	-1.01	-4.70	-1.13
6.00	6.00	-12.00	9.80	-1.23	0.81	-0.51	-4.80	-1.09
-6.00	6.00	-12.00	9.81	0.77	1.24	0.51	-4.82	-0.99
-12.00	6.00	-12.00	9.65	1.77	1.43	1.01	-4.76	-0.92
12.00	-6.00	-12.00	9.66	-1.79	-1.44	-1.01	-4.75	-0.91
6.00	-6.00	-12.00	9.83	-0.80	-1.24	-0.50	-4.82	-0.98
-6.00	-6.00	-12.00	9.84	1.21	-0.60	0.52	-4.80	-1.09
-12.00	-6.00	-12.00	9.96	2.20	-0.50	1.02	-4.72	-1.13
12.00	-12.00	-12.00	9.52	-1.58	-2.44	-0.98	-4.77	-0.80
6.00	-12.00	-12.00	9.69	-0.59	-2.26	-0.48	-4.83	-0.92
-6.00	-12.00	-12.00	9.70	1.42	-1.82	0.52	-4.79	-1.14
-12.00	-12.00	-12.00	9.54	2.40	-1.57	1.01	-4.69	-1.23

END OF DATA

Table 3-D. (Continued)

INPUT DATA			COMPUTED OUTPUT DATA		
SENSOR GIMBAL ANGLES			SENSOR ANGLE ERRORS		
(DEGREES)			(DEGREES)		
AZIMUTH	ELEVATION	ROLL	AZIMUTH ERROR	ELEVATION ERROR	ROLL ERROR
12.00	12.00	-6.00	-0.15	0.25	-0.23
6.00	12.00	-6.00	-0.08	0.23	-0.22
-6.00	12.00	-6.00	0.02	0.08	-0.27
-12.00	12.00	-6.00	0.16	0.06	-0.18
12.00	6.00	-6.00	-0.16	0.14	-0.20
6.00	6.00	-6.00	-0.17	0.09	-0.08
-6.00	6.00	-6.00	0.11	-0.01	-0.04
-12.00	6.00	-6.00	0.11	0.06	-0.25
12.00	-6.00	-6.00	-0.50	0.03	-0.01
6.00	-6.00	-6.00	-0.12	-0.10	0.00
-6.00	-6.00	-6.00	0.06	-0.08	0.01
-12.00	-6.00	-6.00	0.21	-0.02	-0.09
12.00	-12.00	-6.00	-0.20	-0.21	0.04
6.00	-12.00	-6.00	-0.04	-0.19	0.00
-6.00	-12.00	-6.00	0.16	-0.15	-0.05
-12.00	-12.00	-6.00	0.24	-0.10	-0.10
12.00	12.00	-12.00	-0.13	0.15	-0.29
6.00	12.00	-12.00	-0.07	0.17	-0.27
-6.00	12.00	-12.00	0.07	0.13	-0.26
B A D D A T A					
12.00	6.00	-12.00	-0.12	0.13	-0.23
6.00	6.00	-12.00	-0.02	0.12	-0.16
-6.00	6.00	-12.00	0.12	0.10	-0.24
-12.00	6.00	-12.00	0.17	0.05	-0.21
12.00	-6.00	-12.00	-0.07	-0.10	-0.12
6.00	-6.00	-12.00	0.02	-0.07	-0.11
-6.00	-6.00	-12.00	0.15	-0.02	-0.16
-12.00	-6.00	-12.00	0.46	0.51	-0.71
12.00	-12.00	-12.00	-0.09	-0.19	-0.03
6.00	-12.00	-12.00	0.03	-0.16	0.01
-6.00	-12.00	-12.00	0.20	-0.09	-0.09
-12.00	-12.00	-12.00	0.32	-0.07	-0.14

END OF DATA

STANDARD DEVIATIONS

WITH BIAS	0.18	0.16	0.17
WITHOUT BIAS	0.18	0.15	0.10

BIAS 0.02 0.02 -0.14

D-12A

CHANGE

Table 4-D. Results of Test B1, Measured Data

INPUT DATA			MEASURED OUTPUT DATA					
SENSOR GIMBAL ANGLES (DEGREES)			SENSOR VOLTAGE READINGS (VOLTS)					
AZIMUTH	ELEVATION	ROLL	XX	YX	ZX	XY	YY	ZY
6.00	6.00	6.00	4.94	-0.47	0.56	-0.38	-3.62	0.31
0.00	6.00	6.00	4.97	0.05	0.49	0.00	-3.64	0.36
-6.00	6.00	6.00	4.94	0.57	0.46	0.37	-3.62	0.40
6.00	0.00	6.00	4.97	-0.52	0.04	-0.38	-3.62	0.36
0.00	0.00	6.00	5.00	0.00	0.01	0.00	-3.64	0.36
-6.00	0.00	6.00	4.97	0.52	-0.07	0.38	-3.62	0.36
6.00	-6.00	6.00	4.94	-0.57	-0.48	-0.37	-3.61	0.51
0.00	-6.00	6.00	4.97	-0.06	-0.55	0.01	-3.64	0.38
-6.00	-6.00	6.00	4.95	0.47	-0.60	0.38	-3.62	0.33
6.00	6.00	0.00	4.94	-0.53	0.52	-0.38	-3.64	-0.05
0.00	6.00	0.00	4.96	-0.01	0.52	0.00	-3.66	-0.01
-6.00	6.00	0.00	4.94	0.52	0.52	0.38	-3.64	0.02
6.00	0.00	0.00	4.97	-0.52	0.01	-0.37	-3.64	-0.01
0.00	0.00	0.00	5.00	0.00	0.00	0.00	3.66	0.01
-6.00	0.00	0.00	4.98	0.52	0.00	0.38	-3.64	-0.01
6.00	-6.00	0.00	4.95	-0.52	-0.52	-0.36	-3.63	0.03
0.00	-6.00	0.00	4.99	-0.01	-0.55	0.00	-3.66	-0.01
-6.00	-6.00	0.00	4.95	0.52	-0.53	0.38	-3.65	-0.05
6.00	6.00	-6.00	4.94	-0.59	0.46	-0.38	-3.62	-0.44
0.00	6.00	-6.00	4.97	-0.07	0.51	0.00	-3.65	-0.40
-6.00	6.00	-6.00	4.94	0.45	0.57	0.37	-3.64	-0.36
6.00	0.00	-6.00	4.97	-0.53	-0.08	-0.38	-3.62	-0.40
0.00	0.00	-6.00	5.00	-0.01	-0.01	0.00	-3.65	-0.40
-6.00	0.00	-6.00	4.97	0.51	0.04	0.38	-3.63	-0.40
6.00	-6.00	-6.00	4.95	-0.47	-0.58	-0.38	-3.63	-0.36
0.00	-6.00	-6.00	4.98	0.05	-0.53	0.00	-3.65	-0.40
-6.00	-6.00	-6.00	4.95	0.57	-0.47	0.38	-3.62	-0.44

END OF DATA

Table 5-D. Results of Test B1, Computed Data

INPUT DATA			COMPUTED OUTPUT DATA		
SENSOR GIMBAL ANGLES			SENSOR ANGLE ERRORS		
(DEGREES)			(DEGREES)		
AZIMUTH	ELEVATION	ROLL	AZIMUTH ERROR	ELEVATION ERROR	ROLL ERROR
6.00	6.00	6.00	0.00	-0.08	-0.48
0.00	6.00	6.00	-0.02	-0.34	-0.35
-6.00	6.00	6.00	0.01	-0.06	-0.30
6.00	0.00	6.00	-0.01	-0.13	-0.33
0.00	0.00	6.00	0.01	0.11	-0.35
-6.00	0.00	6.00	-0.02	-0.21	-0.30
B A D D A T A					
0.00	-6.00	6.00	0.03	-0.35	-0.02
-6.00	-6.00	6.00	-0.06	-0.33	-0.13
6.00	6.00	0.00	0.07	0.03	-0.16
0.00	6.00	0.00	0.10	-0.01	-0.16
-6.00	6.00	0.00	0.01	-0.01	-0.16
6.00	0.00	0.00	-0.03	0.13	-0.14
0.00	0.00	0.00	0.00	0.00	-0.16
-6.00	0.00	0.00	0.04	-0.02	-0.16
6.00	-6.00	0.00	-0.02	0.02	-0.12
0.00	-6.00	0.00	0.13	-0.29	-0.16
-6.00	-6.00	0.00	0.05	-0.13	-0.14
6.00	6.00	-6.00	0.16	0.03	-0.30
0.00	6.00	-6.00	0.16	-0.09	-0.25
-6.00	6.00	-6.00	0.14	-0.02	-0.26
6.00	0.00	-6.00	0.15	-0.24	-0.33
0.00	0.00	-6.00	0.13	-0.10	-0.25
-6.00	0.00	-6.00	0.13	-0.18	-0.27
6.00	-6.00	-6.00	0.09	-0.05	-0.30
0.00	-6.00	-6.00	0.09	-0.10	-0.25
-6.00	-6.00	-6.00	0.09	-0.11	-0.29
END OF DATA					
STANDARD DEVIATIONS					
WITH BIAS			0.09	0.16	0.26
WITHOUT BIAS			0.07	0.13	0.10
BIAS			0.05	-0.10	-0.24

Table 6-D. Results of Test B2, Measured Data

INPUT DATA			MEASURED OUTPUT DATA					
SENSOR GIMBAL ANGLES (DEGREES)			SENSOR VOLTAGE READINGS (VOLTS)					
AZIMUTH	ELEVATION	ROLL	XX	YX	ZX	XY	YY	ZY
6.00	6.00	6.00	4.94	-0.46	0.56	-0.51	-4.94	0.44
0.00	6.00	6.00	4.96	0.06	0.51	0.00	-4.96	0.50
-6.00	6.00	6.00	4.95	0.59	0.46	0.52	-4.95	0.55
6.00	0.00	6.00	4.98	-0.51	0.04	-0.50	-4.92	0.49
0.00	0.00	6.00	5.00	0.01	-0.01	0.00	-4.96	0.50
-6.00	0.00	6.00	4.98	0.54	-0.06	0.53	-4.94	0.50
6.00	-6.00	6.00	4.95	-0.56	-0.48	-0.50	-4.91	0.53
0.00	-6.00	6.00	4.97	-0.04	-0.54	0.02	-4.95	0.50
-6.00	-6.00	6.00	4.96	0.49	-0.59	0.53	-4.94	0.45
6.00	6.00	0.00	4.94	-0.52	0.52	-0.51	-4.96	-0.07
0.00	6.00	0.00	4.97	0.00	0.52	0.00	-5.00	-0.10
-6.00	6.00	0.00	4.96	0.54	0.52	0.49	-4.99	0.04
6.00	0.00	0.00	4.98	-0.51	-0.01	-0.50	-4.96	-0.02
0.00	0.00	0.00	5.01	0.01	-0.01	0.01	-4.99	-0.01
-6.00	0.00	0.00	4.99	0.54	-0.01	0.43	-4.97	-0.02
6.00	-6.00	0.00	4.95	-0.51	-0.53	-0.50	-4.96	0.04
0.00	-6.00	0.00	4.98	0.02	-0.54	0.01	-4.99	-0.01
-6.00	-6.00	0.00	4.97	0.54	-0.54	0.50	-4.97	-0.07
6.00	6.00	-6.00	4.94	-0.57	0.46	-0.51	-4.93	-0.58
0.00	6.00	-6.00	4.97	-0.05	0.52	0.00	-4.97	-0.53
-6.00	6.00	-6.00	4.96	0.47	0.57	0.57	-4.97	-0.48
6.00	0.00	-6.00	4.96	-0.52	-0.05	-0.51	-4.94	-0.53
0.00	0.00	-6.00	5.00	0.00	0.00	0.00	-4.97	-0.53
-6.00	0.00	-6.00	4.98	0.54	0.06	0.52	-4.95	-0.53
6.00	-6.00	-6.00	4.97	-0.46	-0.58	-0.50	-4.95	-0.43
0.00	-6.00	-6.00	4.97	0.07	-0.53	0.01	-4.96	-0.53
-6.00	-6.00	-6.00	4.96	0.59	-0.47	0.52	-4.95	-0.58

END OF DATA

Table 7-D. Results of Test B2, Computed Data

INPUT DATA			COMPUTED OUTPUT DATA		
SENSOR GIMBAL ANGLES			SENSOR ANGLE ERRORS		
(DEGREES)			(DEGREES)		
AZIMUTH	ELEVATION	ROLL	AZIMUTH ERROR	ELEVATION ERROR	ROLL ERROR
6.00	6.00	6.00	-0.10	-0.09	-0.30
0.00	6.00	6.00	-0.10	-0.09	-0.24
-6.00	6.00	6.00	-0.21	-0.04	-0.28
6.00	0.00	6.00	-0.14	-0.12	-0.32
0.00	0.00	6.00	-0.13	-0.10	-0.24
-6.00	0.00	6.00	-0.23	-0.06	-0.21
6.00	-6.00	6.00	-0.16	-0.15	-0.23
0.00	-6.00	6.00	-0.17	-0.22	-0.21
-6.00	-6.00	6.00	-0.27	-0.18	-0.13
6.00	6.00	0.00	-0.04	0.03	-0.19
B A D D A T A					
-6.00	6.00	0.00	-0.19	-0.03	-0.13
6.00	0.00	0.00	-0.15	-0.09	-0.24
0.00	0.00	0.00	-0.11	-0.11	-0.11
-6.00	0.00	0.00	-0.18	-0.14	-0.22
6.00	-6.00	0.00	-0.13	-0.10	-0.15
0.00	-6.00	0.00	-0.22	-0.19	-0.10
-6.00	-6.00	0.00	-0.15	-0.22	-0.18
6.00	6.00	-6.00	-0.05	-0.02	-0.09
0.00	6.00	-6.00	-0.06	0.00	-0.09
-6.00	6.00	-6.00	-0.05	-0.06	-0.20
6.00	0.00	-6.00	0.01	0.07	-0.12
0.00	0.00	-6.00	0.00	0.00	-0.09
-6.00	0.00	-6.00	-0.23	0.02	-0.11
6.00	-6.00	-6.00	-0.07	-0.06	-0.15
0.00	-6.00	-6.00	-0.15	-0.14	-0.09
-6.00	-6.00	-6.00	-0.15	-0.09	-0.04
END OF DATA					
STANDARD DEVIATIONS					
WITH BIAS			0.15	0.11	0.19
WITHOUT BIAS			0.07	0.07	0.07
BIAS			-0.13	-0.08	-0.17

Table 8-D. Results of Test B3, Measured Data

INPUT DATA			MEASURED OUTPUT DATA					
SENSOR GIMBAL ANGLES (DEGREES)			SENSOR VOLTAGE READINGS (VOLTS)					
AZIMUTH	ELEVATION	ROLL	XX	YX	ZX	XY	YY	ZY
6.00	6.00	6.00	9.91	-0.91	1.15	-0.52	-4.96	0.48
0.00	6.00	6.00	9.97	0.13	1.04	0.00	-4.99	0.54
-6.00	6.00	6.00	9.93	1.18	0.92	0.52	-4.95	0.59
6.00	0.00	6.00	9.99	-1.03	0.13	-0.52	-4.96	0.54
0.00	0.00	6.00	10.05	0.01	0.00	0.00	-4.99	0.55
-6.00	0.00	6.00	10.01	1.08	-0.12	0.52	-4.97	0.54
6.00	-6.00	6.00	9.95	-1.14	-0.92	-0.52	-4.96	0.61
0.00	-6.00	6.00	10.03	-0.09	-1.05	0.00	-5.00	0.55
-6.00	-6.00	6.00	10.00	0.96	-1.17	0.51	-4.98	0.49
6.00	6.00	0.00	9.88	-1.04	1.06	-0.51	-4.97	-0.05
0.00	6.00	0.00	9.95	0.01	1.05	0.00	-4.99	0.00
-6.00	6.00	0.00	9.90	1.06	1.04	0.52	-4.97	0.05
6.00	0.00	0.00	9.94	-1.04	0.03	-0.55	-4.97	0.00
0.00	0.00	0.00	10.00	0.01	-0.01	0.00	-4.99	0.00
-6.00	0.00	0.00	9.95	1.05	-0.01	0.52	-4.97	0.01
6.00	-6.00	0.00	9.92	-1.04	-1.04	-0.52	-4.97	0.07
0.00	-6.00	0.00	9.99	0.01	-1.06	0.00	-5.00	0.01
-6.00	-6.00	0.00	9.94	1.06	-1.06	0.52	-4.97	-0.05
6.00	6.00	-5.00	9.90	-1.13	0.96	-0.52	-4.96	-0.47
0.00	6.00	-5.00	9.96	-0.10	1.05	0.00	-4.99	-0.43
-6.00	6.00	-5.00	9.92	0.96	1.13	0.52	-4.97	-0.37
6.00	0.00	-5.00	9.97	-1.04	-0.08	-0.52	-4.96	-0.41
0.00	0.00	-5.00	10.03	0.00	0.00	0.00	-4.99	-0.42
-6.00	0.00	-5.00	9.99	1.05	0.09	0.51	-4.96	-0.42
6.00	-6.00	-5.00	9.93	-0.96	-1.12	-0.52	-4.96	-0.36
0.00	-6.00	-5.00	10.00	0.09	-1.04	0.00	-4.99	-0.40
-6.00	-6.00	-5.00	9.95	1.15	-0.96	0.52	-4.96	-0.48
END OF DATA								

Table 9-D. Results of Test B3, Computed Data

INPUT DATA			COMPUTED OUTPUT DATA		
SENSOR GIMBAL ANGLES			SENSOR ANGLE ERRORS		
(DEGREES)			(DEGREES)		
AZIMUTH	ELEVATION	ROLL	AZIMUTH ERROR	ELEVATION ERROR	ROLL ERROR
6.00	6.00	6.00	-0.11	0.02	0.16
0.00	6.00	6.00	-0.10	0.00	0.18
-6.00	6.00	6.00	-0.14	-0.01	0.17
6.00	0.00	6.00	-0.07	0.10	0.22
0.00	0.00	6.00	-0.06	0.01	0.29
-6.00	0.00	6.00	-0.20	-0.01	0.20
6.00	-6.00	6.00	-0.12	0.03	0.39
0.00	-6.00	6.00	-0.14	0.00	0.28
-6.00	-6.00	6.00	-0.14	-0.04	0.24
6.00	6.00	0.00	-0.02	0.12	0.05
0.00	6.00	0.00	-0.06	0.02	0.00
-6.00	6.00	0.00	-0.08	-0.01	-0.05
6.00	0.00	0.00	-0.03	0.17	0.02
0.00	0.00	0.00	-0.06	-0.06	0.00
-6.00	0.00	0.00	-0.02	-0.04	0.12
6.00	-6.00	0.00	-0.07	0.00	0.18
0.00	-6.00	0.00	-0.07	-0.06	0.11
-6.00	-6.00	0.00	-0.06	-0.08	0.06
6.00	6.00	-5.00	0.00	0.06	0.22
0.00	6.00	-5.00	0.05	0.04	0.07
-6.00	6.00	-5.00	-0.02	0.01	0.11
6.00	0.00	-5.00	-0.03	0.03	0.28
0.00	0.00	-5.00	0.00	0.00	0.19
-6.00	0.00	-5.00	-0.02	0.01	0.16
6.00	-6.00	-5.00	0.00	0.04	0.22
0.00	-6.00	-5.00	-0.04	0.04	0.42
-6.00	-6.00	-5.00	-0.07	-0.05	0.11

END OF DATA

STANDARD DEVIATIONS

WITH BIAS	0.08	0.06	0.20
WITHOUT BIAS	0.05	0.05	0.11

BIAS -0.06 0.01 0.16