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FINAL REPORT

L–BAND

ATS-5 – ORION – S. S. MANHATTAN
MARINE NAVIGATION AND COMMUNICATION EXPERIMENT

by O. J. Hanas, M. E. Illikainen, D. L. Kratzer, E. A. Spaans

June 1970

Prepared for: Electronic Research Center
National Aeronautics and Space Administration
Cambridge, Massachusetts

CONTRACT NAS 12-2260

Prepared by:
APPLIED INFORMATION INDUSTRIES
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ACKNOWLEDGMENTS

The L-band ATS-5 - ORION - S. S. Manhattan marine navigation and data communication experiment was a result of the concerted effort of many people. The list of engineers and scientists who played a major part in making this experiment unique and successful follows.

Mr. L. M. Keane of NASA Electronics Research Center, Mr. H. L. Anderton of NASA Office of Advanced Research and Technology, and Mr. Eugene Ehrlich of NASA Office of Space Science and Applications were responsible for the timely sponsorship of this experiment.

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Mr. Stanley B. Haas of Humble Oil & Refining Company's Marine Division and Dr. H. C. Baker of Humble's General Services Department were responsible for Humble's interest and contributions to the experiment.

The following team of engineers of Applied Information Industries, Moorestown, New Jersey, conceived and developed the ORION system:

J. D. Barnla
R. B. Hines
D. L. Kratzer
E. A. Spaans
D. H. Westwood
O. J. Hanas
M. E. Illikainen
P. Malnati
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M. Howe
M. Diezel

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1.0 SUMMARY

1.1 Objectives

The objective of this program was to conduct a series of navigation and communications experiments on an ocean craft via the ATS-5 spacecraft over wide variations in latitude, longitude, elevation angle, and weather conditions, to provide the basis for demonstrating the feasibility of navigation and traffic control services via synchronous satellites, by correlation of the measured quantitative data with the theoretical expectations.

1.2 Abstract

A unique experiment is described in which L-band signals relayed by synchronous satellite were successfully used for navigation and data communication for the first time. RF signals containing ranging modulation were transmitted from NASA's STADAN Station at Mojave, California, relayed through the ATS-5 synchronous satellite and received by two stations. One was stationary, located at the Applied Information Industries laboratory in Moorestown, New Jersey, and the other was marine mobile, installed on the Humble Oil & Refining Company's icebreaking tanker, S. S. Manhattan. This experiment demonstrated to a precision never before achieved the feasibility of position fixing by making range measurements between a fixed ground station, a satellite in a known position and a moving platform on the surface of the Earth. Also notable in this experiment was the simultaneous transmission and reception of data communications on the ranging signal. Figure 1 depicts the experiment.

The experiment took place during the S. S. Manhattan's Spring 1970 Arctic Voyage, starting on March 31, 1970, when the S. S. Manhattan was docked at Newport News, Virginia, at latitude 37°N

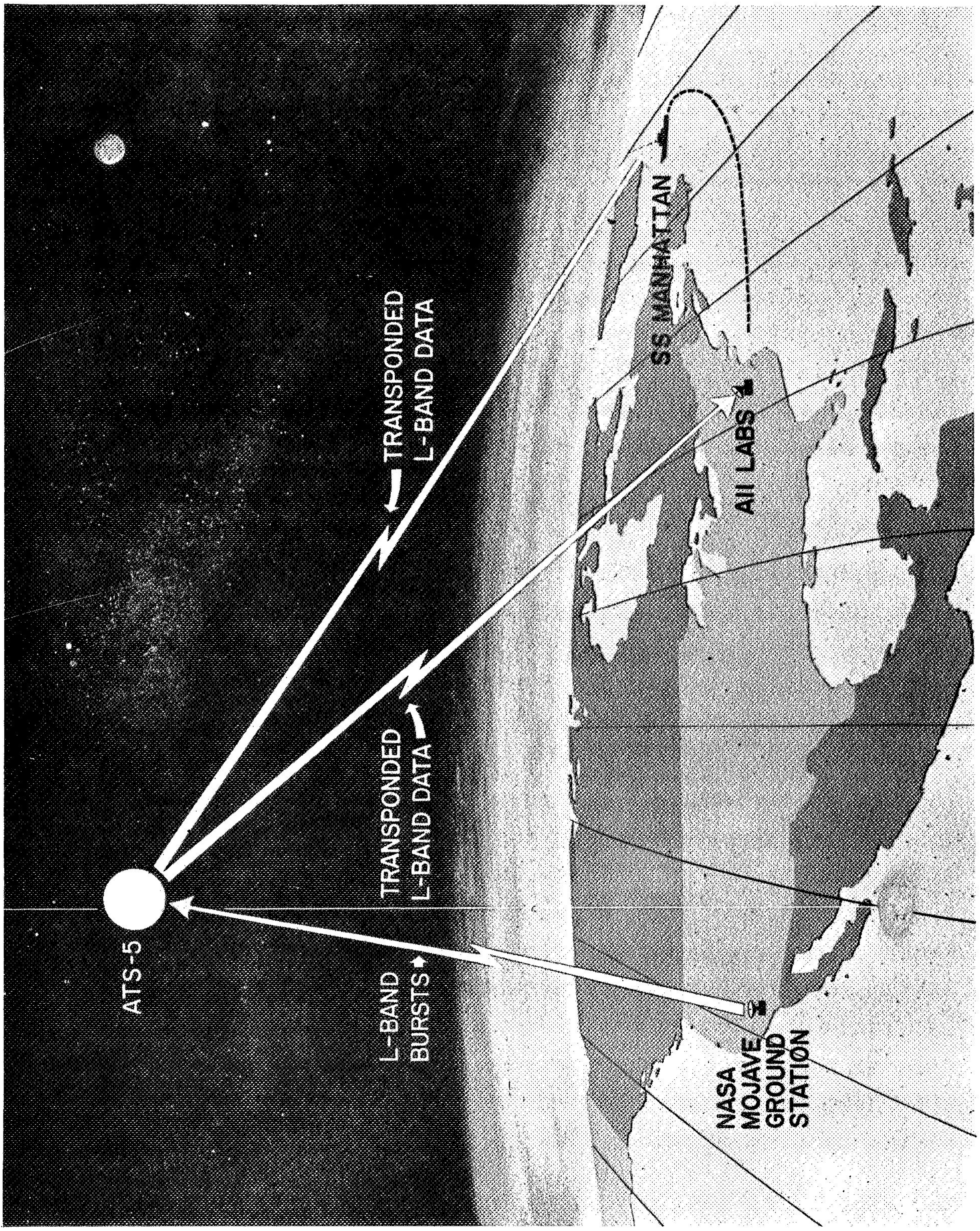


FIGURE 1 ATS-5--ORION--S. S. Manhattan Experiment

and longitude 76.5°W. The system was calibrated in a stationary reference mode prior to sailing on April 3, 1970. From the sailing date through April 24, 1970, the experiment was conducted while the S. S. Manhattan traveled through wide variations of geography, weather and antenna angles of elevation to the satellite. The equipment utilized was capable of providing high precision range measurements which were converted to navigational lines of position. The fact that only one satellite was available for these tests yielded data in terms of lines of position. When additional satellites become available, the intersecting lines of position will provide precision position data.

The experiment was concluded on April 24, 1970, at latitude 73.5°N and longitude 60°W. The results and conclusions are described in later sections in terms of carrier-to-noise ratios of the signal, the precision of the system, a relative comparison of accuracy, the effects attributed to multipath and the quality of data transmission. The experiment used the ORION system as developed by Applied Information Industries (AII) at Moorestown, New Jersey. This system consists of a modulator which generates a composite ranging and data signal, and one or more receiving stations which demodulate and track the received signal as relayed through the ATS-5 L-band transponder. A peculiar constraint is imposed on this sytem by virtue of the spinning of the satellite. ATS-5 is rotating at 76 rpm with its directional antenna sweeping the Earth with each rotation; unique receiving circuitry is thereby required to lock up and produce range measurements. The sweeping antenna pattern modulates signals transmitted to and from the satellite. The main lobe occurs for about 5% of the scan time, and for the remainder of the scan the signal is essentially nulled.

The successful accomplishment of receiving ranging signals under the above conditions was made possible by the use of the ORION receiver. This receiver makes extensive use of digital tracking techniques to provide stable holding of the range measurements between samples of received signal from the spinning ATS-5 satellite. These digital techniques, together with proportional error correction in the loop, assures rapid lock-up, made necessary by the burst transmission from the spinning spacecraft. The receiver is designed to receive and decode signals which have all of the useful energy in the side bands, making a more efficient system under conditions of marginal signal reception. The use of digital circuitry also makes the stability and reproducibility of the receiver more uniform than those which rely heavily on analog circuits.

2.0 GENERAL DESCRIPTION OF THE EXPERIMENT

2.1 Background

Emphasis on L-band synchronous satellite navigation and communication concepts has been increasing over the past several years. The launching of the ATS-5 promised to afford the opportunity for many useful experiments to prove out the feasibility of L-band application. Due to the peculiar spinning mode of the ATS-5 following its launching, many of the planned experiments no longer appeared to be feasible. Until NASA-ERC, Cambridge, Massachusetts, undertook the sponsorship of the marine nav-com experiment described herein, the usefulness of the ATS-5 for this original intended purpose was in doubt. The successful completion of the tasks set forth in the NASA contract with Applied Information Industries (AII) has shown the feasibility of deriving useful data at L-band and has opened the way for a number of additional experiments for the future.

The ORION receiving system which contains the unique modulation and demodulation scheme was demonstrated to lock-on and produce precision ranging information early in January of 1970. Following first demonstrations, refinements were added in the form of data communication capability, automatic range recording instrumentation and other peripheral equipment which was essential to enabling operation on the mobile marine vehicle.

2.2 Resume of Events

The experiment was conducted on board the S. S. Manhattan by Mr. Richard Waetjen, Chief, Experiments Branch, NASA-ERC, Cambridge, Massachusetts; and by Mr. Orest J. Hanas, Project Engineer, Applied Information Industries, Moorestown, New Jersey. The experiment, which lasted from March 30, 1970, through April 24, 1970, received ranging signals from ATS-5 from latitude 37°N and longitude 76.5°W through latitude 75°N and longitude 65°W, with the satellite elevation angle of 38° through 1.8°, respectively. Figure 2 shows the route which the S. S. Manhattan followed. At the same time, a second ORION receiving system located at Applied Information Industries' laboratories in Moorestown, New Jersey, served as an "anchor" or reference station for data reduction obtained during the experiment.

The following table describes briefly the sequence of events comprising the experiment.

TABLE I

RESUME OF EVENTS IN THE ATS-5--ORION--S. S. MANHATTAN EXPERIMENT
MARCH - JUNE 1970

DATE:	March 21 through March 25, 1970
EVENT:	Calibration* of the ORION system, including the two receivers and comparison of the relative stability of the two Rubidium frequency standards.
DESCRIPTION:	The two receiving systems, including the Rubidium frequency standards were evaluated and calibrated side by side at AII laboratories using the ORION modulated, ATS-5 transponded signals. The drift rate of the two Tracor Type 304B Rubidium frequency standards was determined.

---

* NOTE: In order not to lose this calibration and continue the same drift of these two Rubidium frequency standards, both were kept ON for the duration of the experiment. The Rubidium frequency standard which was on the S. S. Manhattan was constantly connected (even during transport between installations) to a standby battery power supply which automatically and instantly provided power to it when AC power was interrupted.

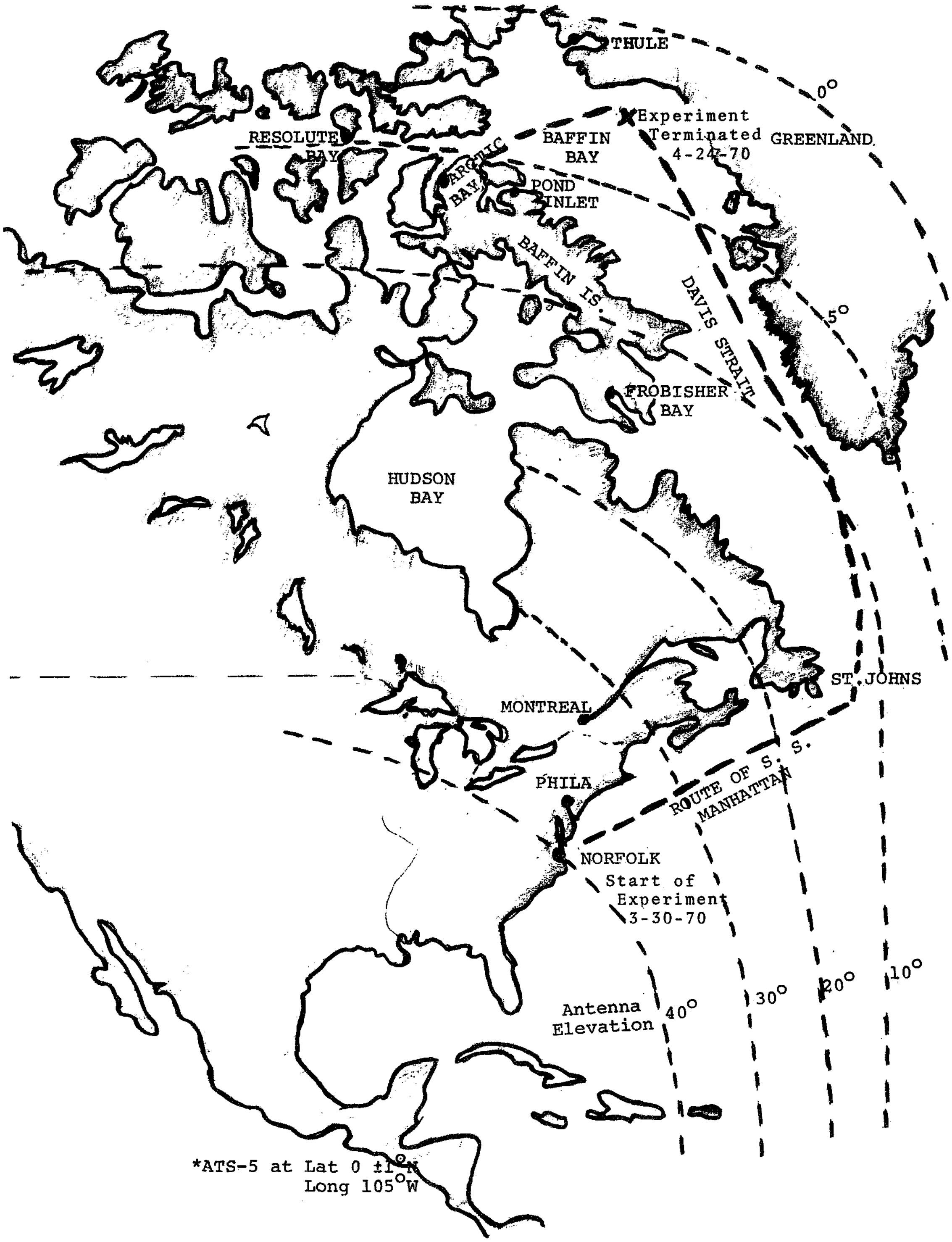


FIGURE 2 ROUTE OF THE S. S. MANHATTAN SPRING 1970 ARCTIC VOYAGE

DATE: March 31 through April 3, 1970

EVENT: In-port calibration of ORION receiving system on board the S. S. Manhattan at Newport News, Virginia. Comparison of this data was made with the lines of position (LOPs) data obtained at AII laboratory, Moorestown, New Jersey.

DESCRIPTION: The ATS-5 ORION modulated signals were received for two hours each day. Both systems, i.e., on the S. S. Manhattan and at AII, Moorestown, were checked out, calibrated and sample data was fed into the computer program for determination of the reference lines of position. Ranging information from the S. S. Manhattan was called into AII by phone. The computer programs took the following data into account: range information from SSM and AII receivers (in order to take out the movement of the ATS-5), the ephemeris data of the satellite, the instability data of the frequency standards and the last firm reference point.

DATE: April 3, 1970, through April 24, 1970

EVENT: Gathering of navigation and communications data on board the S. S. Manhattan from Newport News, Virginia, to the Baffin Bay, Arctic area.

DESCRIPTION: ORION signals were received for 19 days. The duration of signal availability from ATS-5 was from 2 to 7.7 hours a day. The ranging data was recorded every day on the S. S. Manhattan and the AII laboratory. Each day the range data values were phoned in from S. S. Manhattan to AII (via the HF radio link) for initial LOP determination in almost real time.

Data channel converter was installed at the Mojave Station on March 17, 1970, and teletype data was sent from Mojave via ATS-5 and received at AII on the 18th, 21st, 22nd and 23rd of March 1970.

The vessel traveled from altitude 37°N and longitude 76.5°W to latitude 73.5°N and longitude 60°W, while the satellite elevation angle varied from $38^{\circ}$to 1.83°, respectively. The effects of EMI and multipath were noted and carrier-to-noise ratios, received frequency, and pulse amplitude and duration were recorded all through the voyage. The effects of weather were also recorded.

Normally, a three-foot diameter parabolic dish antenna was used. On April 7 and 8, 1970, only, a two-foot diameter dish was employed. Also, the position of the S. S. Manhattan as determined by other on-board systems was noted each day.

On April 12 and 13, 1970, the ATS-5 satellite was in a free-running mode having no modulation on the signal. The strength of the signal was monitored during these two days.

No equipment failures occurred during the voyage. A loose cable in the second injection chain caused interruption of reception for 16 minutes out of the 62.3 hours of reception time.

DATE: April 25 through June 10, 1970

EVENT: Data reduction and preparation of the final report

DESCRIPTION: The data which was recorded during the previous three events on board the S. S. Manhattan and AII laboratories was reduced and final report on the experiment was prepared.

2.3 Summary of Results

The following test results were obtained:

a. Continuous and instantaneous ranging information was obtained through the ATS-5 L-band transponder using the ORION system. The receiver, after tuning to the satellite frequency, locked on the received signal within 100 milliseconds of signal, or within two revolutions of ATS-5. Lines of position (LOPs) of S. S. Manhattan were determined on the basis of the range information measured at the mobile and stationary ORION stations. Computer-aided methods were used to determine the lines of position and to take out the instabilities of the system. Precision to within 1% of lanewidth was measured.

b. Ranging signals were continuously received throughout various weather and sea and ice conditions. All functions of the receiver operated properly over variations of satellite elevation angles from 38° to 1.8°.

c. Signal strength was measured throughout the course of the 3,500-mile voyage. Small variations of signal strength (± 2 dB) had no effect on the ranging or communication functions of the ORION System.

d. Effects attributed to multipath were noticed at high latitudes in solid ice and at low elevation angles. Maximum degradation of signal strength due to these effects was 4 dB from peak. Only amplitude effects and no ranging, communications or lock-on effects were noted due to multipath.

e. Good reception of data communications was achieved through the ORION--ATS-5 system at the AII laboratories on the four scheduled days. Data modulation was superimposed on top of ranging modulation without adversely affecting either function.

f. Accurate received frequency was measured on a daily basis. A drift of 500 Hz per hour to 100 Hz per hour of the ATS-5 L-band master oscillator was measured. Due to this oscillator shift and the satellite position drift, no doppler measurements on the moving platform were possible.

g. The receiver on board the S. S. Manhattan was ON for 750 hours continuously. The ORION modulated signals were received for 62.3 hours out of the 68.6 hours which were transponded. 6.1 hours of signals were not received due to blockage of the antenna by the ship's superstructure, and 0.2 hour of signals were not received due to a loose cable in the second injection chain of the receiver.

h. No adverse effects on any of the functions of the ORION receiver were noticed due to weather conditions or due to geographical area variations.

2.4 Conclusions

Three general conclusions resulting from this experiment are presented below. A more detailed list of technical conclusions is contained in Section 9.

a. L-band signal transmission via a synchronous satellite can produce precise and stable range measurements which are the foundation for precision navigation systems of the future.

b. The ATS-5 synchronous satellite, although presently in a spinning mode, fulfills all essential requirements for feasibility experimentation to prove concepts involved in L-band position fixing experiments. Additionally, data relaying concepts can also be demonstrated and evaluated.

c. The relative simplicity of the equipment involved in this experiment leads to the conclusion that an uncomplicated equipment complement involving simple procedures is possible for widespread marine use in the future. This passive navigation system will provide instantaneous position fixing across broad areas of the globe at relatively low cost for each user.

2.5 Recommendations

The successful completion of this experiment on board the S. S. Manhattan employing signals transponded through the ATS-5 satellite has produced the conclusions above and has led to the formulation of several broad recommendations for future programs.

a. System Accuracy. Additional experimental work should be conducted under controlled conditions to assess the absolute accuracy of the L-band ranging system. These tests should concentrate on identifying and evaluating errors contributed by transmitting, receiving and transponding equipment. Evaluation of range measurement, stability, granularity and other hardware parameters is necessary to specify an optimum user system.

b. Multipath. The quantitative effect of multipath should be evaluated, particularly for future systems involving aircraft where multipath may have more severe effects. These experiments should use higher gain, remotely steerable antennas and additional receiving equipment as is necessary to separate the main signal from the multipath signal. Other platforms such as airborne vehicles and portable vans should be considered.

c. Ionospheric Effect. Quantitative effects of the ionosphere and other signal path effects should be thoroughly understood. It is in order to evaluate these by means of comparative L-band and C-band transmissions. To the extent that it is of interest, these results should be compared with VHF results obtained to date.

d. Surveillance Applications. An experimental two-way nav-com system evaluation is recommended to enable evaluation of a two-way ranging capability. The two-way system has additional merit in ultimate requirements for data communications on top of the ranging signal.

e. Position Fixing. Ranging from two or more synchronous satellites should be conducted to confirm the capability of a user to establish his position under operational conditions. Prior to the specification of an operational satellite navigation system substantial data must be accumulated on candidate approaches. User terminal costs in the aggregate will represent the major investment in the deployment of an operation system. Proper selection of satellite parameters which directly affect user instrumentation must emphasize minimum cost to the user while providing high reliability and simplicity in operation and equipment. We, therefore, strongly urge the conduct of position fixing tests to form the required data base.

3.0 LIST OF SYMBOLS AND ABBREVIATIONS

The symbols and abbreviations which were used in this report are listed in this section.

ERC	Electronic Research Center
AII	Applied Information Industries
STADAN	Space Tracking and Data Acquisition Network
ATS-5	Applied Technology Satellite 5
ORION	AII's Navigation and Communication System
LOP	Line of Position
ERP	Effective Radiated Power
LAT N	Latitude North
LONG W	Longitude West
Az	Azimuth
El	Elevation
C/N	Carrier-to-Noise
Δ	Change in
θ	Difference Angle
Z	Zulu time
NMI	Nautical Miles
TTY	Teletype
DPSK	Differential Phase Shift Keyed
EMI	Electro-magnetic Interference
RFI	Radio Frequency Interference
HF	High Frequency
Nav-Com	Navigational-Communication
σ_N	Error due to noise in the system
$\varepsilon\Delta f$	Error due to frequency misalignment
εf	Frequency drift of the system
σ_Q	Error due to quantization
Δ_L	Mean path length
ψ	Grazing angle
σ_m	Error due to multipath
σ_{sp}	Error due to satellite
σ_R	Total Range Error

4.0 THE EXPERIMENT

4.1 Description of the Experiment Setup

Figure 3 shows a block diagram of the overall ATS-5--ORION--S. S. Manhattan Marine Nav-Com Experiment. As was mentioned before, the system consisted of the ORION modulator at the Mojave STADAN station, Barstow, California, a receiver at AII laboratories in Moorestown, New Jersey, which served as reference station and a receiver on the S. S. Manhattan, which was marine-mobile. Both receiving stations were nearly identical in equipment, both contained the ORION receiving system and the test equipment necessary to record and evaluate received signals. The individual test setups were arranged as shown in Figure 4. The equipment on board the S. S. Manhattan, shown in the block diagram, consisted of an antenna, adjustable tripod which was capable of supporting either the two-foot diameter or the three-foot diameter parabolic dish antenna. The azimuth and elevation angles were adjustable from 0 to 360° and -6° to $+90^\circ$, respectively. The cable from the antenna to the ORION receiver was a 35-foot semi-rigid cable with approximately 2.5 dB of loss. The ORION receivers had a noise figure of 4.5 dB and predetection bandwidths of 20 MHz in the L-band front end, 4 MHz in the first IF, and 200 KHz in the second IF. The post detection bandwidth is 1.6 KHz. The ORION receivers obtained the reference frequency from a Rubidium frequency standard which was kept ON at all times. Standby power supplies with instantaneous switch-over capabilities were connected to the Rubidium standards in case a primary power failure occurred. The ORION receivers were connected to special data buffers which converted the data information obtained through the ATS-5 satellite to a form which is acceptable for a teletype printout. Also, a range readout recorder was used on the S. S. Manhattan to record all the values of the range readout output. At the AII laboratory, the range readout was directly converted to punched tape. Other

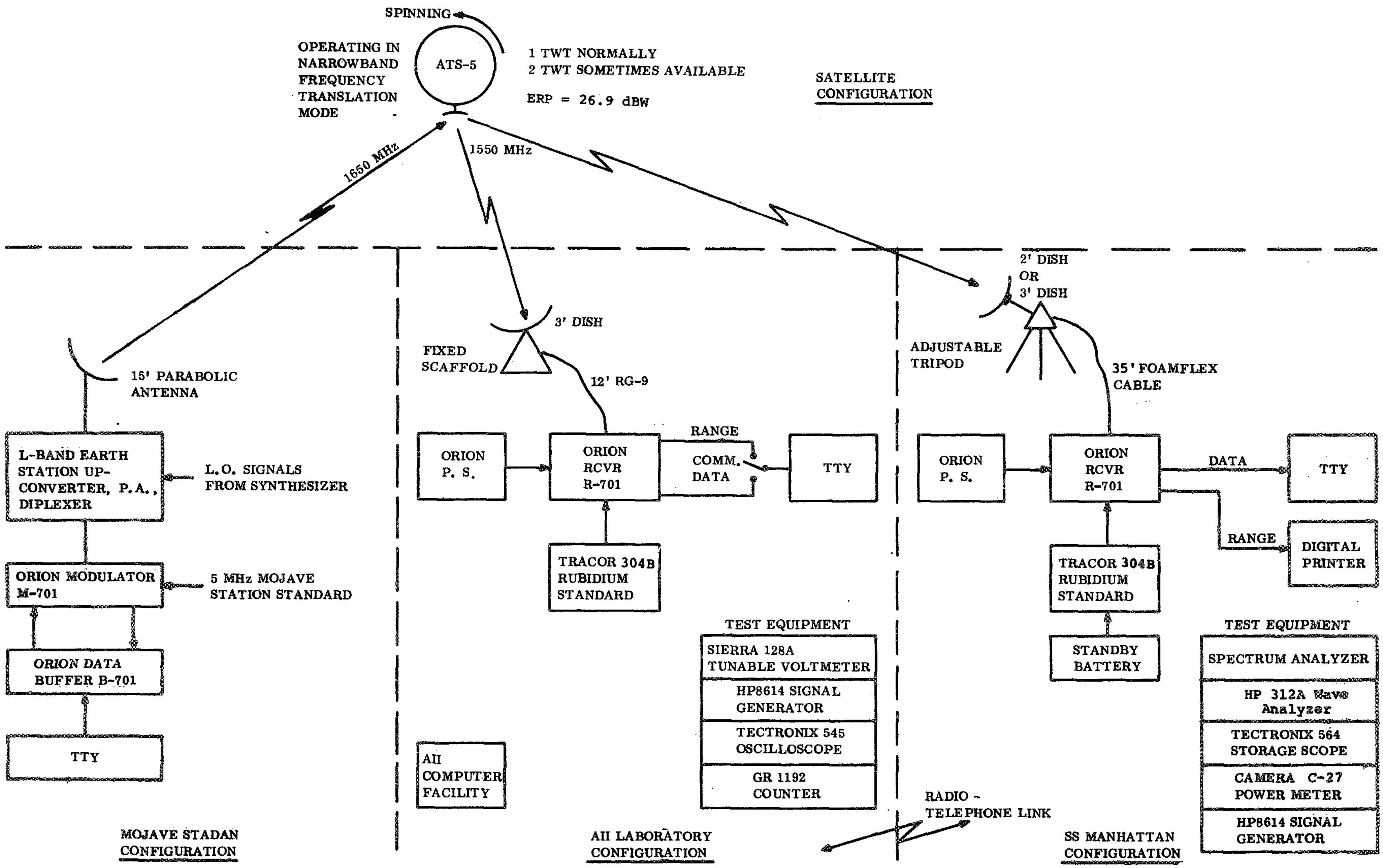


FIGURE 3

EQUIPMENT CONFIGURATION FOR S. S. MANHATTAN ARCTIC TEST EXPERIMENTATION

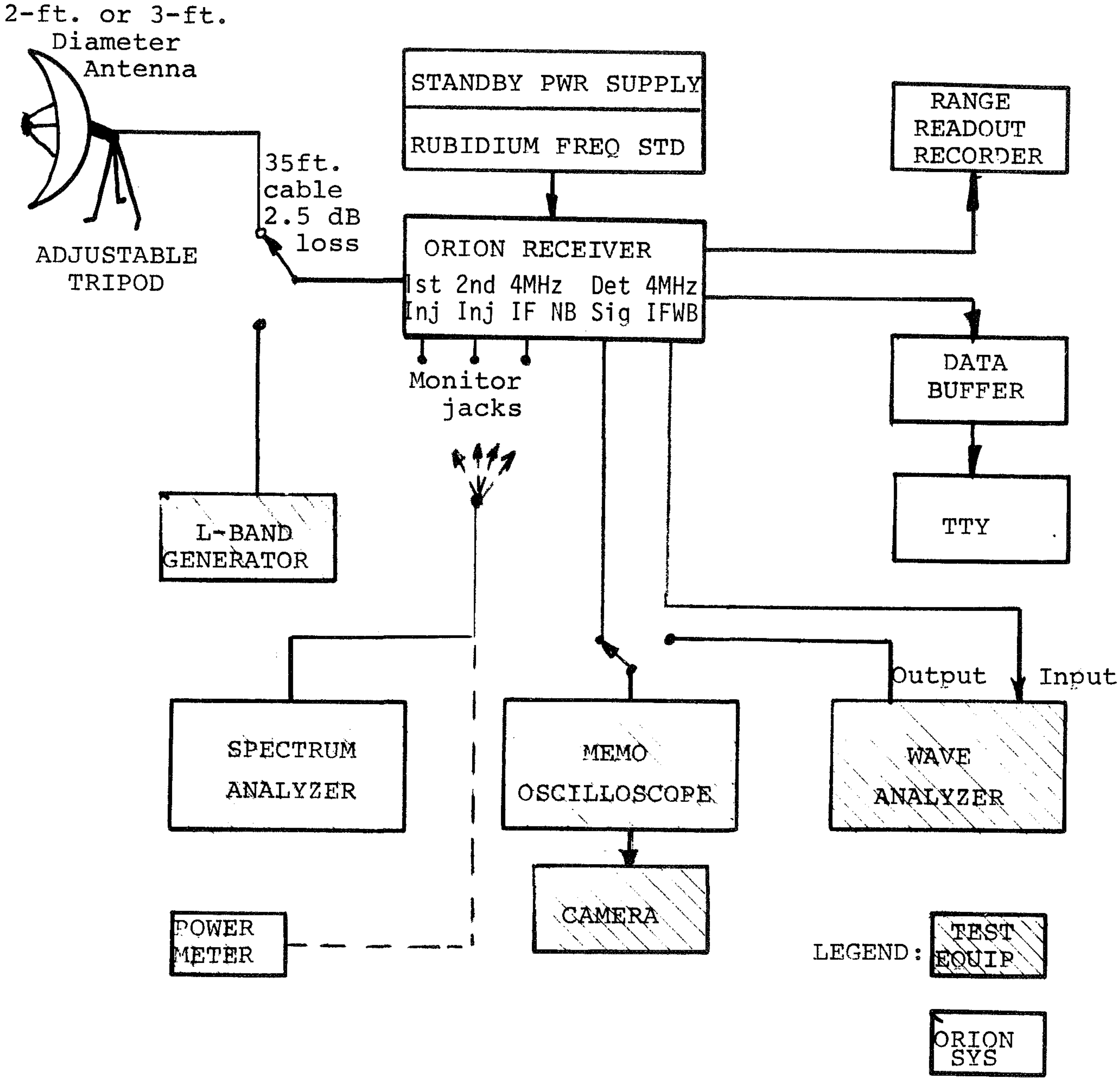


FIGURE 4 BLOCK DIAGRAM OF THE EXPERIMENT SETUP ON BOARD THE S. S. MANHATTAN (AND AII LABS)

equipments which were in support of the test setup are listed in Tables II, III and IV. The functions of the equipments are also listed in the above mentioned tables.

A more detailed description of the ORION receiver system is given in Section 7.0 of this report. The ORION receiver system on board the S. S. Manhattan utilized, besides the 3-foot dish antenna, the 2-foot dish antenna in order to evaluate the effect of broader beam and the lower gain on the 2-foot dish.

Figures 5a through 5d show a series of photographs of the actual ORION system installation on board the S. S. Manhattan. Figure 5a shows the interior of the navigation room with the ORION systems installation. Figure 5b shows the antenna installation and in particular the 2-foot dish mounted with the 3-foot dish stored nearby. The photograph was taken on the 8th of April and shows the antenna being pointed at 18° elevation angle. Figure 5c is a photograph of the antenna at approximately 3° elevation angle, which was the lowest optimum elevation angle of the experiment. (This corresponded to 1.83° of true satellite elevation angle with ephemeris data being taken into account.) Figure 5d is a photograph of the most marginal operating position of the antenna at which the ORION receiver was functioning. The carrier-to-noise ratio during this day's experiment was approximately 14 dB in 1.6 KHz bandwidth. The antenna, as it can be seen from the photograph, is pointing into a "hole" in the bulkhead, but the lock-on capability of the receiver was not impaired by the low carrier-to-noise ratio.

Day-to-day position fixes of the S. S. Manhattan as they were indicated using other navigation systems on board were also recorded. (This information is contained in Appendix C.)

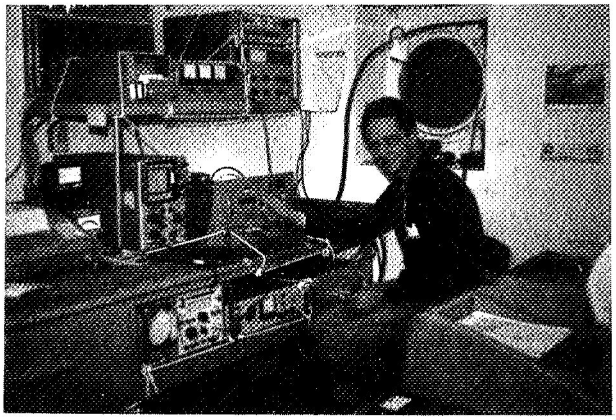


Figure 5a

Figure 5b

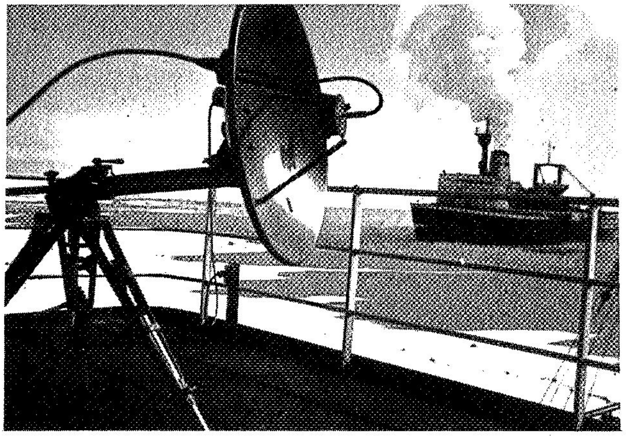


Figure 5c

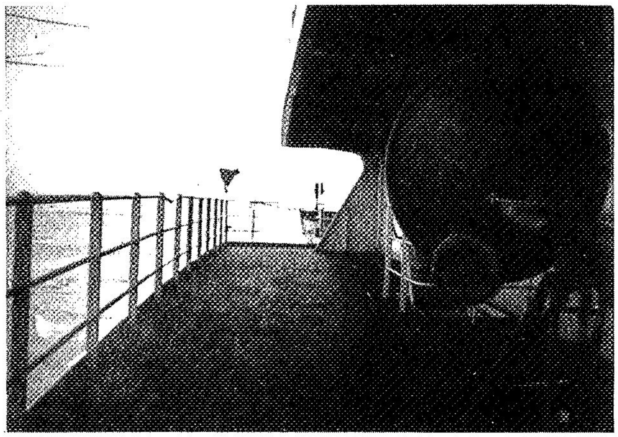


Figure 5d

FIGURE 5 PHOTOGRAPHS SHOWING THE ORION SYSTEM INSTALLATION ON-BOARD THE S. S. MANHATTAN

TABLE II PERFORMANCE CHARACTERISTICS OF ORION SUBSYSTEMS

1. Antenna - 3-foot diameter parabolic, cavity backed spiral feed, gain: 21 dB nom.
   Beamwidth: 17° nom. RHCP
   Antenna to L-band amplifier cable loss: 2.3 dB
   2-ft. dia. dish: Gain - 17 dB nom.; Beamwidth 25° nom.
2. L-Band Front End - Center frequency: 1550 MHz; Bandwidth: ±20 MHz
   Noise Figure: 4.5 dB, Gain: 24 dB @1550 MHz
   Local oscillator frequency: 1480 MHz
   Local oscillator power: 4 to 8 mw
   First intermediate frequency: 70 MHz
   First IF gain: 50 dB min., First IF bandwidth: ±4 MHz

3. Second Mixer and Second IF: Center frequency: 4 MHz
   2nd IF bandwidth: ±200 KHz
   2nd IF gain (before splitting): 30 dB
   Noise level at output of 4 MHz IF amplifier: -10 dBm

4. First Injection Chain: Output frequency: 1480 MHz
   Output power: 6 mw min.
   Input frequency: 5 MHz and 1 MHz
   Input power: 10 mw and 20 mw, respectively, derived from a Rubidium frequency standard (Tracor Model 304-B)

5. Second Injection Chain: Output frequency: 66 MHz
   Output power: 6 mw min.
   Input frequency: 1 MHz or 3 MHz
   Input power: 1 mw
   Input source: TC-VCXO or Rubidium frequency standard

6. Correlator: Input frequency: 4 MHz; Output: DC; Bandwidth: 1.6 KHz
   Externally adjustable threshold. Adjusted for approximately 100 milliseconds positive response time.

7. Correlation and Ranging Computer: Input frequency: 5 MHz
   Output frequency: 83,333 Hz, 8,333 Hz and 833 Hz
   Computes ranging information, controls phase locking and tracking of signals

8. Data Demodulator: Input frequency: 4 MHz; Bandwidth: 5 KHz
   Output: demodulated data pulses at 4.5 characters per second rate, suitable for processing in the data buffer, and hence to be printed on the teletype machine.

TABLE III LIST OF TEST EQUIPMENT USED IN THE ATS-5--ORION--S. S. MANHATTAN EXPERIMENT

Item	Description	Mfg.	Model	Specification and Function
1	L-Band Generator	HP	8614 A	880 MHz to 2400 MHz - Variable signal from 0 dBm to -132 dBm - Used to test the RF and IF portions of ORION receiver
2	Spectrum Analyzer	HP NR	140A 531	Frequency range: 1 MHz to 4.5 GHz, 60 dB dynamic range; Resolution: 1 KHz, 5 KHz, 10 KHz, 20 KHz, 200 KHz; Scan width/cm: .5 KHz -100 MHz, Used for measuring C/N ratio, also used for testing and monitoring RF and IF portions of ORION rcvr
3	Wave Analyzer	HP	312A	Frequency range: 0 to 18 MHz, phase lock; IF bandwidths: 200 Hz, 1000 Hz, 3000 Hz Sensitivity: +20 dBm to -110 dBm Used to determine signal strength, exact received frequency, analyze modulated signal
4	Storage Oscilloscope	TEK	564B	Vertical: .05V to 20V/Div dual trace Horizontal: 1 usec to 5 sec/div, memo Used to record detected signal from ORION detector and wave anal. detector.
5	Camera	TEK	C-27	Polaroid type, used in photographing the pulses recorded on the memoscope
6	Power Meter	HP	432A	+10 dBm to -20 dBm range
7	VTVM	RCA	98C	R, V - DC and AC
8	Volt-Ohm-Ammeter	Simpson	260	

TABLE IV LIST OF PERIPHERAL EQUIPMENT ASSOCIATED WITH THE ORION SYSTEM

Item	Description	Mfg.	Model #	Specification and Function
1	Rubidium Frequency Standard	TRACOR	304B	Output freq: 100 KHz, 1 MHz, 5 MHz, P_{out}=20 mw ea. Short term stability: 7 x 10^{-12} per second Long term stability; 2 x 10^{-11} per month Function: Provides the reference clock for the ORION demodulator and L.O. injection chains
2	Rubidium Standard Stand-by Power Supply (Battery)	TRACOR	312C	Power capacity: 8 hours Function: Provides automatic and instantaneous primary power need for the frequency standard in case of primary (A-C) power failure
3	Digital Printer	Anadex	DP-600	Record Rate: 50 per minute Number of Channels: 7 Function: Records range output and status of ORION receiver
4	Data Buffer	AII	DB-701	Input: ORION receiver data channel output Output: 5 char/sec. TTY signal Function: Stores data information and converts it to TTY compatible signal.
5	Teletypewriter set	Teletype Corp.	ASR-33	Type: Automatic receive, 8-level tape printer, keyboard Function: Receiver data communication information from Data Buffer. Produces typed copy and punched tape of received data.

Navigation systems which were present and used on the S. S. Manhattan were the Transit satellite system, the Loran and the Omega navigational systems. Also, dead reckoning was used for position fixing at high latitudes in the Davis Strait and Baffin Bay area. Use of the sextant in shooting the sun for position fixes was also employed.

Photographs of the appropriate signals recorded on the storage oscilloscope were taken to show the signal strength and pulse duration of the ATS-5 radiation. As mentioned previously, the photographs show the signal at the detected signal port of the ORION receiver front panel and also at the detected signal port of the HP 312A wave analyzer.

4.2 Receiver Test Points

The receiver contains five major test points on the front panel; they are: first injection chain test point, second injection chain test point, 4 MHz wide band test point (which allowed for the wide band characteristics of the receiver to be tested), detected signal test point (which allowed the performance of the receiver after the threshold has been broken to be tested), and 4 MHz narrow band test point (implemented to provide an output after the signal was passed through the 1.6 KHz-wide band pass filters).

Figure 6 shows a block diagram of the ORION receiver with special emphasis on the indicators, controls and the test points of the front panel.

All the functions of these front panel items are described in detail in this section. All of the experimental data during the S. S. Manhattan project, of course, was obtained through these indicators and test points.

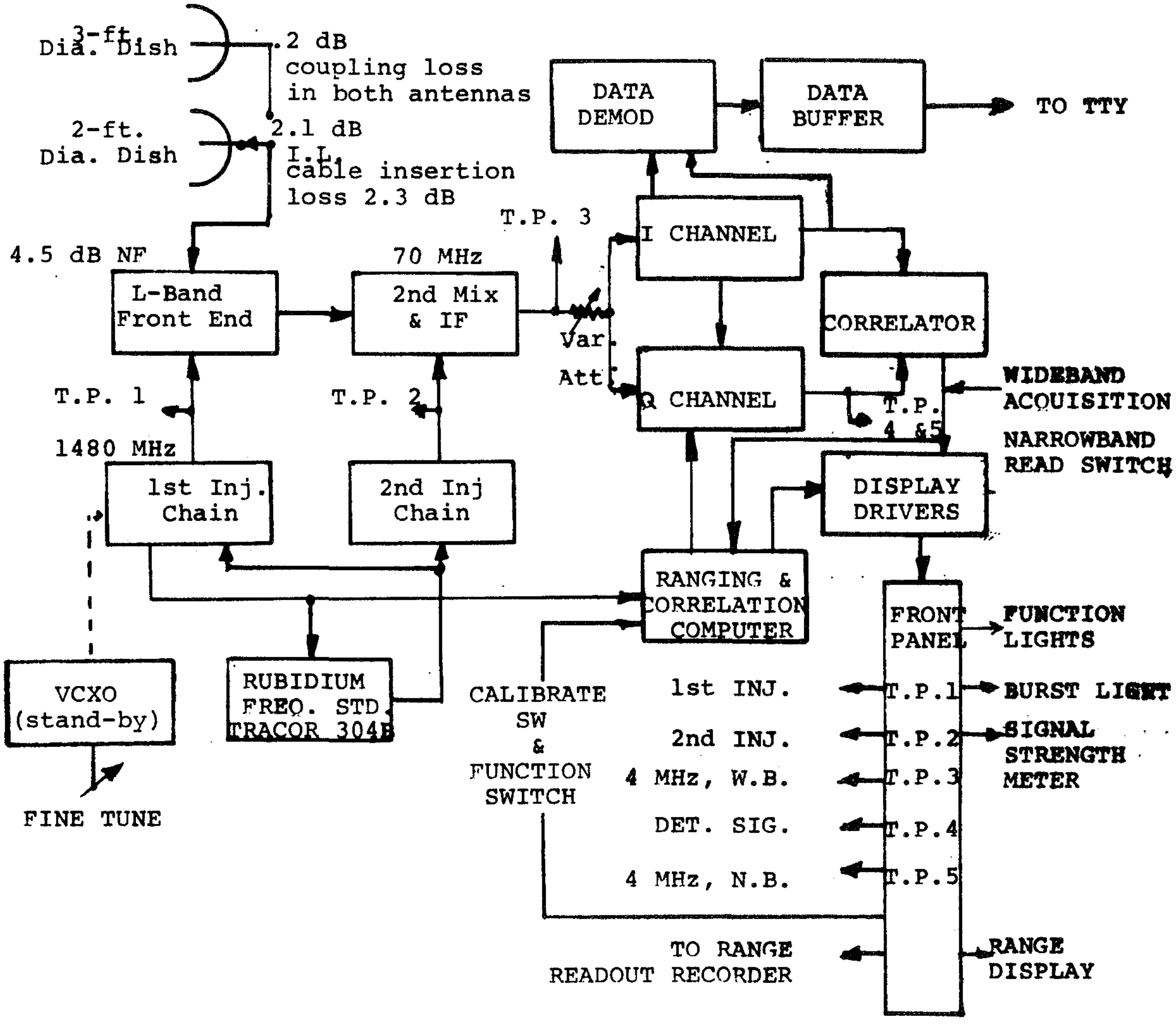


FIGURE 6 BLOCK DIAGRAM OF ORION RECEIVER SYSTEM SHOWING TEST POINTS AND FRONT PANEL CONTROLS

4.2.1 Variable Receiver Sensitivity Function

A variable sensitivity (threshold) control was implemented in the ORION receiver. This was a manually variable attenuator placed in the 4 MHz line after the second IF amplifier (shown in Figure 6).

4.2.2 Indicators

Signal Threshold

ON:	Signal above threshold for 100 ms of a three-second period.
OFF:	No signal above threshold for at least 24 seconds.

Burst Reception

Signal threshold on and signal above threshold received.

Phase Lock

ON:	No error signal generated by correlator for 1.2 seconds.
OFF:	Error signal generated by correlator.

Data

ON:	Data received.
OFF:	No data received for 1.2 seconds.

Power

ON:	AC power activated
OFF:	AC power not activated

Signal Threshold

Relative signal strength.

Range

Range from reference point to present position.

Coarse mode	< 97 nmi
Medium	< 9.7 nmi
Fine	$\leq .97$ nmi

Ranging Mode

Active light indicates frequency receiver expects.

4.2.3 Controls

Wide Band - Acquisition

40 cycle filter in correlator.

Narrow Band - Read

4 cycle filter in correlator.

Reset

Returns automatic cycle to start position.

Mode Selection:

Auto: Receiver frequency cycles

1 minute coarse
1 minute medium
8 minutes fine
data channel activated 2½ minutes into cycle

Initiated by threshold being surpassed.

Terminated by loss of signal for at least 24 seconds or completion of 10-minute cycle.

Coarse: Receiver frequency is 833.3 Hz.

Medium: Receiver frequency is 8333.3 Hz.

Fine: Receiver frequency is 83.333 KHz.

Data: Receiver frequency is 83.333 KHz and data channel is activated.

Calibrate

Place desired reference reading in thumbwheel switches.

When light extinguishes, RANGE should read desired reference.

(Reference must be consistent with frequency, i.e., <97 for coarse, <9.7 for medium, <.97 for fine.)

4.2.4 Test Points

1st Injection

1480 MHz sine wave
22 dB below mixer injection level

2nd Injection

66 MHz sine wave

4 MHz IF

Out of linear amp on doppler channel. Burst of 4 MHz carrier. Bandwidth 1 KHz.

Detected Signal

Rectified 4 MHz carrier

Data

Output of Data channel

4.3 The Conduct of the Experiment

As was described in Table I, the experiment consisted of two major parts: (1) the calibration of the system at AII laboratories and at dockside at Newport News, Virginia, from March 25 through April 2, 1970, and (2) the conduct of the experiment commencing on April 3 and ending on April 24, 1970, near Thule, Greenland. During the latter period, the ORION modulation was transponded via ATS-5 satellite on the basis of five days a week, Tuesday through Saturday, and for a duration of between 2 and 7½ hours a day. Each day the following readings were taken at both the AII laboratory and on board the S. S. Manhattan:

(1) Range readout in nautical miles within the lanewidth of the predetermined ORION modulation, i.e., the COARSE, MEDIUM or FINE. The range readout was displayed on the numerical

display tubes on the front panel, and also the same information was fed to a digital recorder (printer) which printed out all the range values fifty times a minute. Also, the following information was printed out:

(a) Time in minutes since last reset (0-99).

(b) Mode information which indicated unequivocally the type of mode that the ORION receiver was in, i.e., COARSE, MEDIUM or FINE.

(c) The state of operation of the receiver, i.e., the information on threshold, the receiver phase lock and the reception of the data information was recorded continually in each mode.

(See Appendix B for specific example.)

(2) Carrier-to-noise ratio in 1.6 KHz bandwidth was monitored constantly and recorded at points where new information about this condition was being indicated on the test instruments.

(3) IF frequency output was monitored at all times at the 4 MHz wideband port. This measurement indicated the precise frequency at which the system was operating.

(4) Signal burst level and duration was detected at random and recorded on a storage oscilloscope and in turn photographed. Typical readings which were most informative were taken at 20 milliseconds per centimeter or 5 seconds per centimeter setting on the horizontal scale.

Each day, prior to the day's experiment, the ORION system (including the power supply) was checked for normal operation and all readings, such as voltages, current and RF power levels, were recorded.

The weather conditions as well as observations relating to the state and stability of the ship were also noted and recorded. At the beginning of each day's experiment, the antenna azimuth and elevation angles were optimized to produce highest carrier-to-noise ratio. Ordinarily the 3-foot diameter parabolic dish antenna was used for the experiment except for two days. On the 7th and 8th of April the 2-foot diameter antenna was used in order to discover the effects of wider beamwidth and lower gain of this antenna on the carrier-to-noise ratio due to possible multipath. Also during the last few days of the experiment, i.e., from the 19th of April to the 23rd of April, the elevation angles of the antenna were purposely misadjusted downward in order to discover and determine the effects of multipath as the signal was reflected off the solid ice.

The modus operandi of a typical day was as follows. Just before the scheduled ON time of the ATS-5, the system was checked out for normal operation and the antenna was aligned to the optimum azimuth and elevation angle using the data of the ship's position and the ship's heading. When the ATS-5 signal came on, the ORION receiver indicated it immediately on the burst light and then the digital recorder was turned on. The carrier-to-noise ratio was determined on the spectrum analyzer at the narrowband IF (i.e., 1.6 KHz bandwidth) port of the ORION receiver. The HP 312A wave analyzer at the same time was connected to the 4 MHz wide-band port of the ORION receiver and the deflection of the wave analyzer's front panel meter also measured the carrier-to-noise ratio in either the 1 KHz or 3 KHz bandwidth. The wave analyzer also measured the frequency at this port. The detected signal port of the ORION receiver was always connected to one of the two inputs into the storage oscilloscope. The other input of the storage oscilloscope was connected to the detected signal output port of the wave analyzer. These signal bursts were monitored and recorded on the storage oscilloscope and then were photographed if they contained interesting information. The ORION modulation cycle, as previously described, was set up to transmit one minute of COARSE lane information, one minute of MEDIUM lane information and eight minutes of FINE lane information. During the last six minutes of FINE lane information, the data transmission was taking place. The cycle started over again after the FINE lane information ended. The ORION receiver could be monitored in automatic or manual modes.

In addition to the hard copy obtained from the digital printer, another data sheet was maintained where the summary of the range readings, the mode of the operation, the carrier-to-noise ratios and the frequencies were recorded. Other comments such as weather, the position of the ship during that day's experiment was also recorded on this data sheet.

Each day after the period of signal reception was over, the data was summarized and phoned in to AII laboratories via the ship's HF radio telephone link. This data consisted of summary of the range readings, the ship's positions, heading and speed, as well as other observations such as the weather conditions. The information was fed into the computer program at AII laboratory for the determination of the lines of position of the S. S. Manhattan, taking into account at the same time similar data which was recorded at AII. Ephemeris information of the satellite and the various instabilities of the system were also taken into account in the process of determination of the LOPs. The ephemeris data for this duration of the experiment is listed in Appendix C. Appendix A gives full disclosure of the data reduction methods using the computer.

5.0 DESCRIPTION OF THE TEST RESULTS

5.1 Introduction

The results given in this section describe the events and measurements taken on board the S. S. Manhattan. The measurements taken at AII laboratory served only as reference and supplement, wherever applicable.

As the S. S. Manhattan proceeded on its journey from Newport News, Virginia, to the Baffin Bay area, certain geographical zones proved to be more favorable than others for providing good data for the various objectives of the experiment. Thus, the following conditions prevailed in two important areas of measurements:

a. Accuracy and lines of position (LOPs). The best and most meaningful data for the determination of LOPs and, hence, the accuracy of the system, was obtained during the early part of the experiment from April 4, 1970, through April 10, 1970. This was due to the fact that the ship was in an area where good position fixing of the ship could be obtained from other navigational systems to serve as reference for accuracy comparison. Also, EMI and other interferences, such as power failures, were not noted during this portion of the voyage as they were noted during the latter part. (EMI interferences are described later in this report.)

b. Multipath effects were not noticed or measured during the first part of the journey because the antenna elevation angles were too large. However, good and interesting multipath data was obtained when the satellite elevation angles were less than 10°, which was from April 9 through April 24, 1970.

Other parameters such as signal strength (carrier-to-noise ratio), pulse duration, received frequency and data communications were considered to have no favorable time or area of performance and good meaningful data was obtained during the entire trip.

Table V is a summary of data of the overall experiment of the ATS-5--ORION--S. S. Manhattan. This data was taken on board the S. S. Manhattan from March 31 to April 24, 1970. It lists pertinent information as it was obtained during each of the nineteen days of signals received through ATS-5. There were a total of 68.6 hours of satellite signal scheduled, of which 62.3 hours were received on board the S. S. Manhattan. 6.3 hours of the signals were not received, mostly due to antenna blockage by the ship's superstructure.

The ship's position listed in Table V is the ship's "official" one, which is usually listed at noon local time. It is given here for a general reference of the ship's position on that day. Appendix C gives a more detailed list of ship's position which was measured by other navigational systems on board.

The ship's heading is listed in degrees when it was constant during the time of the experiment. The constant heading occurred when the ship was in open water. When the ship was in ice, the heading is marked as variable (Var.) because she was maneuvering in search of easier sailable ice areas. When the ship was stationary (i.e., speed = 0) during the testing period then the ship's heading is indicated for the antenna azimuth alignment reference.

The ship's speed is given as it was noted from the Transit system readings during the day's experiment.

TABLE V ATS-5--ORION--S. S. MANHATTAN OVERALL EXPERIMENT SUMMARY

Date	ATS-5 On Time Zulu		ATS Sig. Hrs.	Sig. Rec. Hrs.	Down Time Hrs.	Down Time Reason H-Head Z-ZigZag MF-MalFn	Ship's Position		Ship Avg. Head Deg.	Ship's Speed Knots	Antenna Alignment		C/N - dB		Water and Weather Conditions OW - Open Water
							Lat N	Long W			AZ Deg.	EL Deg.	Max dB in 1.6 KHz	Min dB	
3-31-70	1200	1400	2	2	0	--	36.98°	76.44°	60	0	223	39	18	16	Rain - OW
4-1-70	1200	1400	2	2	0	--	36.98°	76.44°	60	0	223	39	19	16	Clear - OW
4-2-70	1200	1400	2	2	0	--	36.98°	76.44°	60	0	223	39	18	14	Rain - OW
4-3-70	1200	1400	2	1.9	0.1	Z	36.98°	76.44°	60	0 to 15	223	39	19	16	Clear - OW
4-4-70	1200	1400	2	2	0	--	37°37'	76°06'	55	16.2-16.8	225	39	19	14	Clear - OW
WEEKEND															
4-7-70	1200	1400	2	2	0	--	47.99	52.27	4	11.5-12.2	240 2-ft Dish	18	16	15	Clear - OW
4-8-70	1200	1400	2	2	0	--	52.78	51.31	3	12.0	232 2-ft Dish	12	16	12	Clear Partly Ice
4-9-70	1200	1400	2	2	0	--	58°09'	51°00'	3	14.9-15.0	234 3-ft Dish from now on	12	17	14	Rain Partly Ice
4-10-70	2200	0030	2.5	2.5	0	--	63.40°	53.43°	347	13.7	245	5	17	13	Cloudy - OW
4-11-70	1000	1400	4	4	0	--	67.85°	56.10°	347	0 to 10	245	5	20	14	Clear Partly Ice
4-12 - 4-13-70 FREE RUNNING SATELLITE SIGNAL															
4-14-70	1420	2200	7.7	7.7	0	--	70.0°	56.92°	348	0	238	5	19	10	Clear Solid Ice
4-15-70	1400	1730	3.5	3.0	0.5	Z	69.83	56.99°	348	0	238	4	20.5	14	Clear, Ice
2 TWTs	2300	0100	2	1.5	0.5	H	70.30°	56.38°	324	0	268	4	17	14	Clear, Ice

TABLE V (continued) ATS-5--ORION--S. S. MANHATTAN OVERALL EXPERIMENT SUMMARY

Date	ATS-5 On Time Zulu	ATS Sig. Hrs.	Sig. Rec. Hrs.	Down Time Hrs.	Down Time Reason H-Head Z-ZigZag MF-MalFn	Ship's Position		Ship Avg Head Deg.	Ship's Speed Knots	Antenna Alignment		C/N - dB		Water and Weather Conditions OW - Open Water
						Lat N	Long W			AZ Deg.	EL Deg.	Max dB in 1.6 KHz	Min dB	
4-16-70	1400 160	2TWTs 2	1.5	0.5	Z	70.60°	56.75°	var.	0-6	238	5	22	18	Clear, Ice
	1600 1700	1TWT 1	1	0	--	70.60°	56.75°	var.	0-6	238	5	18.5	17	Clear, Ice
4-17-70	1530 2000	4.5	2.8	1.5	Z	70.70°	57.45°	var.	0-6	253	5	19.5	16	Hazy - Ice
4-18-70	1400 2000	6	5.3	0.2 0.5	MF* Z	71.00°	57.50°	var.	0-6	238	3 - 4	18	12	Clear Ice
4-21-70	1400 1730	5.5	5.0	0.5	Z	71.85°	58.50°	var.	0-8	218	4	17	12	Snow - Ice
4-22-70	1400 1800	6	5.0	1.0	Z	72.20°	58.85°	var.	0-14	222	4	20.5	10	Clear - Ice
4-23-70	1400 1800	6	5.6	0.4	Z	72.59°	58.56°	var.	0-6	Var	3	20.5	11	Clear - Ice
4-24-70	2307 0100	1.9	1.5	0.5	H	73.50°	59.34°	var.	0-8	247	3	19	11	Fog - Ice
	TOTALS	68.6 hrs. sat. sig. 100%	62.3 hrs. rcvd 91%	6.3 hrs. not rcvd 9%	* MF was loose cable in 2nd inj chain	△ 36.5° Lat.	△ 27.1° Long.				△ 36° El. Angle	△ 4.5 dB	△ 7 dB	

THE ORION RECEIVER WAS IN 24-HOUR-TYPE OPERATION FOR APPROXIMATELY 750 HOURS WITHOUT FAILURE (OR 30 STRAIGHT DAYS).

TABLE VI

TRUE ELEVATION AND AZIMUTH ANGLES FOR S. S. MANHATTAN FROM 4-3-70 THROUGH 4-24-70

Date	Elevation From Horiz. Degrees	Azimuth From True North Degrees
4-3-70	38.0	223.6
4-4-70	35.9	226.3
4-7-70	15.7	241.3
4-8-70	13.0	240.7
4-9-70	9.6	239.0
4-10-70	6.0	233.7
4-11-70	5.0	232.21
4-14-70	6.1	230.5
4-15-70	6.0	230.6
4-16-70	5.8	230.6
4-17-70	6.1	230.0
4=18-70	5.6	229.1
4-21-70	5.5	229.0
4-22-70	5.5	228.4
4-23-70	5.24	228.61
4-24-70	1.83	226.71

The antenna alignment lists the local antenna azimuth and elevation angle values as they were read on the respective antenna indicators. The true satellite azimuth and elevation an angles are listed in Table VI. The values in Table VI were obtained using a computer program which took into account the satellite ephemeris data. The carrier-to-noise ratio (C/N - dB) lists the range of measurements noted on the day indicated. The lower reading usually occurred due to antenna misalignment rather than due to some signal attenuating effect.

5.2 Lines of Position (LOPs)

Lines of position of the S. S. Manhattan were determined on the basis of range data obtained on the vessel during her voyage and at AII laboratory in Moorestown, New Jersey. Computer program was used to calculate the LOPs. All known factors and constraints which could affect the determination of the LOPs or their accuracy were taken into account. The most important factors were:

a. Motion of the ATS-5 satellite (taken out by using AII lab's range reading as reference)

b. Clock instabilities and alignment

c. Noise and quantization

(Other factors, such as ionospheric and multipath errors, are analyzed in detail in Section 6 of this report.)

The discussion of the LOPs will be divided into the following subsections:

First, the figures where the LOPs of each day are plotted will be discussed and described in detail;

Second, the results shown in these figures will be summarized in terms of their accuracies; and

Third, conclusions pertaining to range measurements will be drawn.

Figures 7 through 11 show plots of the LOPs of the S. S. Manhattan with latitudes and longitudes as y and x axes, respectively. These plots were made on the basis of the computer-aided determination of the lines of position whose detail printouts are given in Appendix B.

The method of plotting the LOPs is as follows:

1. Latitude-longitude grid is used and a scale adjustment is made for the longitude to approximately reflect actual latitude-longitude relationship for a given map area. Thus, Figures 7, 8 and 9 use a 1:1 relationship between the latitude and longitude units and Figures 10 and 11 use a 4:3 latitude to longitude, respectively, relationship.
2. The plots were made by taking the REFERENCE LATITUDE (see Appendix B) for each day, locating the corresponding longitude intercepts and drawing the LOP at an azimuth angle which is specified for that intercept. The times of the LOPs are indicated on the graphs.
3. ⊗ symbol indicates the position fix of the ship as per other navigational systems on board, at the times indicated. These fixes were not necessarily determined by the same navigational system on the same day.
4. In general, one day's LOPs were plotted, using solid lines and the following day's LOPs were plotted using dashed lines.
5. All times indicated on the graphs are Zulu.

Figure 7 shows the LOPs for April 3 and 4, 1970. On April 3, the S. S. Manhattan was maneuvering out of Newport News, Virginia, port area and therefore the LOPs are bunched together. The next

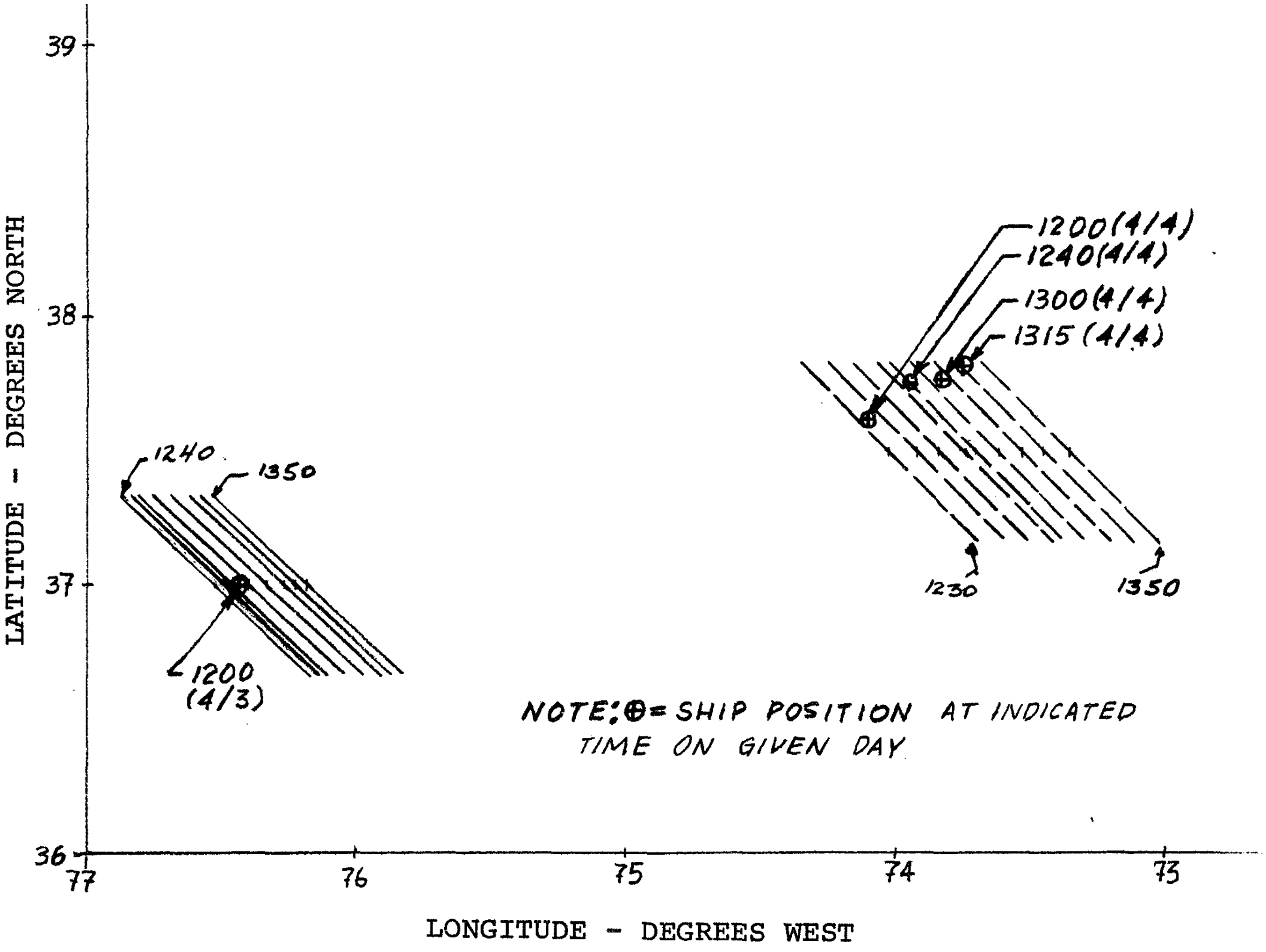


FIGURE 7 LOPs FOR APRIL 3 AND 4, 1970

day the ship was in open water and moving approximately perpendicular to the LOPs.

Figure 8 shows the LOPs for April 7 and 8, 1970. During both of these days the ship was in open water,and the reference position of the ship was taken using Loran and Transit systems. No irregularities were noted for the determination of these LOPs.

Figure 9 is a plot of the LOPs for April 9, 1970. No LOP irregularities were noted. The position fixes of the ship at 1200 Z was according to Loran, at 1225 Z was according to Transit and at 1244 Z was according to Omega systems. The ship's heading of 004° on that day is also indicated on the graph by the large arrow.

Figure 10 shows the LOPs for April 10, 11 and 14. On April 10 the LOPs which are shown represent a two-hour duration of range measurements. The last LOP is called out at "2420" rather than the correct "0020" for convenience of correlating it with the computer printout (given in Appendix B).

The ship's position at 2140 (4-10) was according to the Transit system and at 2417 (i.e., 0017) was according to the Omega system. LOPs for April 11 and 14 are quite regular and indicate no anomalies in the ranging system. The ship was in solid ice on April 14, 1970, and moving very slowly which is indicated by the small distance separation between the LOPs at 1428Z and at 1831Z.

Figure 11 shows the LOP plots for April 15, 16, 17, 18, 21, 22, 23 and 24, 1970. The LOPs for each day are close together because of the slow movement of the ship during the testing period. On 4-21-70 and 4-22-70, only one LOP is plotted for clarity of the graph even though many were determined for the duration of the day's tests.

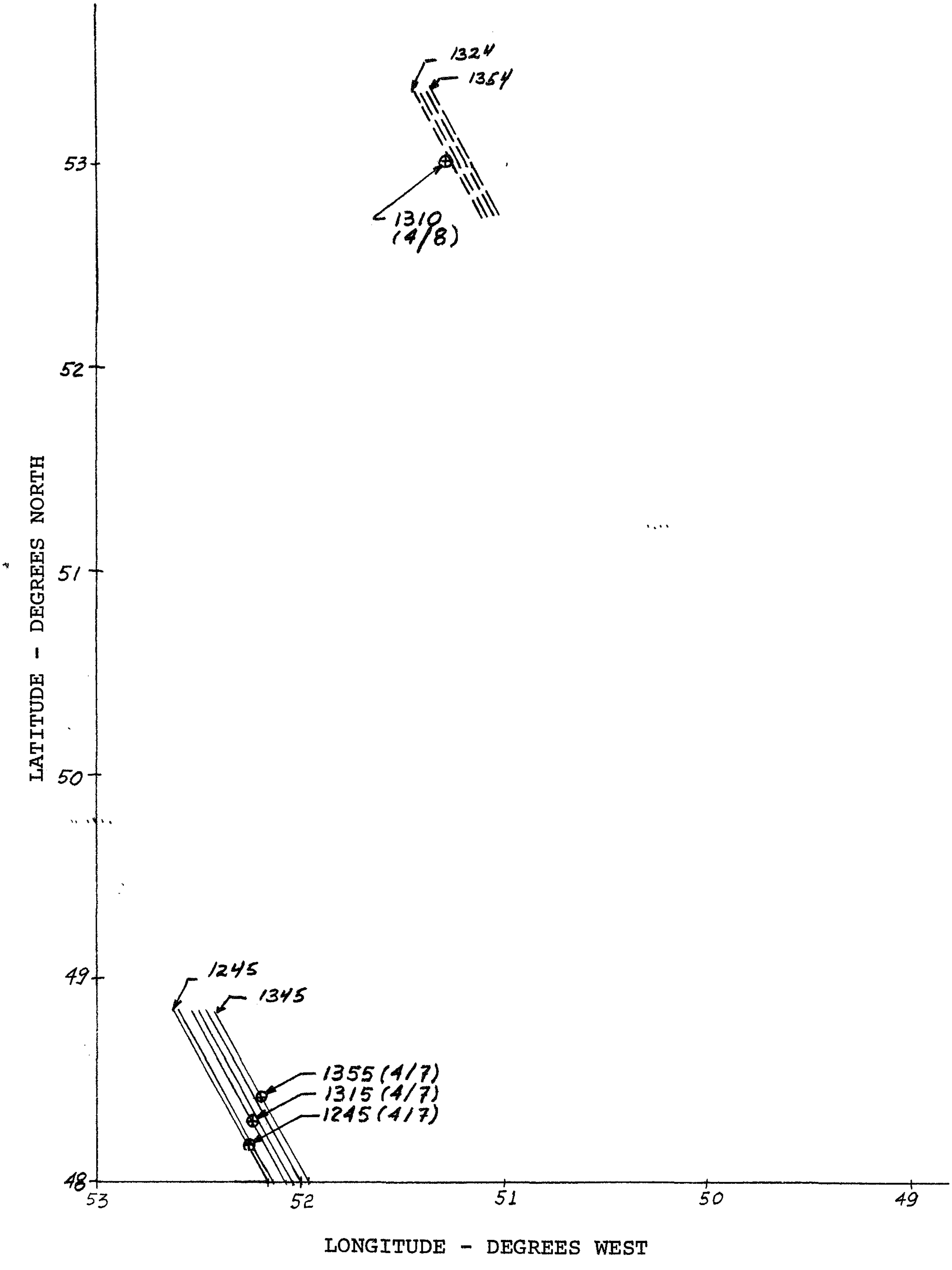


FIGURE 8 LOPs FOR APRIL 7 AND 8, 1970

Note: ⊕ = Ship Position at Indicated Time on Given Day

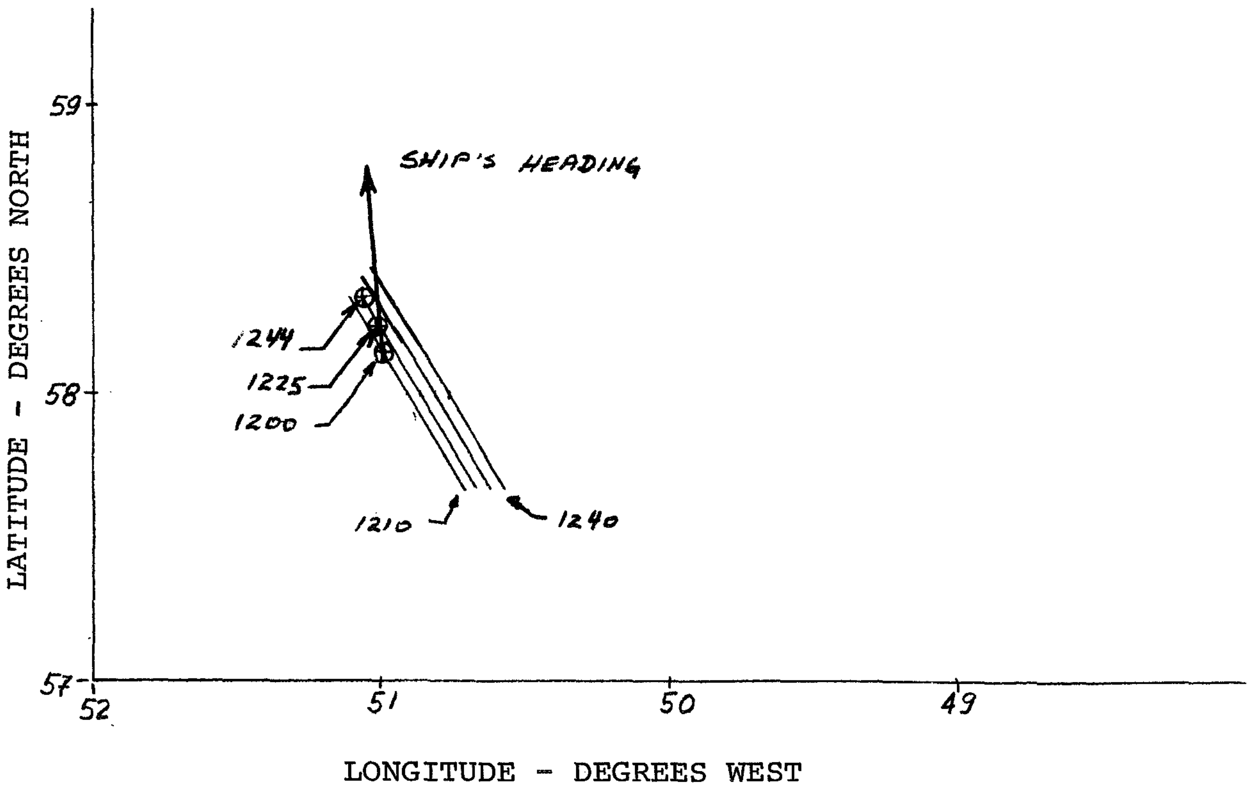


FIGURE 9 LOPs FOR APRIL 9, 1970

Note: = Ship Position at Indicated Time

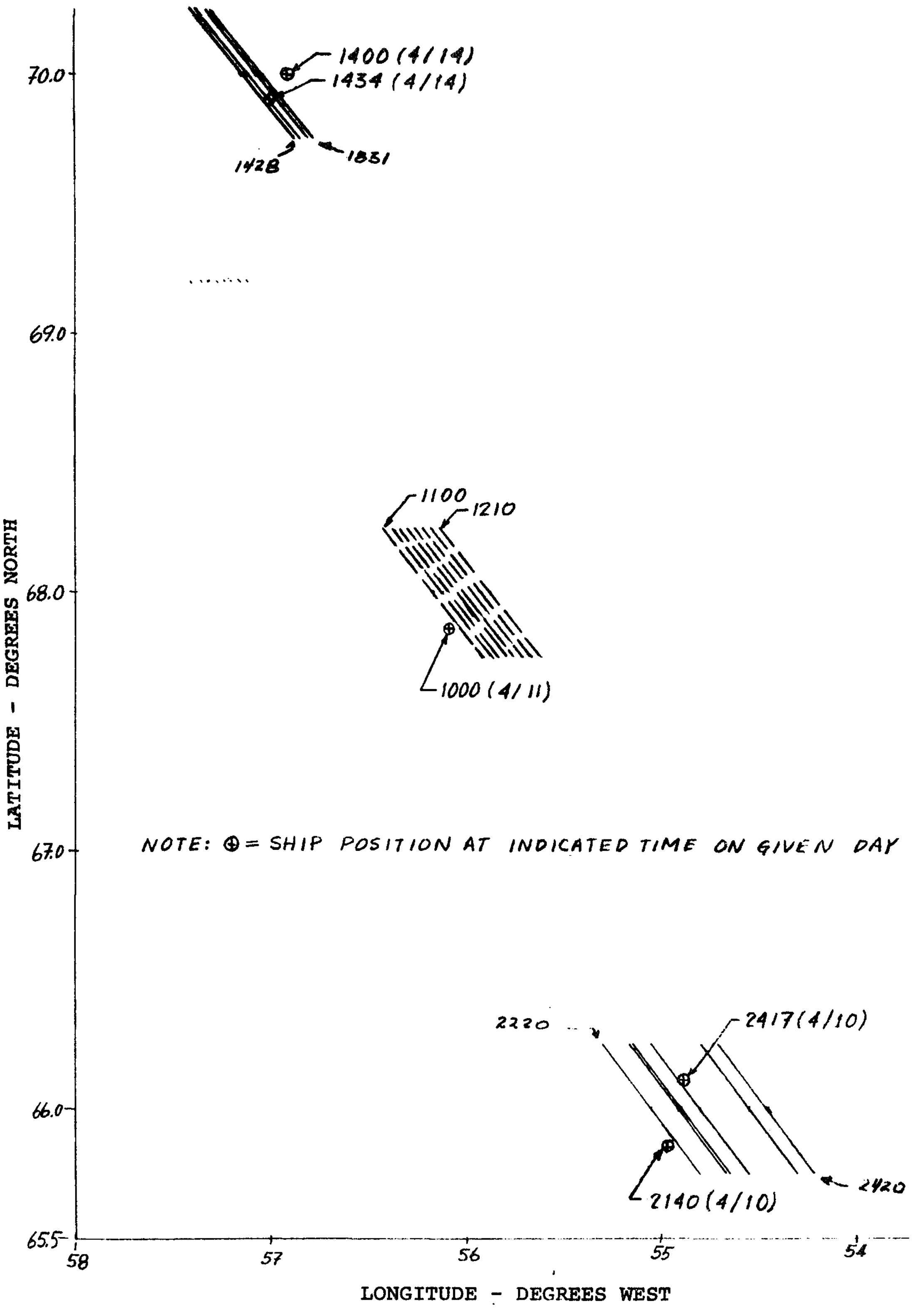


FIGURE 10 LOPs FOR APRIL 10, 11 AND 14, 1970

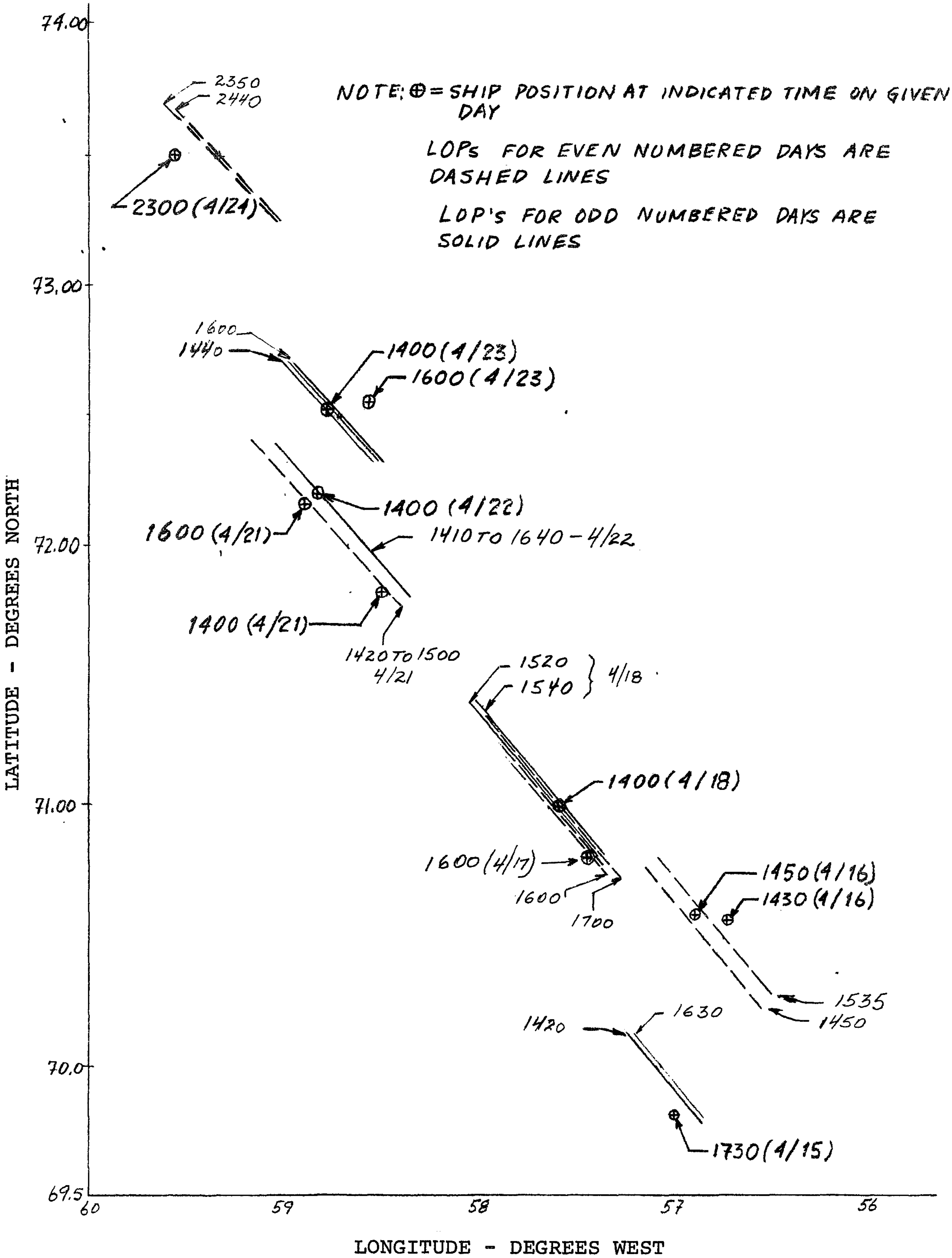


FIGURE 11 LOPs FOR APRIL 15, 16, 17, 18, 21, 22, 23 AND 24, 1970

Table VII summarizes the results which are plotted in Figures 7 through 11 and listed in Appendices B and C. Because Table VII contains reduced data, notes of explanation are given here for some of the columns. These notes are as follows:

Note 1: "LOP Speed" is the speed (in knots) that the LOP is moving away from daily reference point.

Note 2: "Ship's heading" and "ship's speed" define the ship's velocity vector and were obtained from S. S. Manhattan's other navigational systems.

Note 3: "Difference Angle θ" defines the angle which exists between the perpendicular to the LOPs and ship's velocity vector (i.e., ship's heading).

θ = (LOP az angle - 90°) ± ship's heading (in degrees)

Note 4: "ORION speed vector" is the ORION-determined velocity vector calculated using ORION LOP data, and is:

$$\text{ORION Speed} = \frac{\text{LOP Speed}}{\text{Cos } \theta} \text{ (in knots)}$$

Note 5: This column lists the difference (in nautical miles) between the ship's velocity vector (called "vector" in the column) and the ORION calculated velocity vector. This difference is calculated from the data in the other columns of this table. If the ship's velocity vector coincided in direction and magnitude with ORION velocity vector, then the "ORION LOP difference" is noted as "0."

Note 6: Special abbreviations used in this table are:

Var. = variable
N.A. = not applicable

Other abbreviations are listed in Section 3.

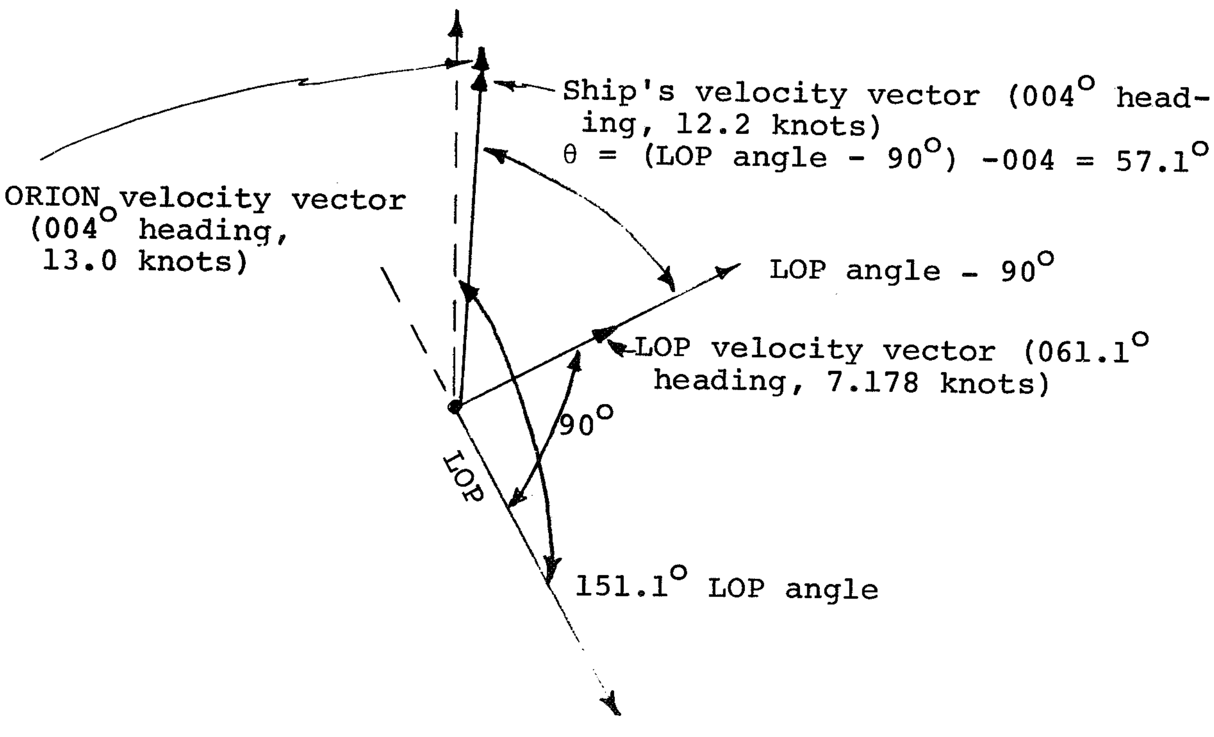
The following example illustrates the method of calculating the values in Table VII (date 4-7-70).

Given: LOP speed = 7.178 knots) from Appendix B
LOP angle = 151.1°)

Ship's heading = 004°) from Appendix C
Ship's speed = 12.2 knots)

Solve for: Difference angle θ, ORION speed vector, and difference between the magnitudes of the ORION speed vector and the ship's speed vector.

North = 0° = Reference



Magnitude of ship's vector = 12.2 knots
Magnitude of ORION vector = <u>13.2 knots</u>
Difference = +1.0 knots

TABLE VII - LINES OF POSITION ORION SYSTEM - A SUMMARY

DATE	TIME	LOP DISTANCE N MI	LOP SPEED KNOTS (NOTE 1)	LOP AZ.ANGLE DEGREES	SHIP'S HEADING DEGREES (NOTE 2)	SHIP'S SPEED KNOTS	DIFF. ANGLE DEGREES (NOTE 3)	ORION SPEED VECTOR KNOTS (NOTE 4)	DIFF. BETWEEN SHIP'S VECTOR & ORION VECTOR (NOTE 5)	COMMENTS
4-03-70	1240	0								
	1250	8.798	7.35	133.4	Var.*	Var.	Var.	N.A.*	N.A.	*See note 6. The ship was maneuvering out of port. She was on a 12 hour cruise.
4-04-70	1230	0								
	1350	23.116	16.838	135.5	055	16.8	11.5	17.4	+0.6	Loran reference, ship in open water.
4-07-70	1245	0								
	1245	7.178	7.178	151.1	004	12.2	57.1	13.2	+1.0	Loran reference, ship in open water.
4-08-70	1324	0								
	1354	3.2	6.4	150.5	003	12.0	57.5	11.9	-0.1	Loran reference, ship in open water.
4-09-70	1210	0								
	1240	4.267	8.534	148.8	004	15.0	54.8	15.0	0	Loran reference, ship in open water.
4-10-70	2220	0								
	2420	11.95	5.96	143.5	347	13.7	66.5	14.9	+1.2	Transit reference, ship in open water.
4-11-70	1100	0								
	1210	5.00	4.3	141.4	347	10	65	10.5	+0.5	Sun fix reference, ship in partial ice.
	1210	5.00								
	1350	4.949	-0.051	141.4	347	0	N.A.	-0.051	-0.051	Ship stationary in partial ice for the duration of this measurement. Ship's heading listed here for information only.

Continued

TABLE VII - LINES OF POSITION ORION SYSTEM - A SUMMARY

DATE	TIME	LOP DISTANCE N MI	LOP SPEED KNOTS (NOTE 1)	LOP AZ.ANGLE DEGREES	SHIP'S HEADING DEGREES (NOTE 2)	SHIP'S SPEED KNOTS	DIFF. ANGLE DEGREES (NOTE 3)	ORION SPEED VECTOR KNOTS (NOTE 4)	DIFF. BETWEEN SHIP'S VECTOR & ORION VECTOR (NOTE 5)	COMMENTS
4-14-70	1428	0								
	1831	1.358	0.34	140.6	348	0	N.A.	0.34	+0.34	Ship stationary in solid ice during the experiment.
4-15-70	1420	0								
	1630	0.405	0.2	140.5	348	0	N.A.	0.2	+0.2	Ship stationary in solid ice during the experiment.
4-16-70	1450	0								
	1535	1.531	1.15	140.5	Var.	Var.	N.A.	N.A.	N.A.	*The ship was maneuvering in the ice during the experiment (i.e., heading and speed was variable). Therefore the difference between the ORION velocity Vector and ship's velocity vector could not be determined.
4-17-70	1600	0								
	1700	0.112	0.112	140.0	337	0	N.A.	0.112	+0.112	The ship was stationary during the time of this LOP sample.

Continued

TABLE VII - LINES OF POSITION ORION SYSTEM - A SUMMARY

DATE	TIME	LOP DISTANCE N MI	LOP SPEED KNOTS (NOTE 1)	LOP AZ.ANGLE DEGREES	SHIP'S HEADING DEGREES (NOTE 2)	SHIP'S SPEED KNOTS	DIFF. ANGLE DEGREES (NOTE 3)	ORION SPEED VECTOR KNOTS (NOTE 4)	DIFF. BETWEEN SHIP'S VECTOR & ORION VECTOR (NOTE 5)	COMMENTS
4-18-70	1520	0								
	1540	0.876	1.74	139.80	350	Var.	N.A.	N.A.	N.A.	The ship was moving very slowly during the time of this sample. The speed of the ship was not precisely determined and therefore no ORION vs ship's velocity Vector difference can be determined.
4-21-70	1420	0								
	1500	0.08	0.1	138.6	010	0	N.A.	0.1	+0.1	Ship stationary in solid ice during the time of range measurements. Ship was maneuvering during the test outside this time sample.
4-22-70	1410	0								
	1640	0.017	0.042	138.22	006	0	N.A.	0.042	+0.042	Same as directly above.
4-23-70	1440	0								
	1600	0.538	0.41	138.3	340	0	N.A.	0.41	+0.41	Same as directly above.
4-24-70	2350	0								
	2440	0.269	0.3	137.3	340	0	N.A.	0.3	+0.3	Same as directly above.

The last column of Table VII lists the difference between ship's velocity vector and ORION velocity vector and is, in effect, a measure of accuracy of the ORION system. The reference point for each day is the position of the ship at the start of the day's experiment, and the day's LOPs are compared to that point. This method of relative accuracy determination was chosen because of the following reasons:

a. The other navigational systems are not, according to their specifications, as accurate as the ORION system was calculated to be and, therefore, absolute accuracy comparison from day to day would be inconclusive.

b. Absolute fixes were especially difficult in the Arctic regions.

c. It was possible to accurately note the speed and heading of the ship for the duration of one day's experiment and thus determine the unperturbed velocity vector for one day. To do this in a continuing way from day to day was impossible due to the many course and speed changes of the ship throughout the voyage.

d. Random interruptions due to EMI and primary AC power on the ship made the referencing on the previous day's data impossible.

Figure 12 shows a plot of the last column of Table VII. +1.2 nmi on 4-10-70 is the largest relative difference between the ORION-determined LOPs and other systems' fixes, and 0 nmi on 4-9-70 is the smallest. The trend of these differences indicates that the ORION LOPs were in the majority of cases ahead of the ship by an average of +0.336 nmi/day's experimentation.*

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* To arrive at this average, all the differences were added and divided by 14 (i.e., the number of days).

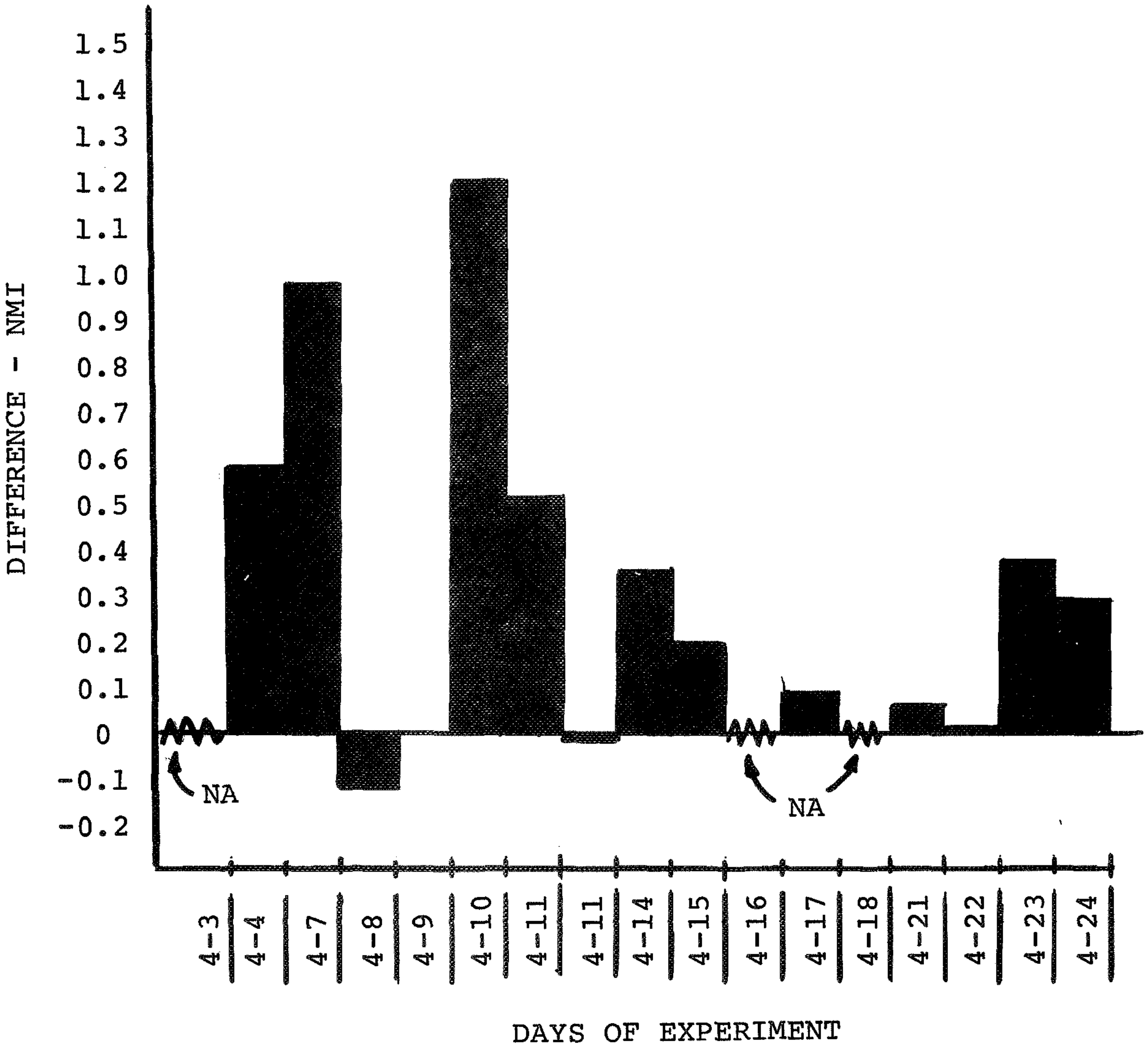


FIGURE 12 DIFFERENCES BETWEEN ORION LOPs AND OTHER SYSTEMS FOR THE 16 MEASUREMENT PERIODS ABOARD THE S. S. MANHATTAN

This fact tends to indicate a small unaccounted for bias in the system. This bias may be due to accumulated difference in the frequency drift of the two Rubidium standards which were used -- one at AII and one on the S. S. Manhattan. Also, a small effect may be ascribed to the linear--rather than sinusoidal--interpolation between satellite ephemeris points. Linear interpolation was necessary because the ephemeris data was taken every 30 minutes only. It must be also recalled that the satellite position is known to within an ellipsoid of 1 x 1 x 2 km. Other sources of error are discussed in Section 6 of this report.

5.3 Carrier-to-Noise Ratio

Figure 13 is a summary of carrier-to-noise ratio which was measured during the experiment and is noted for each day. The receiver noise bandwidth was 1.6 KHz and the antenna was the 3-foot diameter dish unless otherwise indicated on the figure. The range of the carrier-to-noise ratio is plotted for each day and the satellite elevation angle is noted at the same time. This graph shows the fact that the carrier-to-noise ratio was higher at 1.83° elevation angle (up to 20.5 dB) than it was at Newport News, Virginia, at 38° elevation angle (19 dB). This increase of the carrier-to-noise ratio is judged to be due to multipath enhancement at the low elevation angle. (Signal amplitude variations of ± 2 dB from average due to multipath were measured. This aspect will be discussed later in the section.) It also clearly indicates the decrease in carrier-to-noise ratio when the 2-foot dish was used on the 8th and 9th of April, 1970. On April 16 the ATS-5 was operated in a 2-TWT mode as well as the 1-TWT mode. The carrier-to-noise ratio difference was 4 dB and was clearly distinguishable between the two modes. The range of the carrier-to-noise ratio values indicated on the graph are those which were noted during

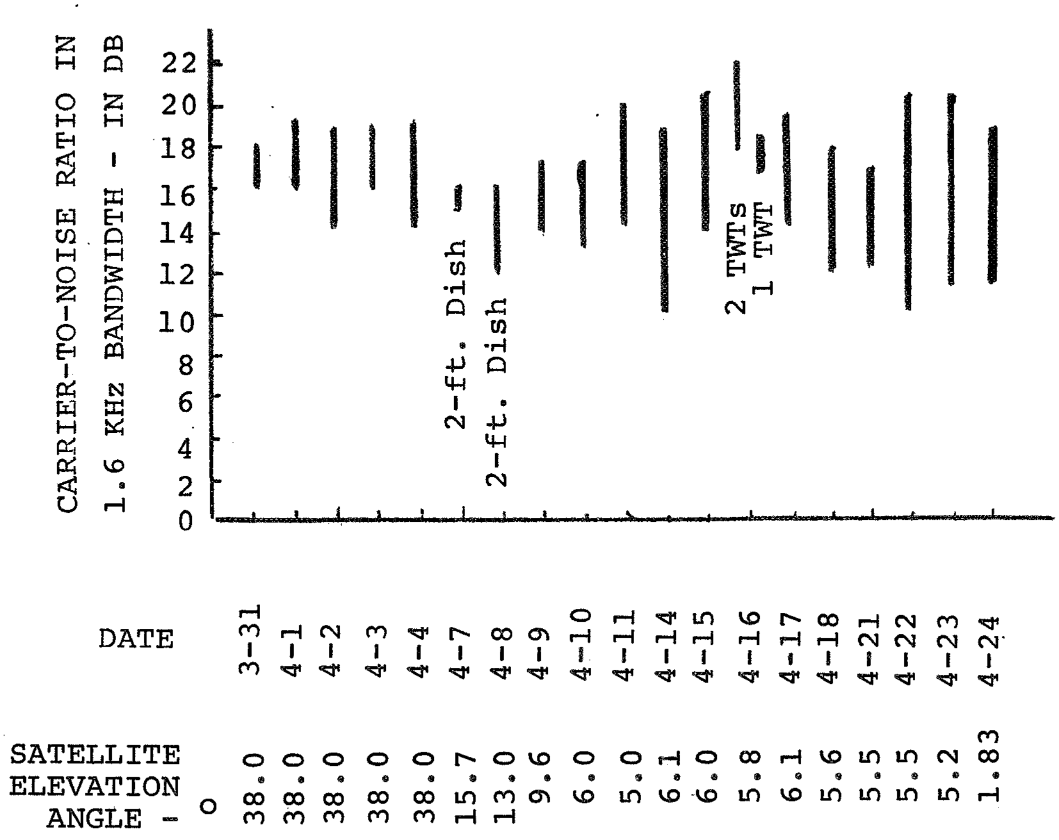


FIGURE 13 CARRIER-TO-NOISE RATIO IN 1.6 KHz BANDWIDTH DURING THE EXPERIMENT

that day's testing. Wider fluctuations in carrier-to-noise ratios are noted for the latter part of the experiment because the low C/N ratios occurred when the antenna pointing was not optimum while the ship was turning or maneuvering in ice. The low values were recorded just prior to the readjustment of the antenna azimuth angle to a more optimum position.

5.4 Pulse Amplitude and Duration

Figures 14 through 17 show the actual photographs taken on board the S. S. Manhattan at the indicated outputs of the ORION receiver setup. The photographs were taken with a Polaroid oscilloscope camera and show the images which were recorded on the storage oscilloscope. The captions under each of the photographs are for the most part self-explanatory; however, some additional explanation is given in the following paragraphs.

Figures 14a through 14d show signal strength and pulse width of the ATS-5 signal as it was received from April 4, 1970, through April 24, 1970, i.e., from approximately the position of 50 miles east of Atlantic City, New Jersey, to the Baffin Bay area in the Arctic. These figures are presented here to show clearly that the pulse duration and the pulse amplitude signal at 35° elevation angle were almost the same as was observed at 1.83° elevation angle. The antenna sidelobes are present in each of the photographs signifying that, again, the signal strength was high on 4-24-70.

Figures 15a through 15d show signals on the last day of the experiment. It was the farthest northern point at latitude 73.5°N and longitude 59°W. The satellite elevation angle was

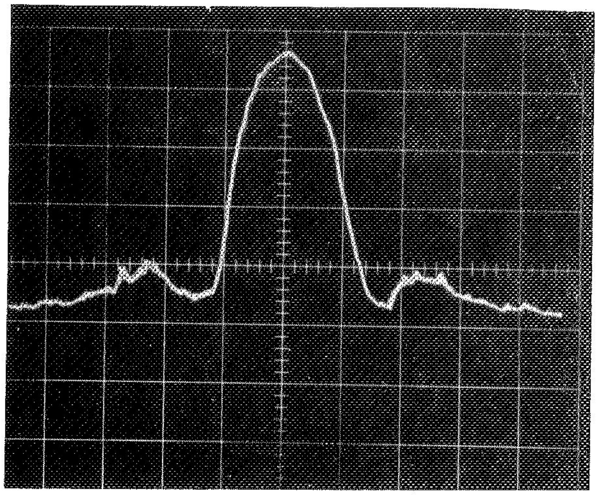


Figure 14a

DATE: 4-4-70 TIME: 1307Z
VERT: 0.2 V/cm MODE: FINE
HORIZ: 50 Msec/cm
NOTES: Detected Signal Output
Sat. Elevation Angle 35.9°

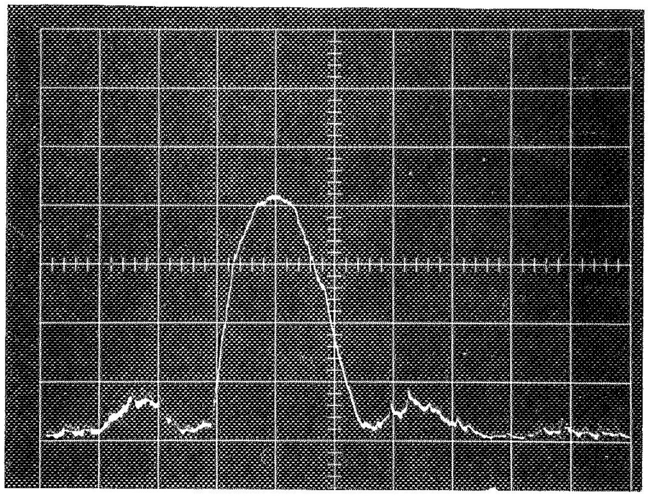


Figure 14 b

DATE: 4-9-70 TIME: 1313Z
VERT: 0.2 V/cm MODE: FINE
HORIZ: 50 Msec/cm
NOTES: Detected Signal Output
Sat. Elevation Angle 9.6°

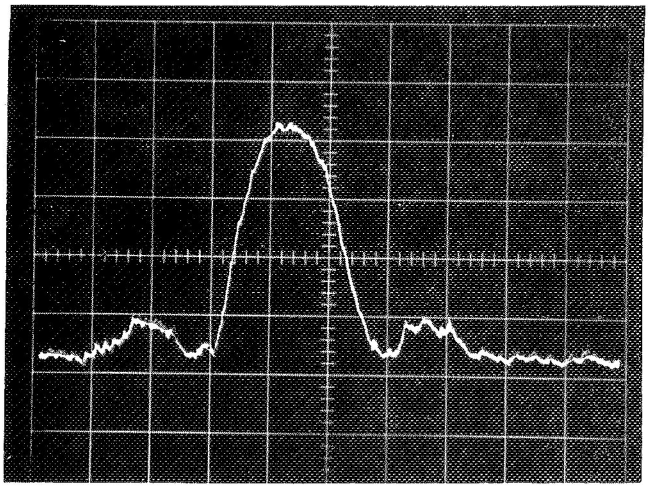


Figure 14c

DATE: 4-15-70 TIME: 1654Z
VERT: 0.2 V/cm MODE: FINE
HORIZ: 50 Msec/cm
NOTES: Detected Signal Output
Sat. Elevation Angle 6°

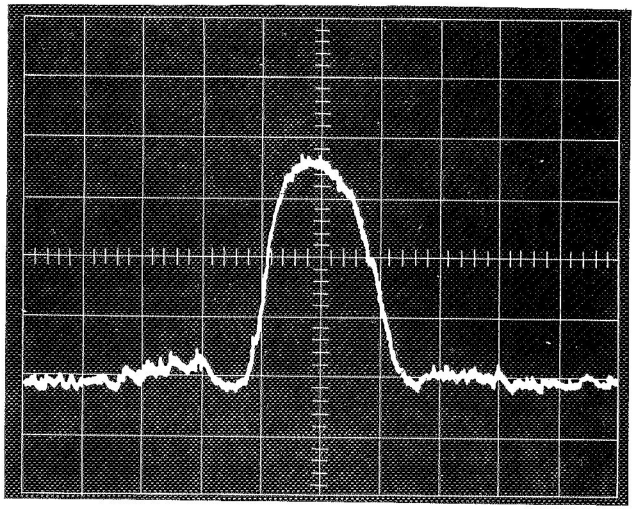


Figure 14 d

DATE: 4-24-70 TIME: 0006Z
VERT: 0.2 V/cm MODE: FINE
HORIZ: 50 Msec/cm
NOTES: Detected Signal Output
Sat. Elevation Angle 1.83°

FIGURE SIGNAL STRENGTH AND PULSE WIDTH VS DECREASING SATELLITE ELEVATION ANGLE

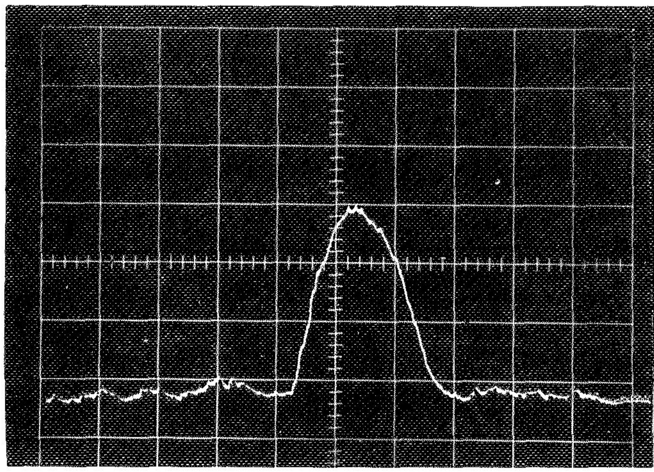


Figure 15a

DATE: 4-24-70 TIME: 0005Z
VERT: 0.2 V/cm MODE: FINE
HORIZ: 50 Msec/cm
NOTES: Detected Signal Output
Elevation Angle 1.83°
IF atten: 8 dB

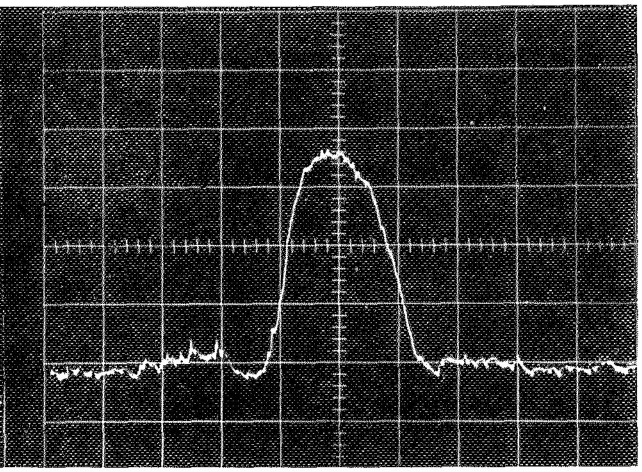


Figure 15b

DATE: 4-24-70 TIME: 0006Z
VERT: 0.2 V/cm MODE: FINE
HORIZ: 50 Msec/cm
NOTES: Detected Signal Output
Elevation Angle 1.83°
IF atten: 5 dB

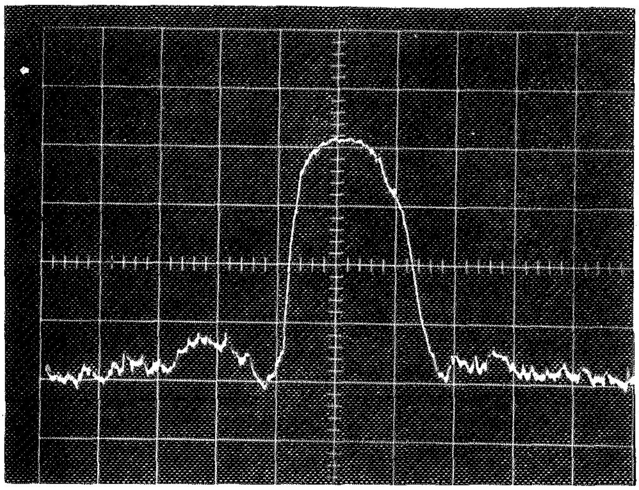


Figure 15c

DATE: 4-24-70 TIME: 0007Z
VERT: 0.2 V/cm MODE: FINE
HORIZ: 50 Msec/cm
NOTES: Detected Signal Output
Elevation Angle 1.83°
IF atten: 2 dB

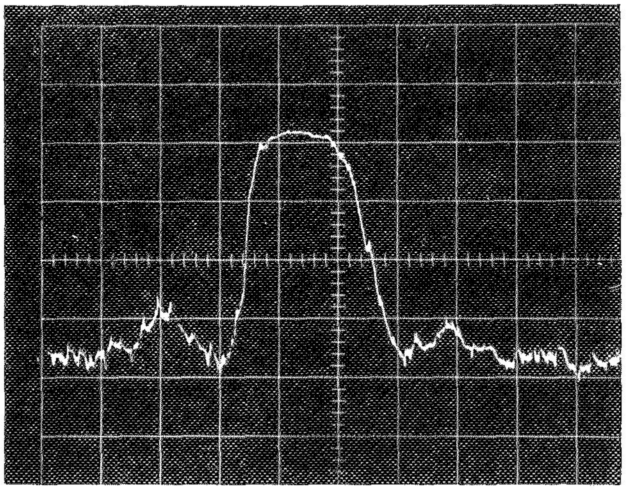


Figure 15d

DATE: 4-24-70 TIME: 0008Z
VERT: 0.2 V/cm MODE: FINE
HORIZ: 50 Msec/cm
NOTES: Detected Signal Output
Elevation Angle 1.83°
IF atten: 0 dB

FIGURE 15 SIGNAL STRENGTH AND PULSE WIDTH VS IF ATTENUATOR SETTINGS, ON THE SAME DAY, FARTHEST NORTH (Lat 73°N, Long 59° W)

1.83°. Figure 15a shows the normal operating level of the receiver with the variable threshold IF attenuator setting at 8 dB. Figure 15b shows the signal burst with the variable threshold attenuator setting at 3 dB less than in Figure 15a. Figure 15c shows an operating level with another 3 dB taken out of the IF path. After 6 dB of IF attenuation was taken out of the circuit the signal detector was overdriven, producing rounded pulses. This was done in order to examine the antenna sidelobes. In Figure 15d the operating level is with 0 dB IF attenuation, i.e., the threshold setting is completely wide open. This setting creates a pronounced rounding of the top of the detected signal burst and clearly shows that the signal burst is approximately 100 milliseconds wide near the top of the burst of this particular figure. It was observed that the pulsewidth was approximately 100 milliseconds (at 10 dB level from the top of the peak) throughout the voyage.

Figures 16a through 16d show the signal bursts when the ATS-5 used 2 TWTs and 1 TWT on the same day (April 16, 1970). Figures 16a and 16b have comparable settings of the receiver sensitivity (i.e., IF attenuator) for the 2 TWT mode and 1 TWT mode, respectively. Figures 16c and 16d are corresponding pictures with another IF attenuator setting.

Figure 17 shows the traces of the peaks of pulse bursts which were taken from the actual photograph. This figure compares the duration of the satellite bursts as they were received on board the S. S. Manhattan as she was traversing satellite elevation angles from 35.9° through 1.83°.

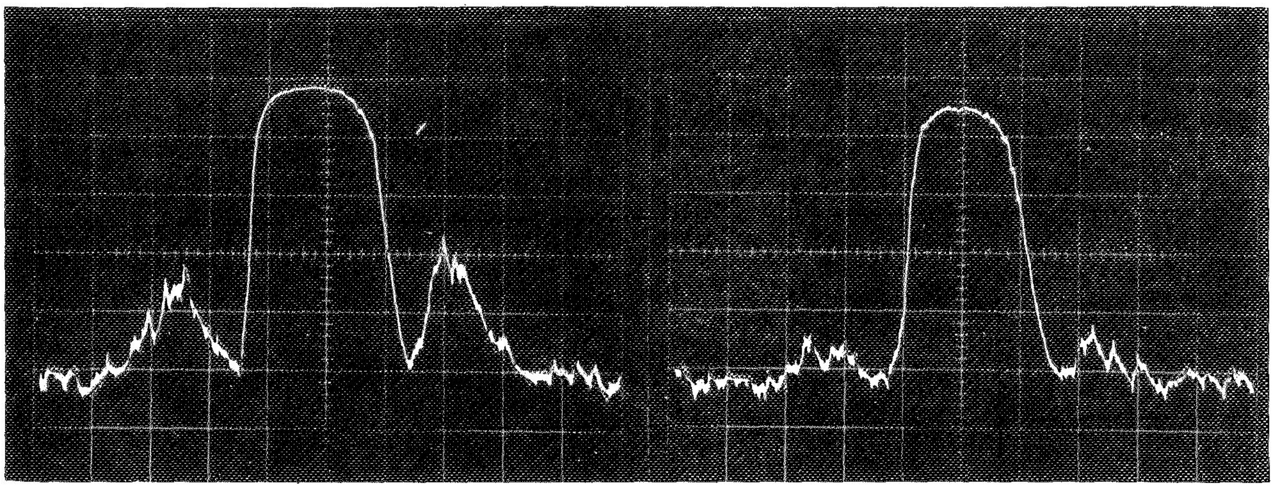


Figure 16 a

DATE: 4-16-70 TIME: 1506Z
VERT: 0.2 V/cm MODE: FINE
HORIZ: 50 Msec/cm
NOTES: Detected Signal Output
ATS-5 Emission: 2 TWTs
IF attenuation: 0 dB

Figure 16 b

DATE: 4-16-70 TIME: 1425Z
VERT: 0.2 V/cm MODE: FINE
HORIZ: 50 Msec/cm
NOTES: Detected Signal Output
ATS-5 Emission: 1 TWT
IF attenuation: 0 dB

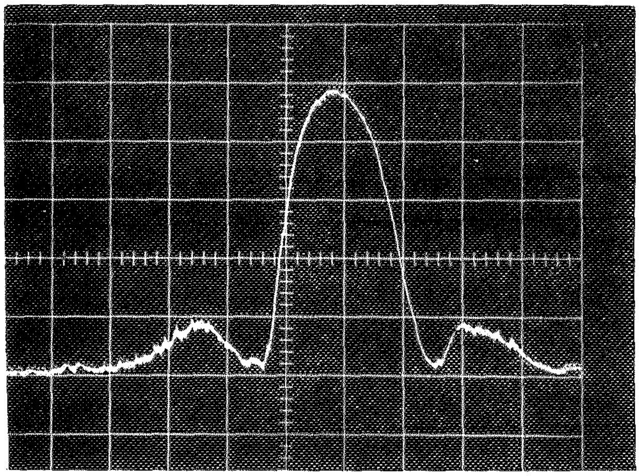


Figure 16 c

DATE: 4-16-70 TIME: 1458Z
VERT: 0.2 V/cm MODE: FINE
HORIZ: 50 Msec/cm
NOTES: Detected Signal Output
2 TWTs; IF atten: 10 dB

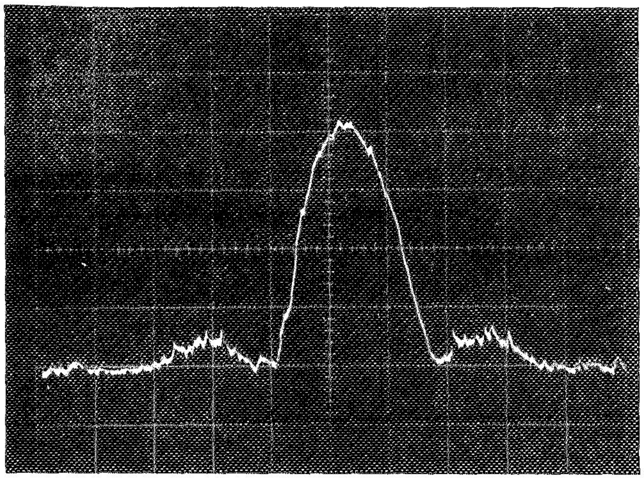
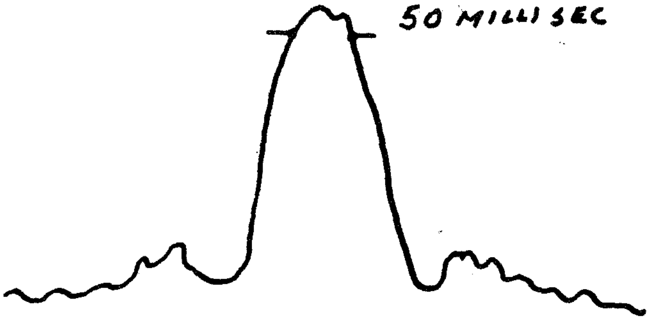


Figure 16 d

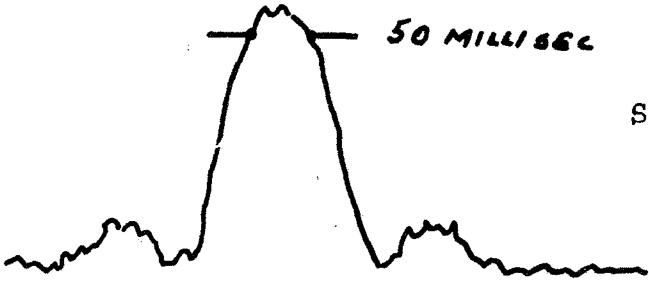
DATE: 4-16-70 TIME: 1622Z
VERT: 0.2 V/cm MODE: FINE
HORIZ: 50 Msec/cm
NOTES: Detected Signal Output
1 TWT; IF atten: 7 dB

FIGURE 16 SIGNAL STRENGTH AND PULSE WIDTH, 2 TWTs and 1 TWT ON THE SAME DAY

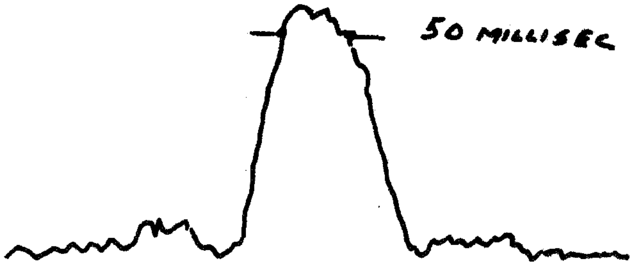


Satellite Elevation Angle
35.9°
4-4-70

Satellite Elevation Angle
9.6°
4-9-70



Satellite Elevation Angle
6.0°
4-15-70



Satellite Elevation Angle
1.83°
4-24-70

FIGURE 17 PULSE WIDTH AND AMPLITUDE VS SATELLITE ELEVATION ANGLE

5.5 Multipath

Figures 18a through 18d show what is judged to be specular and diffused multipath effects over water and over ice on the high seas. The top traces on each picture show the output of the threshold signal detector of the ORION receiver and the bottom traces show the output of the detector of the HP 312A wave analyzer. As described before, the wave analyzer was connected at the 4 MHz wideband IF port and essentially monitored the same signal as the threshold detector. However, both traces were recorded on the oscilloscope as a double check of the measuring method. It must be noted here that the horizontal time scale setting of the oscilloscope is 5 seconds per centimeter and each centimeter, therefore, represents approximately 6 bursts of the ATS-5 signal. The vertical scale setting was calibrated to be 3 dB per centimeter. Figure 18a shows a 50-second recording of the signal bursts when the ship was moving through open water. The water surface on that day was relatively rough with white caps appearing on the sea. Variation in the amplitude of the detected signal shows up to be about 4 dB and is surmised to come from two sources: (1) from the pitch and roll of the ship, which was approximately 6° on that day, causing a variation of the direct signal, and (2) from the multipath as the ship rolled and forced the antenna to point into the sea. The antenna elevation angle was 6.1°. Figure 18b on the other hand shows steady detected signal bursts when the ship was stopped in calm water. Figure 18d shows a comparable trace of signals which were recorded when the ship was stopped in the area of total ice coverage.

Figures 19a through 19d show the detected signal traces comparable to Figures 18a through 18d. However, in this portion of the experiment the elevation angle of the antenna was purposely varied between $+5^{\circ}$, which was the optimum antenna adjustment for that day, and -4°.

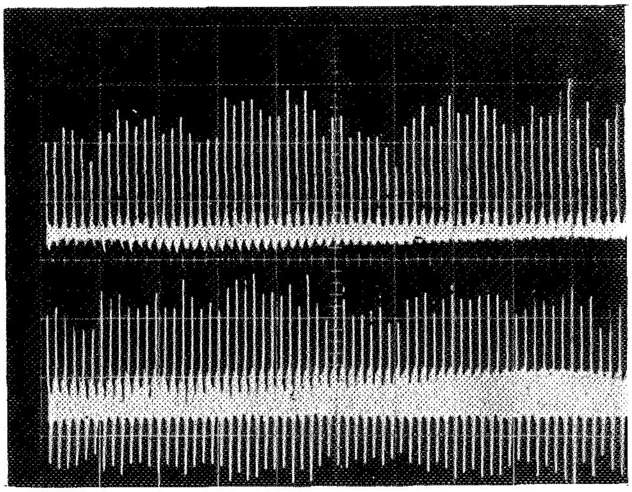


Figure 18a

DATE: 4-10-70 TIME: 1200Z
VERT: 0.2V/cm=3dB/cm MODE: FINE
HORIZ: 5 sec/cm Sat. El. Angle=6.1°
NOTES: Top: Det.Sig.Output (ORION)
Bottom: Det.Sig.Output (HP312A Wave Analyzer)
SHIP MOVING THROUGH ROUGH WATER

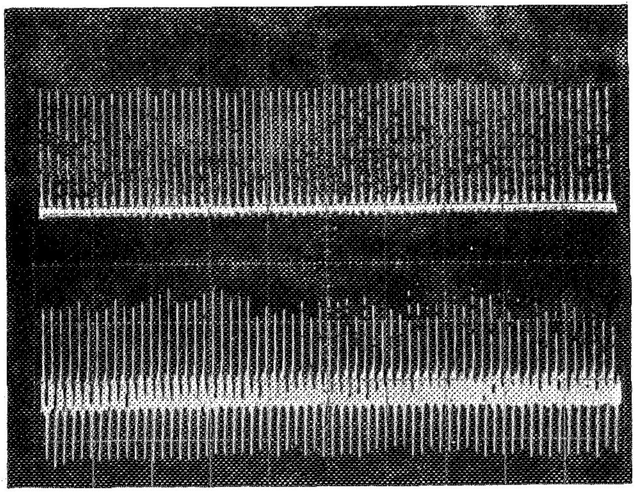


Figure 18 b

DATE: 4-11-70 TIME: 1247Z
VERT: 0.2V/cm=3dB/cm MODE: FINE
HORIZ: 5 sec/cm Sat. El. Angle=5.0°
NOTES: Top and bottom same as 18a

SHIP STOPPED IN CALM WATER

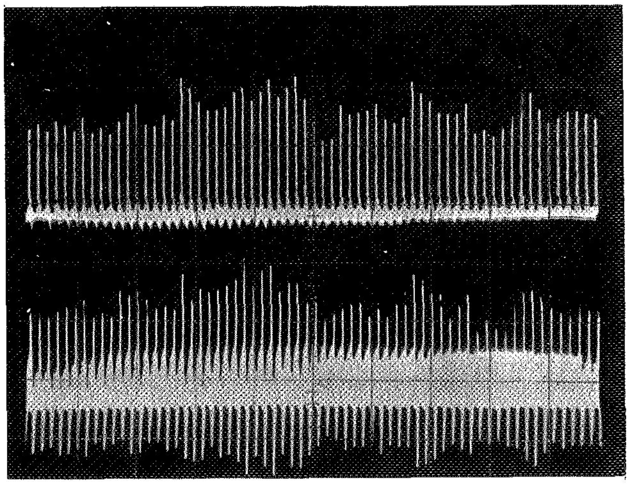


Figure 18 c

DATE: 4-11-70 TIME: 1048Z
VERT: 0.2V/cm=3dB/cm MODE: FINE
HORIZ: 5 sec/cm Sat.El.Angle = 5.0°
NOTES: Top and bottom same as 18a
SHIP MOVING THROUGH ROUGH WATER, PEAKS TO VALLEYS VARIATION IS 3 dB.

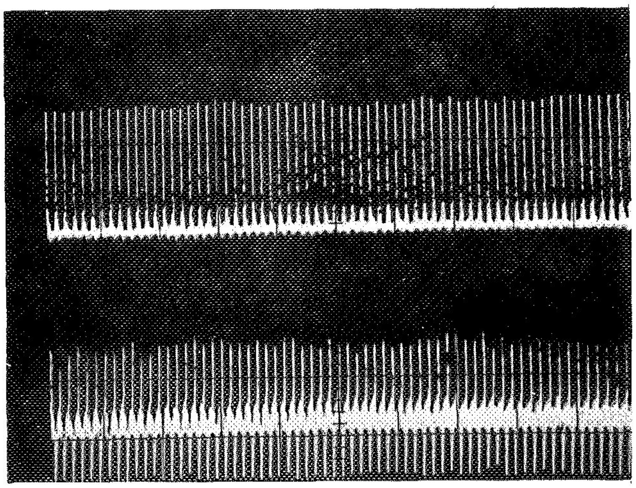


Figure 18 d

DATE: 4-15-70 TIME: 1420Z
VERT: 0.2V/cm=3dB/cm MODE: FINE
HORIZ: 5 sec/cm Sat.El.Angle=6.0°
NOTES: Top and bottom same as 18a

SHIP STOPPED IN ICE, STRONG SIGNAL

FIGURE 18 MULTIPATH EFFECTS OVER WATER AND OVER ICE

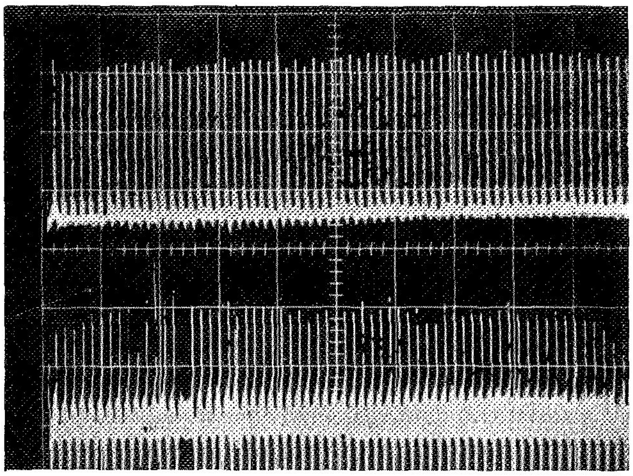


Figure 19a

DATE: 4-23-70 TIME: 1454Z
VERT: 0.2 V/cm MODE: FINE
HORIZ: 5 sec/cm
NOTES: Top: Det. Signal Output (ORION)
Bottom: Det. Sign.Output(HP312A)
Satellite El.Angle +5°

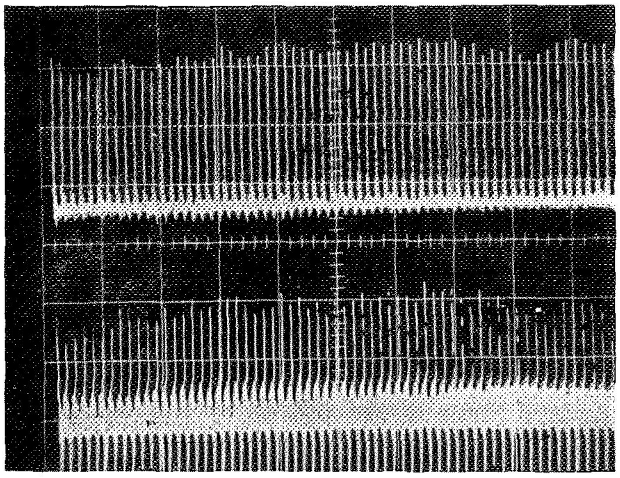


Figure 19 b

DATE: 4-23-70 TIME: 1455Z
VERT: 0.2 V/cm MODE: FINE
HORIZ: 5 sec/cm
NOTES: Top and bottom same as 19a
Satellite El. Angle +2°

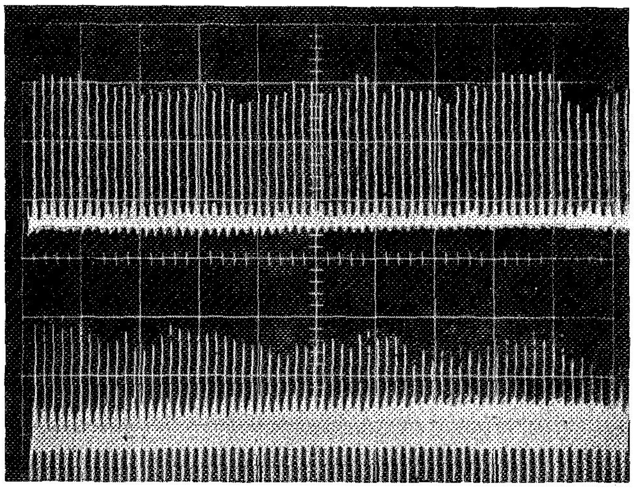


Figure 19c

DATE: 4-23-70 TIME: 1457Z
VERT: 0.2 V/cm MODE: FINE
HORIZ: 5 sec/cm
NOTES: Top and bottom same as 19a
Sat. El.Angle -1°

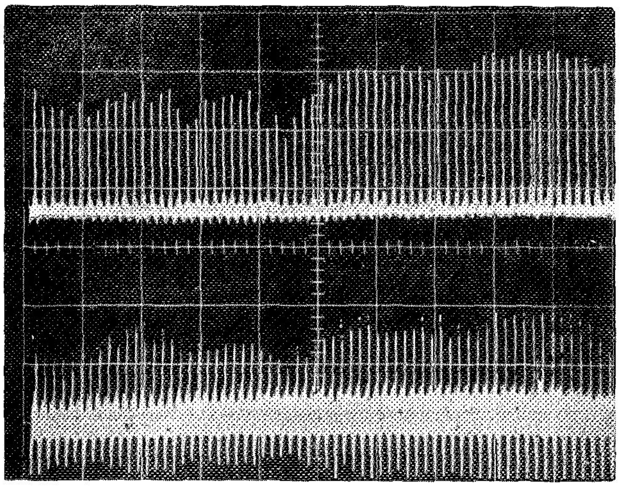


Figure 19 d

DATE: 4-23-70 TIME: 1459Z
VERT: 0.2 V/cm MODE: FINE
HORIZ: 5 sec/cm
NOTES: Top and bottom same as 19a
Sat. El. Angle -4°

FIGURE 19 CONTROLLED MULTIPATH EFFECTS OVER ICE, SAME DAY

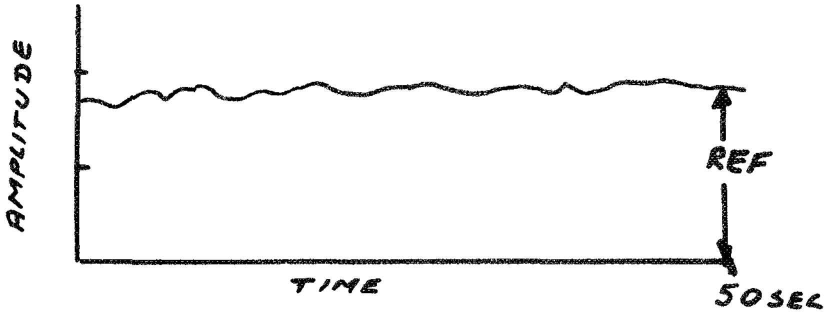
The four photographs shown in Figure 19 were taken within 5 minutes of time. The vessel was moving on a steady heading and the speed of the vessel was approximately 2 knots. The surface of the ice was solid and ruffled with ridges. The carrier-to-noise ratio during this specific test was measured to be 20.5 dB in 1.6 kHz bandwidth. (This was the highest carrier-to-noise ratio recorded during the whole experiment and apparently is due to multipath enhancement.) All four photographs were taken during the same FINE mode of the cycle. Figure 19a shows a steady stream of satellite signal bursts at +5° antenna elevation angle. The top trace which served as the refernece for all other photographs was taken at the detected signal output of the ORION receiver, the bottom trace was taken at the detected signal output of the HP 312A wave analyzer. The missing bursts on the bottom trace of Figure 19a were probably caused by the functional misfiring of either the 312A or the scope's tube memory coding. Figure 19b shows the detected signals when the antenna elevation angle was adjusted to +2°. The top and bottom traces again are comparable to top and bottom traces, respectively, of Figure 19a. All the settings were identical to Figure 19a as they will be in Figures 19c and 19d. (The horizontal time scale is 5 sec/cm and vertical amplitude scale is 3 dB/cm.) It is by now apparent that ripples occur in the stream of bursts and are assumed to be caused by multipath. In Figure 19c, the antenna elevation angle was adjusted to -1° (i.e., below the reference horizon) with all other settings remaining the same. In Figure 19d, the antenna elevation angle was adjusted to -4°. The antenna was the 3-foot dish in all cases which has a beamwidth of approximately 17° at the 3 dB points. Figure 19d shows that its lowest amplitude burst was approximately 4 dB lower than the highest amplitude burst. Because the amplitude of the bursts varied during the same 50-second period, it is judged that the variations were due to multipath effects and not due to the misalignment of the antenna elevation angle off its beam center. Figure 20 is a summary of the events that took place in Figures 19a through 19d. These traces show only the peaks of the bursts.

The variations of the amplitude of the signal due to multipath had no detectable adverse effect on the ranging function of the ORION receiver. The ORION receiver remained locked onto the modulation at all times and the ranging information contained no apparent errors due to this condition. (See Section 9.0 on Error Analysis for predicted error due to multipath.) This fact can also be supported by the amplitude modulation of the burst itself which was caused by the data transmission over the ORION--ATS-5 link. This fact is shown in Figure 21 where 43 Hz amplitude modulation appeared superimposed on top of the burst during the data transmission. The range information, that is, the range readings, were not affected by this superimposed modulation.

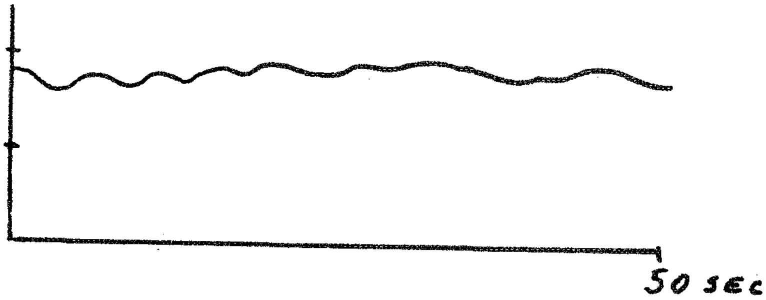
5.6 Data Channel

On April 17 the ORION Data Buffer B-701 and a teletype unit were installed at Mojave STADAN in conjunction with the previously installed ORION Modulator M-701 with the L-band equipment. Teletype data was superimposed on the FINE ranging tone modulation by these units and data communication tests were conducted on April 18, 21, 22 and 23. These teletype messages were successfully received at the AII laboratories on all of these days. (meaningful data communication was not received aboard the S. S. Manhattan because of improper data buffer circuit configuration.)

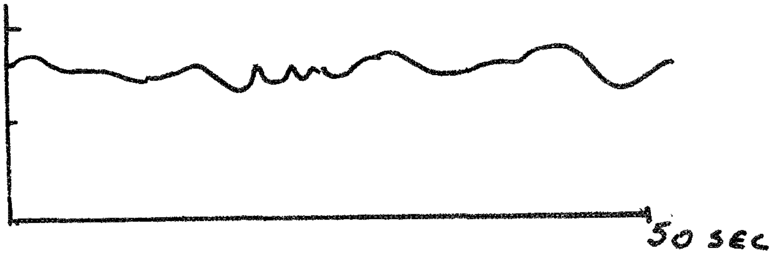
Samples of the received data TTY printouts for two of the four days of testing are shown in Data Sheets A, B, C and D. As illustrated, the received data is very readable and intelligible but does contain some errors.



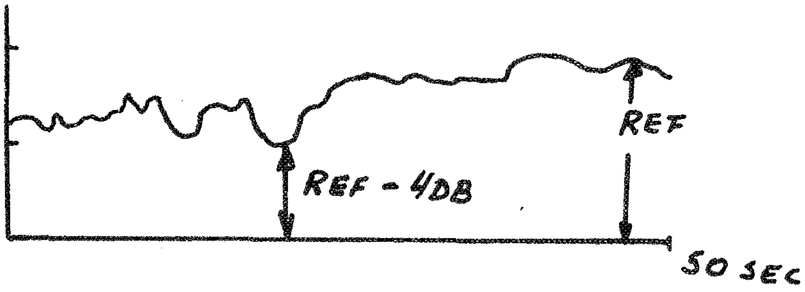
SATELLITE ELEVATION +5°



SATELLITE ELEVATION +2°

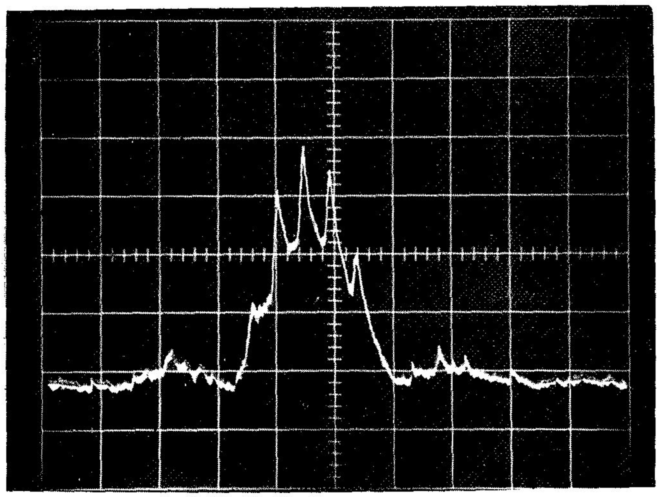


SATELLITE ELEVATION -1°



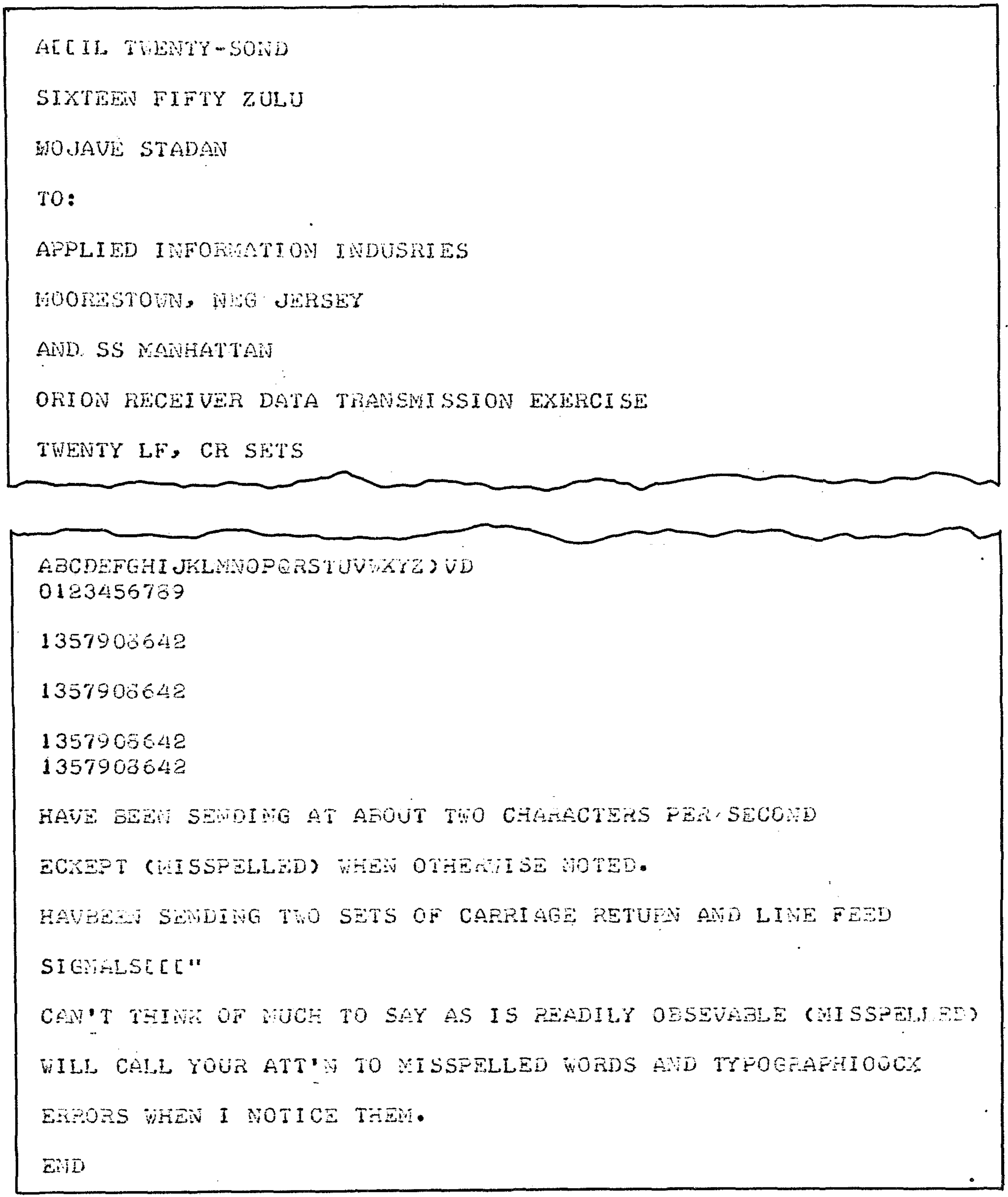
SATELLITE ELEVATION -4°

FIGURE 20 MULTIPATH EFFECTS



DATE: 4-18-70 TIME: 1507Z
VERT: 0.2 V/cm MODE: FINE
HORIZ: 50 Msec/cm
NOTES: Detected Signal Output (ORION)
Satellite Elevation Angle 5.6°
43 Hz modulation on top of FINE burst

FIGURE 21 SUPERIMPOSED MODULATION DUE TO DATA TRANSMISSION ON TOP OF FINE MODE MODULATION



```
ACCIL TWENTY-SOND

SIXTEEN FIFTY ZULU

MOJAVE STADAN

TO:

APPLIED INFORMATION INDUSRIES

MOORESTOWN, NEG JERSEY

AND SS MANHATTAN

ORION RECEIVER DATA TRANSMISSION EXERCISE

TWENTY LF, CR SETS
```

```
ABCDEFGHIJKLMNOPQRSTUVWXYZ)VD
0123456789

1357908642

1357908642

1357908642
1357908642

HAVE BEEN SENDING AT ABOUT TWO CHARACTERS PER/SECOND

ECXEPT (MISSPELLED) WHEN OTHERWISE NOTED.

HAVBEEN SENDING TWO SETS OF CARRIAGE RETURN AND LINE FEED

SIGNALS[[["

CAN'T THINK OF MUCH TO SAY AS IS READILY OBSEVABLE (MISSPELLED)

WILL CALL YOUR ATT'N TO MISSPELLED WORDS AND TYPOGRAPHIOOCX

ERRORS WHEN I NOTICE THEM.

END
```

DATA SHEET A

```
ARIL TWENTY-THI←RD

FIOOFN FIFTY ZULU
MOJAVE STADAN

TO:

APPLIED INFORMAIO INDUSTRIES

MOORESTOWN NEW JERSEY

AND SS MANHTDAN

ORION RECEIVER DATA TRANSMISSION EXERCISE

ABCDEFGHIJKLMNOPQRSTUVOWXYZ

NMMM
     FASTER:

ABCDEFGHIJKLMNOPQPSTUVOOG

2 AT A TIME RAPIDLY:

AA BB CC EE FF GG HH II JJ KK LL MM NN OO PP QQ RR SS TT UU OOFF

W X Y ZZ

11← 22 33 44 55 66 77 88 99 00

4 AT A TIME RAPIDLY:

1011 2222 3333?P4444 5555 XYY 7777 8888 9989 0000
!!!! """" #### $$$$ %HO@@& '''' (((( )))) "*
                                            * ====

:::: ---- ←←←← @@@@ [[[[[[[ \\\\ ++++ ;;;; =↑↑↑ ]]]]<<<<

,,,, .... >>>> //// ?
SLOWLY:

1111 2222 3232 44CK555 6666 7776 8888[[;@ 9199 0000

END
```

DATA SHEET B

L TWENTY-THIRD

FIFTEEN HUNDRED ZULU

MOJAVE STADAN

TO:

APPLIED INFORMAN INDUSTRIES

ORESTOWN, NEW JERSEY
AND SS MANHATTAN

BIG LOCAL BARSTOW POLITICAL ISSUE AT PRESENT IS WHETHER TO ALLOW A TOPLESS BAR IN TOWN. THE EDITORIALS IN THE LOCAL

NEWSPAPAR ARE QUITE AMUSING. MOTHEND CLERGY ARE ASKING

WHY ANY NEW FORM O[[## ENT-ERTAINMENT IS NEEDED FOR THE BOYS AT

CAMP IRWIN. AFTER ALL THEY HAVE TWO MOVIES AND "MOOGOOD

WHOLESOME CHURCH SPONSERED - ACTIVITIES." ONE MOTHER [[[["OF

FOUR FINE YOUNG CHILDREN I DON'T WANT TO BE INFLUENCED BY

PRURIENT INTERESTS" ASKS: FIRST TOPLESS, THEN BOTTOMLESS,

AND SONN - SOON WHAT ELSE?"

END

DATA SHEET C

```
APRIL TENT-THIRD

FIFTEEN TEN ZULU

XOJAVE STADAN

TO:

APPLIED INFORMATION INDUSTRIES

MOORESTOWN, NEW JERSEY

AND S'AMANHATTAN

ORION RECEIVER DATA TRXANSMISSIOOZERCISE

ABCDEFGHIJKLMNOPQRSTUVWXYZ

0123456789;?!+-%$

THE QUICK BROWN FOX JUMPS OVER THE LAHAOG

ABCDEFGHXKLMNOPQRSTUVWXYZ

0123456789 .;?]+-%$

THIS MESSAGE SEN AT ABOUT 2 1/2 CHAR/SEC.

CUTTING OUT EARLY THIS TIME FOR COFFAE AND NECESSITIES
END
```

DATA SHEET D

A count of the errors contained in the four sample messages was made. The messages contained 18, 75, 31 and 24 characteristic errors, respectively. Since each character is made up of 8 bits, the corresponding bit error rates are 1×10^{-3}, 5×10^{-3}, 2×10^{-3} and 2.5×10^{-3}, respectively.

These error rates indicate that the data channel was not operating at the theoretical 10^{-5} error rate for DPSK channel with a 12 dB carrier-to-noise ratio.

Further examination of the data channel verified this fact. This examination showed that character errors were originating in the receiver, being caused by the signal threshold pulses. This problem has been corrected.

Additional inspection of the data channel also indicated that the data rate 1.667 Kbs was not compatible with the 1.6 KHz correlator channel filters. When the data signal contained a long string of "0"s (which causes square wave modulation of the RF signal and suppressed carrier for DPSK) the signal energy passing through these narrowband crystal filters is reduced. This reduction can be noticed in photographs in Figure 21. The message from the transmitter repeats every 24 ms, thus causing the apparent 43 Hz modulation rate.

5.7 Received Frequency

Received frequency was measured at both receiving stations--AII and S. S. Manhattan. Appendix D lists all the readings which were taken on S. S. Manhattan using the wave analyzer (HP 312A) in the phase-lock mode and connected to the 4 MHz wideband port (test point) of the ORION receiver. The values shown in Appendix D indicate the upper sideband of the 4 MHz carrier when the system was in FINE mode. The values measured on 4-3-70 and 4-4-70 are plotted in Figure 22. As can be seen from the figure, the received frequency was on the low side of the expected 4083.33 KHz most of the time. No adverse effect on the performance of the receiver was noticed because of the slightly different received frequency. An upward drift trend in the frequency can be seen for each day's experiment.

Comparing the corresponding days of the received frequency measured at AII and on S. S. Manhattan, it can be seen that the two measurements are in close agreement. The almost identical frequency drift which was measured on both the moving vessel (16.2 knots on 4-4-70) and the non-moving receiving station at AII proves that the doppler shift due to ship's motion was swamped out by the received frequency drift which is mainly due to the ATS-5 L-band master oscillator offset.*

5.8 Interferences

EMI and other interferences such as primary power interruptions were present during the voyage and had a measurable effect on the performance of the receiver.

The EMI was mostly due to the high power HF transmitter on board the S. S. Manhattan and the associated equipment with it such as the TTY converter and power switching mechanisms. The EMI was found to be almost always conductive through the power lines and, hence, through the power supply of the ORION receiver. It should be noted, however, that the S. S. Manhattan carried unusually powerful transmitters with up to 3 kW emission which interfered with other electronic equipment on board. (It rendered one oscilloscope in the radio repair room inoperative.) The power lines into the navroom where the ORION installation was located

---

* The average drift rate of the ATS-5 L-band master oscillator is between 100 Hz/hr to 500 Hz/hr depending on length of time that the satellite has been ON. Initial off-set is 4000 Hz from nominal after one hour of ON time, and 800 Hz after ten hours of ON time. The initial offset was corrected for by STADAN by using a frequency synthesizer as the basic frequency exciter. No corrections for the drift were made during the daily experiments.

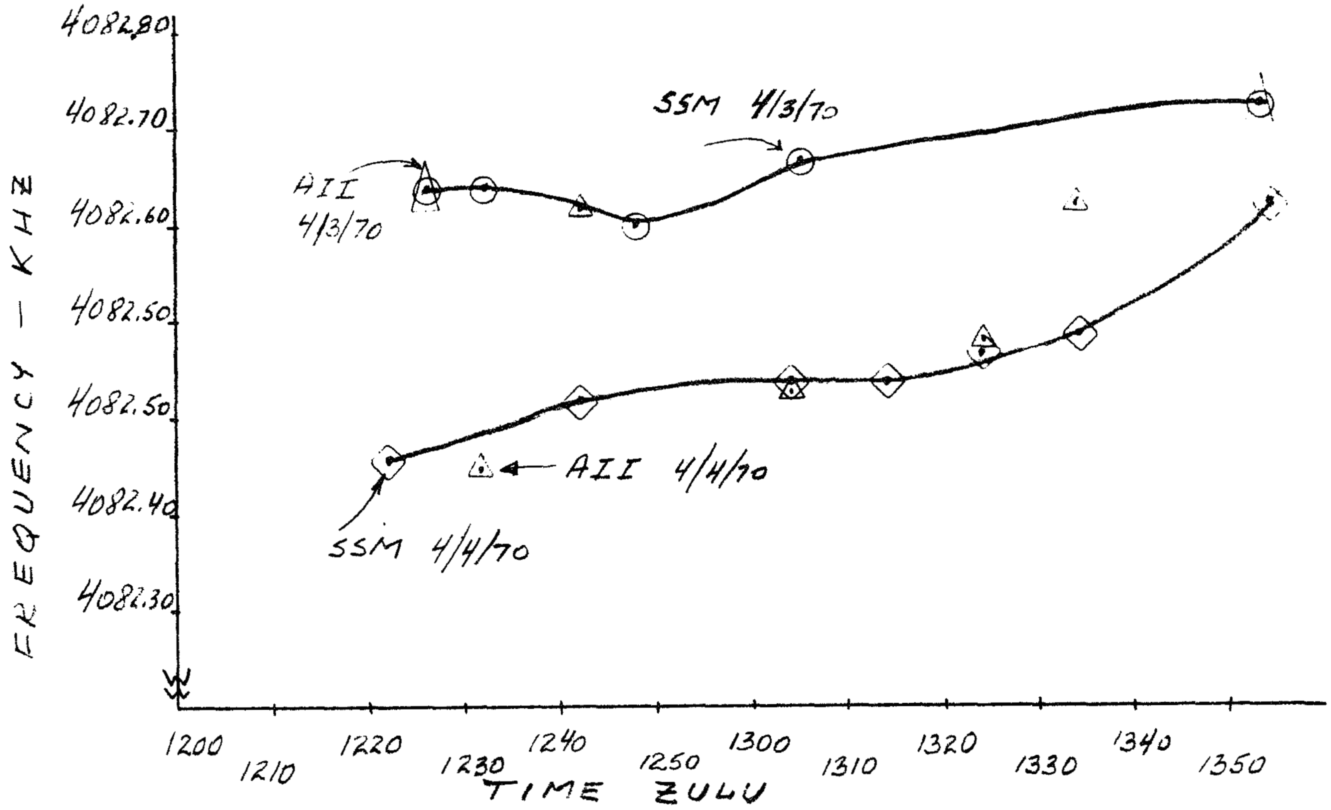


FIGURE 22 RECEIVED FREQUENCY VERSUS TIME

contained a special filter-transformer for the protection of the equipment. Thus, the ORION receiver was protected against burn-outs.

The effects were detectable in the range determination where the range readout changed everytime an especially powerful random pulse of EMI would get into the reference counter of the computer subsystem of the ORION receiver. This meant that the phase tracking was interrupted (just the same as it would be interrupted by a power failure) and the range readout indicated a different position within the lanewidth from the previous last position. This type of erroneous indication was readily detectable in the COARSE mode (lane) of operation.

During the 62.3 hours of signal reception, which consisted of 374 mode cycles, there were 41 "lane change" interferences of the EMI type which calculates to be 10.9% of the total.

This means that 10.9% of the time during which the ranging information was being gathered the phase reference was interrupted. Due to the presence of this type of interference and also to primary power failure (which occurred 3 times during the trip while the signal was not on) the determination of LOPs was referenced to the vessel's daily position fixes from other navigation systems. This problem can be and will be solved in future models by better filtering of the power lines and/or by providing standby power supplies not dependent on the available AC power. In operational three-satellite navigational systems, problems of this type will be minimized because reference will be continually updated from the satellites. As mentioned previously the Rubidium frequency standard was provided with a standby battery power supply which automatically supplied the power in case of the primary power failure.

6.0 ERROR ANALYSIS

We are concerned in this section with estimating how well the tests demonstrated accurate navigation with the ORION system over large variations of latitude, longitude and elevation angles.

Measurements of navigation accuracy can be made by comparing the measured position with a more accurate measurement standard. Since there is no known standard more accurate than ORION operating in the Arctic, the direct measurement of system accuracy is not feasible.* It can only be referenced to available on-board navigation systems. The direct measurements of accuracy should be done in the near future by comparison with precise radar positions or with well defined optical or map systems. Relative navigation comparisons are the only contemplated accuracy measurements.

The overall systems error will be derived from a comparison of the known motion of the ship and the motion of the lines of position over a period of time.

Noise error will be determined from the repeatability of successive range measurements again over a short time base. Clock instability errors will be estimated from theoretical and, when known, measured data.

6.1 Overall Systems Errors

While a more complete description of the derivation and analysis of the measured lines of position is given in Appendix A a comparison of ship's motion with successive lines of position will be made. The results are relative over the span of LOPs and such factors as ionospheric, tropospheric, long-term clock stability, and alignment errors are not apparent in these measurements since these

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* The Transit navigation system was not always able to get a positive position fix at high latitudes. This was due to the fact that the Transit satellites were close to one another in their orbital position and the receiver did not have ample time to acquire and process fixes from two consecutive satellites.

factors are expected to be slow functions of time and the measurement time interval is short. The extension of times of observation was prevented by power interruptions and radio frequency interference on the S. S. Manhattan.

Selection of data on days when no RFI and ship's power failures interrupted the system was made and a comparison of lines of position and expected motion of lines of position are shown in Tables VIII and IX. One day the ship was stopped in the ice, and on the other day the ship was moving at constant velocity.

6.2 Navigation Accuracy

There are a number of factors in the system that prevent perfect measure of position. These perturbations are internal (machine) errors, external (environmental) and geometric errors. A list of important error sources is as follows:

- (a) Internal Errors
    - (1) Noise
    - (2) Clock Stability
    - (3) Alignment
    - (4) Quantization
- (b) External Errors
    - (1) Multipath
    - (2) Ionospheric Delay
    - (3) Tropospheric Delay
- (c) Geometric Errors
    - (1) Satellite Position Uncertainty
    - (2) Geometric Dilution

6.2.1 Internal Errors

Noise

The error due to noise can be calculated from the relation

$$\sigma_N = \frac{W}{2\sqrt{2 \frac{S}{N}}}$$

TABLE VIII

S. S. MANHATTAN DEAD IN THE ICE - 14 APRIL 1970

ERROR ANALYSIS

Z Time	LOPs from Apparent Motion of the Ship	Measured Distance between LOPs	Apparent Error
1428	Reference Position		
1438	0	.07	+126 meters
1448	0	.20	+360
1630	0	.09	+162
1730	0	.79	+1420
1830	0	.20	+360

TABLE IX

S. S. MANHATTAN COURSE 055°, SPEED 16.5 KNOTS - 4 APRIL 1970
ERROR ANALYSIS

Z Time	LOPs from Apparent Motion of the Ship	Measured Distance between LOPs	Apparent Error
1230	Reference Position		
1240	2.70 nmi *(5000 m)	3.60 nmi	+1620 meters
1250	2.70	3.34	+1150
1300	2.70	3.64	+1698
1310	2.70	1.09	-2910
1320	2.70	3.36	+1160
1330	2.70	2.94	+ 422
1340	2.70	2.95	+ 430
1350	2.70	3.31	+1100

* One nautical mile = 1852 meters

where W is the narrowest effective lane width and S/N is the system signal to noise ratio.

The average signal to noise ratio in the 1600 Hz filter was 16 dB. After the sample and hold filter has been gated on for 25 ms, the minimum time the system is expected to have a signal available during one rotation of the satellite, the 20 samples will provide an improvement of signal to noise of 14 dB and the integrated signal to noise ratio is 30 dB at the 40 Hz filter.

The noise error in the minimum lane width (0.97 nmi = 1800 m) is:

$$\sigma_N = \frac{1800}{2\sqrt{2000}} = 20 \text{ m}$$

The noise error in the widest lane width (97 nmi) is:

$$\sigma_N = \frac{180{,}000}{2\sqrt{2000}} = 2{,}000 \text{ m} = 1.08 \text{ nautical miles}$$

Data was taken on the S. S. Manhattan before getting underway and subsequently during the voyage. Using the COARSE range reading the standard deviation about the mean was calculated and Table X lists the results.

TABLE X

Date	Standard Deviation (s) (nmi)
31 March 1970	.78, .59, .60, .89, .95
14 April	1.52, 1.18, 1.16, 1.50
15 April	1.04, 3.05, 2.31, .89
21 April	.57, .68, 2.24, 3.11, 1.05
22 April	2.44, 2.04, 2.27, 2.44
23 April	1.23, .34, .42, .84, 1.77
24 April	.61, 2.75, .56, .33

The data is in good agreement with the estimated value, 1.08 nmi. <u>This is 1% of lane width.</u> (This noise error in the FINE lane is masked by the quantization error.)

<u>Clock Stability</u>

The error due to clock instability is due primarily to two factors, initial frequency misalignment and frequency drift.

The error due to frequency misalignment is given by

$$\varepsilon\Delta_f = \frac{\Delta f}{f} \cdot \varepsilon\, t$$

where Δf is the initial frequency error between the two oscillators, f is the carrier frequency, ε is the speed of light and t is the elapsed time from the initial setting.

When the clocks are Rubidium frequency standards, the initial alignment can be made to two parts in 10^{12}. Hence

$$\varepsilon\Delta_f = 2 \times 10^{-12} \cdot 3 \times 10^{8} \cdot 3600 \cdot 24 \text{ meters/day}$$

$$\varepsilon\Delta_f = 50 \text{ m/day}$$

Two standards were compared in the AII laboratory before the voyage. No attempt was made to align the initial frequencies. Instead the frequency difference was compensated in the computer program. The results of the tests are shown in Table XI below.

The compensation used in the computer program was 1650 m/day; 825 m/12 hr. period. The last two days of the data agree closely with this number. The standard deviation about this number is $\sigma = 60$ m.

The frequency drift relation is given by

$$\varepsilon_{\cdot f} = \frac{\Delta f}{f} \cdot \frac{CT}{2} \left(\frac{t}{T}\right)^2$$

TABLE XI
RUBIDIUM FREQUENCY STANDARDS INSTABILITIES

Time Interval	Change of Time Between Zero Crossings	Equivalent Range
0 - 12 hrs.	2245 nanoseconds	674 m
12 - 24	2312	694
24 - 36	2410	723
36 - 48	2645	794
48 - 60	2515	754
60 - 72	2885	866
72 - 84	2620	786
84 - 96	2820	846
96 - 108	2722	817

where the rate of drift of one oscillator with respect to the other is $\frac{\Delta f}{fT}$. The frequency standard drifts about 10^{-11} in a month. Hence

$$\varepsilon._f = 10^{-11} \cdot \frac{3 \times 10^8 \times 3 \times 10^6}{2} \cdot \left(\frac{t}{T}\right)^2$$

$$= 4500 \left(\frac{t}{T}\right)^2 \text{ meters}$$

where T is one month.

Table XII describes the error due to frequency drift.

TABLE XII

t	ε_f
1 day	5 m
2	20
3	45
5	125
10	500

Alignment errors

Alignment errors if not properly compensated give a bias to range readings. When the system is slightly non-linear, there is usually a change in readings due to delays through equipments changing with the signal strength. The alignment error of the system is expected to be about 1% of the lane width due primarily to the linearity of the phase detector of the correlator. The uncorrected alignment error is expected to be about 20 meters, assuming the ATS-5 delays remain as measured prior to launch.

Quantization

Final quantization to 300-foot intervals in the system will give an error of about

$$\sigma_Q = \frac{q}{\sqrt{12}} = \frac{300}{3.4} = 89 \text{ ft.} = 25 \text{ m}$$

where q is the quantization interval (quantum).

6.2.2 External Errors

Multipath

The error due to multipath is caused by the simultaneous reception of the signal over more than one path. One path is normally the direct signal path and the other the principal reflected signal path. The reflected signal is normally reflected from the ocean and arrives later than the direct signal traversing at least an extra mean path length

$$\Delta_L = 2\ h \sin \psi$$

where ψ is the grazing angle and h is the height of the antenna.

The reflection appears to be concentrated at a specular point in the smooth ocean, similar in behavior to the reflection of the sun in the water. The ocean away from the specular point (hot spot), which is located at the negative grazing angle, also contributes but to a lesser extent than the region near the grazing angle. If the sea were perfectly smooth only the hot spot which would then approach a point would operate. The roughness of the ocean (the usual state) will contribute a diffusion to the mirror-like reflection causing a reduction in the signal strength of the reflected signal, a spreading in frequency and time of arrival.

The measurement program carried out on the S. S. Manhattan provided an opportunity to measure the effects of multipath a t low grazing angles from ocean as well as ice surfaces.

Errors from multipath will be considered to be statistical rms errors. The period of independence is not known but is closely related to the motion of the antennas on the aircraft or ship. The estimated error is approximately

$$\sigma_m = \frac{W}{2} \sqrt{\frac{\rho G\ (-\psi)}{2}}\ R\ (\tau)$$

where W is the lane width, ρ is the reflection coefficient of the principal reflection , G $(-\psi)$ is the relative antenna gain at the negative grazing angle and R (τ) is the autocorrelation function of the reflected signal. Measured extreme cancellation of 4 dB implies a reflection coefficient, $\rho = .2, G(-\psi) = 1$ when the elevation is 5^{o}, r (τ) has a value of .01. Then,

$$\sigma_m = \frac{1800}{2} \sqrt{\frac{.2}{2}} \; (.01)$$

$$\sigma_m = 4 \text{ meters}$$

This is a single sample estimate of multipath from measured sea reflections during the Manhattan tests.

Effects of the Ionosphere and Troposphere

The principal effect of the ionosphere and troposphere on the proposed measurement program is to increase the effective path length between the ATS-5 satellite and ground station or ship. While a part of the refractive delay is predictable with a priori knowledge of the geometry between the ground station or ship and the satellite, time of day and year, sun spot activity and surface conditions, a portion of the effect will be unpredictable, varying with anomalies in the ionosphere and troposphere. Extensive literature exists on refraction phenomena representing enormous amounts of modeling and data. The following sections on ionosphere and tropospheric effects are a condensation of many references reviewed to arrive at a reasonable estimate of both ionosphere and the troposphere refraction effects.

Ionospheric Effects

The incremental path length (difference between effective path length and free space path length), ΔL, due to ionospheric refraction is (1)

$$\Delta_L = \frac{135\ N_T\ Q\ (\psi)}{f^2}$$

where N_T is "total electron content." Number of free electrons in a vertical column of one square meter cross-section through the ionosphere;

$Q(\psi)$ is "obliquity factor," a function of elevation angle, ψ, to the satellite; and

f is carrier frequency.

The total electron content, N_T, varies about its approximate mean of $10^{17}/m^2$ by at least a factor of ten in each direction. Figure 23 presents a plot of the variation in incremental path length versus elevation angle for a nominal value of N_T of 10^{17} and extreme values of 0.7×10^6 and 1.3 and 10^{18}. The principal variation of N_T in the ionosphere is with sun spot number, time of day, season and latitude. In addition, there are day-to-day fluctuations, simultaneous spatial variations due to ionospheric irregularities, and short term (order of minutes) variations due to motion of the irregularities.

At 5° elevation angle from the ship to the ATS-5 satellite, the mean path length deviation is anticipated to be approximately 20 feet with extreme values between 1 and 300 feet possible. Little change in path length is expected as the elevation angle varies between its maximum excursions of ± 2 degrees.

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(1) R. S. Lawrence, C. G. Little, H. J. A. Chivers, "A Survey of Ionospheric Effects Upon Earth-Space Radio Propagation" Proc. IEEE, Jan. 1964, pp 4-27.

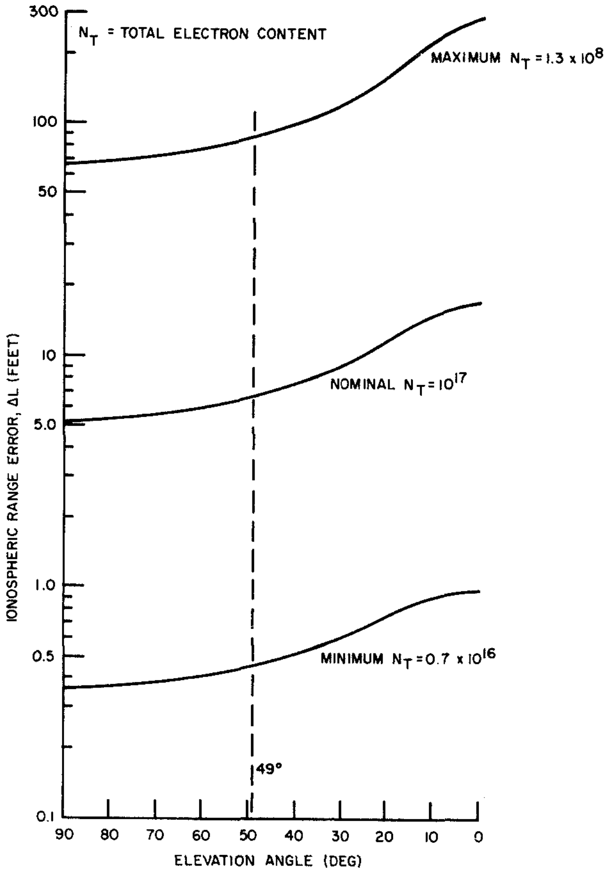


FIGURE 23 VARIATION IN INCREMENTAL PATH LENGTHS VERSUS ELEVATION ANGLE FOR VARIOUS N_T, THE TOTAL ELECTRON CONTENT

The uncertainty in N_T at a particular time and place is estimated to be approximately 30%. The uncertainty includes a ±20% day-to-day variation, the uncertainty in smoothed sun spot number (which at the time of use is a predicted quantity), and uncertainties in the model itself. In addition, at any one time there will be a random spatial variation of N_T due to the presence of irregularities in the ionosphere. This variation is in the order of ± 5% with a correlation length of a few kilometers.

Tropospheric Effects

The incremental path length due to the troposphere is, in comparison to the ionosphere, well predictable and independent of carrier frequency in the range of 100 MHz to 10 gHz. The refractivity of the troposphere is given by

$$N = 77.6 \frac{P}{T} + 3.73 \times 10^5 \frac{e}{T^2}$$

where P is total atmospheric pressure in millibars
e is water vapor pressure in millibars
T is temperature in degrees Kelvin

The Central Radio Propagation Laboratory of the National Bureau of Standards developed and adopted for prediction of refraction phenomena in the troposphere the CRPL Exponential Reference Atmosphere model. The results of this model is plotted in Figure 24 for two extremes of surface refractory versus elevation angle. With a priori knowledge of the approximate elevation angle to the satellite, barometric pressure and humidity at the receiver, the error to the tropospheric path length can be reduced to very small values.

With reference to Figure 24 at 5° elevation angle the incremental path length anticipated will be approximately 90 feet with extreme value expected of ± 10 feet depending on tropospheric conditions at the time of the measurement. As is the case with the ionospheric

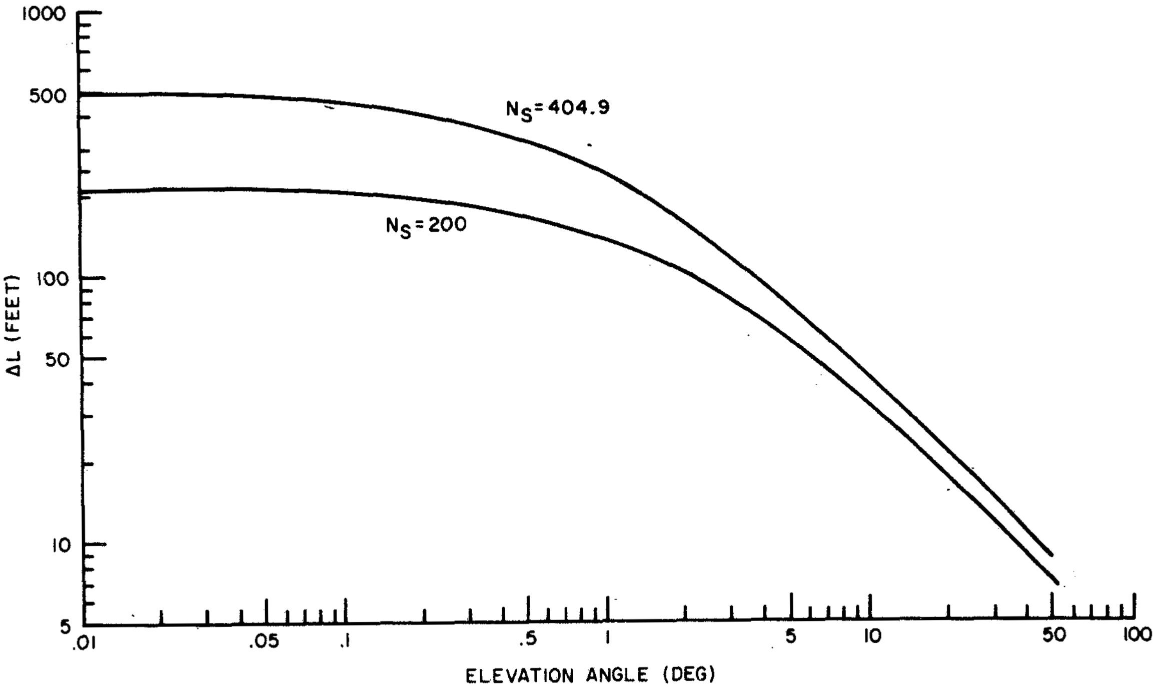


FIGURE 24 TROPOSPHERIC EFFECTS, ELEVATION ANGLE VERSUS INCREMENTAL LENGTH

delay, a variation in incremental path length of ± 10 feet is expected due to elevation angle variation between 3^{o} and 7^{o} as the satellite goes through one orbital period.

Table XIII presents a summary of the range errors due to internal and external sources

TABLE XIII

RANGE ERROR SUMMARY BASED ON 1 NMI LANEWIDTH

Source	Error
Noise	20 m
Clock Stability	50 m/day *
Alignment	20 m
Quantization	18 m
Multipath	4 m
Ionospheric Delay	6 m
Tropospheric Delay	28 m
TOTAL - RMS Range Error	71 m

* Residual after compensation

6.2.3 Geometric Errors

Errors caused by the geometry of the measurement will cause additional dilution of accuracy.

Satellite Position Uncertainty

The position of the ATS-5 satellite is known to an accuracy defined by an ellipsoid with semi axes of 2, 1, and 1 km. The actual position of the satellite is the estimated position at the center of the ellipsoid plus a vector whose rms length is defined by the intersection of the vector and the ellipsoid. This vector at a given time may be shorter or longer than the rms length and its direction can be any direction whatsoever.

The range to the satellite from any observer is the range to the estimated position of the satellite plus the scaler product of the error vector and the direction unit vector from the observer to the satellite. The range error is given by that scaler product

$$\sigma_{SP} = r_o \cdot r_e$$

where r_o is the unit direction vector and r_e is the error vector.

Two observers at different geographic locations will measure range with different errors because their unit direction vectors are different. The error in taking range differences between observers is hence

$$\sigma_{SP\Delta} = r_{01} \cdot r_e - r_{02} \cdot r_e$$

$$= r_e \cdot (r_{01} - r_{02})$$

The S. S. Manhattan at 70° N and the AII plant at Moorestown, New Jersey, at 40° N are separated by about 1800 miles on the earth. Their unit direction vectors diverge by about 3.4° while observing the ATS-5. The mean vector length $||r_e||$ is 1.4 km. The expected value of range error caused by satellite position uncertainty is given by

$$\sigma_{SP\Delta} = (1400)\ (\frac{1}{17}) = 82 \text{ m}$$

maximum.

Geometric Dilution

The dilution of accuracy of lines of position from equatorial synchronous satellites is given approximately by

$$\sigma = \sigma_R \text{ CSC } L$$

where σ_R is the total rms error of range including satellite uncertainty and L is latitude of the observer. In the Arctic, say at 70° N latitude

$$\sigma = 1.13\ \sigma_R$$

The total range error is given by

$$\sigma_R^2 = (71)^2 + (82)^2$$

$$\sigma_R = 110 \text{ m}$$

The net error in the LOPs is given by

$$\sigma = (1.13)\ (110) = 124 \text{ m}$$

7.0 RECEIVER DESCRIPTION - MODEL R-701

7.1 Introduction

The ORION receiver shown in Figure 25 is a highly sensitive L-band, all solid state equipment using a double hetrodyne configuration. The actual receiver input frequency is 1550 MHz and the first and second intermediate frequencies are 70 and 4 MHz, respectively. The first and second injection chains at 1480 MHz and 66 MHz are directly synthesized from the 1 MHz and 5 MHz outputs of the frequency standard. The receiver is a correlation type and is coherent with regard to the carrier modulation codes which are transmitted using a two-phase PSK modulation format. The ranging modulation rates used are 833 Hz, 8,333 Hz and 83,333 Hz corresponding to 97, 9.7 and 0.97 nautical mile transmission path increments. The receiver is of the sample-and-hold type using a digital modulation tracking loop and operating only when the decoded received signal exceeds a predetermined signal-to-noise ratio.

The characteristics of the receiver are outlined in Table XIV. The following major subassemblies make up the present ORION receiver:

- RF and first mixer IF
- Local oscillator injection system
- Second mixer and IF
- Correlator
- Digital ranging computer

7.2 RF and First Mixer - IF

The RF preamplifier used is a broadband unit centered at 1550 MHz providing a 4.5 dB noise figure. The 3 dB bandwidth is 40 MHz and the gain at 1550 MHz is 25 dB. A filter follows the RF amplifier

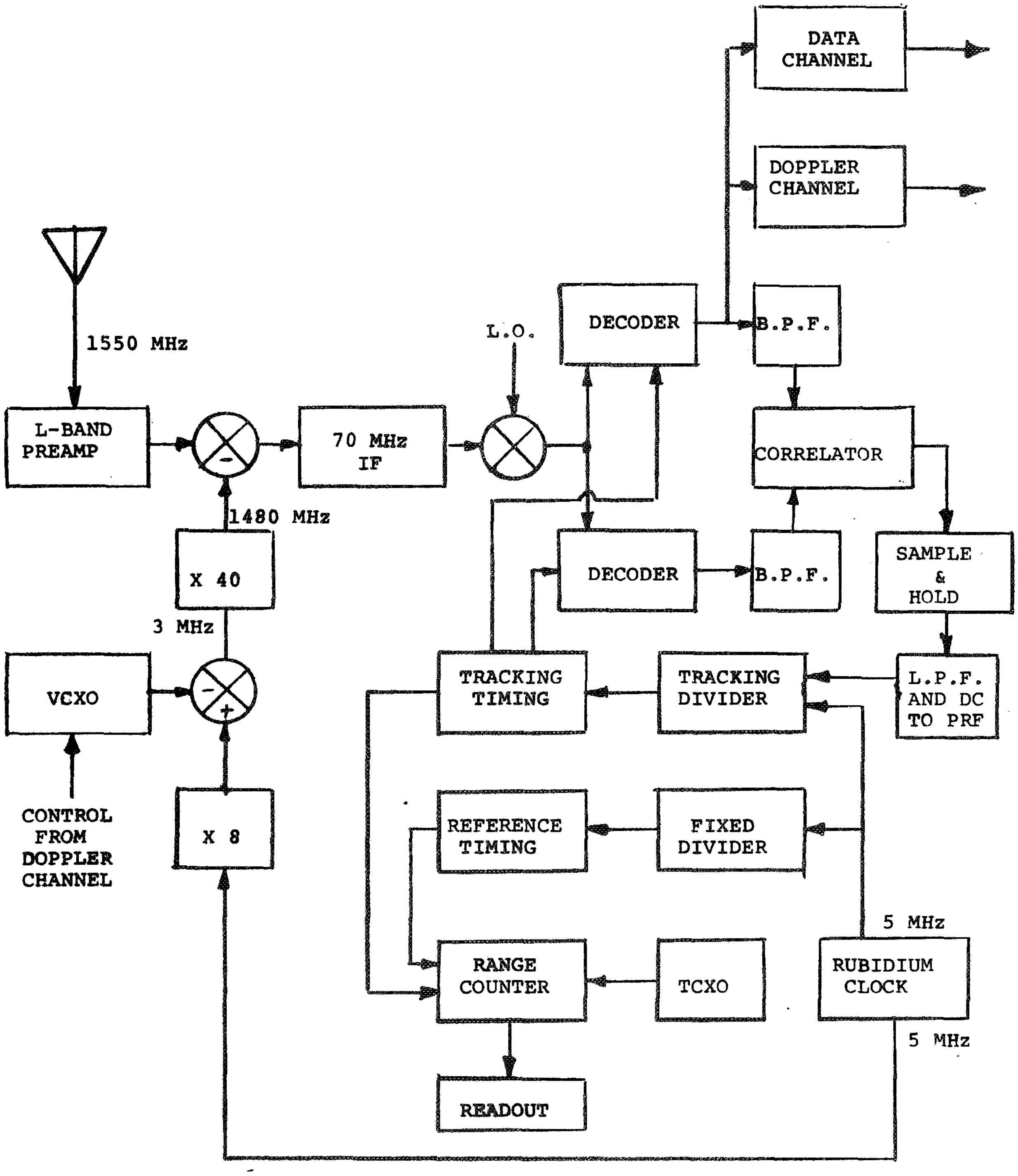


FIGURE 25 RECEIVER BLOCK DIAGRAM

TABLE XIV

RECEIVER CHARACTERISTICS

Range Resolution	0.05 nmi
Range Accuracy	0.01 nmi
Range Lanewidth	97, 9.7, 0.97 nmi
Maximum Range	Global
Lock-up Time	100 ms (continuous signal or spinning ATS-5)
Communication Rate	5 characters/sec TTY with spinning ATS-5
Navigation Tone Frequencies	833 Hz, 8,333 Hz and 83,333 Hz
Acquisition Bandwidth	1.6 KHz
Lock-on Bandwidth	40 or 4 Hz
Noise Figure	4.5 dB
Frequency	1550 MHz
I.F., First	70 MHz
I.F., Second	4 MHz
Decoders	2
Modulation	Phase Shift Keying
Clock Stability	1×10^{-11} per day
Initial Alignment	1×10^{-12}
Antenna Gain	17 dB (two-foot diameter dish) 20 dB (three-foot diameter dish)
Antenna to Receiver Cable Loss	2.5 dB
Polarization	Right Hand Circular
Antenna Beamwidth	25° (two-foot diameter dish) 17° (three-foot diameter dish)

to remove the image noise. The first mixer has a balanced configuration and uses Schottky-barrier junction diodes. It has an 8 dB conversion loss and an 8 dB optimum noise figure when driven with a local oscillator injection of proper power level. The down converter is functionally packaged with a 70 MHz IF preamplifier.

A 70 MHz IF amplifier with 8 MHz 3 dB bandwidth and 50 dB of gain follows the preamplifier.

7.3 Local Oscillator/Injection Chains

Two frequency multiplier chains are used on the ORION receiver to provide the local oscillator injection signals to the first and second mixers respectively. The first chain using x 40 configuration provides a nominal 10 mw 1480 MHz signal. The 5 MHz and 1 MHz drive signals for this chain are obtained from the frequency standard. Special attention has been directed at removing undesirable multiplication products and spurious signals in this chain. Adequate filtering using quartz crystal, lumped constant, resonant cavities and microwave stripline structures provides at least 60 dB of rejection to unwanted signals.

The second local oscillator injection signal is generated from the 1 MHz frequency standard output using circuitry with x 66 frequency multiplication ratio. 10 mw of 66 MHz signal is provided and undesired spurious and harmonically related outputs are suppressed 45 dB.

7.4 Second Mixer and IF

A double balanced mixer provides the second receiver frequency translation to a 4 MHz IF. The output of this mixer is amplified in a 4 MHz IF amplifier which provides 50 dB of gain. AGC function is incorporated in the amplifier so that total signal and noise energy can be normalized at the output of the amplifier. The amplifier can accommodate ± 15 dB input level variation. The 4 MHz IF frequency chain contains crystal filters of 1.6 KHz bandwidth. (The response curves of the crystal filters are shown in Figure 26.)

7.5 Correlator

A block diagram of the correlator is shown in Figure 27 and the correlator specifications are listed in Table XV.

TABLE XV

CORRELATOR REQUIREMENTS

Input Frequency	4 MHz
Pre-correlated BW	1.6 KHz, 3 dB
2 Channels	In-phase, Quadrature
Input Impedance	50 ohms
Peak Output	± 2.5 V
Output Impedance	1 K ohm
Linear Channel Gain	40 dB
Linear Channel DC Output	DC coupled

The correlator measures the error between the incoming modulated 4 MHz and the locally referenced 4 MHz. The output of the correlator is a d-c voltage proportional to the phase error between the two signals.

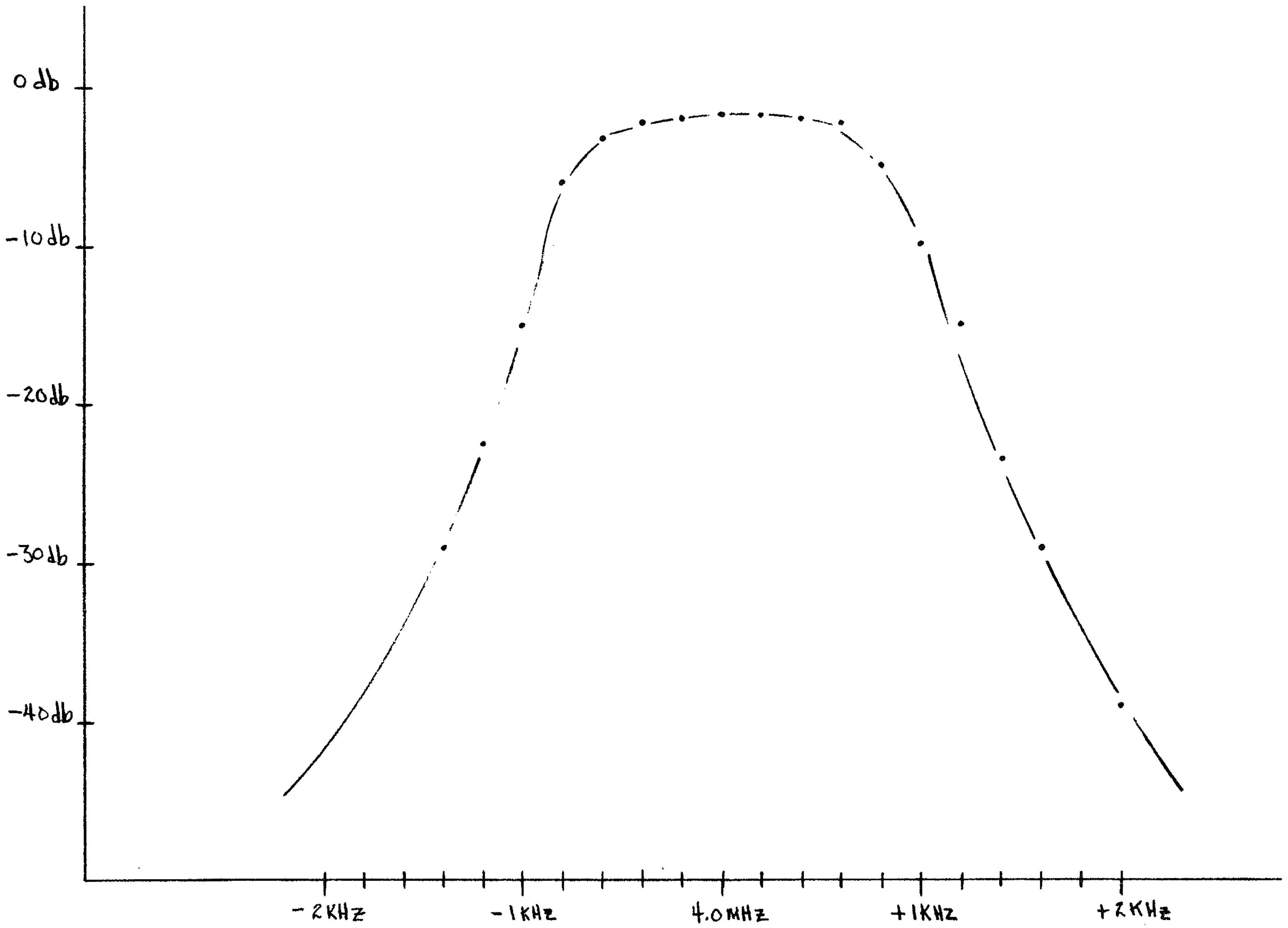


FIGURE 26 ACTUAL MEASURED RESPONSE CURVE OF THE CRYSTAL FILTERS IN THE CORRELATOR OF THE ORION RECEIVER ON BOARD THE S. S. MANHATTAN

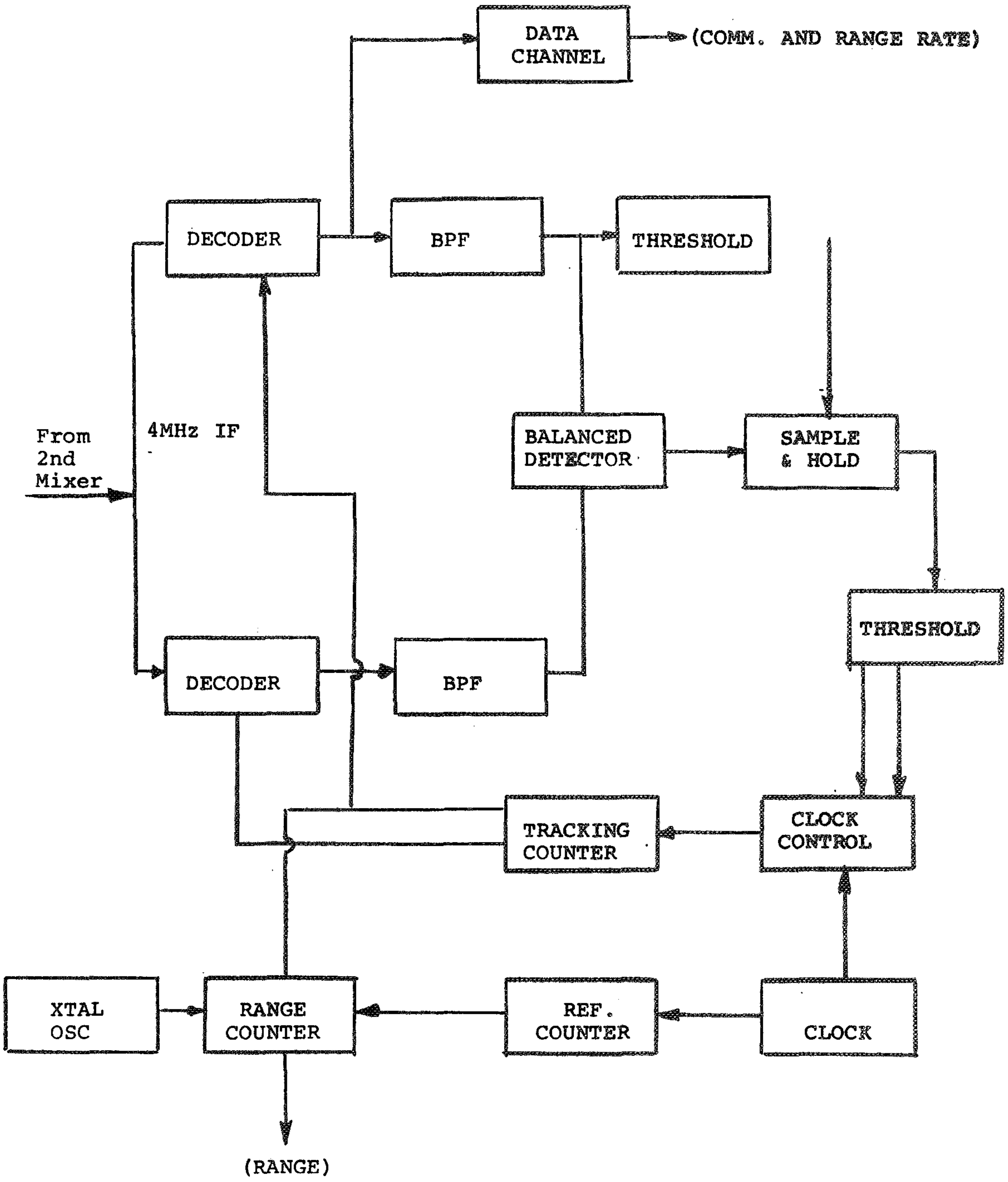


FIGURE 27   ORION CORRELATOR AND DIGITAL SECTIONS

7.6 Digital Tracking Loop

When a received signal appears at some arbitrary phase of the modulation code, the output of the correlator will produce either a positive or negative error voltage indicating a direction which the tracking counter must be moved in order to exactly match the phase of the received signal. This error voltage causes a frequency counter to insert or delete pulses in the computer and thus move the tracking counter to a position which will ultimately coincide with that of the received signal modulation.

7.7 The Sample and Hold Function

The essential characteristic of the control loop is its ability to maintain a memory of the signal at any point at which the signal disappears; thus, as the satellite beam sweeps through the receiver the closed loop action proceeds at its normal rate and continues until the signal disappears. The loop remains at this position until the signal reappears and then proceeds to move closer to lock-up. This action is unique in the ORION receiver, and it provides the entire basis for the ability of this receiver to lock-up onto the spinning satellite and perform precise ranging measurements.

7.8 Range Counter

Following lock-up of the digital control loop, the ranging computer performs the function of precisely measuring the phase displacement of the tracking wave with respect to the reference wave which is synchronized with that at the Mojave transmitter. The range counter provides a 0.05 nautical mile granularity to the range readout. The display on the front panel of the receiver is thus nautical miles to the nearest 0.05 and is approximately the same as the range computer granularity of 0.2 microseconds or approximately 300 feet.

Range Rate Operation

It is of interest in most applications of a passive navigational system to be able to derive the velocity of the vehicle on which the receiver is located. The ORION receiver is provided with an output port where the doppler shift from the received carrier can be measured and thereby the radial velocity component of the vessel can be determined. The doppler signal is measured at the 4 MHz IF signal point. This signal is precisely at 4 MHz for stationary condition to an accuracy determined by the frequency standards in the system. Any deviation from 4 MHz should be produced by the doppler shift. However, at the present time, the translation of frequency in the ATS-5 satellite produces a frequency error which tends to mask the doppler during the periods in which the satellite offset oscillator is warming up. As this stabilizes to a constant frequency, the doppler component may possibly be accurately measured.

7.9 Data Channel Operation

The data channel has the function of taking the received signal from the reference channel and deriving the data information from the signal. The ATS-5 satellite, as it rotates on its axis, sweeps a beam through the receiver for a period of approximately 50 milliseconds on each rotation. (The rotation rate is 76 RPM, or once every 800 milliseconds). However, the Mojave Station is in common time with the receiving stations (for this experiment) for only 30 out of the 50 milliseconds,and ranging and communications is possible only during these 30 milliseconds. In order to transmit useful data during this period, it is necessary on the transmitting end to buffer the low data rate and transmit it at a higher rate during the period of common time radiation.

The function of the data channel in the ORION receiver is to demodulate the burst data signal. The ORION data channel output must be processed in an external box to reconstitute the original data rate and drive a teletype which will operate at approximately 40% of its normal speed. Figure 28 shows a block diagram of the data encoder and Figure 29 shows a block diagram of the decoder.

7.10 Data Demodulator

A one-way data communication link was established in the ORION link by superimposing the data information on the ranging code utilizing differential-phase shift key modulation. DPSK modulation follows the rule that the phase of the transmitted signal, in this case the range code, is changed for a data "mark" and is not changed for a data "space." DPSK modulation provides error rates only slightly poorer than coherent phase shift key modulation. This communication technique was designed and incorporated in the ORION receiver and was demonstrated to be easily workable. Testing prior to the ship's sailing indicated that adding the communication data to the range code did not affect either the accuracy of the range measurements or degrade the probability of detection of the data communication signal.

7.11 Threshold Detector

Figure illustrates the circuitry which measures the RF signal strength, the frequency and the doppler shift of the incoming carrier. The circuit operates by sampling the 4 MHz signal at the narrowband point of the chain.

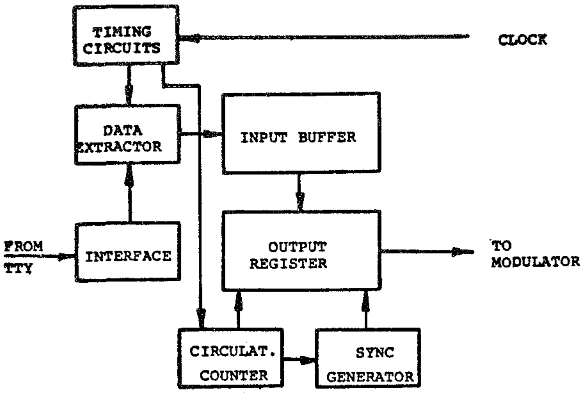


FIGURE 28

DATA ENCODER

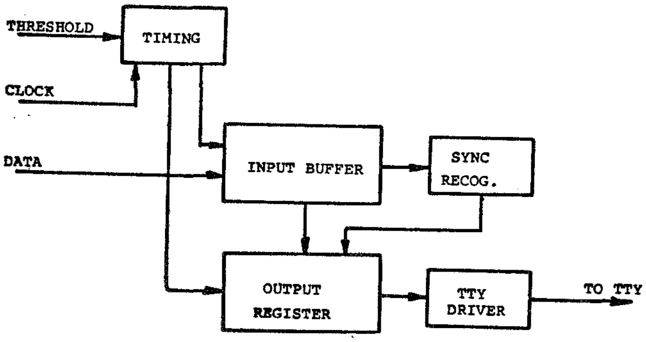


FIGURE 29

DATA DECODER

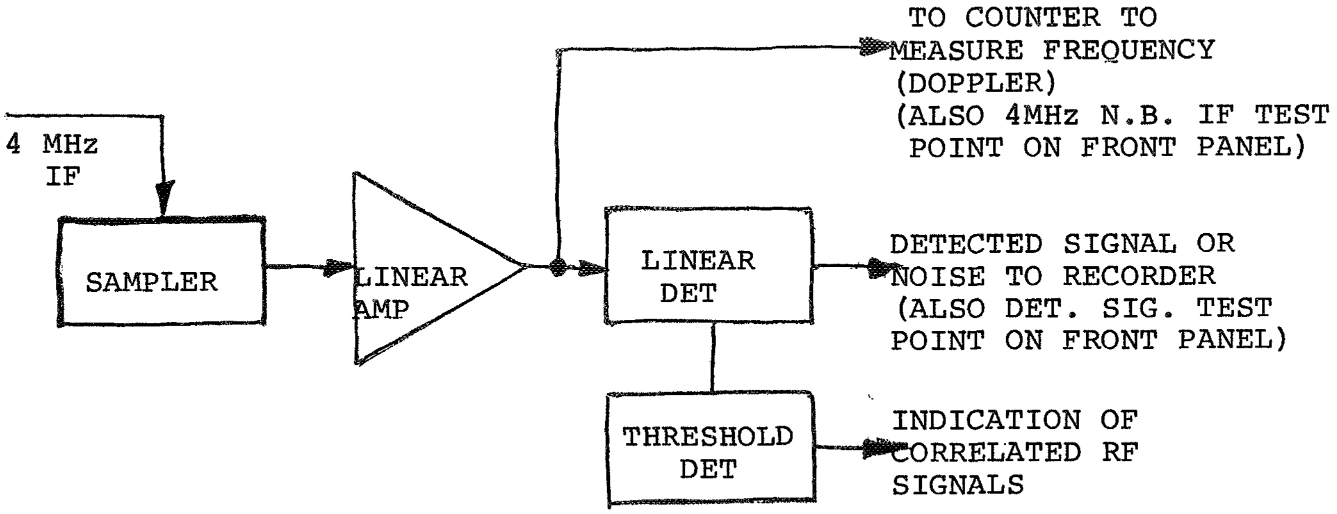


FIGURE 30 FREQUENCY DOPPLER, RF SIGNAL, SIGNAL THRESHOLD MEASURING CIRCUITRY

7.12 Reference Oscillator

The accuracy of the absolute range measurement capability provided by this equipment is directly related to the stability of the reference oscillators. More exactly, it is directly related to the relative frequency stability of the reference oscillator used to generate the transmitted range code and the reference oscillator used to generate the receiver ranging code. For the tests where the receiver and the transmitter modulator are in close proximity, it is possible to use the same reference oscillator for both equipments. In this case the factor of the stability of the reference oscillators is non-existent except for long-term data collection and correlation. However, in most navigation systems special attention must be paid to the stability of the reference frequency sources. Table XVI compares the following four types of high quality frequency sources: the quartz oscillator, the Rubidium gas cell resonator controlling a crystal oscillator, the cesium atomic beam resonator controlling a crystal oscillator, and the atomic hydrogen maser. As the table shows, the smallest, most rugged and least expensive is the quartz oscillator which has a stability of three parts in 10^{10} per day. The next choice is the Rubidium standard which is also compact and light and has a stability of 2 parts in 10^{11} per month. The cesium atomic standard and the hydrogen maser standard are primary standards. These standards are accurate to within one part in 10^{11} per life of the tube. The hydrogen maser has greater intrinsic reproducibility but it is much larger in size.

Comparing these sources with regard to their effect on system range accuracy indicates that the quartz oscillator would provide a range error of approximately 900 meters per day. The Rubidium gas resonator would have an error of 1.8 meters per day. Using two of these sources, one at the transmitter and one at the receiver, the error in range would be cumulative from day to day. This is not true for the primary standards. They would provide a range error of approximately ±1 meter and this inaccuracy would not change or be cumulative over a long-term period.

For the ORION equipments, AII utilized reference signals from Rubidium standards for both of the L-band receivers. At the STADAN station a frequency standard, Type GR 115B, was used to drive the modulator. The Rubidium standards are rugged enough and reliable enough to be moved around without having their stability degraded. The primary frequency standards are not rugged enough to be transported.

Figure 31 shows a curve of the measured relative drift of the two TRACOR Model 304B Rubidium standards which were used during this experiment, converted to error in range in feet/day.

TABLE XVI

REFERENCE OSCILLATORS

TYPE	STABILITY	ADVANTAGES	DISADVANTAGES
Quartz Oscillator	3 x 10^{-10}/day	Inexpensive, light	Long-Term stability
GR 1115B Oscillator (Mojave STADAN Equipment)	5 x 10^{-10}/day after aging		
Rubidium Gas Cell Resonator Controlled Oscillator (TRACOR Model 304D)	2 x 10^{-11}/mo	Compact and light	Not a primary standard
Cesium Atomic Beam Resonator Controlled Oscillator	±1 x 10^{-11}/life	Primary Standard	Not rugged
Atomic Hydrogen Maser	±1 x 10^{-11}/life	Best intrinsic reproducibility Primary Standard	Size and Weight

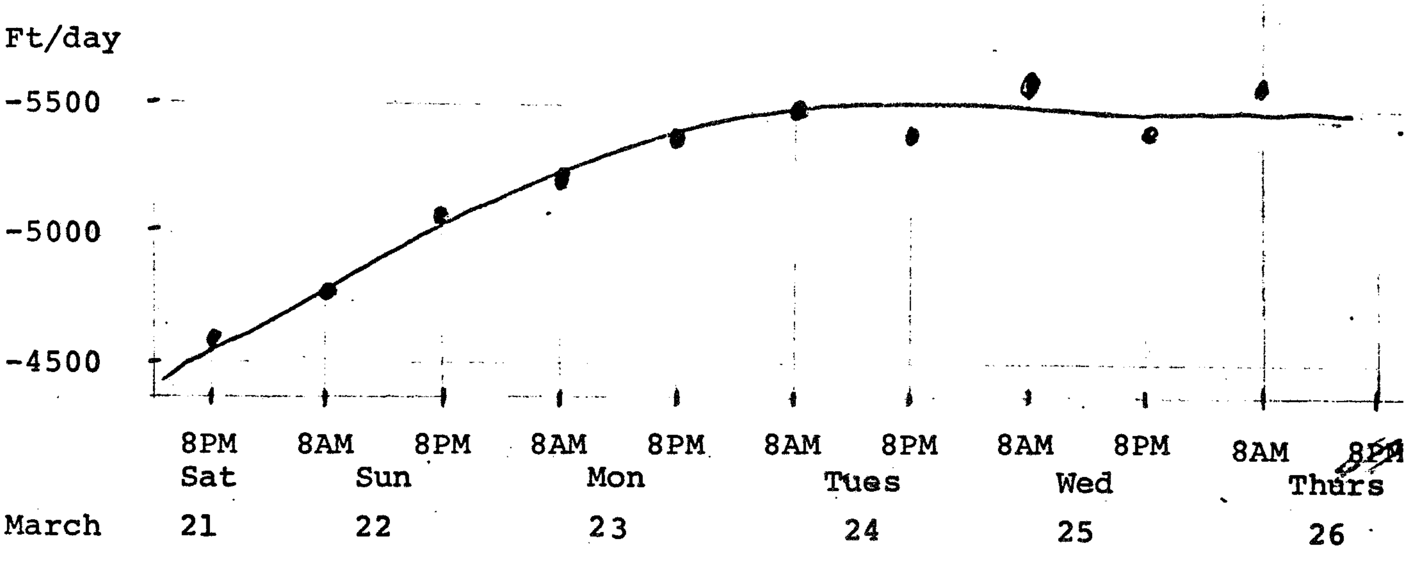


FIGURE 31 RUBIDIUM FREQUENCY STANDARD DRIFT CURVE

7.13 RFI-EMI Design

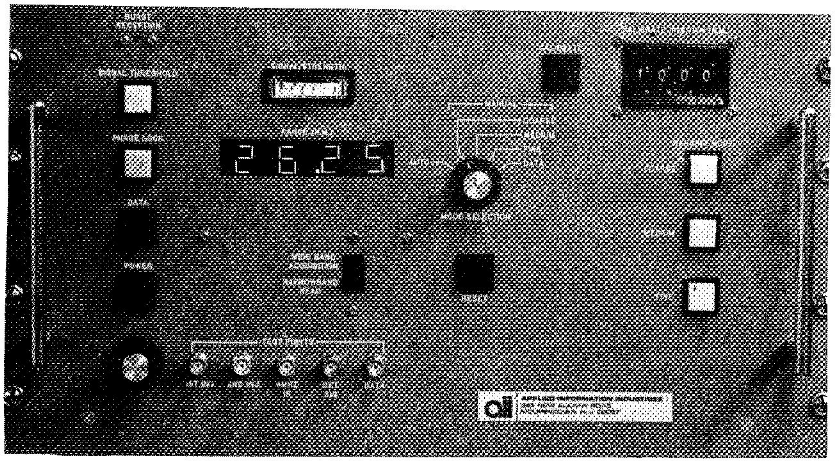
Special attention has been directed at the areas of radio frequency interference (RFI) and electromagnetic interference (EMI) in the design of the ORION receiver and modulator. All of the circuits in the equipment are operated from regulated power supplies which will provide high isolation between the primary A-C power busses and the equipment circuitry. Shielding is provided so that radiated interference is controlled. The internal signal levels within the equipment are less than 1 watt, and the shielding integrity controls the radiated signals.

7.14 Mechanical Design

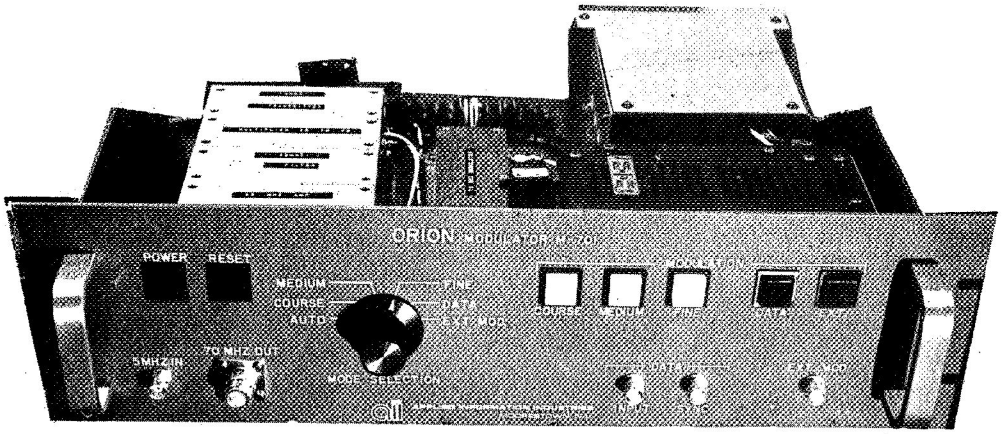
The ORION receiver and modulator are rack mounted equipments, where all the subsystems use maximum number of standard size "AII" modules (boxes). Only the circuits, requiring special considerations due to wave lengths, such as stripline filters, are of other than "AII" boxes.

The individually packaged circuit modules can be easily modified or replaced with new designs where necessitated by additional performance specifications. The modularized concept expedites the fabrication and testing phases and provides rapid maintenance capability. The individually shielded modules also provide satisfactory RFI integrity.

Figures 32 and 33 show actual photos of the ORION equipment illustrating the above packaging concept. The mechanical design of the modules utilizes extruded aluminum frames which have an irridite finish for corrosion resistance. Most of the modules are identical in size so that all of the mechanical parts are completely interchangeable.

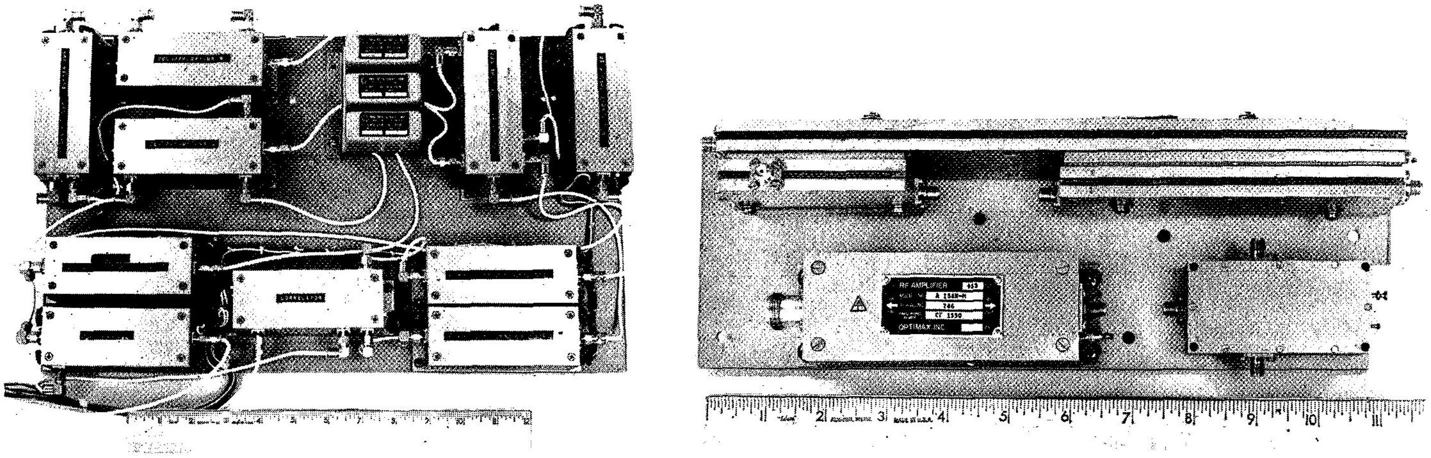


(a) ORION Receiver

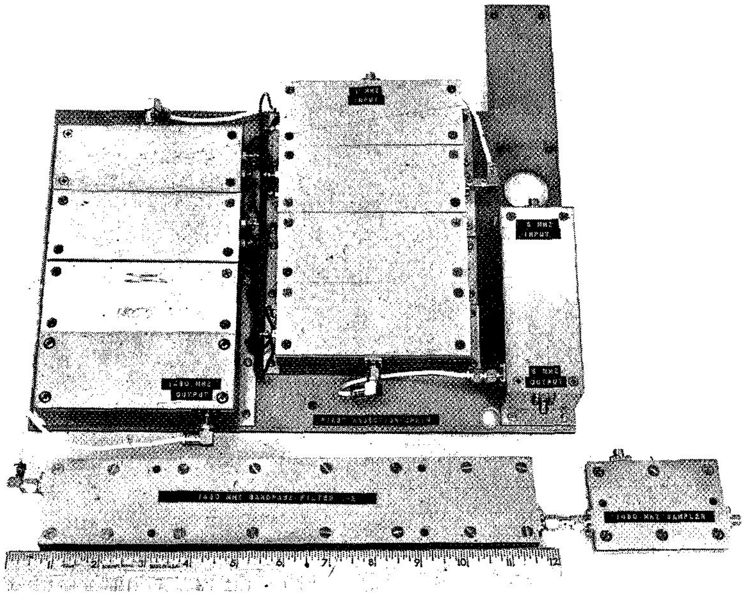


(b) ORION Modulator

FIGURE 32 ORION SYSTEM EQUIPMENT



(a) Correlator Assembly (b) L-Band Front End



(c) L. O. Injection Chain

FIGURE 33 ORION SUBASSEMBLIES

8.0 MODULATOR - MODEL M-701

This section describes the ORION modulator Model M-701 which was delivered and installed at STADAN NASA station as part of this contract.

8.1 Specifications

RF Input:	
Frequency:	5.0 MHz
Power:	0 dBm minimum +10 dBm maximum
Impedance:	50 ohms nominal max VSWR 2:1
Connector:	Front panel female BNC
RF Output:	
Frequency:	70 MHz carrier
Power:	0 dBm max -6 dBm nominal -10 dBm minimum
Impedance:	50 ohms or 75 ohms max VSWR 3:1
Connector:	Front panel female 75 ohm type N
Modulation:	
Internal:	ORION compatible range tone generation of COARSE, MEDIUM and FINE tones, i.e., 833 Hz, 8,333 Hz and 83,333 Hz manually controlled, or automatically controlled one minute of 833 Hz, one minute of 8,333 Hz and eight minutes of 83,333 Hz cycled until interrupted.

Data Input:

0 volts to +5 volts (TTL compatible) at a 1666 Hz rate, superimposed on the FINE modulation tone.

Power Requirements:

105-125 volts AC
60-400 Hz

Size:

Rack Mount, 19" wide, 5¼" high, 14" deep

Weight:

15 pounds (approximate)

Operating Temperature:

0 to +55°C

8.2 Modulator Description

8.2.1 Introduction

The Model M-701 Modulator can provide a -10 dBm to 0 dBm 70 MHz PSK modulated carrier capable of driving a transmitter. The only inputs that are required are a 5 MHz standard signal and 115 VAC. Internally, the model is capable of providing three modulation rates for ranging. External modulation can be accepted and data at a 1666 Hz rate can be superimposed on the FINE modulation tone.

8.2.2 Description of Front Panel Controls

The modulator front panel is shown in Figure 34. The modulator equipment has been shown in Figure 32. The controls and indicators are as follows:

Power Light

ON:	AC Power Activated
OFF:	AC Power Not Activated

Reset

Returns automatic cycle to start position

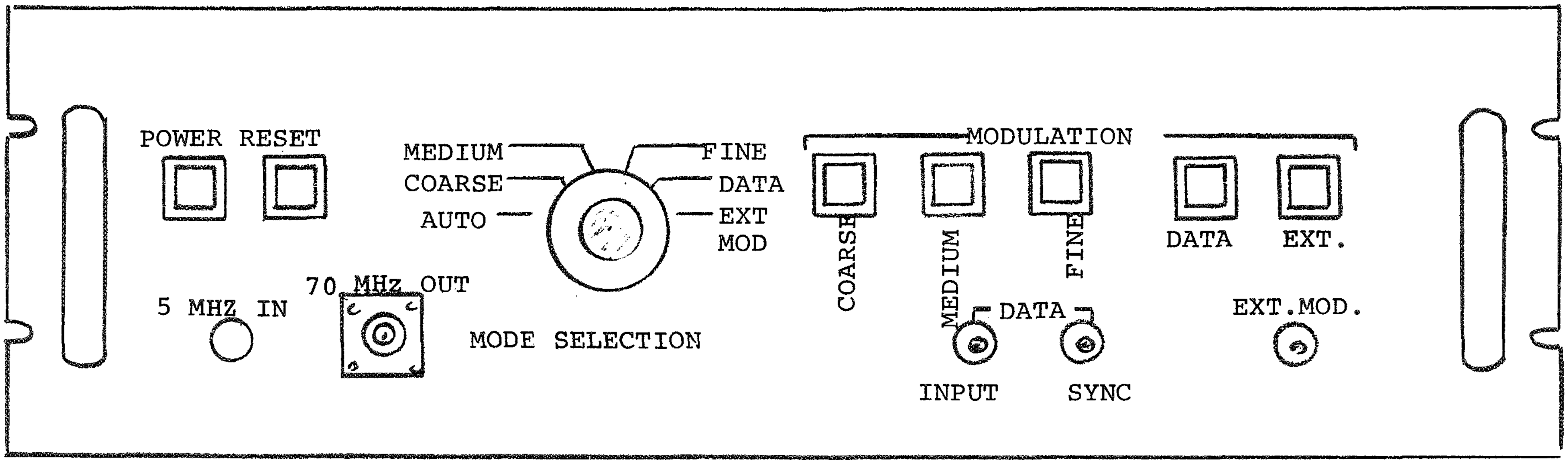


FIGURE 34 FRONT PANEL

Modulation Mode Selection

Auto: Modulation frequency cycles (1 minute COARSE, 1 minute MEDIUM, 8 minutes FINE, data channel activated 2½ minutes into cycle. The cycle then repeats.)

Manual:
- COARSE: (Modulation frequency is 833.3 Hz.)
- MEDIUM: (Modulation frequency is 8333.3 Hz.)
- FINE: (Modulation frequency is 83,333 Hz.)
- DATA: (Modulation frequency is 83,333 Hz and data channel is activated.)
- EXTERNAL: The 70 MHz carrier can be modulated externally at any rate from DC to 4.0 MHz.

Modulation mode lights indicate the actual mode of operation of the modulator.

Connectors

5 MHz in: Connection for signal from 5 MHz standard.

70 MHz out: Connection for 70 MHz PSK signal output.

Data input: Connection for input data at a 1666 Hz rate, TTL level compatible.

Sync: Signal at 1666 Hz for clocking in data. TTL level compatible.

External Mod: Connector for external modulation. TTL level compatible.

8.3 General Description

The AII Model M-701 Ranging Modulator is an all solid state signal processor designed to generate the range code pattern required by the ORION navigation system. The modulator accepts a 5 MHz reference standard and multiplies it to 70 MHz where it is PSK modulated. The unit is designed to operate automatically in the ORION mode, completely unattended, or it can be controlled manually while generating ORION range tones.

In addition, a front panel modulation input provides a means of externally supplying a signal to PSK the carrier. This input is compatible with TTL logic levels, i.e., a signal level of zero volts represents a "0" and a signal level of +3 volts represents a "1."

The 70 MHz modulated carrier output will deliver -10 dBm to 0 dBm into a 75-ohm load.

The M-701 modulator is self contained, requiring only AC power and clock frequency to operate.

Model M-701 modulator utilizes shielded modular type design for RF (analog) stages for RFI integrity and easy maintainability. The tone-code generator utilizes standard plug-in printed circuit boards generally associated with digital circuitry. Self test features, such as mode indication lights, are provided on the front panel.

8.3.1 Description of the Block Diagram

The block diagram of the M-701, shown in Figure 35, can be divided into five major sections: (1) the multipler chain, (2) the PSK modulator, (3) the digital frequency generator, (4) the transmitter control and (5) the power supplies. The following paragraphs present a description of the circuit details of each of these sections.

8.3.2 Multiplier Chain

The multiplier chain generates a stable 70 MHz carrier from the 5 MHz standard frequency utilizing a x7, x2 multiplication configuration.

The 5 MHz clock input enters the ORION modulator through a BNC connector located on the front panel. This signal is divided equally in a power splitter, one half being furnished to the digital frequency generator and the other half being used to drive the multiplier chain. The multiplier drive signal in the -3 dBm to +7 dBm level excites a step recovery diode multiplier having a multiplication ratio of seven. The circuit requires no external voltages and has a nominal conversion loss of 7 dB.

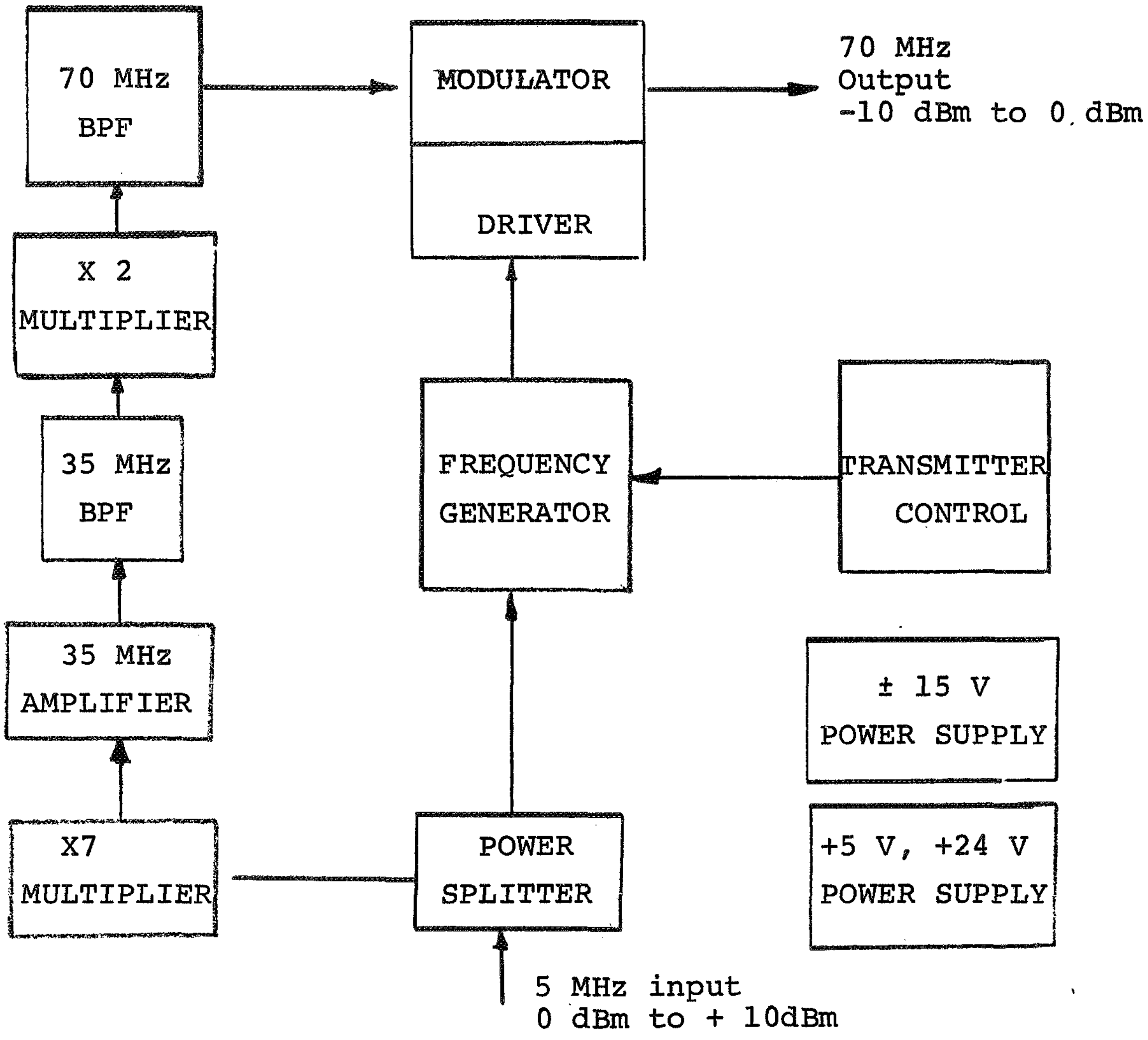


FIGURE 35 MODULATOR CONFIGURATION

The output of the x 7 multiplier at 35 MHz is then amplified in a class AB amplifier that is matched into and out of 50 ohm impedances. The amplifier has a gain of 24 dB and is capable of furnishing up to 400 mw of output. The amplifier is of very conservative design, being biased so that it is unconditionally stable and using components derated well below the recommended levels. The output of the 35 MHz amplifier is passed through a 35 MHz band pass filter, to remove any undesired multiplication products. The filter is a five-section lumped constant design, has a 3 dB bandwidth of 1 MHz and has an insertion loss of 2 dB.

The 35 MHz signal is then multiplied by two to 70 MHz in the transistor circuit designed similar to a series varactor diode multiplier circuit. The main elements in this design are an input matching circuit, an input idler circuit tuned to the second harmonic, an output impedance transformer and an output idler circuit tuned to the input fundamental frequency. The transistor is biased close to cut-off in a Class B mode. This insures that the input signal will easily drive the transistor into cut-off and into its nonlinear region, thus producing the desired multiplication.

The power dissipated is less than 800 mw and does not require a heat sink for operation over the temperature range of 0 to +55°C. The 70 MHz carrier is then attenuated and filtered in a 70 MHz three-section bandpass filter. The output of this filter provides a clean carrier which will be PSK modulated.

8.3.3 PSK Modulator

The actual phase shift key modulation of the 70 MHz signal is done in a double balanced mixer. Switching the diode pairs in the mixer from one state to the other causes the phase shift through the device to change by 180°. The proper drive level to switch the diodes is provided by the modulator driver. The driver consists of 4 transistors and converts standard TTL logic levels into a symmetrical drive signal with the current capability of fully switching the diodes. The input modulation signal is internally furnished by the digital frequency generator at the rates of 833 Hz, 8,333 Hz or 83,333 Hz. External modulation may also be utilized, by applying an appropriate digital signal to the external modulation BNC connector and switching the front panel mode control to the external modulation position.

8.3.4 Digital Frequency Generator

The digital frequency generator produces the required internal modulation signals for the modulator and provides timing (sync) so that external data may be clocked in properly.

The 5 MHz sinusoidal signal from the power splitter is counted down to provide the proper signals and timing. This signal is shaped using a DC comparator and buffer and is then divided by three to 1.6666 MHz. This signal is divided by 10^3 to 1.666 KHz. The 1.666 KHz is divided by two to obtain the 833 Hz COARSE modulation tone. Likewise 8.333 KHz is obtained from the second divide-by-ten to provide the MEDIUM modulation tone; 166.666 KHz is divided by two to provide the FINE modulation tone. This division is performed in a flip-flop which also superimposes any data present on the FINE ranging tone. This circuitry, consisting of eleven dual-in-line IC packages, is mounted on a printed circuit board.

8.3.5 Transmitter Control Board

The transmitter control board contains the required circuitry to control and program the digital frequency generator. When in the manual mode (when the modulation tones are selected manually) gates on this card selected the proper modulation tone. The major functions provided by the board circuitry is the timing and switching required by the automatic mode. When this mode is used, the modulation sequence is COARSE for one minute, MEDIUM for one minute and FINE for eight minutes. Thirty seconds after the FINE modulation starts, data may be superimposed on this tone. To provide the timing, a counter of ten minutes duration driven from the 1.666 KHz signal from the frequency generation is used.

This counter provides outputs at one minute, two minutes and two and one-half minutes during ten-minute intervals. These outputs provide the recycling required for the automatic mode. The counter may be reset by pushing the reset button on the front panel.

8.3.6 Power Supplies

Two dual power supplies internally furnish all required DC power for the modulator. Both of these supplies operate from 105 - 125 VAC, 60 to 400 Hz. The output voltages provided are ± 15 VDC at 100 ma, +5 VDC at 1.0 amp, and + 24 VDC at 350 ma. These voltages are brought out and distributed from a terminal strip at the rear of the modulator.

9.0 RESULTS AND CONCLUSIONS

The following results, conclusions and reasonable deductions have been derived from the results of this experiment.

a. It is possible to achieve reliable lock-up and demodulation of signals from the ATS-5 spinning satellite within approximately 100 milliseconds of accumulated signal time. This is equivalent to two or three bursts of signal produced as the beam sweeps through the receiver antenna.

b. Stable and repeatable range measurements can be obtained from the correlation receiver which enable computation of lines of position (LOPs) to a precision of 1% of the lanewidth.

c. The LOPs as determined from the satellite navigational signals can be reconciled to position fixes obtained from other navigation systems on board to within values ranging from zero to 1.3 nautical miles from day to day. This is a relative measure of accuracy inasmuch as the references being compared against do not have confirmable accuracy values.

d. Carrier-to-noise ratios of 18.5 dB are achievable in a 1.6 KHz bandwidth at elevation angles as low as 1.8° using a three-foot diameter dish antenna.

e. Effects attributed to multipath produce a variation on the value of no greater than ± 2 dB.

f. The ORION system can perform reliably with a signal margin as low as 6.5 dB C/N.

g. A three-foot diameter parabolic dish antenna is sufficient to produce the required signal levels for reliable system operation through all variations in satellite elevation angles. Evidence exists that under many operating conditions a two-foot dish may be satisfactory. Antenna pointing appears to be a relatively simple task to be performed either manually or with a simple mechanical positioner.

h. It is entirely feasible to superimpose data communication signals on the ranging modulation to achieve effective simultaneous ranging and data reception.

i. The potential simplicity and reliability of a passive user navigational system is evidenced by the fact that the ORION receiver operated for 750 hours continuously with no down time due to electronic malfunction.

j. The present frequency drift in the ATS-5 master oscillator together with the motion of the satellite prevents the measurement of doppler frequency shift measurements. Thus, it is concluded that velocity measurements under present satellite conditions must be made by deriving the best estimate of the range slope. This can be readily accomplished by computation of range slope over a number of rotations of the satellite.

Three general conclusions resulting from this experiment are presented below.

a. L-band signal transmission via a synchronous satellite can produce precise and stable range measurements which are the foundation for precision navigation systems of the future.

b. The ATS-5 synchronous satellite, although presently in a spinning mode, fulfills all essential requirements for feasibility experimentation to prove concepts involved in L-band position fixing experiments. Additionally, data relaying concepts can also be demonstrated and evaluated.

c. The relative simplicity of the equipment involved in this experiment leads to the conclusion that an uncomplicated equipment complement involving simple procedures is possible for widespread marine use in the future. This passive navigation system will provide instantaneous position fixing across broad areas of the globe at relatively low cost for each user.

APPENDIX A

RANGE DATA REDUCTION METHOD

INTRODUCTION

This section shall describe the range data reduction method which was employed for the determination of lines of position (LOPs) of the S. S. Manhattan during the ATS-5--ORION--S. S. Manhattan experiment. An attempt will be made to trace the ORION range reading from the moment at which they were recorded until the lines of positions were determined.

LINES OF POSITION

A line of position is defined to be a straight line containing the ship's position. The line of position is plotted by first taking the nearest half degree value of the latitude near the ship. On the latitude line a point of longitudinal intersection is located and a line which has a given azimuth angle is drawn through this point. Two range readings, one from S. S. Manhattan and one from AII laboratory, are taken for the determination of the LOP.

DATA RECORDING

A computer terminal was connected to the ORION receiver at the AII laboratories so that the range reading could be directly and automatically transferred to a punched tape. The range data on the S. S. Manhattan was recorded on the digital printer and then manually key punched to paper tape. Then, both tapes were fed into the computer which printed out each day's range information as well as the RMS, mean, and noise variance of the ranging information recorded for that date. Sample printer data sheets as well as the converted data is shown in Appendix B.

LINES OF POSITION DETERMINATION

The lines of position determination is based upon the composite range readings which takes into account the smooth composite readings which were calculated from the COARSE, MEDIUM and/or FINE lanewidth positions. The COARSE reading is an approximate measure of actual range. Range bins of width of 9.7 nautical miles are defined and the bin containing the COARSE reading and defined by its lower value is taken. The MEDIUM reading is added to that number, resulting in a better estimate of the true range. The procedure may be repeated in order to add the FINE tone reading. If the composite value differs from the original COARSE reading by 5 or more the procedure is repeated by increasing or decreasing the COARSE reading bin by one.

One computer program is designed for real time processing. ORION COARSE, MEDIUM and FINE readings which were obtained on the S. S. Manhattan were transmitted to AII by radio telephone and entered into the processing along with direct range readings taken at AII. The computer formed the composites and returned the LOP azimuth angle, as well as the assumed latitude and the calculated longitude of a point which could be located on a chart and through which the LOP can be drawn. Due to the time lag between the actual reading on the S. S. Manhattan and the radio telephone call to AII laboratories, real time determination of LOPs was next to impossible and, therefore, batch processing for position determination was implemented.

BATCH PROCESSING FOR LINES OF POSITION DETERMINATION

Computer printed data, such as shown in Appendix B, was the basis for the determination of lines of position. Noise in the system was taken into account by averaging and calculating the mean values of the range readings. It should be noted at this point that some range readings which were obtained on the S. S. Manhattan were not smooth and continuous because of EMI and power interruptions discussed elsewhere in this report.

DERIVATION OF THE COMPUTER PROGRAM

Introduction

This section describes the method of position determination of the S. S. Manhattan using a computer. The computer program had to take into account all factors which had a direct or indirect effect on the position determination. These factors were satellite ephemeris data, which is given in Appendix D, systems errors and biases, which are described in Section 6, and the day-to-day range reading values, which were specially processed for the computer. Since the shape of the earth is not spherical, three unknowns are to be determined: latitude, longitude and geocentric range. One unknown can be determined on the basis of range measurements to the satellite. The other two unknowns must be assumed using approximate known position of the ship so if the latitude is assumed known, the geocentric range of the ship may be determined by using the ellipsoid of revolution model of the earth.

Mathematical Derivation of the Computer Program

The instantaneous position of the S. S. Manhattan is given by the three quantities, a_S, ψ_S and λ_S where a_S is the radius of the earth at the ship, while ψ_S and λ_S represent its latitude and longitude, respectively.

Since the shape of the earth is approximately an ellipsoid of revolution, a_S may be approximated by

$$a_S = [(E_e \cos \psi_S)^2 + (E_p \sin \psi_S)^2]^{\frac{1}{2}} \qquad (1)$$

where

E_e = equatorial radium = 3443.92 nmi
E_p = polar radius = 3432.37 nmi.

Hence two unknowns, ψ_S and λ_S, need to be determined in order to specify the ship's position. Since range measurements to only one satellite are available, one of the unknowns needs to be assumed. It is convenient to assume that the latitude is known. The significance of this choice is explained later in this section. We note that the latitude only needs to be known to the nearest half degree.

Additional subscripts A and M refer to quantities pertaining to the ATS-5 satellite and the AII laboratories at Moorestown, New Jersey, respectively. From geometric considerations, it follows that the distance between ship and satellite is given by

$$||r_S - r_A|| = [a_S{}^2 + R_A{}^2 - 2a_S R_A \cos \gamma_{SA}]^{\frac{1}{2}} \tag{2}$$

where R_A is the satellite geocentric range. The angle γ_{SA} is the geocentric angle between rays a_S and R_A and is related to the various latitudes λ and longitudes ψ by

$$\cos \gamma_{SA} = \cos \psi_S \cos \psi_A \cos (\lambda_S - \lambda_A) + \sin \psi_S \sin \psi_A \tag{3}$$

A corresponding range equation holds for the relations pertaining to the range of the ship. The range readings at the S. S. Manhattan and AII contain errors introduced by the Rubidium frequency clocks. Thus at a particular instance we really measure

$$\begin{aligned} R_{MS} &= ||r_S - r_A|| + R_{\phi S} \\ R_{MM} &= ||r_M - r_A|| + R_{\phi M} \end{aligned} \tag{4}$$

Because the distance to the nearest lane boundary is measured and not the actual range to the satellite, the range readings are ambiguous. However, relative reference points may be established by determining range readings at a known location (preferably when the platform is stationary and then subtracting these readings from subsequent range determinations). The relationship governing this calculation is:

$$R_{MS} - R_{M,0} = ||r_S - r_A|| - ||r_{S0} - r_{A0}|| + R_{\phi S} - R_{\phi S0} \qquad (5)$$

where subscript "0" denotes the reference point.

If the range equation for AII is subtracted from equation (5) for the ship, a term of the following form will result:

$$(R_{\phi S} - R_{\phi S0}) - (R_{\phi M} - R_{\phi M0}) \qquad (6)$$

This term represents the behavior of the clock on the S. S. Manhattan relative to the clock at AII. Since both clocks are good Rubidium standards, original (i.e., t = 0) frequency offset and phase drift can be minimized and, of course, measured. Hence the satellite-to-ship range

$$||r_S - r_A|| = (R_{MS} - R_{MM}) - (R_{MS0} - R_{MM0}) + ||r_M - r_A||$$
$$+ ||r_{S0} - r_{A0}|| - ||r_{M0} - r_{A0}|| - (At + Bt^2) \qquad (7)$$

is corrected by the factor $At + Bt^2$ representing clock errors.

Equations (7) and (3) may be used to determine the ship's location in longitude or latitude, provided the other coordinate is known. In a two-satellite geometry the position can be uniquely determined since two equations in two unknowns are available.

Solving equation (2) for cos γ_{SA}

$$\cos\gamma_{SA} = \frac{A_S{}^2 + R_A{}^2 - ||r_S - r_A||^2}{2a_S R_A} \tag{8}$$

If the latitude of the ship is known, the ship's longitude follows from Equation (3)

$$\lambda_S = \lambda_A - \cos^{-1}\left[\frac{\cos\gamma_{SA} - \sin\psi_S \sin\psi_A}{\cos\psi_S \cos\psi_A}\right] \tag{9}$$

(NOTE: The above equation's signs are valid only for the smaller western longitudes.)

If known longitude was assumed instead of latitude, a fourth degree polynominal in sines and cosines of ψ_S would result owing to the fact that the earth's radius at the ship is not known for this set of assumptions.

With the S. S. Manhattan located in the northern hemisphere and east of subsatellite point, the line of position extends from east of south to west of north. The azimuth angle of the LOP Az_{LOP}, is thus between 90^o and 180^o of true north. If β_1 represents the angle on the earth's surface between the arc from subsatellite point to the S. S. Manhattan and the local longitude circle, we find from spherical trigonometry that:

$$\beta_1 = \sin^{-1} \frac{\sin (\lambda_A - \lambda_S) \cos\psi_S}{\sin\gamma_{SA}} \tag{10}$$

and $Az_{LOP} = \pi/2 + \beta_1$ (11)

Therefore, the azimuth of the satellite is

$$Az_A = \pi + \beta_1 \tag{12}$$

while the elevation is given by

$$E = \cos^{-1} \frac{R_A \sin \gamma_{SA}}{||r_S - r_A||} \tag{13}$$

The distance from the satellite to the S. S. Manhattan is determined as follows. We assume a left handed coordinate system with the x-axis passing through the meridian of Greenwich and in the equatorial plane. The z-axis is along the polar axis. The y-axis completes the coordinate system. The x and y coordinates of the ship's position are given by

$$\begin{aligned} x &= a_S \cos \psi_S \cos \lambda_S \\ y &= a_S \cos \psi_S \sin \lambda_S \end{aligned} \tag{14}$$

We now consider the state of affairs in the local tangent plane. The LOP passes through the point for which the longitude was just determined (x_1, y_1). The equation of the LOP in normal form is

$$x \sin \beta_1 + y \cos \beta_1 - (x_1 \sin \beta_1 + y_1 \cos \beta_1) = 0 \tag{15}$$

Hence the distance from the ship's position (x_2,y_2) to the line is

$$\lambda = a_S \cos \psi_S \, [|x_1 - x_2| \sin \beta_1 + |y_1 - y_2| \cos \beta_1] \tag{16}$$

where $| \quad |$ indicate the absolute value.

The conversion of this mathematical derivation into a computer program is given in the next section. The program accounts for all the biases of the system and only the satellite ephemeris data and the ORION range readings (from both AII and S. S. Manhattan) are required for lines-of-position determination.

Computer Program for Determining Lines of Position

An analysis was presented in previous section, leading to equations by which the lines of position of the S. S. Manhattan can be calculated. The computer program of these equations and its execution is discussed in this section.

The program is written in the XTRAN language for time-sharing and executed by an XDS 940 computer. Comment statements are included at various locations within the program, indicated by *. They refer to the immediately following program section. An attempt was made to assign, wherever possible, meaningful names to the various calculated quantities.

After some constants are defined, Moorestown and Mojave parameters are given: Moorestown latitude (ALAT), corrected for map error (ERLAT), (see equation 8) longitude (ALNG), and earth radius (ARE). ALTMJ, ALNGMJ, and AREMJ have the corresponding meaning for Mojave. (In passing, we note that the Mojave data is not essential to determine the LOPs. It is included in order to calculate the Mojave-to-ATS-5-to-AII range, which provides a check on the Rubidium standard at AII.)

If both Rubidium standards keep running continually from day to day, the LOPs may be calculated on the basis of reference values established at the earlier date. These values are entered as BIAS and RSHA1:

BIAS = Manhattan reading - AII reading
RSHA1 - (Range from Manhattan to ATS-5) - (range from AII to ATS-5)

Otherwise, these reference values are to be re-established. When no clock failure has occurred, XDAY is entered as a fraction of multiple of days since last execution. Otherwise, XDAY is zero. IO refers to the number of ephemeris data points to be read and JPNTS refers to the number of range readings to be used in LOP calculations.

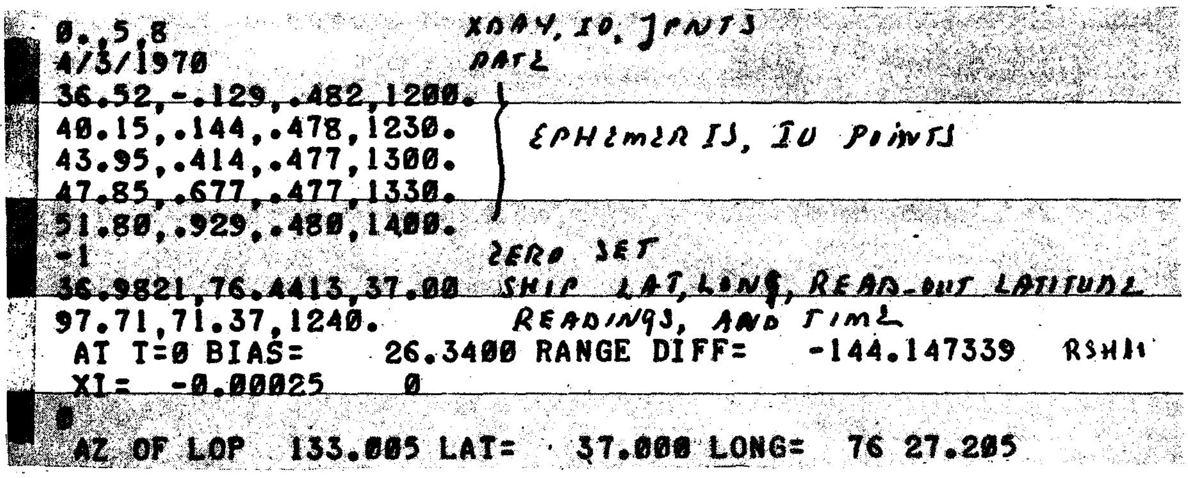
The next value accepted from the console is IPOS. If this variable is assigned a negative value, reference values (BIAS and RSHA1) are to be calculated, at Format Number 6. If this value is zero or one, reference values are assumed to be available. For IPOS $\leq$ 0, ship latitude, longitude, reference latitude and reference time are accepted. The reference latitude represents the nearest latitude to within 1/2 degree to be used in LOP calculations. Reference time is the time corresponding to the ship's position, which was just entered. The radius of the earth at the Manhattan is then calculated as SHRE. Range readings from the ship (SHMOD), AII (AMMOD) at time TIM are entered next for the JPNTth (≤ JPNTS) execution. The satellite ephemeris is interpolated for the time at which the readings were taken. The next item of particular interest is RSHS1, which represents the range from the ATS-5 to the S. S. Manhattan.

This value is compared to the same range based upon the geometry. When either clock has suffered a casualty, the difference between these two ranges becomes very large. The same situation results when the S. S. Manhattan moves from one COARSE lane into the next one. This difference divided by 100, called XI, and the nearest integer I ≤ XI are exhibited to the programmer. It is his option at this point to eliminate as many lanes as deemed necessary. A change of 1 in I corresponds to about four degrees in longitude. In practice, it was found however that when clock failure had occurred initialization of the program was the only answer.

The quantities of interest are the azimuth angle of the LOP, its longitude at the intersection with the reference latitude, satellite azimuth and elevation and are calculated next.

The last two calculations before printout or acceptance of a new data point are Mojave-ATS-5-AII range, RAMJ, and distance from ship's position to the just-determined LOP.

The following computer printout shows a typical execution cycle.



```
0.,5,8                      XDAY, IO, JPNTS
4/3/1970                    DATE
36.52,-.129,.482,1200.  }
40.15,.144,.478,1230.   }   EPHEMERIS, IO POINTS
43.95,.414,.477,1300.   }
47.85,.677,.477,1330.   }
51.80,.929,.480,1400.   }
-1                          ZERO SET
36.9821,76.4413,37.00       SHIP LAT, LONG, READ-OUT LATITUDE
97.71,71.37,1240.           READINGS, AND TIME
 AT T=0 BIAS=    26.3400 RANGE DIFF=   -144.147339   RSHH
 XI=  -0.00025    0
0
 AZ OF LOP  133.005 LAT=   37.000 LONG=  76 27.205
```

The computer program follows.

```
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      DIMENSION SRE(22),SLAT(22),SLNG(22),SLATD(22),SLNGD(22),TIME(22),F
 A(3),
 EL(20),AZ(20),ILN(20),FLN(20),TIM(20),SHMOD(20),AMMOD(20),AZLOP(20),
 DIST(20),RAMJ(20),SHLNGN(20)
* CONVERSION CONSTANTS, MOORESTOWN AND MOJAVE DATA
      PI=3.1415926536
      DRAD=0.017453292520
      FTNMI=6076.1154860
      EER=3443.933585
      EPR=3432.388384
      ERLAT=(EER-EPR)*.000290888
      ALAT=39.97*DRAD
      ALAT=ALAT-ERLAT*SIN(2.*ALAT)
      ALNG=74.98*DRAD
      ARE=3439.212
      CSALT=COS(ALAT)
      SNALT=SIN(ALAT)
      ALTMJ=35.297*DRAD
      ALTMJ=ALTMJ-ERLAT*SIN(2.*ALTMJ)
      ALNGMJ=116.8992*DRAD
      AREMJ=3440.08
      CSLTMJ=SIN(ALTMJ)
      SNLTMJ=SIN(ALTMJ)
* CLOCK OFFSET AND DRIFT
      A=-5500.
      ANMI=A/FTNMI
      B=0.0
      BNMI=B/FTNMI
* T=0 REFERENCE VALUES
      BIAS=28.26
      RSHA1=1532.571361
1     ACCEPT XDAY,IO,JPNTS
* SATELLITE EPHEMERIS
      READ (1,(3A6))FA
      JPNT=0
      DO 2 ITM=1,IO
      ACCEPT RANGE,SLATD(ITM),SLN,TIME(ITM)
      SRE(ITM)=22700.+RANGE
      SLNGD(ITM)=105.+SLN
      SLAT(ITM)=SLATD(ITM)*DRAD
2     SLNG(ITM)=SLNGD(ITM)*DRAD
* READ SHIP'S POSITION AND READ-OUT LAT. MAP ERROR ETC.
3     ACCEPT IPOS
      IF (IPOS) 4,4,5
4     ACCEPT SHLATD,SHLNGD,SHLATN,REFTIM
      S=SHLATD*DRAD
      ERMAP=ERLAT*SIN(2.*S)
      ERMAPD=ERMAP/DRAD
      SHLAT=S-ERMAP
      CSSHLT=COS(SHLAT)
      SNSHLT=SIN(SHLAT)
      SHLNG=SHLNGD*DRAD
      DLAT=SHLATN-SHLATD
      SHRE=SQRT((EER*CSSHLT)**2+(EPR*SNSHLT)**2)
```

```
6/29          /F1/                    PAGE 2

* SHIP POSITION DEG AND MIN
      SHLT1=IFIX(SHLATD)
      SHLT2=(SHLATD-SHLT1)*60.
      SHLN1=IFIX(SHLNGD)
      SHLN2=(SHLNGD-SHLN1)*60.
5     JPNT=JPNT+1
      ACCEPT SHMOD(JPNT),AMMOD(JPNT),TIM(JPNT)
      TM=TIM(JPNT)
* INTERPOLATE SATELLITE EPHEMERIS
      T=IFIX(TM/100.)*100.
      T=.6*(T-TIME(1))+TM-T
      ITM=T/30.
      ITM1=ITM+1
      ITM2=ITM+2
      ADJST=AMOD(T,30.)
      SREN=SRE(ITM1)+(SRE(ITM2)-SRE(ITM1))*ADJST/30.
      SLATN=SLAT(ITM1)+(SLAT(ITM2)-SLAT(ITM1))*ADJST/30.
      SLNGN=SLNG(ITM1)+(SLNG(ITM2)-SLNG(ITM1))*ADJST/30.
      CSSLAT=COS(SLATN)
      SNSLAT=SIN(SLATN)
      SSHR=SHRE/SREN
      SAR=ARE/SREN
      T=T/1440.+XDAY
      IF (IPOS) 6,8,8
* HERE TO (RE)SET T=0.
6     BIAS=SHMOD(JPNT)-AMMOD(JPNT)
      COSSHS=CSSHLT*CSSLAT*COS(SHLNG-SLNGN)+SNSHLT*SNSLAT
      RSHS1=SREN*SQRT(1.+SSHR**2-2.*SSHR*COSSHS)
      COSAS1=CSALT*CSSLAT*COS(ALNG-SLNGN)+SNALT*SNSLAT
      RAS1=SREN*SQRT(1.+SAR**2-2.*SAR*COSAS1)
      RSHA1=RSHS1-RAS1
      WRITE (1,7) BIAS,RSHA1
7     FORMAT($ AT T=0 BIAS=$,F11.4,$ RANGE DIFF=$,F14.6)
8     COSASI=CSALT*CSSLAT*COS(ALNG-SLNGN)+SNALT*SNSLAT
* DETERMINE SHIP-SATELLITE RANGE
      RASI=SREN*SQRT(1.+SAR*SAR-2.*SAR*COSASI)
      RSHSI=SHMOD(JPNT)-AMMOD(JPNT)-BIAS+RSHA1+RASI-T*(ANMI+BNMI*T)
* GEOM SHIP-SAT RANGE TO DETERMINE CLOCK FAILURE OR LANE SKIPPING
      ANGLE=CSSLAT*CSSHLT*COS(SLNGN-SHLNG)+SNSLAT*SNSHLT
      RANGE=SREN*SQRT(1.+SSHR**2-2.*SSHR*ANGLE)
      XI=(RANGE-RSHSI)/100.
      I=XI
      WRITE (1,9) XI,I
      ACCEPT I
9     FORMAT($ XI=$,F10.5,I5)
* ADD-IN APPROPRIATE NUMBER OF LANES,LOP,LONG,SAT AZ AND EL
      RSHSI=RSHSI+I*100.
      RNGSN=RSHSI/SREN
      C1=(SSHR*SSHR+1.-(RNGSN)**2)/(2.*SSHR)
      COSDL=(C1-SNSHLT*SNSLAT)/(CSSHLT*CSSLAT)
      SINDL=SQRT(1.-COSDL*COSDL)
```

```
      DL=ATAN(SINDL/COSDL)
      SHLNGN(JPNT)=SLNGN-DL
      SINSHS=SQRT(1.-C1*C1)
      SINB1=SINDL*CSSLAT/SINSHS
      COSB1=SQRT(1.-SINB1*SINB1)
      B1=ATAN(SINB1/COSB1)
      AZLOP(JPNT)=(PI/2.+B1)/DRAD
      SHLNGT=SHLNGN(JPNT)/DRAD+DLAT*COSB1
      ILN(JPNT)=SHLNGT
      FLN(JPNT)=(SHLNGT-ILN(JPNT))*60.
      COSEL=SINSHS/RNGSN
      SINEL=SQRT(1.-COSEL**2)
      EL(JPNT)=ATAN(SINEL/COSEL)/DRAD
      AZ(JPNT)=AZLOP(JPNT)+90.
      WRITE (1,79) AZLOP(JPNT),SHLATN,ILN(JPNT),FLN(JPNT)
79    FORMAT($ AZ OF LOP$,F9.3,$ LAT=$,F9.3,$ LONG=$,I4,F7.2)
* DETERMINE MOJAVE-AII RANGE FOR LOCAL CLOCK CHECK
      SMJR=AREMJ/SREN
      ANGMJ=CSLTMJ*CSSLAT*COS(ALNGMJ-SLNGN)+SNLTMJ*SNSLAT
      RMSI=SREN*SQRT(1.+SMJR**2-2.*SMJR*ANGMJ)
      RAMJ(JPNT)=RASI+RMSI
* CALCULATE LOP DISTANCE BETWEEN LOPS
      IF (JPNT) 80,80,81
80    DIST(1)=0.00
      GO TO 82
81    DIST(JPNT)=ABS(SHLNGN(JPNT)-SHLNGN(1))*COS(SHLATN*DRAD)*SINB1*3437
.75
      WRITE (1,82) DIST(JPNT)
82    FORMAT(F10.5)
      IF (JPNT.LT.JPNTS) GO TO 3
      WRITE (1,(^))
      WRITE (1,10) FA,SHLT1,SHLT2,SHLN1,SHLN2,REFTIM
10    FORMAT(10X,$AII-MANHATTAN EXPERIMENT$,12X,3A6/10X,$SHIP POSITION
:N. LAT=$,F4.0,F6.2,$ W. LNG=$,F4.0,F6.2/10X,$REFERENCE TIME:$,F8.1
,$ ZULU$/)
      WRITE (1,11)
11    FORMAT(10X,$ATS-5 EPHEMERIS$/10X,$TIME$,3x,$SAT RANGE   LATITUDE
    LONGITUDE$/10X,$ZULU$,6X,$NMI$,8X,$DEG$,9X,$DEG$)
      WRITE (1,12) (TIME(K),SRE(K),SLATD(K),SLNGD(K),K=1,IO)
12    FORMAT(8X,F6.1,4X,F8.2,6X,F5.3,5X,F7.3)
      WRITE (1,13) SHLATN,ERMAPD
13    FORMAT(/10X,$REFERENCE LATITUDE=$,F7.2,$ DEG, MAP ERROR=$,F6.2,
$ DEG$/)
      WRITE (1,14)
14    FORMAT(1X,$TIME$,5X,$READINGS$,3X,$LONGITUDE$,$ LOP ANGLE$,2X,
$EL SAT AZ$,3X,$LOP DIST$, $ R(MOJ-AII)$/1X,$ZULU$,3x,$MANH$,4X,
$AII$,1X,$DEG$,3X,$MIN$,4X,$DEG$,4X,$DEG$,5X,$DEG$,4X,$NMI$,7X,$NMI
      WRITE (1,15) (TIM(K),SHMOD(K),AMMOD(K),ILN(K),FLN(K),AZLOP(K),EL(K
),
AZ(K),DIST(K),RAMJ(K),K=1,JPNTS)
15    FORMAT(F5.0,2F7.2,I4,F6.2,F10.2,F6.2,F7.2,F9.3,F11.2)
      WRITE (1,(^))
      GO TO 1
      STOP
      END
```

MAP ERROR

Maps and charts are designed to be used with stellar position fixing. The local horizon is used to measure the heights of several stars or planets. The location is determined by calculating the circles of position on a spherical earth and then the intersection of the several small circles. The charts and maps are hence derived from and agree with a spherical earth model.

Since the earth more closely approximates an ellipsoid of revolution about the polar axis the charts and maps are in error by a calculable amount. There is essentially no map error in the longitude measurement. The latitude numbers used by cartographer and geometrician will be in agreement only at the equator and poles. The maximum error of the map will occur at latitudes of 45°.

The relation giving the map error is given by

$$\Delta S = 12 \sin 2L \text{ (miles/minutes of arc)}$$

The true latitude is map latitude minus ΔS, where L is positive in the northern hemisphere. Latitudes indicated on the map are too large.

APPENDIX B

Detail Printout of Lines of Position and the ATS-5 Ephemeris Data

The computer printouts presented in this Appendix contain detail calculated information of the position of the S. S. Manhattan and ATS-5. The computer program and its derivation which was used to obtain these printouts is described in Appendix A. The following is the explanation of the printout.

Each day's pertinent ship position and the reference time is printed out. Also the ATS-5 ephemeris data for the times corresponding to the time of LOP determination is given. The reference latitude is the latitude rounded off to the nearest half degree. Readings taken at the Manhattan (MANH) and at the AII laboratories (AII) together with the time at which these readings were taken are inputs to the computer program. The longitude in degrees (DEG) and minutes (MIN) is a computer calculated value which provides one point through which the LOP is to be drawn when combined with the reference latitude. The azimuth angle of the LOP to be drawn is given in the next column (LOP ANGLE, DEG.). The two columns following give the true elevation and azimuth angles of the ATS-5 (EL SAT AZ) from the point of position of the S. S. Manhattan at the listed time. The LOP distance (LOP DIST) is the distance between the reference or first LOP and any successive LOP. It indicates the cumulative effect of ship's motion. R(MOJ-AII) is the range from Mojave to AII. This value provides a check on the clock at AII. If the clock at AII would suffer an interrupt, the difference between total range and clock would show a jump from one nearly constant level to another level. These levels are constant within the limits of residual noise and atmospheric effects, which are discussed in Section 6.

As described in Appendix A, the values printed out are smoothed values over ten samples for both the S. S. Manhattan and AII readings.

An occasional reading in excess of the lane width of 97.21 nmi may be observed. This is a mathematical convenience to maintain the relative difference in ship and AII readings. This occurs whenever a lane boundary was passed.

```
           AII-MANHATTAN EXPERIMENT             4/3/1970
           SHIP POSITION:N. LAT= 36. 58.93 W. LNG= 76. 26.48
           REFERENCE TIME:  1200.0 ZULU

           ATS-5 EPHEMERIS
           TIME   SAT RANGE   LATITUDE   LONGITUDE
           ZULU      NMI        DEG         DEG
          1200.0   22736.52     -.129     105.482
          1230.0   22740.15     0.144     105.478
          1300.0   22743.95     0.414     105.477
          1330.0   22747.85     0.677     105.477
          1400.0   22751.80     0.929     105.480

           REFERENCE LATITUDE=  37.00 DEG, MAP ERROR=  0.18 DEG

  TIME      READING    LONGITUDE LOP ANGLE  EL SAT AZ   LOP DIST R(MOJ-AII)
  ZULU   MANH     AII DEG    MIN      DEG     DEG      DEG    NMI         NMI
 1240.  97.71  71.37  76 27.21     133.00 37.76 223.00   0.000    41601.96
 1250.  92.84  67.97  76 31.11     133.00 37.89 223.00   2.124    41597.32
 1300.  88.90  62.97  76 29.14     133.10 37.95 223.10   1.058    41592.69
 1310.  85.66  57.57  76 24.63     133.26 37.99 223.26   1.409    41588.32
 1320.  83.43  53.07  76 19.87     133.42 38.02 223.42   4.024    41583.97
 1330.  80.63  48.56  76 16.42     133.56 38.07 223.56   5.934    41579.62
 1340.  77.74  44.36  76 13.87     133.67 38.12 223.67   7.352    41575.63
 1350.  75.17  40.46  76 11.28     133.79 38.17 223.79   8.798    41571.65
```

```
           AII-MANHATTAN EXPERIMENT             4/4/1970
           SHIP POSITION:N. LAT= 37. 37.00 W. LNG= 74.  6.00
           REFERENCE TIME:  1200.0 ZULU

           ATS-5 EPHEMERIS
           TIME   SAT RANGE   LATITUDE   LONGITUDE
           ZULU      NMI        DEG         DEG
          1200.0   22736.85     -.091     105.471
          1230.0   22740.57     0.182     105.467
          1300.0   22744.44     0.451     105.466
          1330.0   22748.40     0.713     105.467
          1400.0   22752.39     0.962     105.470

           REFERENCE LATITUDE=  37.50 DEG, MAP ERROR=  0.19 DEG

  TIME      READING    LONGITUDE LOP ANGLE  EL SAT AZ   LOP DIST R(MOJ-AII)
  ZULU   MANH     AII DEG    MIN      DEG     DEG      DEG    NMI         NMI
 1230.  78.83  57.15  74  1.03     135.23 35.79 225.23   0.000    41604.22
 1240.  76.60  51.80  73 54.61     135.41 35.81 225.41   3.634    41599.64
 1250.  74.51  47.64  73 50.50     135.56 35.85 225.56   5.981    41595.08
 1300.  72.27  42.29  73 44.14     135.75 35.86 225.75   9.622    41590.52
 1310.  69.59  38.73  73 42.62     135.85 35.93 225.85  10.512    41586.24
 1320.  67.26  33.53  73 36.79     136.02 35.94 226.02  13.875    41581.96
 1330.  66.20  29.93  73 31.70     136.19 35.97 226.19  16.838    41577.69
 1340.  64.43  25.63  73 26.63     136.35 35.99 226.35  19.805    41573.81
 1350.  62.78  21.18  73 20.99     136.52 36.01 226.52  23.116    41569.93
```

```
           AII-MANHATTAN EXPERIMENT             4/7/1970
           SHIP POSITION:N. LAT= 48. 11.29 W. LNG= 52. 15.24
           REFERENCE TIME:  1245.0 ZULU

           ATS-5 EPHEMERIS
           TIME   SAT RANGE   LATITUDE   LONGITUDE
           ZULU      NMI        DEG         DEG
          1200.0   22737.24     0.051     105.439
          1230.0   22741.15     0.287     105.437
          1300.0   22745.22     0.554     105.435
          1330.0   22749.36     0.811     105.436
          1400.0   22753.51     1.054     105.439

           REFERENCE LATITUDE=  48.00 DEG, MAP ERROR=  0.19 DEG

  TIME      READING    LONGITUDE LOP ANGLE  EL SAT AZ   LOP DIST R(MOJ-AII)
  ZULU   MANH     AII DEG    MIN      DEG     DEG      DEG    NMI         NMI
 1245.  98.21  93.49  52  9.75     151.18 15.61 241.18   0.000    41589.90
 1255.  94.56  89.19  52  7.84     151.27 15.67 241.27   1.132    41585.53
 1305.  89.36  84.19  52  7.44     151.33 15.74 241.33   1.371    41581.34
 1315.  87.32  80.68  52  4.11     151.44 15.78 241.44   3.338    41577.32
 1325.  83.98  76.67  52  2.20     151.52 15.83 241.52   4.476    41573.31
 1335.  81.10  72.97  52  0.04     151.61 15.88 241.61   5.760    41569.50
 1345.  78.31  69.22  51 57.65     151.69 15.92 241.69   7.178    41565.89
```

```
           AII-MANHATTAN EXPERIMENT             4/8/1970
           SHIP POSITION:N. LAT= 53.  2.40 W. LNG= 51. 17.40
           REFERENCE TIME:  1322.0 ZULU

           ATS-5 EPHEMERIS
           TIME   SAT RANGE   LATITUDE   LONGITUDE
           ZULU      NMI        DEG         DEG
          1200.0   22737.45     0.049     105.428
          1230.0   22741.39     0.321     105.424
          1300.0   22745.47     0.586     105.423
          1330.0   22749.65     0.892     105.425
          1400.0   22753.83     1.083     105.428

           REFERENCE LATITUDE=  53.00 DEG, MAP ERROR=  0.18 DEG

  TIME      READING    LONGITUDE LOP ANGLE  EL SAT AZ   LOP DIST R(MOJ-AII)
  ZULU   MANH     AII DEG    MIN      DEG     DEG      DEG    NMI         NMI
 1324.  55.41  26.96  51 16.12     150.51 12.96 240.51   0.000    41568.45
 1334.  51.95  23.17  51 14.11     150.59 13.02 240.59   1.051    41564.41
 1344.  48.70  19.31  51 11.92     150.67 13.05 240.67   2.203    41562.19
 1354.  45.70  15.85  51 10.02     150.73 13.09 240.73   3.204    41559.98
```

```
AII-MANHATTAN EXPERIMENT            4/9/1970
SHIP POSITION:N. LAT= 58.  9.00 W. LNG= 51.  0.00
REFERENCE TIME:  1200.0 ZULU

ATS-5 EPHEMERIS
 TIME    SAT RANGE   LATITUDE   LONGITUDE
 ZULU       NMI         DEG         DEG
1200.0    22737.77     0.083     105.415
1230.0    22741.71     0.354     105.412
1300.0    22745.81     0.618     105.411
1330.0    22750.00     0.872     105.412
1400.0    22754.19     1.110     105.415

REFERENCE LATITUDE=  58.00 DEG, MAP ERROR=  0.17 DEG

TIME      READING   LONGITUDE LOP ANGLE  EL SAT AZ   LOP DIST R(MOJ-AII)
ZULU    MANH    AII DEG   MIN      DEG    DEG      DEG     NMI        NMI
1210.  76.45  84.46  50 55.33   148.84  9.56 238.84    0.000   41600.98
1220.  72.31  79.88  50 52.21   148.93  9.62 238.93    1.419   41596.39
1230.  68.20  75.25  50 48.92   149.02  9.68 239.02    2.924   41591.81
1240.  64.13  70.80  50 45.98   149.11  9.73 239.11    4.267   41587.54
```

```
AII-MANHATTAN EXPERIMENT            4/10/1970
SHIP POSITION:N. LAT= 65. 50.50 W. LNG= 54. 58.00
REFERENCE TIME:  2140.0 ZULU

ATS-5 EPHEMERIS
 TIME    SAT RANGE   LATITUDE   LONGITUDE
 ZULU       NMI         DEG         DEG
2200.0    22776.40     0.924     105.617
2230.0    22773.77     0.675     105.636
2300.0    22770.77     0.414     105.654
2330.0    22767.44     0.146     105.670
2400.0    22763.84     -.125     105.684
2430.0    22760.03     -.394     105.696

REFERENCE LATITUDE=  66.00 DEG, MAP ERROR=  0.14 DEG

TIME      READING   LONGITUDE LOP ANGLE  EL SAT AZ   LOP DIST R(MOJ-AII)
ZULU    MANH    AII DEG   MIN      DEG    DEG      DEG     NMI        NMI
2220.  41.36  68.19  55  3.61   143.50  7.23 233.50    0.000   41629.21
2230.  50.21  73.17  54 55.28   143.62  7.10 233.62    2.722   41634.13
2240.  56.99  78.39  54 54.18   143.61  7.01 233.61    3.084   41639.13
2300.  71.61  88.67  54 48.22   143.66  6.81 233.66    5.037   41649.15
2410.  23.00  26.63  54 33.32   143.72  6.10 233.72    9.924   41683.58
2420.  31.09  31.49  54 27.16   143.79  5.98 233.79   11.950   41688.32
```

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AII-MANHATTAN EXPERIMENT            4/14/1970
SHIP POSITION:N. LAT= 69. 53.40 W. LNG= 56. 59.40
REFERENCE TIME:  1434.0 ZULU

ATS-5 EPHEMERIS
 TIME    SAT RANGE   LATITUDE   LONGITUDE
 ZULU       NMI         DEG         DEG
1400.0    22756.45     1.249     105.351
1430.0    22760.46     1.452     105.356
1500.0    22764.31     1.630     105.362
1530.0    22767.95     1.780     105.370
1600.0    22771.30     1.899     105.379
1630.0    22774.32     1.985     105.389
1700.0    22776.95     2.038     105.401
1730.0    22779.14     2.056     105.413
1800.0    22780.85     2.038     105.427
1830.0    22782.06     1.986     105.442
1900.0    22782.74     1.899     105.459

REFERENCE LATITUDE=  70.00 DEG, MAP ERROR=  0.12 DEG

TIME      READING   LONGITUDE LOP ANGLE  EL SAT AZ   LOP DIST R(MOJ-AII)
ZULU    MANH    AII DEG   MIN      DEG    DEG      DEG     NMI        NMI
1428.  99.32  49.43  57  3.53   140.57  6.04 230.57    0.000   41542.17
1438.  95.96  47.15  57  3.78   140.58  6.10 230.58    0.068   41540.02
1448.  92.68  45.07  57  4.58   140.59  6.16 230.59    0.279   41537.98
1630.  75.87  35.68  57  4.90   140.73  6.58 230.73    0.367   41528.41
1730.  78.38  40.44  57  7.87   140.72  6.66 230.72    1.155   41532.93
1831.  91.01  52.42  57  8.64   140.72  6.58 230.72    1.358   41544.94
```

```
AII-MANHATTAN EXPERIMENT            4/11/1970
SHIP POSITION:N. LAT= 67. 52.00 W. LNG= 56.  5.00
REFERENCE TIME:  1000.0 ZULU

ATS-5 EPHEMERIS
 TIME    SAT RANGE   LATITUDE   LONGITUDE
 ZULU       NMI         DEG         DEG
1000.0    22725.76     -.902     105.423
1030.0    22728.44     -.650     105.410
1100.0    22731.53     -.387     105.400
1130.0    22734.97     -.118     105.392
1200.0    22738.69     0.157     105.387
1230.0    22742.63     0.422     105.385
1300.0    22746.72     0.683     105.389
1330.0    22750.89     0.932     105.386
1400.0    22755.06     1.165     105.389

REFERENCE LATITUDE=  68.00 DEG, MAP ERROR=  0.13 DEG

TIME      READING   LONGITUDE LOP ANGLE  EL SAT AZ   LOP DIST R(MOJ-AII)
ZULU    MANH    AII DEG   MIN      DEG    DEG      DEG     NMI        NMI
1100.  87.13  53.56  56  9.86   141.38  5.28 231.38    0.000   41630.52
1110.  81.42  48.42  56  7.44   141.45  5.36 231.45    0.707   41625.55
1120.  75.43  43.02  56  5.08   141.51  5.43 231.51    1.400   41620.60
1130.  69.93  38.08  56  2.59   141.57  5.51 231.57    2.127   41615.65
1140.  64.31  33.08  56  0.18   141.64  5.58 231.64    2.838   41610.76
1150.  58.61  28.05  55 57.91   141.70  5.66 231.70    3.503   41605.88
1200.  53.21  23.25  55 55.40   141.77  5.74 231.77    4.244   41601.01
1210.  47.82  18.41  55 52.84   141.84  5.81 231.84    5.000   41596.58
1220.  41.84  13.75  55 52.87   141.87  5.90 231.87    4.991   41592.16
1230.  36.08   9.19  55 52.49   141.90  5.99 231.90    5.106   41587.75
1240.  30.22   4.77  55 52.91   141.92  6.07 231.92    4.983   41583.59
1250.  24.63   0.58  55 53.18   141.94  6.16 231.94    4.904   41579.43
1300. 116.55  93.79  55 53.06   141.97  6.24 231.97    4.938   41575.29
1340.  91.27  73.46  55 53.04   142.07  6.56 232.07    4.948   41560.58
1350.  86.61  70.00  55 53.04   142.10  6.64 232.10    4.949   41557.26
```

```
          AII-MANHATTAN EXPERIMENT              4/17/1970
          SHIP POSITION:N. LAT= 70. 49.00 W. LNG= 57. 27.00
          REFERENCE TIME:  1600.0 ZULU

          ATS-5 EPHEMERIS
          TIME   SAT RANGE   LATITUDE   LONGITUDE
          ZULU     NMI         DEG         DEG
        1600.0   22772.45     1.935     105.350
        1630.0   22775.20     2.007     105.360
        1700.0   22777.56     2.045     105.372
        1730.0   22779.48     2.048     105.385

          REFERENCE LATITUDE=  71.00 DEG, MAP ERROR=  0.12 DEG

 TIME      READING   LONGITUDE LOP ANGLE  EL SAT AZ   LOP DIST R(MOJ-AII)
 ZULU    MANH     AII DEG   MIN     DEG     DEG    DEG     NMI       NMI
1600.  31.18   34.29  57 34.06    140.05  6.05 230.05    0.000    41527.85
1630.  29.95   34.48  57 34.39    140.07  6.12 230.07    0.083    41527.92
1700.  31.14   36.49  57 34.50    140.09  6.16 230.09    0.112    41529.89
```

```
          AII-MANHATTAN EXPERIMENT              4/18/1970
          SHIP POSITION:N. LAT= 71.  0.00 W. LNG= 57. 36.00
          REFERENCE TIME:  1400.0 ZULU

          ATS-5 EPHEMERIS
          TIME   SAT RANGE   LATITUDE   LONGITUDE
          ZULU     NMI         DEG         DEG
        1500.0   22766.60     1.712     105.324
        1530.0   22769.92     1.845     105.332
        1600.0   22772.92     1.946     105.342

          REFERENCE LATITUDE=  71.00 DEG, MAP ERROR=  0.12 DEG

 TIME      READING   LONGITUDE LOP ANGLE  EL SAT AZ   LOP DIST R(MOJ-AII)
 ZULU    MANH     AII DEG   MIN     DEG     DEG    DEG     NMI       NMI
1520.  11.71    8.30  57 35.95    139.80  5.84 229.80    0.000    41530.65
1530.   9.76    7.50  57 37.45    139.79  5.89 229.79    0.373    41529.46
1540.   7.95    6.80  57 39.47    139.77  5.93 229.77    0.876    41528.90
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          AII-MANHATTAN EXPERIMENT              4/15/1970
          SHIP POSITION:N. LAT= 69. 49.80 W. LNG= 56. 59.40
          REFERENCE TIME:  1730.0 ZULU

          ATS-5 EPHEMERIS
          TIME   SAT RANGE   LATITUDE   LONGITUDE
          ZULU     NMI         DEG         DEG
        1400.0   22757.06     1.277     105.339
        1430.0   22761.02     1.477     105.345
        1500.0   22764.81     1.651     105.351
        1530.0   22768.38     1.796     105.359
        1600.0   22771.66     1.911     105.368
        1630.0   22774.60     1.993     105.378
        1700.0   22777.15     2.041     105.390

          REFERENCE LATITUDE=  70.00 DEG, MAP ERROR=  0.12 DEG

 TIME      READING   LONGITUDE LOP ANGLE  EL SAT AZ   LOP DIST R(MOJ-AII)
 ZULU    MANH     AII DEG   MIN     DEG     DEG    DEG     NMI       NMI
1420.  27.24   50.48  57  5.83    140.56  6.06 230.56    0.000    41543.15
1530.   8.30   37.91  57  5.46    140.69  6.43 230.69    0.093    41530.69
1630.   2.60   35.36  57  4.27    140.78  6.62 230.78    0.405    41528.14
```

```
          AII-MANHATTAN EXPERIMENT              4/16/1970
          SHIP POSITION:N. LAT= 70. 35.22 W. LNG= 56. 54.60
          REFERENCE TIME:  1450.0 ZULU

          ATS-5 EPHEMERIS
          TIME   SAT RANGE   LATITUDE   LONGITUDE
          ZULU     NMI         DEG         DEG
        1430.0   22761.63     1.502     105.334
        1500.0   22765.35     1.672     105.341
        1530.0   22768.84     1.813     105.349
        1600.0   22772.03     1.923     105.358

          REFERENCE LATITUDE=  70.50 DEG, MAP ERROR=  0.12 DEG

 TIME      READING   LONGITUDE LOP ANGLE  EL SAT AZ   LOP DIST R(MOJ-AII)
 ZULU    MANH     AII DEG   MIN     DEG     DEG    DEG     NMI       NMI
1450.  35.93   10.01  56 51.21    140.56  5.81 230.56    0.000    41533.71
1504.  33.95    7.68  56 45.43    140.67  5.85 230.67    1.493    41531.90
1535.  28.15    4.08  56 45.29    140.72  5.98 230.72    1.531    41528.96
```

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AII-MANHATTAN EXPERIMENT                 4/21/1970
SHIP POSITION:N. LAT= 71. 50.00 W. LNG= 58. 30.00
REFERENCE TIME:  1400.0 ZULU

ATS-5 EPHEMERIS
 TIME    SAT RANGE   LATITUDE   LONGITUDE
 ZULU       NMI         DEG        DEG
1400.0   22761.76      1.436     105.283
1430.0   22765.42      1.615     105.290
1500.0   22768.83      1.766     105.299
1530.0   22771.93      1.887     105.308

REFERENCE LATITUDE=  72.00 DEG, MAP ERROR=  0.11 DEG

TIME     READING   LONGITUDE LOP ANGLE  EL  SAT AZ   LOP DIST R(MOJ-AII)
ZULU   MANH    AII DEG   MIN     DEG    DEG     DEG     NMI        NMI
1420.  46.83  62.23  58 36.56   138.64  5.28 228.64    0.000   41539.78
1430.  43.83  60.33  58 36.82   138.65  5.34 228.65    0.063   41537.60
1440.  41.03  58.43  58 36.87   138.67  5.39 228.67    0.073   41536.00
1450.  39.26  57.57  58 36.94   138.68  5.43 228.68    0.091   41534.41
1500.  36.92  56.12  58 36.93   138.70  5.48 228.70    0.088   41532.81
```

```
AII-MANHATTAN EXPERIMENT                 4/22/1970
SHIP POSITION:N. LAT= 72. 12.00 W. LNG= 58. 50.00
REFERENCE TIME:  1400.0 ZULU

ATS-5 EPHEMERIS
 TIME    SAT RANGE   LATITUDE   LONGITUDE
 ZULU       NMI         DEG        DEG
1400.0   22762.47      1.459     105.272
1430.0   22766.14      1.634     105.280
1500.0   22769.52      1.781     105.289
1530.0   22772.58      1.898     105.299
1600.0   22775.26      1.982     105.309
1630.0   22777.53      2.032     105.321
1700.0   22779.34      2.048     105.334

REFERENCE LATITUDE=  72.00 DEG, MAP ERROR=  0.11 DEG

TIME     READING   LONGITUDE LOP ANGLE  EL  SAT AZ   LOP DIST R(MOJ-AII)
ZULU   MANH    AII DEG   MIN     DEG    DEG     DEG     NMI        NMI
1410. 108.99  76.59  58 41.97   138.22  5.07 228.22    0.000   41541.49
1420. 105.90  74.52  58 41.96   138.23  5.13 228.23    0.004   41539.43
1430. 102.94  72.59  58 41.98   138.25  5.19 228.25    0.000   41537.37
1440. 100.26  70.78  58 41.97   138.26  5.23 228.26    0.004   41535.86
1450.  97.98  69.38  58 41.99   138.28  5.28 228.28    0.001   41534.35
1500.  95.70  67.97  58 41.96   138.29  5.33 228.29    0.006   41532.84
1510.  93.92  66.90  58 41.95   138.31  5.37 228.31    0.008   41531.90
1520.  92.23  65.92  58 41.94   138.32  5.41 228.32    0.011   41530.97
1550.  89.10  64.56  58 41.95   138.35  5.50 228.35    0.010   41529.37
1610.  88.11  64.44  58 41.96   138.37  5.54 228.37    0.010   41529.33
1630.  88.21  65.22  58 41.94   138.39  5.57 228.39    0.015   41529.90
1640.  91.40  68.56  58 41.93   138.39  5.58 228.39    0.017   41530.77
```

```
AII-MANHATTAN EXPERIMENT                 4/23/1970
SHIP POSITION:N. LAT= 72. 31.20 W. LNG= 58. 46.80
REFERENCE TIME:  1400.0 ZULU

ATS-5 EPHEMERIS
 TIME    SAT RANGE   LATITUDE   LONGITUDE
 ZULU       NMI         DEG        DEG
1430.0   22766.73      1.652     105.268
1500.0   22770.11      1.795     105.278
1530.0   22773.15      1.908     105.288
1600.0   22775.80      1.988     105.299
1630.0   22778.01      2.033     105.311

REFERENCE LATITUDE=  72.50 DEG, MAP ERROR=  0.11 DEG

TIME     READING   LONGITUDE LOP ANGLE  EL  SAT AZ   LOP DIST R(MOJ-AII)
ZULU   MANH    AII DEG   MIN     DEG    DEG     DEG     NMI        NMI
1440.  23.78   5.91  58 45.94   138.27  5.08 228.27    0.000   41533.84
1450.  22.32   4.93  58 44.38   138.31  5.12 228.31    0.349   41532.55
1600.  14.14   0.42  58 43.55   138.40  5.31 228.40    0.538   41529.92
```

```
AII-MANHATTAN EXPERIMENT                 4/24/1970
SHIP POSITION:N. LAT= 73. 30.00 W. LNG= 59. 20.40
REFERENCE TIME:  2300.0 ZULU

ATS-5 EPHEMERIS
 TIME    SAT RANGE   LATITUDE   LONGITUDE
 ZULU       NMI         DEG        DEG
2330.0   22759.14      -.350     105.526
2400.0   22755.23      -.610     105.534
2430.0   22751.26      -.860     105.539
2500.0   22747.28      1.094     105.540

REFERENCE LATITUDE=  73.50 DEG, MAP ERROR=  0.10 DEG

TIME     READING   LONGITUDE LOP ANGLE  EL  SAT AZ   LOP DIST R(MOJ-AII)
ZULU   MANH    AII DEG   MIN     DEG    DEG     DEG     NMI        NMI
2350.  37.58  50.37  59 20.30   137.28  2.12 227.28    0.000   41698.72
2400.  42.99  54.63  59 20.97   137.25  2.04 227.25    0.139   41702.84
2440.  38.80  71.32  59 21.59   137.52  3.31 227.52    0.269   41589.98
```

APPENDIX C

Positions of the S. S. Manhattan as they were determined by other navigational systems on board are listed in this Appendix. Also the ship's heading and speed is listed opposite the times indicated.

Ship's heading is given at specific times on the days during the latter part of the voyage even though the vessel was maneuvering most of the time during those days due to concentrated ice conditions.

The other navigational systems used on board the S. S. Manhattan were: Loran, Transit, Omega, solar fix and dead reckoning.

Positions of S. S. Manhattan
From 3-31-70 through 4-23-70

Date	Time	Lat N	Long W	Type Fix	Ship's Heading	Ship's Speed (knots)
3-31-70	1200Z	36.9821	76.4413	Transit	Stanry	In Port
4-1-70	1200Z	36.9821	76.4413	Transit	Stanry	In Port
4-2-70	1200Z	36.9821	76.4413	Transit	Stanry	In Port
4-3-70	1200Z	36.9821	76.4413	Transit	Manvrg	Out of Port
4-4-70	1200Z	37°37'	74°06'	Loran	055°	16.2
	1240Z	37°45'	73°57'	Loran	055°	16.8
	1300Z	37.777	73.843	Transit	055°	16.2
	1315Z	37.8223	73.1615	Transit		
4-7-70	1200Z	47.992	52.274	Transit		
	1220Z	48.1035	52.2632	Transit	004°	11.5
	1245Z	48.1881	52.254	Transit	004°	11.5
	1315Z	48.2924	52.2382	Loran	004°	12.2
	1355Z	48.4195	52.207	Loran	004°	11.9
4-8-70	1200Z	52.78	51.31	Transit	003°	12.0

Positions of S. S. Manhattan
From 3-31-70 through 4-23-70
(continued)

Date	Time	Lat N	Long W	Type Fix	Ship's Heading	Ship's Speed (knots)
4-8-70	1210Z	52.81	51.30	Transit		
	1310Z	53°01'	51°18'	Loran		
	1322Z	53.04	51.29	Transit		
4-9-70	1200Z	58°09'	51°00'	Loran	004°	15
	1225Z	58.233'	51.027	Transit		
	1242Z	58.336	51.017	Transit	003°	14.9
	1244Z	58°20'	51°04'	Omega		
	1320Z	58.494	51.002	Transit		
	1351Z	58.632	50.987	Transit		
	1410Z	58°43'	51°09'	Omega		
	1410Z	58.658	50.97'	Transit		
4-10-70	2140Z	65°50.5'	54°58'	Transit	347°	13.7
	0017Z	66°09'	54°53'	Omega		
	1032Z	67°58'	56°05'	Dead Rec		
4-11-70	1000Z	67°52'	56°05'	Dead Rec	346°	8
4-14-70	1400Z	70°N	56.92°	Dead Rec	348°	0
	1434Z	69.89°	56.99°	Transit	349°	0
4-15-70	1730Z	69.83	56.99	Transit	348°	0
	2300Z	70.30	56.38	Transit	324°	0
4-16-70	1430Z	70°34'	56°44'	Dead Rec	337°	0 to 6
	1450Z	70.587	56.91	Transit		
	1616Z	70.588	56.915	Transit		
4-17-70	1600Z	70°49'	57°27'	Dead Rec	335°	0 to 6
	1900Z	70.79°	57.48°	Transit		
4-18-70	1400Z	71°00'	57°36'	Dead Rec	350°	0 to 6
4-21-70	1400Z	71°50'	58°30'	Dead Rec	010°	0 to 8
	1600Z	72°10'	58°54'	Dead Rec	355°	0
4-22-70	1400Z	72°12'	58°50'	Dead Rec	0 to 025°	0 to 14
4-23-70	1400Z	72.52°	58.78°	Transit	330°-005°	0 to 6

Positions of S. S. Manhattan
From 3-31-70 through 4-23-70
(continued)

Date	Time	Lat N	Long W	Type Fix	Ship's Heading	Ship's Speed (knots)
4-23-70	1600Z	72.59°	58.56°	Transit		
4-24-70	2300Z	73.50°	59.34°	Transit	280-340°	0 to 8
4-25-70	1600Z	73°48'	60°05'	Dead Rec		
4-26-70	1600Z	74°02'	61°01'	Dead Rec		
4-27-70	1600Z	74°20'	62°00'	Dead Rec		
4-28-70	1600Z	75°00'	65°00'	Dead Rec		

APPENDIX D

The received frequency measurements given in this appendix were made at the wideband second IF test point of the ORION receiver. The wave analyzers, HP 312A model, were used for this purpose at both the AII laboratory and on board the S. S. Manhattan.

PRECISE 2ND IF FREQUENCY DURING SIGNAL RECEPTION

Received Frequency Measurement on Board the S. S. Manhattan

Date	Z Time	IF Frequency KHZ
3-31-70	1230	4082.87
	1243	4082.85
	1256	4082.87
	1305	4082.85
	1349	4082.88
4-1-70	1205	4082.48
	1222	4082.57
	1245	4082.62
	1250	4082.65
	1318	4082.66
	1353	4082.72
4-2-70	1206	4082.53
	1217	4082.25
	1226	4082.65
	1244	4082.69
	1254	4082.68
	1302	4082.72
	1315	4082.62
4-3-70	1226	4082.64
	1232	4082.64
	1248	4082.60
	1305	4082.67
	1353	4082.73
4-4-70	1222	4082.46
	1242	4082.52
	1304	4082.54
	1314	4082.54
	1324	4082.57
	1334	4082.59
	1354	4082.63
4-7-70	1244	4082.64
	1347	4082.58
	1358	4082.72
4-8-70	1229	4082.61
	1355	4082.70
4-9-70	1233	4082.76
	1315	4082.75
	1353	4082.75
4-10-70	2246	4082.62
	2333	4082.63
	2353	4082.63
4-11-70	1012	4082.62
	1045	4082.68
4-11-70	1057	4082.72
	1136	4082.76
	1153	4082.78
4-14-70	1431	4082.68
	1455	4082.44
	1515	4082.50
	1622	4082.65
	1642	4082.59
	1724	4082.68
	1734	4082.68
	1754	4082.67
	1814	4082.67
	1834	4082.67
	2103	4082.72
	2114	4082.73
	2200	4082.74

PRECISE 2ND IF FREQUENCY DURING SIGNAL RECEPTION

Received Frequency Measurement on Board the S. S. Manhattan (continued)

Date	Z Time	IF Frequency KHZ
4-15-70	1412	4082.40
	1442	4082.55
	1504	4082.58
	1514	4082.59
	1654	4082.68
4-16-70	1444	4082.54
	1518	4082.60
	1626	4082.68
4-17-70	1704	4082.70
4-18-70	1457	4083.15
	1544	4183.12
	1814	4083.40
	1834	4083.48
	1844	4083.65
4-21-70	1454	4083.40
	1654	4083.50
	1704	4083.58
4-22-70	1419	4082.80
	1424	4082.80
	1604	4083.20
4-23-70	1442	4084.44
	1602	4083.05
	1702	4084.29
4-24-70	2310	4082.30
	2317	4082.10
	2342	4082.42
	0004	4082.52
	0054	4082.62

PRECISE 2ND IF FREQUENCY DURING SIGNAL RECEPTION

Received Frequency Measurement at AII Laboratory

Date	Time Z	IF Frequency KHz
4-3-70	1226	4082.64
	1353	4082.73
4-4-70	1232	4082.45
	1242	4082.62
	1304	4082.53
	1314	
	1324	4082.59
	1334	
	1348	4082.63