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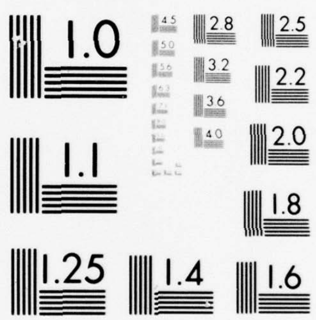

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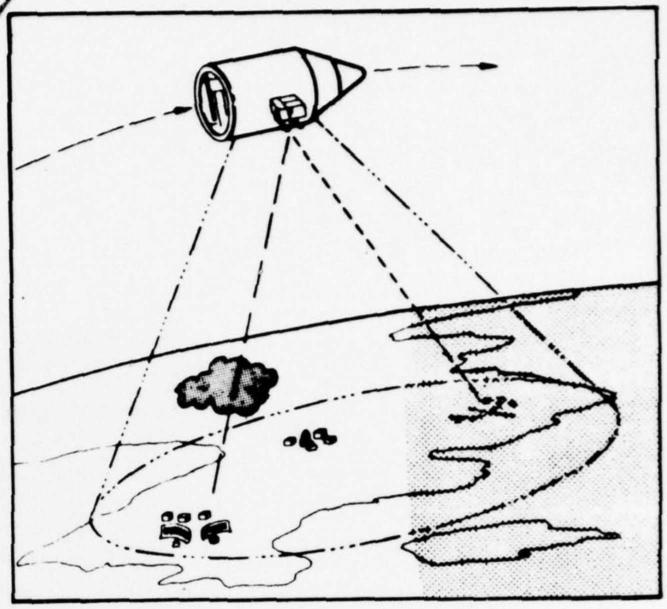

Self-Contained, High-Altitude Navigation System Study: PRAIS Navigation System

Volume I – System Summary

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Abstract: Circuits to add a passive ranging capability to the Interferometric Landmark Tracker (ILT) to form a Passive Range Interferometer Sensor (PRAIS) were built and tested in the laboratory. The laboratory test data were used in a Monte Carlo simulation to demonstrate the performance of the PRAIS Navigation System in a highly eliptical orbit and a synchronous (1° inclination) orbit. Navigation accuracies better than 1000 ft and attitude accuracy better than 10 sec were indicated by the analyses.

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FOREWORD

This report is Volume I of the three-volume final report of the Self-Contained, High-Altitude Navigation System (SCHANS) study published by the IBM Corporation, Federal Systems Division, under Air Force Contract No. F04701-76-C-0106. This report summarizes the SCHANS studies performed from 8 December 1975 through 1 January 1977 and was submitted to the USAF Space and Missile Systems Organization (SAMSO) for review by Captain R. A. Lawhern, USAF.

The Passive Ranging Interferometer Sensor (PRAIS) Navigation System studied by IBM under this contract consisted of the ILT, augmented by passive ranging circuits, a Signal Processor Unit (SPU), and (optionally) an Inertial Reference Unit (IRU). Breadboards of the precision time measurement circuits for passive range measurements were built and tested in the laboratory. The laboratory test data were used in a Monte Carlo simulation to evaluate navigation system performance. An Attitude-Determination algorithm was developed to add the capability for attitude determination to the PRAIS Navigation System.

This report was authored by D. H. Aldrich and J. W. Simmons of Electromagnetic Development Engineering and by N. F. Toda of Advanced Tactical Systems. The authors wish to acknowledge with gratitude the efforts and support of their fellow technical investigators: H. Hill, L. O. Smith, R. E. Dreska, L. Fulk, E. E. Kroman, C. J. Standish, and R. L. Smith. Also, the authors gratefully acknowledge the direction and control provided by Captain R. A. Lawhern of SAMSO DYAG and by Eugene Farr, Aldo Briganti, Howard Hendrickson, and John Barnes of the Aerospace Corporation.

Section 1

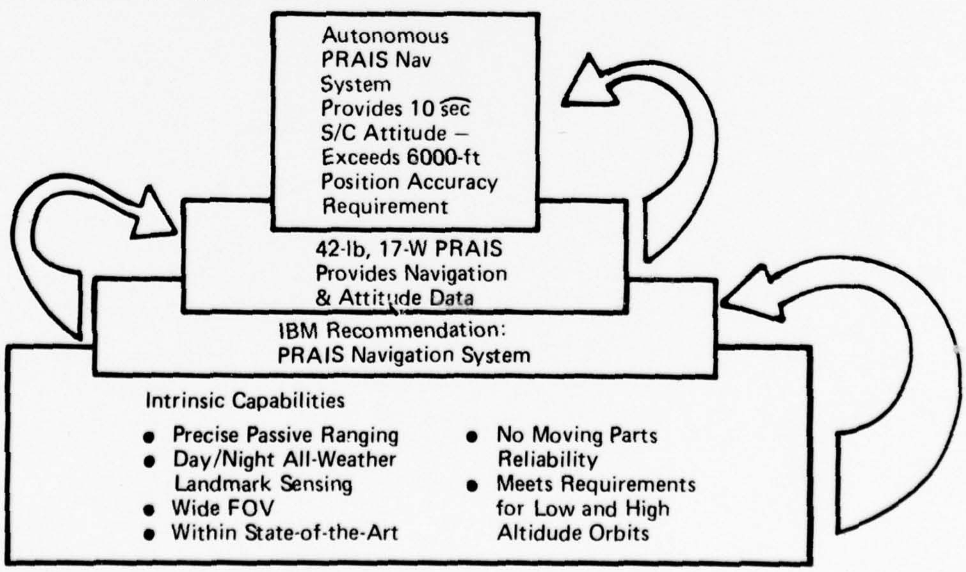
INTRODUCTION

1.1 SCOPE AND BACKGROUND

This document is Volume 1 of the final report on the Self-Contained, High-Altitude Navigation System study. This volume summarizes the study conducted by the International Business Machines Corporation under contract F04701-76-C-0106 for USAF/SAMSO to provide an autonomous navigation and attitude determination system for high (5000 nmi or greater) altitude spacecraft. IBM's recommended approach utilizes the intrinsic capabilities of a strapped-down Passive Range Interferometric Sensor (PRAIS) to measure the line-of-sight and estimate range differential along the arc of the orbit. The PRAIS, combined with a signal processor unit (digital computer) and, optionally, an Inertial Reference unit, forms the PRAIS Navigation System. The figure summarizes the PRAIS Navigation System characteristics and performance.

An Interferometric Landmark Tracker (ILT) has been under study and development by USAF/SAMSO since 1971. The table summarizes the program background. This contract, using as a point of departure the ILT design and HANS simulation developed under these previous contracts, extended the PRAIS concept to provide an attitude determination capability. This required extending the HANS navigation filter from 18 to 24 states. Additionally, the program was redesigned to operate in double precision arithmetic on the IBM 370/158 computer instead of the IBM 7094, which was no longer available. Since the simulation program evolved over 5 years and several contracts the program was streamlined for faster execution. Functions and variables no longer required were deleted. Thus, all subroutines previously developed were modified.

Difficulties were encountered in modifying the filter, and as a result evaluation of system performance using order statistics was not completed under the SCHANS Contract as planned. Therefore, the navigation and attitude performance described in this report reflect typical simulation results. IBM, however, using internal funds, conducted limited order statistical analyses which generally confirm the contract results. These analyses are presented in IBM technical report 77-508-002 Passive Range Interferometer Sensor Navigation System; Simulation Results, March 1977.



Passive Ranging Interferometer Sensor (PRAIS)
Navigation System Summary

SCHANS PROGRAM BACKGROUND

Program Name & Contract Number	Time Period	Scope & Results
Autonomous Navigation Technology (ANT) Phase 0 F04701-71-C-0339	June 71 through Feb 72	Study of spacecraft autonomous navigation with interferometric landmark tracking (ILT) in combination with inertial reference and star tracker. Feasibility demonstrated
ANT Phase 1A F04701-73-C-0221	March 73 through June 74	Laboratory evaluation of ILT sighting accuracy and computer simulation of ANT performance. Navigation errors within 550 ft were demonstrated with convergence time of 50 minutes in a worst-case orbit. Interferometer performance was measured in an anechoic chamber using two orthogonal baselines of 10 λ each. Accuracy was near 1 $\widehat{min}$
High-Altitude Navigation System (HANS) Study F04701-74-C-0565	June 74 through Jan 75	Study of utility of passive ranging (PAR) measurements in conjunction with ILT. System sensitivity and error budget analyses. Simulations demonstrated distinct improvement with PAR tracking landmarks with stable pulse repetition intervals
ANT Phase 1B F04701-75-C-0046	Oct 74 through Nov 75	ILT Receiver design study, analyses, and breadboard tests to yield design specification and preliminary physical configuration suitable for space flight test. Design of three-channel superheterodyne receiver for measurement of landmark pulse arrival angle in two orthogonal baselines, received signal strength, time-of-pulse arrival (TOA), signal quality, and calibration (i.e., measurement of inter-channel phase errors). Description of signal processing functions needed to input ILT measurements into a spaceborne navigation program in an onboard computer.
Self-Contained High-Altitude Navigation System (SCHANS) F04701-76-C-0106	Dec 75 through Dec 76	Critical component breadboard tests: TOA counter error rate and TOA measurement error statistics. Preliminary part 1 development specification. Paper design of principal units: Interferometric Landmark Tracker-Pulse Conversion Unit (ILT-PCU) and Signal Processing Unit (SPU). Preliminary space flight test planning. Space flight software design specifications through top level flows (Part 1 specifications). Demonstration of high-altitude navigation and attitude system performance through simulation. Reliability prediction and preliminary Nuclear Survivability analyses.

1.2 POTENTIAL APPLICATIONS

The PRAIS Navigation system provides a completely autonomous spacecraft navigation and attitude reference system with accuracies presently unobtainable by any operational Air Force system. The autonomy of this navigation system potentially permits a decrease in the workload of the Satellite Control Facility network in tracking and position reporting of numerous systems soon to be launched. The inherent capabilities of this navigation system also holds promise to improve the mission capability of satellite systems themselves.

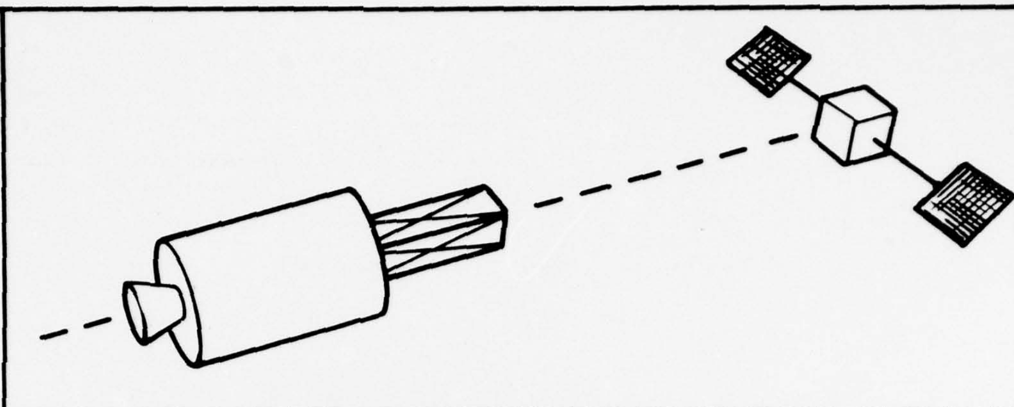
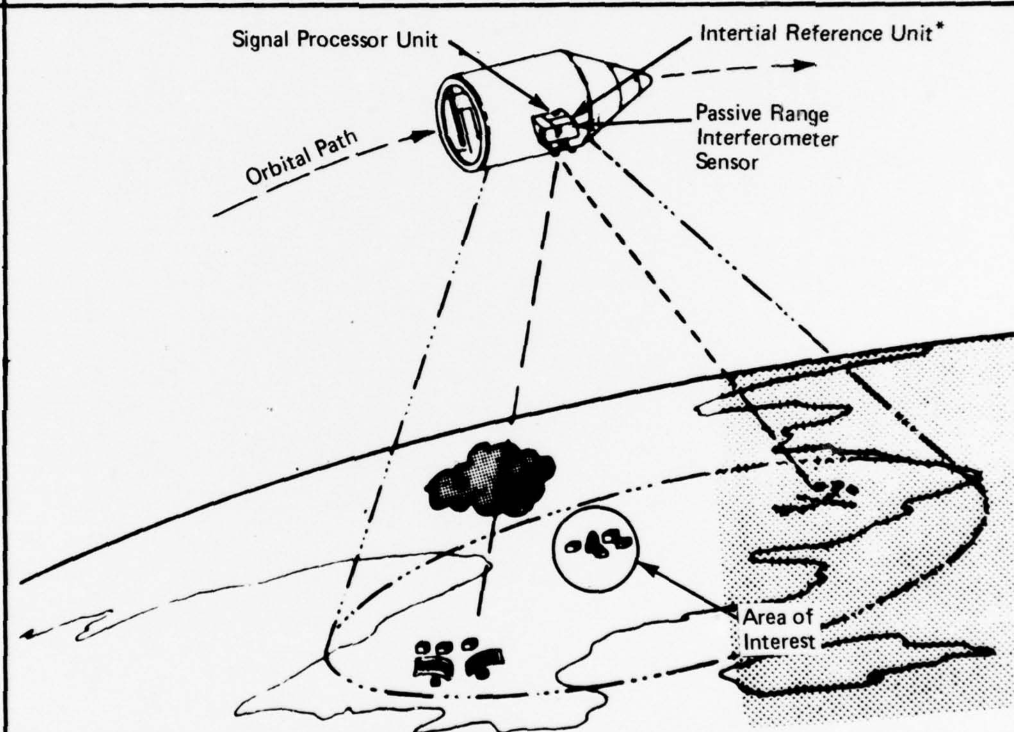
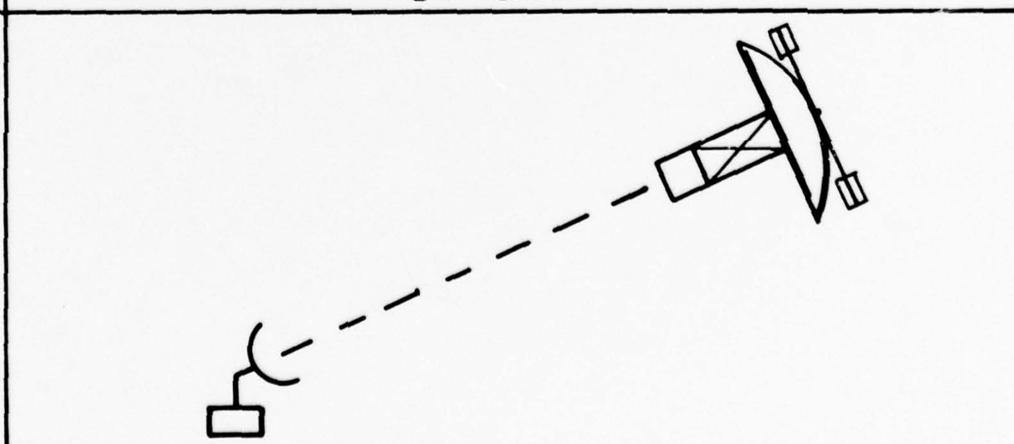
By providing continuously accurate knowledge of the spacecraft position, velocity, and attitude, the PRAIS Navigation system has the potential of extending the performance capabilities on three important generic classes of space missions:

- Position and attitude control of maneuvering spacecraft
- Ground truth determination for earth observations
- Attitude/pointing control of spacecraft/sensors.

Use of the PRAIS in maneuvering space vehicles which must operate for extended periods between maneuvers can provide an update and calibration capability for an inertial measurement unit. In high-altitude orbits, spacecraft attitude can be measured within 10 $\widehat{sec}$ continuously. The PRAIS Navigation System accuracy of 2 km and 10 $\widehat{sec}$ at synchronous altitude is sufficient to permit spacecraft rendezvous with only a short-range (20 km) docking sensor.

Since the PRAIS Navigation System determines the spacecraft position with respect to known ground radar reference points to an accuracy of a few hundred feet in low earth orbits, rectification of earth mapping distortions can be simplified by utilizing these radar locations as control points. The PRAIS can also be used to locate additional radar "control points" to extend the observation grid.

The PRAIS can also provide attitude measurement for attitude control of the spacecraft or pointing control of spacecraft sensors. An IBM-built interferometer experiment is now operational in the ATS-6 satellite. The ATS-6 experimental system demonstrated spacecraft pointing control to an accuracy of 0.0056°. Additionally, independent studies of the ILT led to a recommendation by the study contractor for its inclusion in the NASA Space Tug baseline system.

Position & Attitude Control of Manuevering Spacecraft	
Ground Truth Determination for Earth Observation	
Attitude/Pointing Control of Spacecraft/Sensors	

Potential Mission Applications

Section 2

PRAIS NAVIGATION SYSTEM DESCRIPTION

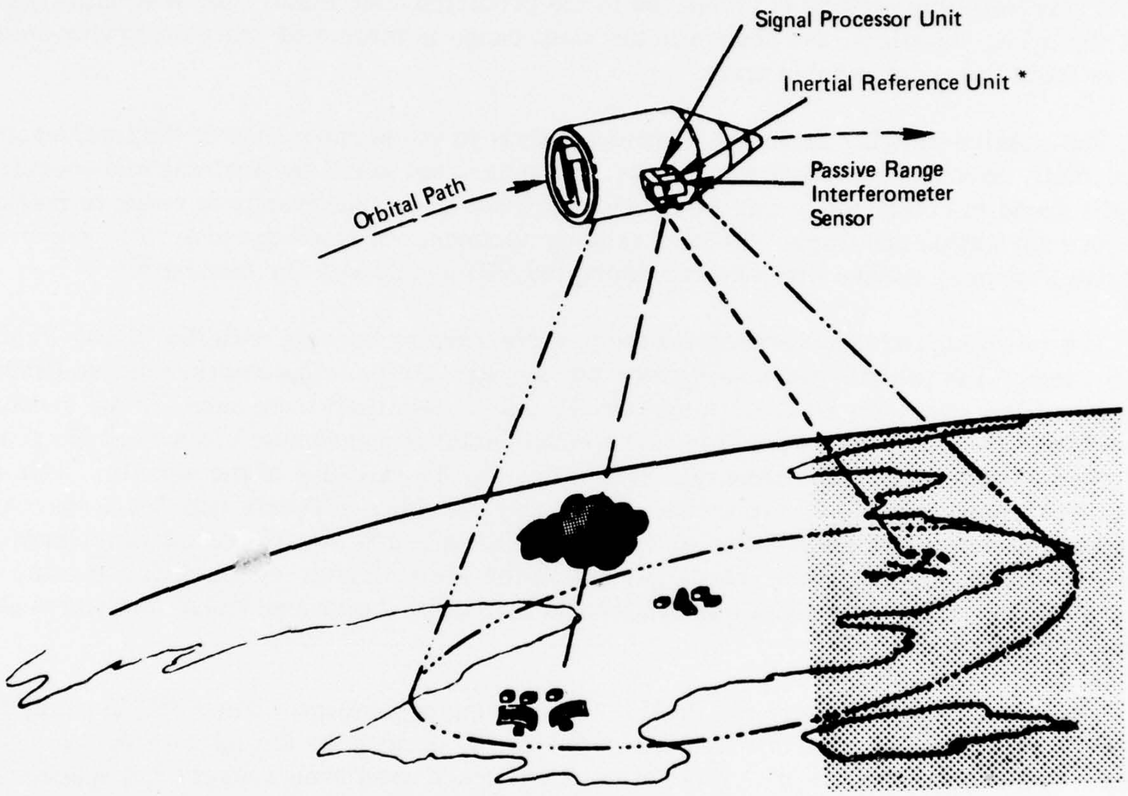
2.1 SYSTEM CONCEPT

The IBM Passive Range Interferometer Sensor Navigation System Concept for SCHANS, shown in the Figure, utilizes a strapped-down orthogonal baseline phase interferometer augmented by precision time-of-arrival circuits to derive line-of-sight angle and passive range measurements to ground-based radars of known location and characteristics. Passive ranging is essentially a range-Doppler technique in which the range change measurements are used to estimate (noncooperatively) the time of emission of the radar pulses. The PRAIS Navigation System consists of

- The Passive Range Interferometer Sensor (PRAIS)
- A Signal Processor Unit (SPU) which processes the PRAIS measurements in a 24-state Kalman filter to derive position, velocity, and attitude
- A strapped-down inertial reference unit (optional) to provide attitude memory between landmark measurements.

In operation, angle data are received by the PRAIS from such landmarks as air traffic control, defense early-warning and coastal-search radars operating in the frequency range of 2.5 to 2.9 GHz. This band was selected since many air traffic control and surveillance radars operate in this bandwidth. These angle data are processed with a Kalman navigation filter to determine spacecraft position, velocity, and attitude vectors. The latitude, longitude, altitude, PRI, and frequency of selected radars of known position are stored in the computer to be used as landmarks. Any of these stored landmarks within the PRAIS field of view can be acquired by simply tuning to the known radar frequency. Day/night, all-weather operation is inherent in this frequency band.

The PRAIS and its associated computer algorithms also provide passive ranging between the spacecraft and the landmarks, using unsynchronized emissions from ground radars that have stable pulse repetition intervals (PRI). The PRAIS Navigation System estimates the time of emission of the radar pulses in the Kalman filter and does not require synchronization of ground or spacecraft clocks nor time tagging of radar pulses.



*This function can be provided by PRAIS in orbits where at least two landmarks are continuously visible or on spacecraft with independent local vertical-oriented attitude control systems.

Passive Range Interferometer Sensor Navigation System Concept

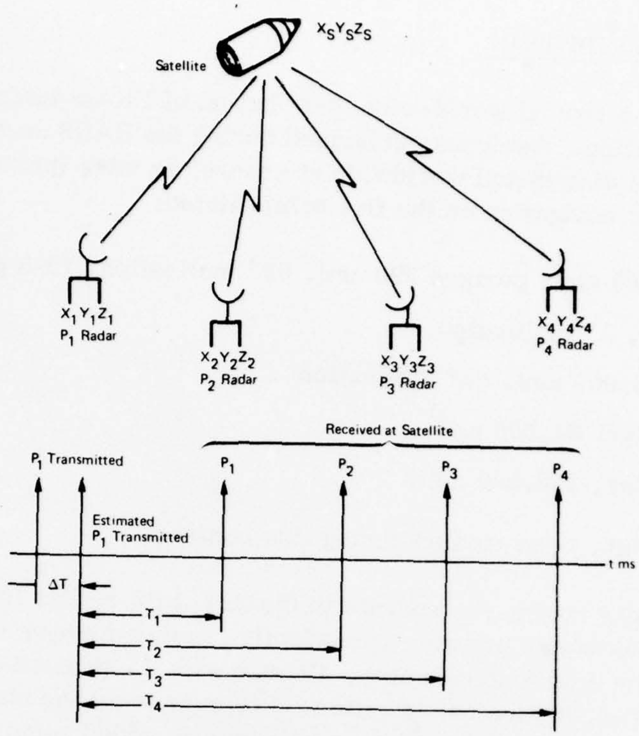
2.1.1 PASSIVE RANGING DESCRIPTION

The passive-ranging technique employed by IBM measures the time history of radar pulses received from ground-based radars. A predicted time history is based on the current best estimate of the position and velocity between the spacecraft and radar landmark and some prior knowledge or prefiltered knowledge of the radar's pulse repetition interval (PRI). This measured time history is compared to the predicted time history to differentially correct the orbit. In effect, the change in the slant range is measured while observing selected pulses from the radar's pulse train.

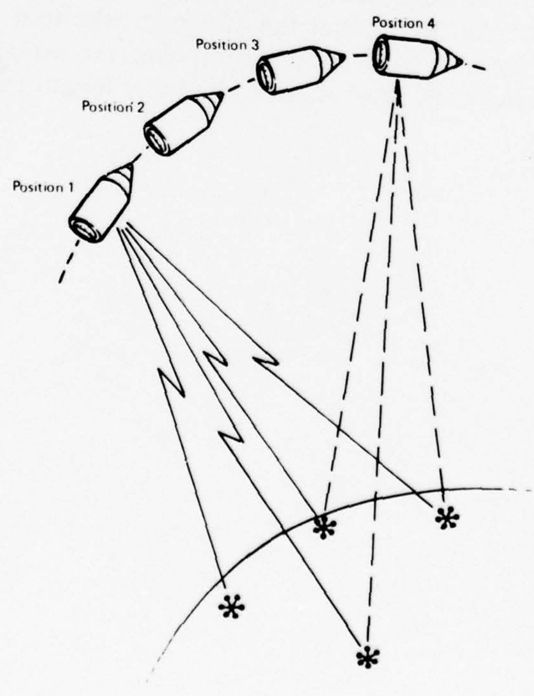
The passive-ranging technique degrades nearly to the performance of the interferometer in perfectly synchronous equatorial orbits. However, the small inclinations and eccentricities usually found in actual geosynchronous orbits provide sufficient change in range to markedly improve navigation accuracy. Passive ranging performance also degrades with poorer PRI stability. Hence, radars with crystal controlled PRI are needed for landmarks.

The following paragraphs contrast the passive-ranging concept with the Global Positioning System (GPS) pseudo-range navigation techniques. Refer to the representative pseudo-range problem geometry figure. A narrow RF pulse is emitted from each of four synchronized transmitters of known position. The fundamental measurement process at the passive receiver is to determine the time of arrival (T_1, T_2, T_3, and T_4) of the signals. This information, along with the known emitter locations, provides sufficient data for a spacecraft computer to determine the position of the passive vehicle and the spacecraft time error, ΔT. The GPS provides such pseudo-range navigation for users in near-earth environments, using four satellites of known positions as landmarks instead of the ground radar (emitters) shown in the upper figure.

The second figure depicts the PRAIS passive ranging concept. When PRAIS navigation is utilized, an initial estimate of the spacecraft location is made by the interferometer equipment. The angle and time-of-arrival of the signals are used over a number of spacecraft positions to estimate the spacecraft position and to synchronize the spacecraft clock to each radar accepted for the PRAIS mode. The minimum number of parameters that must be estimated are the spacecraft coordinates, velocities plus the passive range parameter ΔT_i, for each radar. If four radars are being observed, then 10 parameters must be estimated from a time sequence of four or more measurements. This process of estimating clock bias errors and satellite position from a series of measurements from differing positions is performed onboard the satellite, using Kalman filter techniques. Passive ranging does not require the ground radars to be time synchronized. Hence, PRAIS navigation is autonomous in that ground radars can be utilized as PRAIS landmarks while performing their assigned functions. The stability of the radar clocks need not be as great as for the GPS clocks, since clock stability is needed only during the PRAIS measurement interval.



Representative Problem Geometry-Autonomous Passive-Ranging Timing at Each Observation



Autonomous Passive Ranging Geometry

2.2 LANDMARK DISTRIBUTION

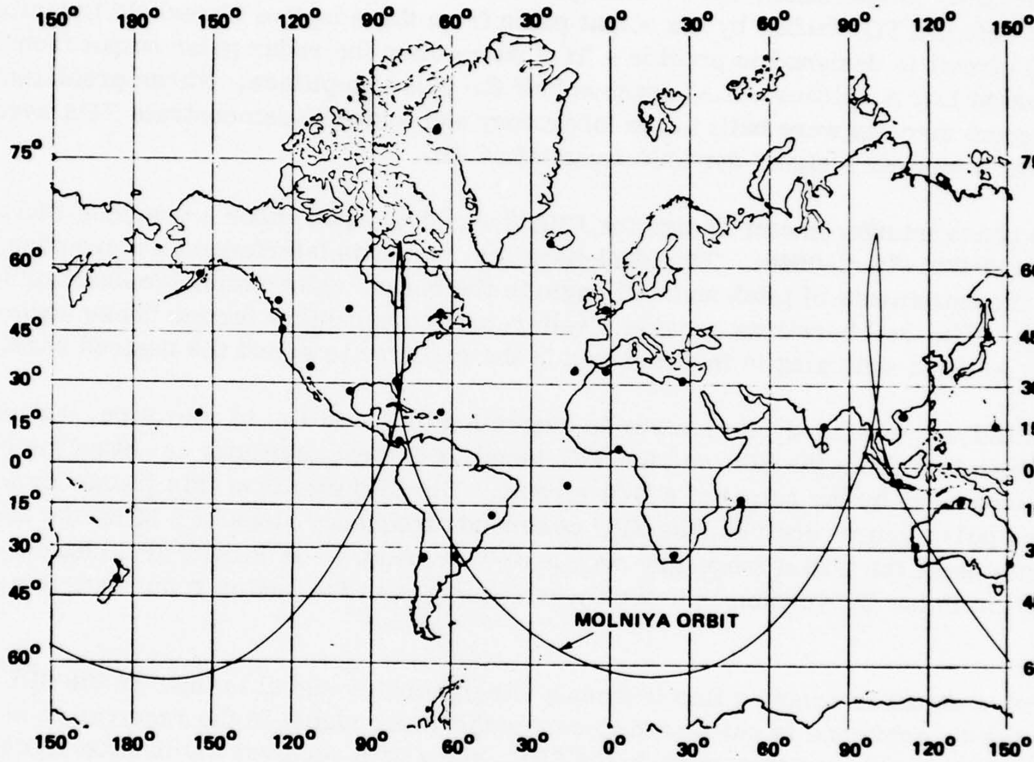
The figure shows a typical world-wide distribution of PRAIS landmarks suitable for high-altitude orbital navigation. Analyses performed during the HANS contract indicate that approximately 32 radars distributed worldwide at accessible sites (primarily air traffic control) are sufficient for navigation on the five orbits listed:

- Apogee 21,406 nmi, perigee 390 nmi, 63° inclination, 12-h period (Molniya orbit)
- Synchronous, 1° inclination
- Circular, 10,000 nmi, 63° inclination
- Circular polar, 68,000 nmi
- Circular polar, 150,000 nmi.

Only the first two orbits were studied during this contract.

The selected radar landmarks operate in the 2.5- to 2.9-GHz frequency band, and have at least a 400-kW peak output power. The effective radiated power from these radars is sufficient to permit navigation to synchronous altitude with the present PRAIS design. By using higher gain antennas, operation can be extended to include all the above orbits; the decreased field of view with such higher gain antennas will impose added requirements on the spacecraft attitude control system only in high altitude-highly elliptic orbits.

Only three 32-bit words of storage are required to store landmark latitude, longitude, altitude, PRI, and frequency. Assuming that the 32 landmarks in the figure are stored, 96 words will permit PRAIS Navigation System operation over the mission envelope defined by the listed orbits. This landmark set can accommodate any length mission without additional storage or storage update.



PRAIS Landmark Locations

2.3 PRAIS DESCRIPTION

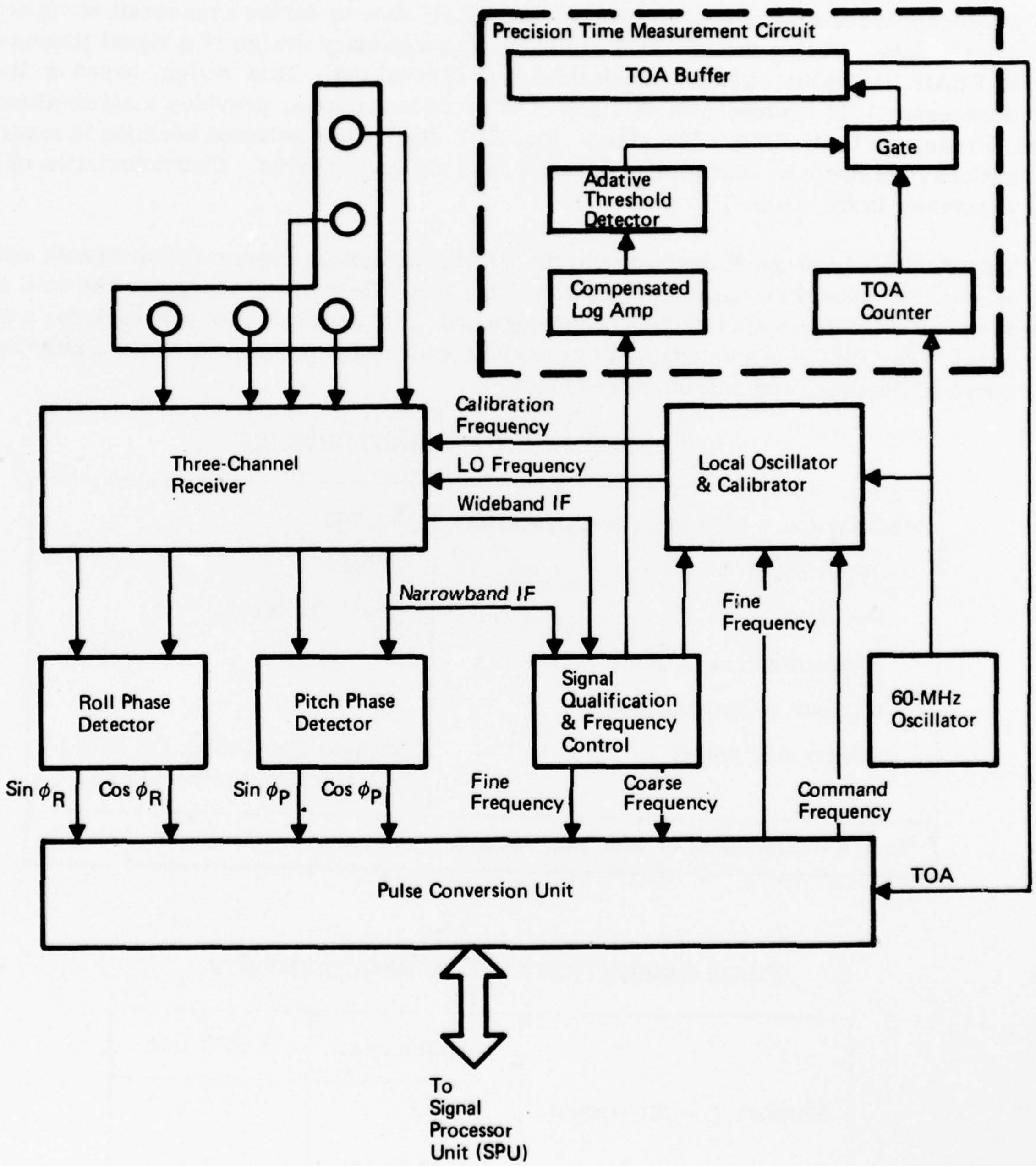
The passive range interferometer sensor consists of a strapped-down, two-axis phase interferometer augmented by precision time measurement circuits. The precision time measurement circuits, shown in the dashed block of the figure, are used to measure the time-of-arrival (TOA) of successive pulses from radar landmarks having stable pulse repetition intervals. In operation, the 60-MHz pulses accumulated in the TOA synchronous counter are gated into the TOA buffer by the output pulse from the Adaptive Threshold Detector (ATD). The ATD circuit is designed to provide a TOA pulse when the radar pulse output from the Compensated Log Amplifier (CLA) reaches half the pulse amplitude. These precision time measurement circuits were built in the laboratory and tested to demonstrate TOA accuracies better than 5 ns over a signal dynamic range of 55 dB.

The phase interferometer design for PRAIS was developed under a previous USAF/SAMSO contract (F04701-75-C-0046). This dual-baseline, two-axis interferometer provides simultaneous measurements of pitch and roll angle to the radar, using either the short or long baselines. The dual baselines provide a self-resolving capability for the phase angle ambiguities. Antenna switching is incorporated in the receiver to select the desired baseline.

The ILT superheterodyne receiver is controlled by the SPU. In operation, a tuning command is received from the SPU and the YIG-tuned VCO local oscillator is set on the commanded frequency by the output of a D/A circuit. The SPU dwells at this frequency for one PRI. If a pulse is not received, the SPU commands frequency steps of 2 MHz (the receiver bandwidth) about the initial frequency over a 10-MHz band. The PRAIS/SPU interface is provided by the Pulse Conversion Unit (PCU), which converts the analog radar data to a digital format.

When a signal is found, a fine frequency discriminator signal is input to the SPU and a fine frequency command is calculated to center the radar signal in the receiver pass band. Pitch and roll angles are then input to the SPU, along with receiver calibration signals.

The pitch and roll angle and TOA measurements are converted from analog to digital and formatted for input to the SPU. Utilizing the SPU for control significantly reduces internal PRAIS control circuitry.



Passive Range Interferometer Sensor (PRAIS)

2.4 SPU DESCRIPTION

A microprocessor is needed to process the PRAIS data to derive spacecraft navigation and attitude data. During the SCHANS contract, a preliminary design of a signal processor for the PRAIS Navigation System calculations was carried out. This design, based on the microprocessor IBM incorporates in many of their ESM systems, provides a stand-alone Signal Processor Unit (SPU). The stand-alone SPU design was selected because in many applications, the onboard spacecraft computer may not be available. Characteristics of the SPU are shown in the table.

This SPU design when compared with the PRAIS Navigation System requirements shows that processing speed is no problem and that there is a 30% memory margin. The SPU design represents available avionics system technology and reflects a low risk approach for a space flight test. The PRAIS can be adapted to interface with computers, such as the Fault-Tolerant Spaceborne Computer, with minimum redesign.

SPU PERFORMANCE CHARACTERISTICS

Modular Core Memory (16-Bit words)	32,768
Cycle Time	300 ns
Precision	16- & 32-bit
Microprogram Control	
Number of Instructions	40
Processing Speed	(Single Precision) 175 kad/s* (Double Precision) 135 kad/s
*kad/s = thousands of adds per second	

PRAIS NAVIGATION SYSTEM REQUIREMENTS

	Requirement	% SPU Use
Memory (16-Bit words)	23,300	71.1
Processing Speed*	4.35 kad/s	2.8
*assumes 50% double precision operations		

2.5 IRU DESCRIPTION

The Inertial Reference Unit characteristics are shown in the table. The IRU performance shown was used in the simulation during the SCHANS contract. As indicated, this performance can be met with either a laser gyro package or with conventional gyros. To meet reliability goals on long missions, the laser gyro is preferred, but even this unit will require redundancy.

Analysis of operation with only the interferometer measurements in a low earth orbit and estimating spacecraft attitude rates instead of using gyros, showed that gyros improved navigation accuracy by only 8% and attitude accuracy by only 20%. These results indicate that in orbits where measurements can be made to two or more landmarks at a rate compatible with spacecraft attitude rates, a gyro package is not required. Alternately, if rate gyros are used in the spacecraft attitude control system, those gyro data could be used to provide attitude memory to reduce the PRAIS measurement rate. The IRU is therefore considered an optional system element.

PRAIS NAVIGATION SYSTEM
STRAPPED DOWN IRU CHARACTERISTICS

PERFORMANCE		
Gyro Drift		0.001°/h
Correlated Gyro Drift		0.0005°/h
Correlation Time		72,000 s
PHYSICAL CHARACTERISTICS		
	Conventional	Laser
Weight	22 lb	15 lb
Power	60 W	40 W
Size	0.52 ft^3	0.22 ft^3

2.6 PHYSICAL CHARACTERISTICS

The PRAIS, including its antenna array as indicated in the table, weighs 42 lb, occupies 1.18 ft^3, and consumes an average of 17 W of electrical power in a typical high-altitude orbit. When the spacecraft has available onboard a digital computer and an (optional) IRU, only the PRAIS need be added to provide onboard autonomous navigation and attitude determination. If a signal processor is not available, then adding the PRAIS Navigation System capability increases physical characteristics to 71 lb, 1.69 ft^3, and 35 W. Finally, when mission precision requires maximum performance, the full PRAIS Navigation System needs to be added, as shown on the bottom line of the table. The last column shows the mean-time-before-failure of simplex PRAIS Navigation System Configurations. Design of the PRAIS is such that redundancy can be added at the subassembly level to obtain the reliability on long missions.

PRAIS NAVIGATION SYSTEM PHYSICAL CHARACTERISTICS

PRAIS Navigation System Configuration		PRAIS Navigation System Requirements				Available Spacecraft Equipment
		Weight (lb)	Volume (ft^3)	Average Power (W)	MTBF (1000 h)	
Minimum Configuration: PRAIS	PRAIS	42	1.18	17	10.3	Digital Computer — IRU
	Total	42	1.18	17	10.3	
Flight Test Configuration: PRAIS — SPU	SPU	29	0.51	18	20.4	IRU
	Total	71	1.69	35	6.9	
Maximum Configuration: PRAIS — SPU — IRU	IRU	15	0.22	40	23.3	None
	Total	86	1.91	75	5.3	

Analysis of the nuclear hardness of PRAIS indicates the design is suitable for surviving the natural space radiation except on long-term (5-year) missions in orbits which continuously pass through the radiation belts. No extensive redesign will be required to provide nuclear hardness even in a weapon-induced environment.

Section 3

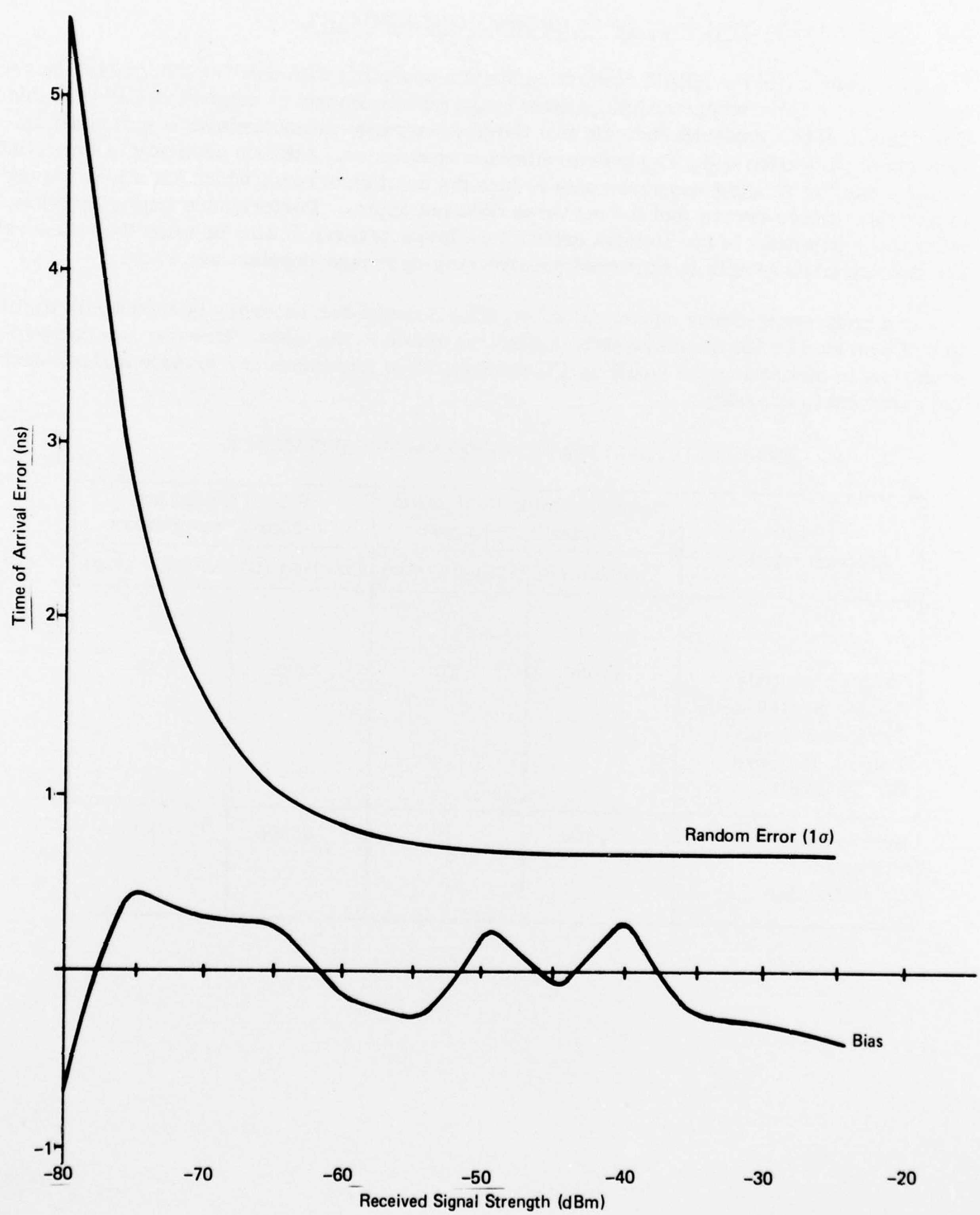
PERFORMANCE CHARACTERISTICS

3.1 PRAIS NAVIGATION SYSTEM PERFORMANCE DEMONSTRATION

During the SCHANS study, critical components of the PRAIS Navigation System were breadboarded and tested in the laboratory. The laboratory test data were taken in a format suitable for use in a Monte Carlo simulation of PRAIS navigation and attitude performance. During the SCHANS study, precision time measurement circuits were built and tested. During a previous contract (F04701-73-C-0221), the accuracy of the interferometer portion of the PRAIS was measured in the laboratory anechoic chamber. (The interferometer tested under that contract was a four-antenna/four-channel receiver configuration; in the succeeding contract a three-channel receiver with antenna switching was designed, breadboarded and tested to confirm the phase accuracy achieved under the previous contract.)

The interferometer bias and random errors are simulated using equations derived from the test data (ILT accuracy is approximately 1 $\widehat{\text{min}}$). The adjacent figure is a plot of the PRAIS errors in measurement of the time-of-arrival of radar pulses vs signal strength. In these tests a compensated log amplifier and adaptive threshold detector were added to the breadboard (built during contract F04701-75-C-0046), and the full PRAIS performance was measured over a temperature range of -5°C to 75°C and with a pulse rise time variation of 10 to 200 ns. The random (rms) error includes the component due to the TOA counter resolution. The bias (variation of the mean) is the residual after calibration for the characteristic performance over the test conditions.

These results indicate that variation in the bias is bounded by an error of -0.65 to 0.42 ns and after 50 pulses are smoothed, the random error does not exceed 5.3 ns. These data were input to the simulation in a tabular format and accessed as a function of orbital altitude, elevation-angle of the radar beam, solar illumination, and pulse rise time.



PRAIS TOA Accuracy

3.2 PRAIS NAVIGATION SYSTEM PERFORMANCE SUMMARY

The accuracy of the PRAIS Navigation System operating with only interferometer measurements and with interferometer and passive range measurements is summarized in the table. Comparison of these results indicate that the passive range measurements significantly improve both navigation and attitude determination accuracies. Attitude accuracy is improved because passive ranging measurements reduce the position errors, which set a lower boundary on the attitude errors (but the converse does not apply). Performance improvement is much more dramatic in the Molniya orbit where large relative motion between the spacecraft and the landmark results in improved passive ranging (range/doppler) accuracy.

In a truly synchronous equatorial orbit, PRAIS navigation accuracy is essentially limited to that provided by the interferometer navigation shown in the table. However, as can be seen even in inclinations as small as 1°, passive range measurements provide a significant improvement in accuracy.

PRAIS vs ILT NAVIGATION SYSTEM PERFORMANCE

Orbit Characteristics	Interferometer Navigation 1-sigma rms Errors		PRAIS Navigation 1-sigma rms Errors	
	Position (ft)	Attitude $(\widehat{sec})$	Position (ft)	Attitude $(\widehat{sec})$
Molniya altitude: Apogee 21,406 nmi; Perigee 390 nmi Period: 12 hours 63° Inclination	7,080	26	225	12
Synchronous altitude 1° Inclination	8,316	16	3,000	10

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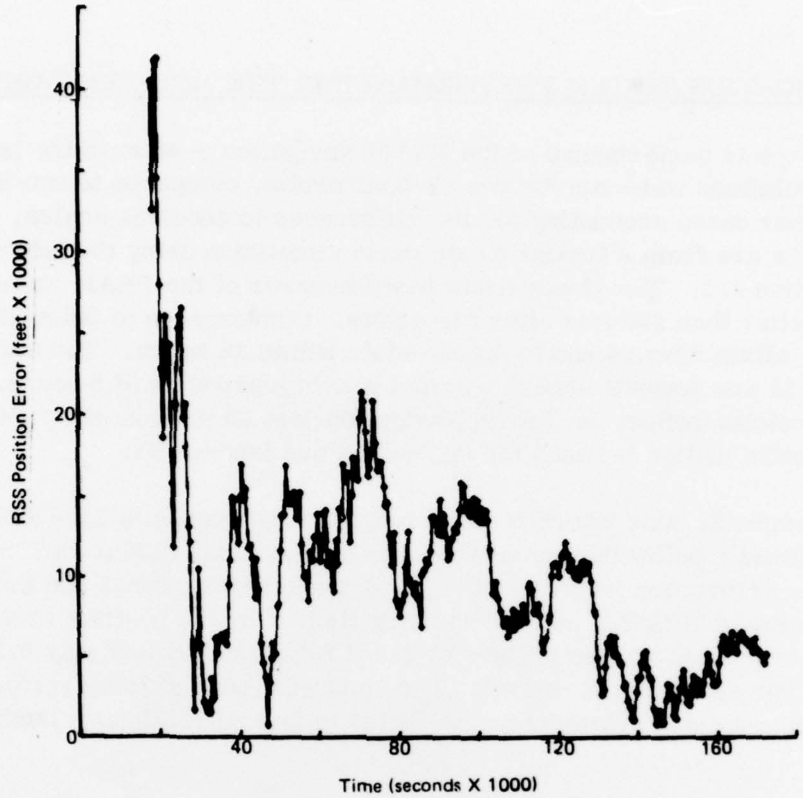
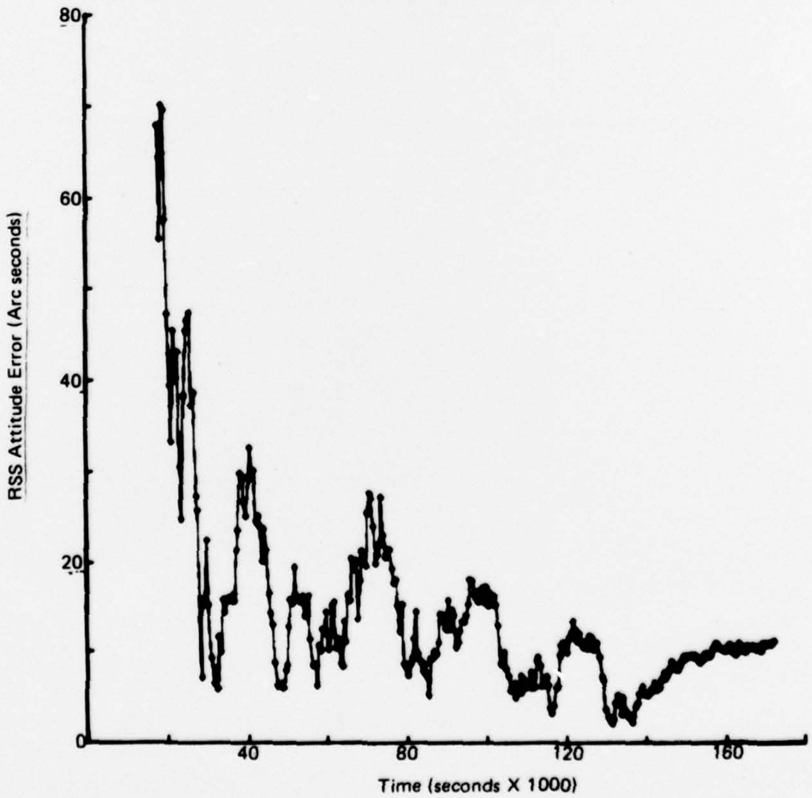
3.3 PRAIS NAVIGATION SYSTEM PERFORMANCE IN SYNCHRONOUS 1° INCLINATION ORBIT

The accompanying figure shows typical performance, in a synchronous (1° inclination) orbit, of the PRAIS Navigation System, obtained from a monte carlo simulation using the laboratory data described in Section 3.1. These curves are members of the ensemble of a monte carlo simulation; other members of the ensemble have noise-like variations of differing shapes about a central tendency. For example, the ratios of the actual position and attitude errors to the filter's estimated values (central tendency) averaged over the simulation are in the neighborhood of unity.

As can be seen, steady-state position accuracy exceeds the required 6000 feet by 2 to 1. Convergence time in this orbit is 1-1/2 orbits, or 36 hours. The slow convergence is due to the limited relative motion of the spacecraft with respect to the landmarks in this orbit. The convergence goal of 10 hours demonstrated in the HANS contract can be met if there is an accurate, independent attitude determination system on board the spacecraft.

Steady-state RSS attitude accuracy, as shown in the accompanying figure, is 10 arc seconds. This attitude determination capability is adequate for many space missions. The slow convergence of the attitude follows that of the position, because in the PRAIS Navigation System, the attitude errors are highly coupled with position errors until passive ranging measurements reduce position errors significantly below those obtainable by the ILT alone. For example, position errors of 15000 ft contribute an equivalent attitude error of 24 arc seconds at synchronous altitude.



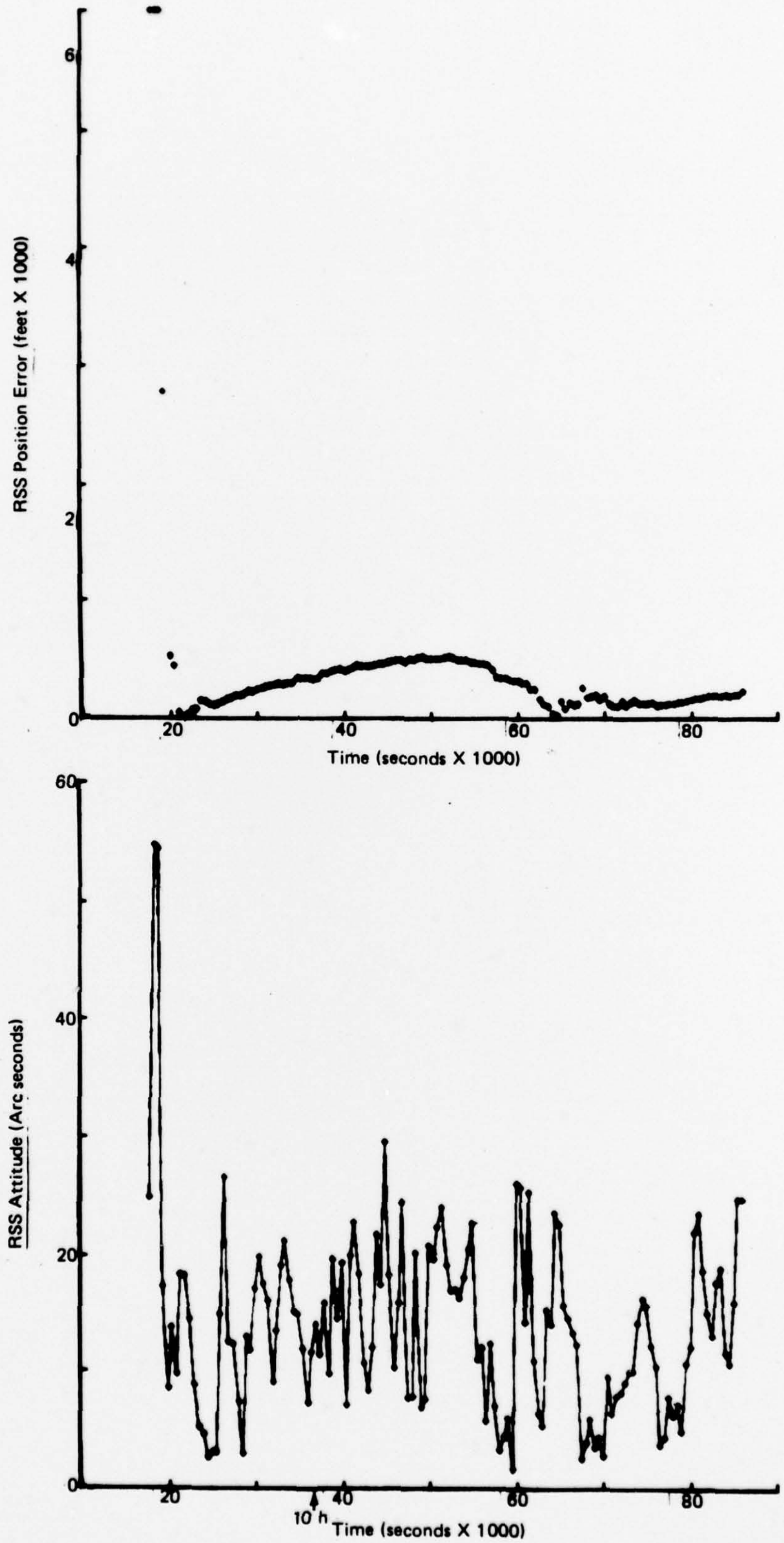


PRAIS Navigation System Performance in the Synchronous 1° Orbit

3.4 PRAIS NAVIGATION SYSTEM PERFORMANCE IN THE MOLNIYA ORBIT

The figure depicts performance of the PRAIS Navigation System in the Molniya orbit. The Molniya simulations were run for two 12-hour orbits, compared to two 24-hour orbits for the synchronous case, accounting for the differences in abscissa scales. Both position and attitude errors are from a typical monte carlo simulation using the laboratory test data described in Section 3.1. The steady-state position error of the PRAIS Navigation System in this orbit is better than 250 feet after two orbits. Convergence to below the required accuracy occurs within 6 hours and to steady-state within 18 hours. The attitude determination accuracy of 12 arc seconds occurs within a convergence time of 6 hours. Both position and attitude accuracies reflect the PRAIS Navigation System performance potential in orbits having large relative motion between the spacecraft and landmarks.

These data show the case where passive ranging measurements have reduced the position error significantly below that obtainable with an ILT alone (225 ft vs 7080 ft). In this case, the attitude errors are limited by the performance of the gyros and interferometer angle sensor portion of PRAIS, rather than being limited by the position error (e.g., the 225-ft position error at an apogee altitude of 1.3×10^8 ft contributes only 0.36 arc seconds to the attitude error shown in the figure). The somewhat poor attitude performance (12 vs 10 arc seconds) in the Molniya orbit can be attributed to lack of continuous landmark tracking at perigee.



PRAIS Navigation System Performance in the Molniya Orbit

Section 4

CONCLUSIONS AND RECOMMENDATIONS

4.0 CONCLUSIONS AND RECOMMENDATIONS

The major conclusions from the SCHANS study are listed in the accompanying table. The results of this study clearly show the potential of the PRAIS Navigation System to provide precise spacecraft position, velocity, and attitude autonomously in high-altitude orbits using ground radars as landmarks. In applications where highly precise position determination is required, this SCHANS approach is indicated. The accuracy of time-of-arrival measurements demonstrated in the laboratory confirmed predicted precision. Further analysis and simulation to extend the attitude performance should be included as part of IBM's recommended PRAIS Navigation Flight Test program. The PRAIS design has been essentially completed; hence, an early flight test is feasible using state-of-the-art system components.

CONCLUSIONS AND RECOMMENDATIONS

SCHANS STUDY CONCLUSIONS

- A passive ranging technique has been designed and integrated with the previously developed interferometric landmark tracker sensor, and a signal processing unit. Laboratory testing has verified that the time-of-arrival circuitry fabricated during the present contract will contribute an acceptably low amount to the error budget of a navigation and attitude reference system based on this sensor. Measured errors of the time-of-arrival circuitry confirm previous analysis (2 ns).
- An attitude reference capability has been designed and integrated in simulations of the PRAIS flight algorithm. This attitude reference capability has been shown to have an accuracy of 10 arc seconds (1 sigma) following a convergence time which varies with orbital dynamics.
- The PRAIS technique, implemented with log-spiral antennas, provides precise spacecraft position, velocity, and attitude exceeding Air Force accuracy requirements, for orbits up to 21,000 nmi in altitude. Implemented with horn antennas of high front-to-back ratio, this technique provides similarly precise position, velocity, and attitude for up to 150,000 nmi altitude, using FPS-47 airport radars as landmarks. A worst-case position accuracy of better than 6000 ft has been demonstrated in synchronous orbit.
- The PRAIS hardware design is complete except for antenna mounting structure compatible with a first space experiment. PRAIS software and algorithms have been functionally tested to prove the feasibility of the technique; optimization is necessary to simplify the programming and sectionalize the algorithms for ease in verifying performance during a space experiment.

RECOMMENDATIONS

- PRAIS Navigation System Flight Test program should be implemented.
- Further simulation and analysis of navigation/attitude interrelationships should continue.