

Unclassified

AD774587



SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFAL-TR-73-281	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) An Electromagnetic Position Sensor		5. TYPE OF REPORT & PERIOD COVERED Final Report
7. AUTHOR(s) Aurale R. DeRuyck Jack Kuipers		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS Polhemus Navigation Sciences, Inc. P. O. Box 1011 Burlington, Vermont 05401		8. CONTRACT OR GRANT NUMBER(s) F33615-73-C-1027
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Avionics Laboratory		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE 30 November 1973
		13. NUMBER OF PAGES
		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES PRICES SUBJECT TO CHANGE		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) SPASYN (Space Synchro), five-degree-of-freedom, transducing technique, transfer alignment, Radiator, Sensor radiator excitation unit (REU), System Control and Display Unit (SCDU).		
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. Extensive 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		

DD FORM 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL
INFORMATION SERVICE
SPRINGFIELD, VA 22161

1

95

Unclassified

AD 774 587

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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.,
Waltham, Massachusetts

M. C. Poppe, Vice-President for Engineering;
PNSI

TABLE OF CONTENTS

<u>Section</u>	<u>Title</u>	<u>Page</u>
	Summary	3
	Preface	4
I	Introduction	9
	Statement of Problem	9
	SPASYN Development Background	9
	Program Scope and Objectives	11
	Technical Requirements and Goals	11
	Summary of Program Results	12
II	System Design	17
	Review of SPASYN Concept	17
	System/Component Design Considerations	19
	System Implementation Scheme	23
III	System Hardware	26
	Radiator and Sensor	26
	Radiator Excitation Unit	26
	System Control and Display Unit	26
IV	System Testing	31
	Test Plans	31
	Test Set-Ups	33
	Test Results	33
V	Conclusions and Recommendations	42
	Bibliography	
<u>Appendix</u>		
A	TAFS Development History	A-1
B	The SPASYN	B-1
C	TAFS Antenna Power Requirements	C-1
D	TAFS Test Results	D-1

LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Low Cost Airborne Alignment of Missile Systems	10
2	A Five Degree-of-Freedom Transducing Scheme	18
3	The SPASYN Five Degree-of-Freedom System	20
4	Functional Block Diagram, TAFS	24
5	Radiator and Sensor	27
6	Radiator Excitation Unit	28
7	System Control Unit (SCDU)	29
8	SCDU Functional Block Diagram	30
9	Radiator/Sensor/Structure Test B-1	34
10	Radiator/Sensor Structure Test B-2	35
11	Radiator/Sensor/Structure Test B-3	36
12	Radiator/Sensor/Structure Test D-1	37
13	Test Set-Up for Test B-3	38
14	Test Set-Up for Test D-1	39
15	Typical Test Set-Up for All Tests Except D-1	40

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Technical Accomplishments	14
2	Detailed System Test Plan	32
3	Summary of TAFS Test Results	41

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

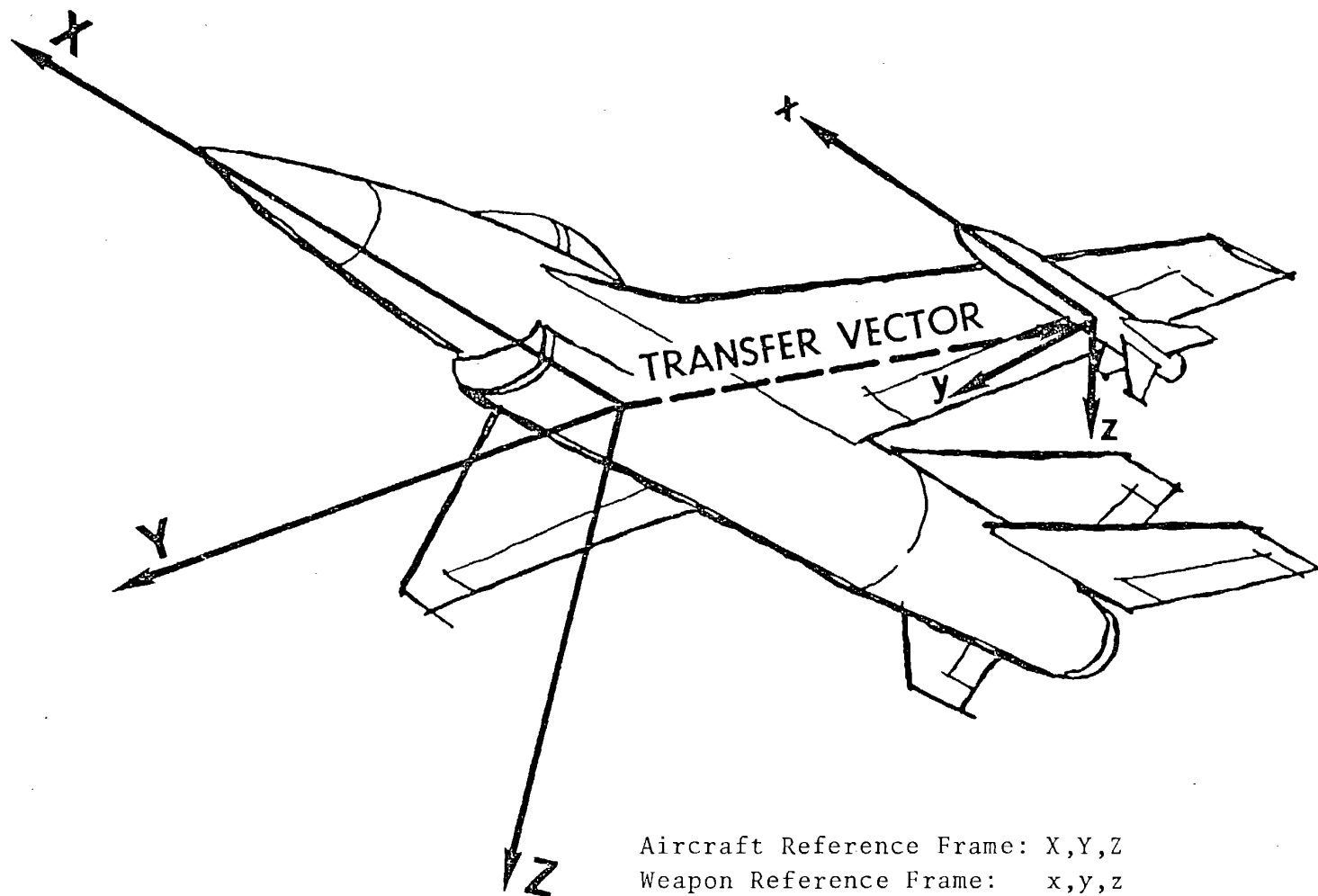


Figure 1. LOW COST AIRBORNE ALIGNMENT OF MISSILE SYSTEMS

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:	(+0.1°)						
Standard Deviation for Small (+6.0°) Angles							
a. For Test Series A*:	<table><tr><td>ψ_e</td><td>θ_e</td><td>ϕ_e</td></tr><tr><td>0.05°</td><td>0.09°</td><td>0.11°</td></tr></table>	ψ_e	θ_e	ϕ_e	0.05°	0.09°	0.11°
ψ_e	θ_e	ϕ_e					
0.05°	0.09°	0.11°					
b. For Test Series B*:	<table><tr><td>0.11°</td><td>0.15°</td><td>0.17°</td></tr></table>	0.11°	0.15°	0.17°			
0.11°	0.15°	0.17°					
c. For Test Series D*:	<table><tr><td><0.18°</td><td><0.22°</td><td><0.24°</td></tr></table>	<0.18°	<0.22°	<0.24°			
<0.18°	<0.22°	<0.24°					
*See listing of system testing tasks above.							

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

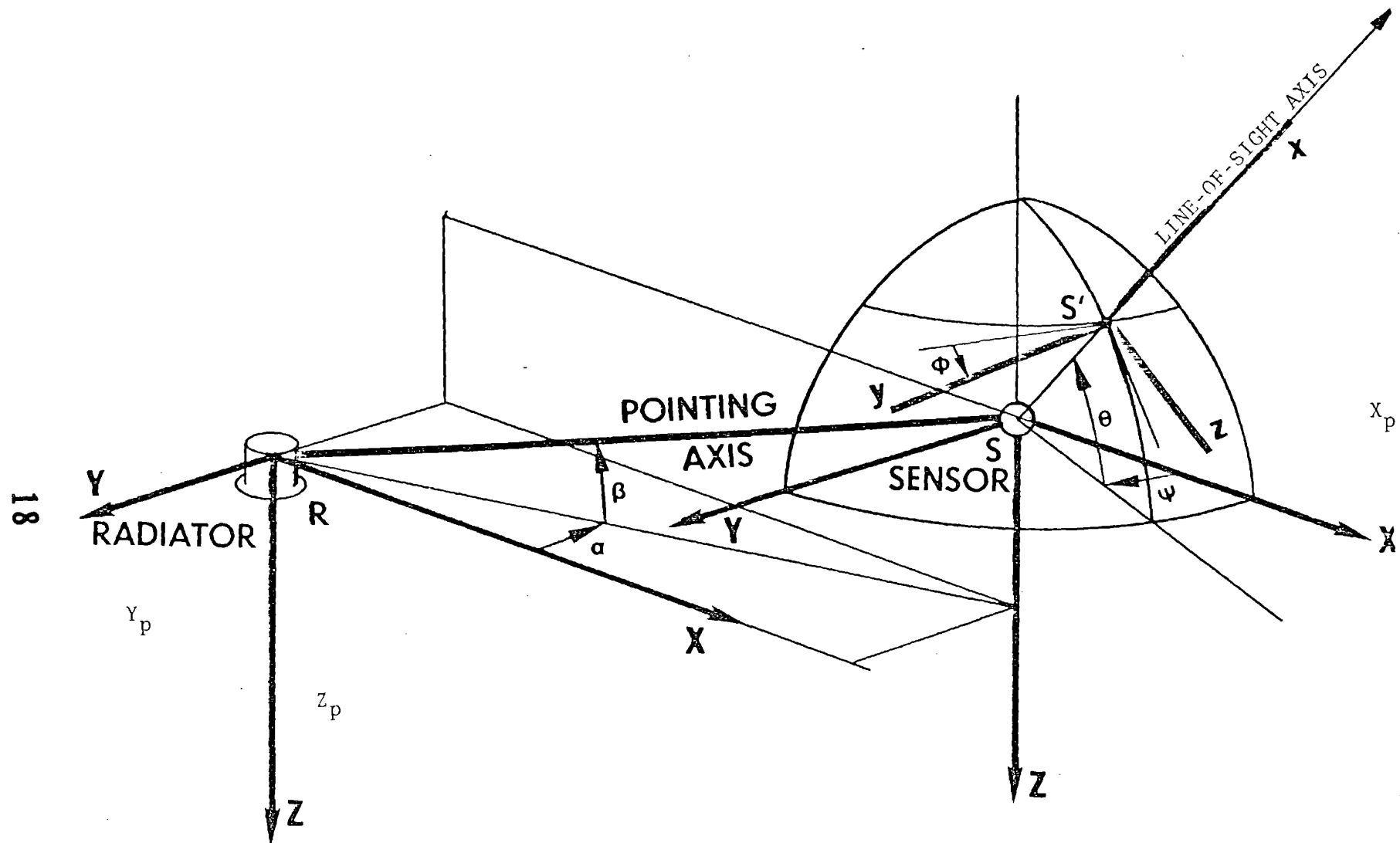


FIGURE 2. A FIVE DEGREE-OF-FREEDOM TRANSDUCING SCHEME

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.

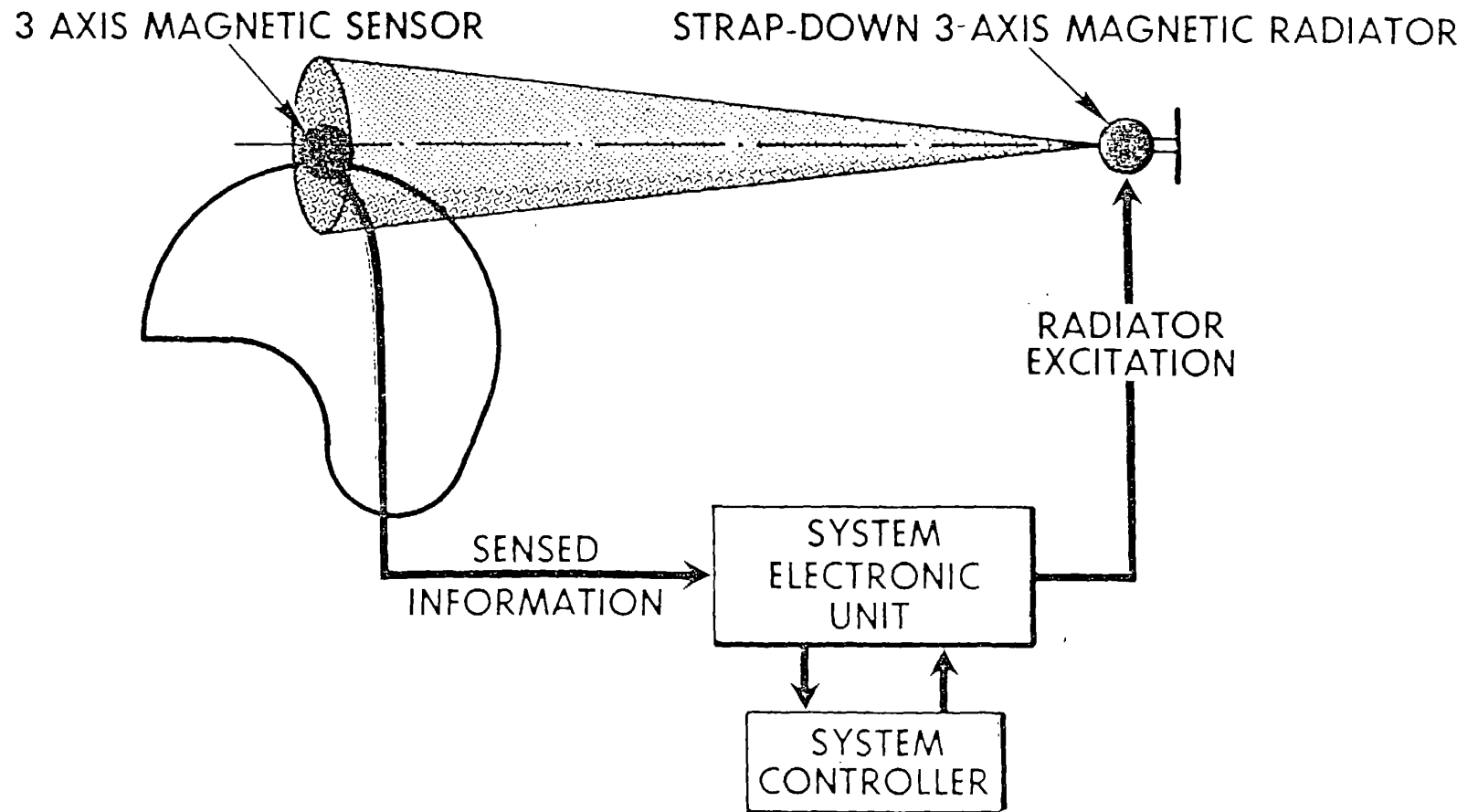


Figure 3. The SPASYN Five-Degree-of Freedom System

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 $20 \mu\text{v/m}/\sqrt{\text{Hz}}$ may be expected. Assuming a processing bandwidth of 100 Hz, a total noise level of $200 \mu\text{v/m}$ 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 empirically 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

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.