ASI-TR-75-22
(NASA CR-132720)

FLIGHT TEST AND EVALUATION OF OMEGA NAVIGATION IN A GENERAL AVIATION AIRCRAFT

VOLUME I: TECHNICAL

FINAL REPORT

April, 1975

Jack D. Howell
William C. Hoffman
Aerospace Systems, Inc.

Peter V. Hwoschinsky
C. Edward Wischmeyer
Massachusetts Institute of Technology

Contract No. NAS 1-13644
National Aeronautics and Space Administration

ASI

AEROSPACE SYSTEMS, INC.
ONE VINE BROOK PARK • BURLINGTON, MASS. 01803 USA
TELEPHONE (617) 272-7517

ASI-TR-75-22
(NASA CR-132720)

FLIGHT TEST AND EVALUATION OF OMEGA NAVIGATION IN A GENERAL AVIATION AIRCRAFT

Volume I: Technical

FINAL REPORT

by

Jack D. Howell
William C. Hoffman
Aerospace Systems, Inc.

and

Peter V. Hwoschinsky
C. Edward Wischmeyer
Massachusetts Institute of Technology

Approved John Zvara

John Zvara
Technical Director

Prepared under
Contract No. NAS 1-13644

for

National Aeronautics and Space Administration
Hampton, Virginia 23365

April 1975

FOREWORD

This report was prepared by Aerospace Systems, Inc. (ASI), Burlington, Massachusetts, for the National Aeronautics and Space Administration (NASA) under Contract No. NAS1-13644. The study was sponsored by the Flight Instrumentation Division, the NASA Langley Research Center (LaRC), Hampton, Virginia. Mr. Wayne L. Kitchen served as Technical Monitor on the contract. This is the first volume of the final technical report which documents the results of research performed during the period October 1974 to March 1975. Volume II contains appendices to this volume.

The effort was directed by Mr. John Zvara, President and Technical Director of ASI. Mr. William C. Hoffman served as Project Engineer and Mr. Jack D. Howell was a co-investigator for the program.

The Massachusetts Institute of Technology (MIT) provided technical support to ASI under Subcontract No. ASI-SC-74-2. Dr. Walter M. Hollister and Dr. Robert W. Simpson both of the MIT Department of Aeronautics and Astronautics contributed to the study as technical consultants. Mr. Peter V. Hwoschinsky and Mr. C. Edward Wischmeyer of the MIT Flight Transportation Laboratory also served as co-investigators.

The authors are indebted to Mr. Paul E. Rademacher and his associates at Dynell Electronics for their assistance with the Omega receiver and data recording equipment. We are also grateful to Mr. Gene E. Godwin and other support personnel at the NASA Wallops Flight Center for their cooperation during the Wallops Island phase of the flight evaluation.

ABSTRACT

A low-cost flight research program was conducted to evaluate the performance of differential Omega navigation in a general aviation aircraft. The flight program consisted of two distinct parts corresponding to the two major objectives of the study:

- Part One - Wallops Flight Program. Obtain Omega signal and phase data in the Wallops Flight Center vicinity to provide preliminary technical information and experience in preparation for a comprehensive NASA/FAA flight test program of an experimental differential Omega system.

- Part Two - Northeast Corridor Flight Program. Examine Omega operational suitability and performance on low altitude area navigation (RNAV) routes developed by ASI for city-center to city-center VTOL commercial operations in the Boston-New York-Washington corridor.

The development, execution and conclusions of the flight research program are described. The results of the study provide both quantitative and qualitative data on the Omega Navigation System under actual operating conditions.

AEROSPACE SYSTEMS, INC. • ONE VINE BROOK PARK • BURLINGTON, MASSACHUSETTS 01803 • (617) 272-7517

TABLE OF CONTENTS

Section		Page
1	INTRODUCTION	1
2	THE OMEGA NAVIGATION SYSTEM	3
	2.1 Hyperbolic Navigation Principles	3
	2.2 Omega Navigation System	5
	2.3 Omega System Advantages and Disadvantages	7
3	PROGRAM OBJECTIVES AND SCOPE	10
	3.1 Part One: Wallops Flight Program	10
	3.2 Part Two: Northeast Corridor Flight Program	11
4	FLIGHT PROGRAM EQUIPMENT AND FACILITIES	13
	4.1 Piper Cherokee 180 Aircraft	13
	4.2 Omega Mark III Navigation System	13
	4.2.1 Clock Generation and Synchronization	19
	4.2.2 Phase Tracking	19
	4.2.3 Position Calculation	20
	4.2.4 Installation	20
	4.3 Custom Interface Unit (CIU) and Data Recorder	22
	4.4 Voice Recorder	25
	4.5 Wallops Island Tracking Radar	25
5	FLIGHT PROGRAM PROCEDURES	28
	5.1 Flight Planning and Checklists	28
	5.1.1 Flight Planning Documents	28
	5.1.2 Operations Checklists	32
	5.2 Data Recording	36
	5.2.1 Omega Data	36
	5.2.2 Voice Recorder	36

AEROSPACE SYSTEMS, INC. • ONE VINE BROOK PARK • BURLINGTON, MASSACHUSETTS 01803 • (617) 272-7517

TABLE OF CONTENTS (Continued)

Section			Page
		5.2.3 Position Plotting	40
	5.3	Navigation Techniques	40
		5.3.1 Visual Navigation	42
		5.3.2 VOR/ILS Navigation	42
		5.3.3 Omega Navigation	43
6	POST-FLIGHT DATA PROCESSING		44
	6.1	Data Processing Equipment	44
	6.2	Data Transcription	47
	6.3	Data Checking	48
		6.3.1 TRNSCHK	48
		6.3.2 DATACHK	48
	6.4	Plotting Routines	49
		6.4.1 Miles-To-Go Plots	49
		6.4.2 Status Flag Plots	50
		6.4.3 Needle Deflection Plots	50
		6.4.4 Map Plots	51
7	WALLOPS AREA FLIGHT PROGRAM RESULTS		52
	7.1	Altitude Effects	55
		7.1.1 Expected Results	55
		7.1.2 Takeoff Phenomenon	56
	7.2	Shore Effects	56
		7.2.1 Expected Results	56
		7.2.2 Course Deviations Observed	58
		7.2.3 Variations With S/N	60

AEROSPACE SYSTEMS, INC. • ONE VINE BROOK PARK • BURLINGTON, MASSACHUSETTS 01803 • (617) 272-7517

TABLE OF CONTENTS (Continued)

Section			Page
	7.2.4	Altitude Effects	60
7.3		Station Pairs and LOP Directions	61
	7.3.1	Expected Results	62
	7.3.2	Observed Results	62
7.4		Diurnal Effects	65
	7.4.1	Expected Results	65
	7.4.2	Errors Observed During Transition	67
	7.4.3	S/N Results	71
7.5		Precipitation Static Effects	71
	7.5.1	Expected Results	71
	7.5.2	Description of Circumstances	71
	7.5.3	S/N Results	77
	7.5.4	Accuracy and Pilot Tracking	77
7.6		Interference and Signal Strength Variations	77
	7.6.1	Expected Results	78
	7.6.2	Interference Observations and Probable Sources	78
	7.6.3	Interference Effects and Altitude	80
	7.6.4	Accuracy and Pilot Tracking During Interference	80
	7.6.5	Signal Strength Variations	85
7.7		Maneuvers	85
7.8		Radar and Accuracy	86

TABLE OF CONTENTS (Continued)

Section		Page
8	NORTHEAST CORRIDOR FLIGHT PROGRAM RESULTS	87
	8.1 Omega Suitability for Commercial VTOL Operations	87
	8.1.1 Signal Availability	91
	8.1.2 Observed Accuracy	91
	8.1.3 Required Pilot Technique	94
	8.2 Altitude Effects	94
	8.2.1 S/N On Takeoff - Ground Versus Airborne Effects	97
	8.2.2 Pilot Tracking	97
	8.3 Terrain Effects	101
	8.3.1 Cities	101
	8.3.2 Water	106
	8.3.3 Mountainous Terrain	106
	8.3.4 Forests	106
	8.4 Maneuver Effects	106
9	CONCLUSIONS	107
	9.1 Omega Signal and Phase Characteristics	107
	9.2 Suitability and Accuracy for VTOL Operations	108
	REFERENCES	111

AEROSPACE SYSTEMS, INC. • ONE VINE BROOK PARK • BURLINGTON, MASSACHUSETTS 01803 • (617) 272-7517

LIST OF FIGURES

No.	Title	Page
1	Line of Position Determination	3
2	Position Determination with Two LOPs	4
3	Example of Poor Geometry for Position Fix	5
4	Omega Navigation Signal Format	6
5	Ambiguity Resolution with Two Omega Frequencies	8
6	Mark III Omega Navigation System Components	15
7	Dynell Mark III Antenna Coupler	16
8	Functional Block Diagram of Mark III Omega Navigation System	17
9	Receiver and Indicator Locations in Test Aircraft	21
10	Airborne Equipment Functional Diagram	23
11	Wallops Tracking Radar Data	27
12	Sample Flight Evaluation Sheet	29
13	Omega Flight Plan	30
14	Sample Flight Map	31
15	Flight Equipment Checklist	32
16	Checklist for Connection and In-Flight Recording with CIU	33
17	Omega Turn-On Checklist	33
18	Receiver Synchronization Checklists	34
19	Ground Operations Checklists	35
20	In-Flight Operations Checklists	35
21	Voice Recorder Checklist: Initial Record on Tape	37
22	Voice Recorder Checklist: Receiver Setting Changes	38
23	Voice Recorder Checklist: General	38
24	Sample Voice Transcript	39

No.	Title	Page
25	Typical Manual Position Plot	41
26	Post-Flight Data Processing Functional Diagram	45
27	Flight 1-9, S/N Station A and B	57
28	Flight 1-10, Needle Deflection Over Coastal Region Along a Fixed VOR Radial	59
29	Flight 1-22 (First 81 min.), Miles to Go and Needle Deflection	63
30	Flight 1-22 (Second 80 min.), Miles to Go and Needle Deflection	64
31	Station Transition Times and Wallops Area Flight Schedule	66
32	Wallops Area Omega Propagation Corrections for 10.2 KHz	68
33	Flight 1-24 (First 63 min.), Miles to Go and Needle Deflection	69
34	Flight 1-24 (Second 62 min.), Miles to Go and Needle Deflection	70
35	Weak S/N Periods for Station A in the Wallops Area	72
36	Flight 1-23 (Second 61 min.), Miles to Go and Needle Deflection	73
37	Flight 1-23 (Second 61 min.), S/N Station A and B	74
38	Flight 1-21, Miles to Go and Needle Deflection	75
39	Flight 1-21, S/N Station A and B	76
40	Flight 1-5, S/N Station A and B	79
41	Flight 1-9, Miles to Go and Needle Deflection	82
42	Flight 1-6 (Second 66 min.), Miles to Go and Needle Deflection	83
43	Flight 1-6 (First 89 min.), S/N Station A and B	84
44	Omega LOPs Plotted on Aeronautical Chart	88
45	Sample VORTAC Coverage, Madison VOR	92

LIST OF FIGURES (Continued)

No.	Title	Page
46	Proposed Helicopter Airway	95
47	Flight 2-Z1-1, S/N Station A and B	98
48	Flight 2-44 (Third 41 min.), S/N Station A and B	99
49	Flight 2-12 (First 61 min.), S/N Station A and B	100
50	Flight 2-12 (Second 60 min.), Miles to Go and Needle Deflection	102
51	Flight 2-12 (Second 60 min.), S/N Station A and B	103
52	Flight 2-12 (Second 60 min.), S/N Station C and D	104
53	Central Connecticut S/N Degradation (Flight 2-12)	105

LIST OF TABLES

No.	Title	Page
1	Piper Cherokee Dimensions and Performance Characteristics	14
2	Mark III Omega Navigation System Specifications	18
3	ASI Wang 2200 Minicomputer System	46
4	Wallops Area Flight Test Objectives	53
5	Wallops Area Omega Flights	54
6	Flights Along LOPs	61
7	NE Corridor Flight Test Objectives	89
8	NE Corridor Omega Flights	90
9	Comparison of VOR/DME and Omega Waypoint Position Errors	94
10	NE Corridor Flight Altitudes	96

AEROSPACE SYSTEMS, INC. • ONE VINE BROOK PARK • BURLINGTON, MASSACHUSETTS 01803 • (617) 272-7517

SECTION 1

INTRODUCTION

Aerospace Systems, Inc. (ASI) as prime contractor with support from the MIT Flight Transportation Laboratory has completed a low-cost Flight Evaluation of Omega Navigation in a general aviation aircraft. The Flight Evaluation program consisted of two major parts:

Part One - The Wallops Flight Program

This part of the program obtained Omega signal and phase data in the area of the NASA Wallops Flight Center. The objective was to provide preliminary technical information and experience in the same geographic area where the performance of an experimental Differential Omega Unit is to be evaluated.

The program used a Dynell Mark III Omega Navigation System installed in a Piper Cherokee 180 aircraft. A custom interface unit provided Omega data for onboard recording. Data reduction was accomplished with the aid of a Wang 2200 minicomputer. The results of Part One evaluated the effects of variables such as altitude, phase anomalies along coastlines, diurnal variations, precipitation, interference, and maneuvers. Also investigated were the influences of using various station-pair combinations, the performance in flights parallel and perpendicular to LOPs, and accuracy compared to radar tracking data.

Part Two - The Northeast Corridor Flight Program

This part of the program examined Omega operational suitability and performance on the VTOL RNAV routes developed by ASI (Reference 1) for city-center to city-center VTOL commercial operations in the Boston-New York-Washington corridor. Previously flown low-altitude Zulu routes were flown to compare Omega performance and VOR-DME results.

Part Two used the same aircraft, data recording and data reduction equipment as Part One. Evaluation of signal and phase information as in Part One was continued. In addition, the performance at various altitudes over and near cities, performance during operational maneuvers, and the effect of terrain were investigated.

The results of the program provide both qualitative and quantitative data on the Omega Navigation System under actual operating conditions. The data obtained directly support current NASA/FAA research programs.

This report consists of two volumes. Volume I: Technical, describes the program in detail, and Volume II: Appendices, contains the detailed results of the flights, the computer programs used in data reduction, and the recorded data format.

Within Volume I, Section 2 describes the Omega navigation system and summarizes some of its strong and weak points. Also included is a basic discussion of hyperbolic navigation basic to the Omega system. Section 3 states the objectives and scope of the two parts of the Omega navigation system flight evaluation program. The equipment and facilities used in the program are described in Section 4. Section 5 discusses the flight planning, data recording procedures, and navigational techniques employed in the program. Section 6 includes brief descriptions of the post-flight data reduction system including the data processing equipment, data reduction software, and plotting routines. The actual results of the flight tests due to various effects are discussed in Section 7 for Part One of the program, and in Section 8 for Part Two of the program. Section 9 presents conclusions relating to Omega signal and phase characteristics as well as the accuracy and suitability of Omega navigation for city-center to city-center VTOL operations. The need for additional analysis is discussed.

SECTION 2

THE OMEGA NAVIGATION SYSTEM

This section includes a basic discussion of the principles of hyperbolic navigation, a brief description of the Omega system, and a summary of some of its advantages and disadvantages.

2.1 HYPERBOLIC NAVIGATION PRINCIPLES

Hyperbolic navigation is a radio navigation technique used by the Omega, Loran, and Decca navigation systems, among others. Based on a distance difference measurement, the navigation receiver determines one or more lines of position along which the receiver is assumed to be located. The term "hyperbolic" refers to the locus of possible receiver locations having a constant distance difference between two transmitter sites. In Figure 1 from any point X_i on the line of position, the difference between the distances to transmitter A and to transmitter B is constant.

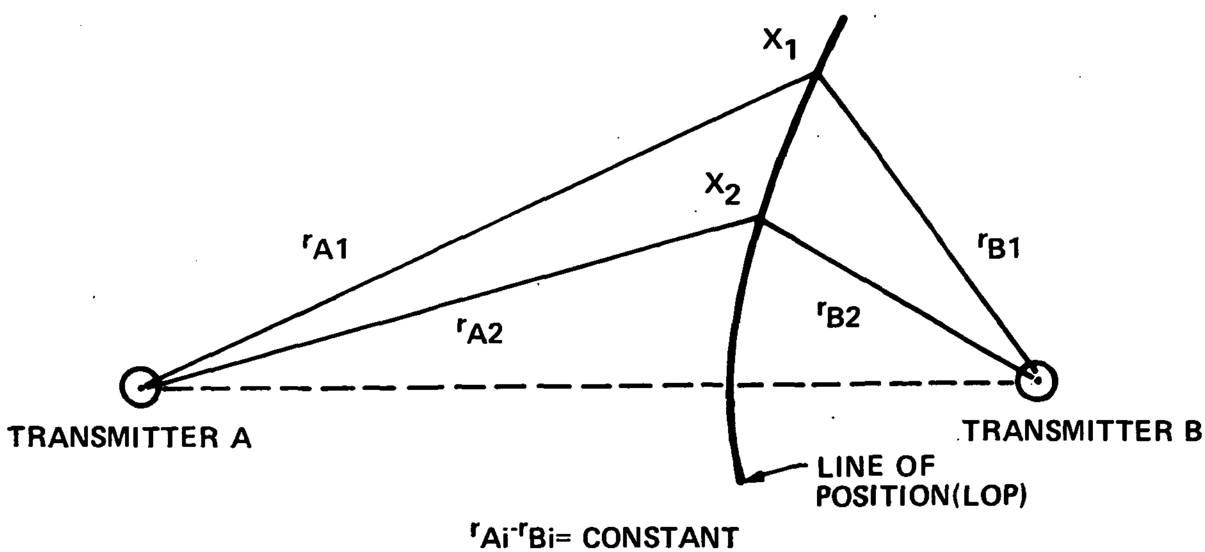


Figure 1. Line of Position Determination.

The distance measurements are not made directly, however. Instead, using the propagation speed of radio waves, time parameters of the received signal are measured relative to a local time standard, such as an oscillator. When two time parameters are measured relative to the local standard and subtracted, they give a time difference, which varies from the distance difference by the speed of propagation. This time parameter can be the leading edge of the received signal, as in Loran, or it can be a phase measurement, as in Omega.

A single position difference measurement defines a hyperbola called a Line of Position (LOP), but one hyperbola cannot specify position uniquely. Two or more hyperbolae or LOPs are required as shown in Figure 2. Figure 3 illustrates the deleterious effects of poor LOP geometry wherein small errors in LOP determination can result in large errors of estimated position. This occurs when the hyperbolae are nearly parallel at their intersection. Such a condition drastically reduces the precision of position measurement.

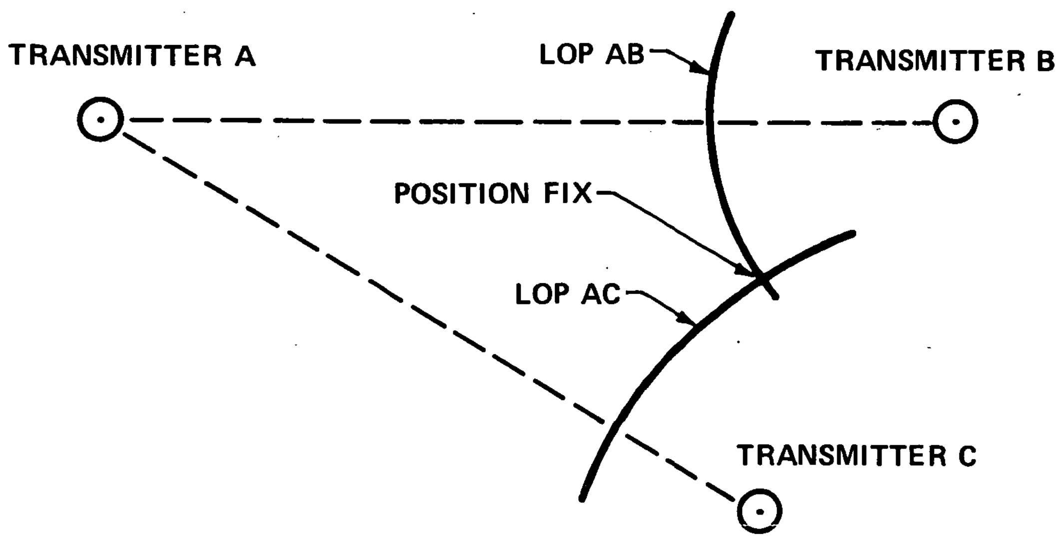


Figure 2. Position Determination With Two LOPs.

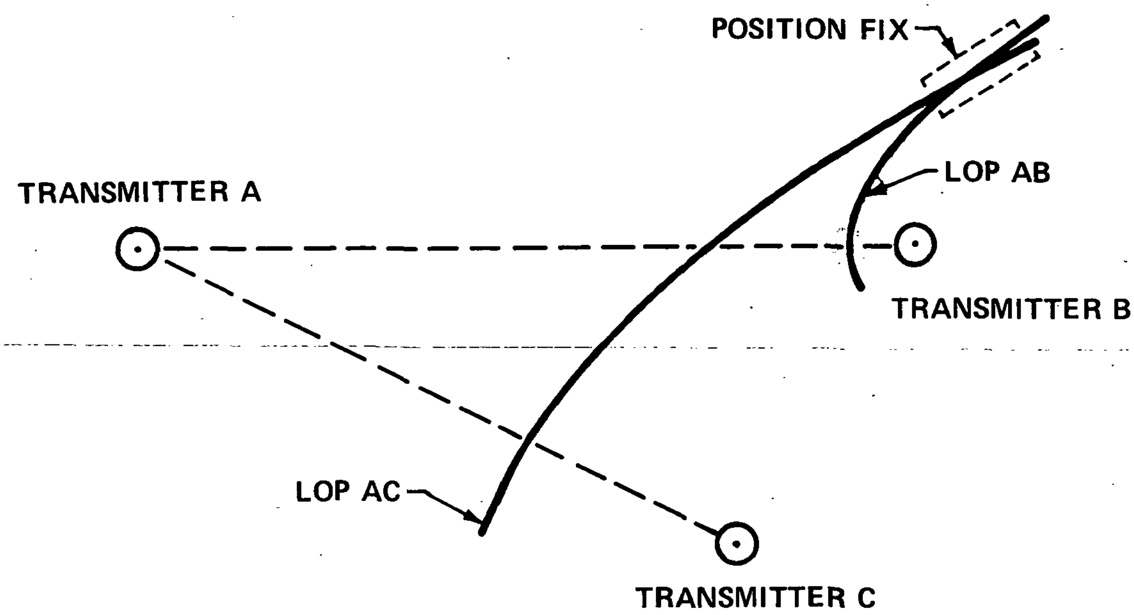


Figure 3. Example of Poor Geometry for Position Fix.

2.2 OMEGA NAVIGATION SYSTEM

Omega is a very low frequency (VLF) hyperbolic navigation system designed for worldwide navigation coverage with eight transmitters. It utilizes phase measurement differences to determine constant distance differences (LOPs). Accuracies of one to two miles are achievable, but with position ambiguities. However, these ambiguities are largely resolved by the use of three frequencies.

Eight stations are planned, each with 10 kw power. These stations, listed in Figure 4, transmit on frequencies of 10.2, 11.33, and 13.6 kHz alternately. The transmitted signals are sinusoidal with tight phase tolerances maintained by quadruple cesium standards. The only modulation is the turn on and turn off of the transmitter. The signals travel in the waveguide formed by the earth's surface and the ionosphere with attendant waveguide phenomena. As the height of the ionosphere varies diurnally, the effective speed of propagation varies, and so does the phase of the signal at the receiver.

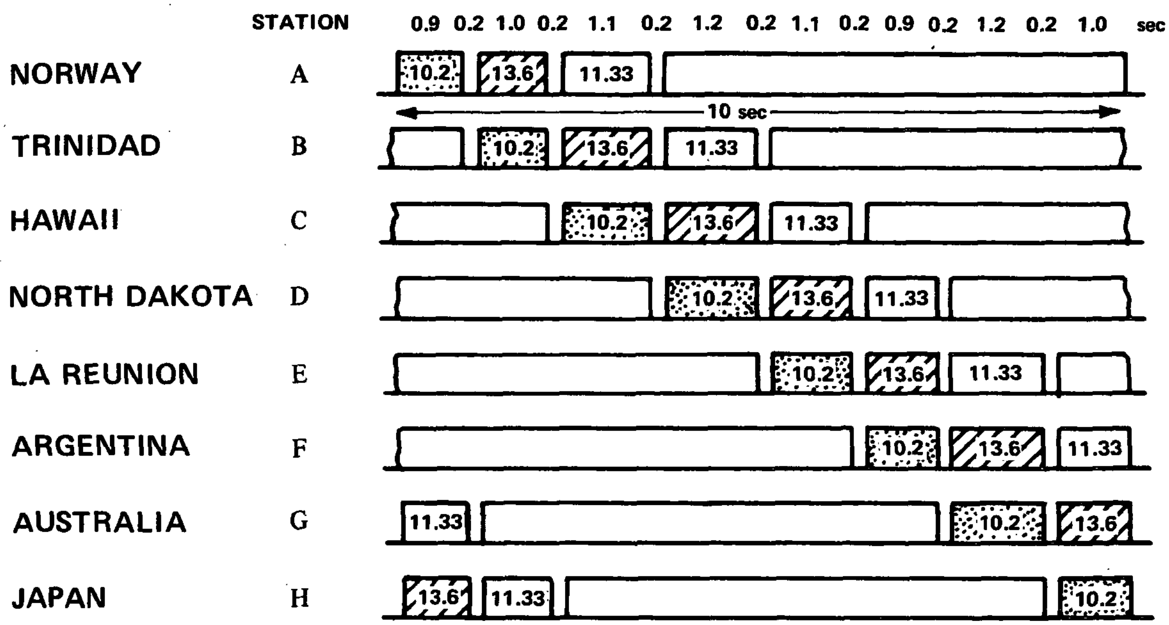


Figure 4. Omega Navigation Signal Format.

Similar variations occur due to the various conductivities of the earth's surfaces: ice, water, and land. Another waveguide phenomenon is the presence of various modes of propagation near the transmitter, which makes each station unusable within several hundred miles (Reference 2).

Distances are derived from differential phase measurements, which have an ambiguity of one cycle. Thus, when obtaining a position fix with the 10.2 kHz signals, the position estimate will be accurate to one or two miles, but with an ambiguity of approximately 8, 16, 24, ... nautical miles. For most applications, many measurements will be taken before the vehicle has traveled eight miles, so the ambiguity problem is not severe. Furthermore, because of the Omega frequency selection receivers utilizing all three frequencies observe ambiguities spaced approximately 72 miles apart.

Figure 5 illustrates ambiguity resolution for a two frequency Omega receiver. If the phase measurements indicate that the receiver is directly on lines of position measured at 10.2 kHz and at 13.6 kHz, the most likely lines of position are those closest to the a priori estimated position. Since the receiver must be on both a 10.2 kHz LOP and a 13.6 kHz LOP, the ambiguity of LOP selection is resolved, and the most likely position is on the two coincident LOPs.

2.3 OMEGA SYSTEM ADVANTAGES AND DISADVANTAGES

As a navigation system, Omega has both advantages and disadvantages for the aviation user. The transmitted signals provide worldwide information for area navigation (RNAV) with no line of sight limitations, and the errors of the system do not increase with time as do those in Doppler and inertial navigation systems. However, the Omega system by itself is not accurate enough for other than enroute navigation, and it has suffered introduction delays for both technical and political reasons.

Most enroute radio navigation in the United States is based on the Very high frequency Omnidirectional Radio Range (VOR) system which provides an obvious benchmark for Omega evaluation. VOR signals provide bearing from the station and are usually augmented by Distance Measuring Equipment (DME) to supply sufficient information to drive an RNAV computer. The accuracy of VOR/DME is roughly 3° and .1 mile, respectively. However, the VOR/DME system is strictly line of sight, and this limits its low altitude coverage. In addition, overall accuracy decreases as distance from the station increases, and the system user is confined to areas with usable signals.

In contrast Omega provides worldwide signal coverage at all altitudes because of its VLF band utilization. Furthermore, Omega requires only eight stations for

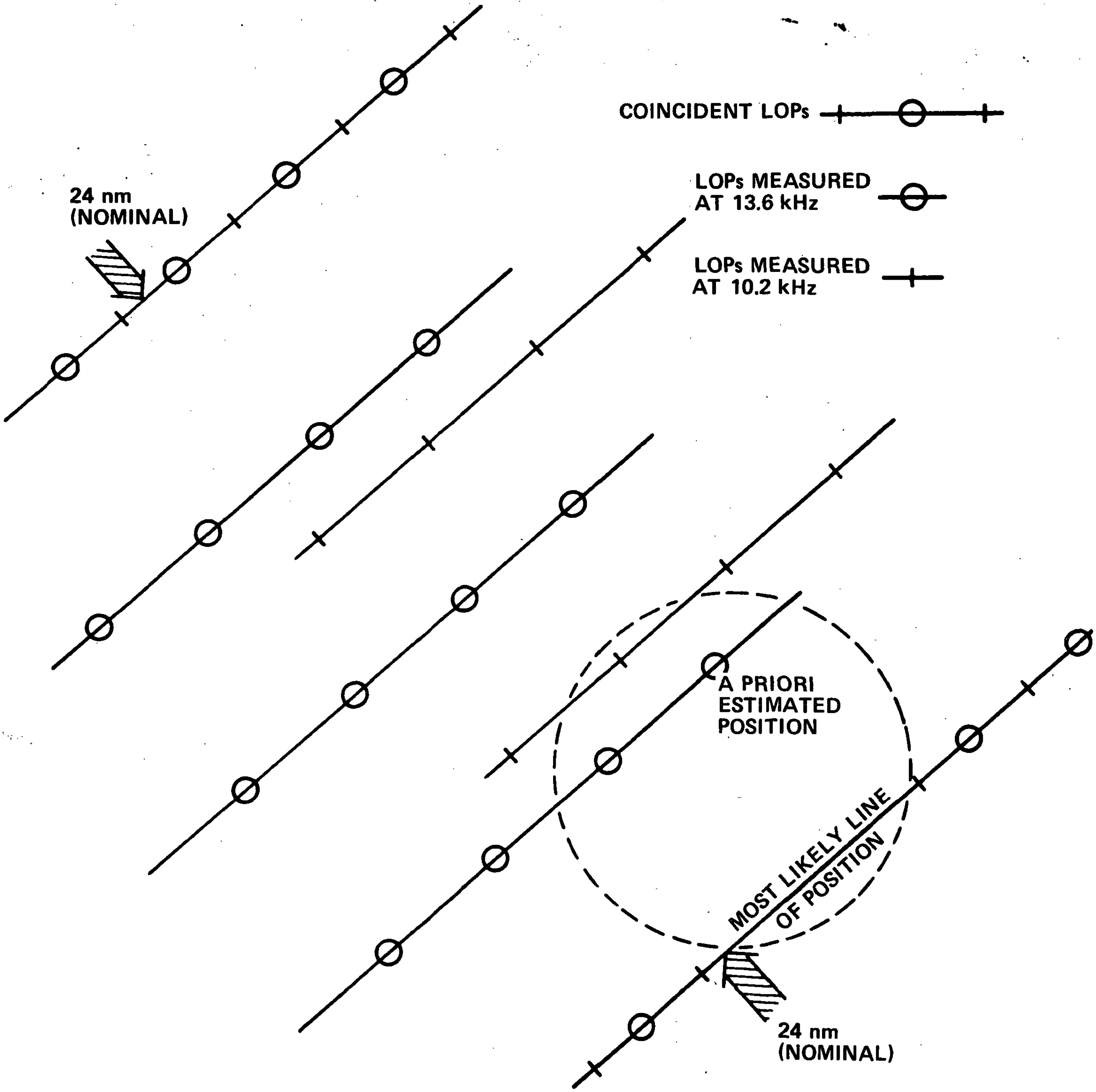


Figure 5. Ambiguity Resolution With Two Omega Frequencies.

worldwide coverage versus more than 600 operational VOR stations in the United States alone. Another favorable aspect is that Omega accuracy can be increased by various means. These include the use of ground monitor stations to broadcast phase correction information (Differential Omega), dead reckoning processors utilizing air data and sophisticated filtering techniques, and improved antennae (H field instead of E field).

The Omega system does have several disadvantages. Each of the eight stations is much more expensive than a VOR/DME station, and present system accuracy is acceptable only for low accuracy operations. Omega is also susceptible to atmospheric and locally-generated noise. Moreover, at the present time, station reliability is not sufficient for aviation use.

One proposed system to improve Omega accuracy is Differential Omega. This system uses a fixed ground station to measure actual Omega phase errors which are then broadcast to users within a radius of several hundred miles, providing increased accuracy at the expense of an additional radio link. The FAA and NASA Langley Research Center will soon be evaluating an experimental Differential Omega system at the NASA Wallops Flight Center (Reference 3).

SECTION 3

PROGRAM OBJECTIVES AND SCOPE

The Omega navigation system flight evaluation program consisted of two major parts: Part One, conducted in the Wallops area, and Part Two, conducted in the Northeast Corridor (Boston-New York-Washington). The objective of each part was slightly different, corresponding to the ultimate application of the information obtained in each of the two geographic areas. The scope of the flight program conducted in each part was consistent with the preliminary nature of the overall effort and with the low-cost emphasis placed on the project.

3.1 PART ONE: WALLOPS FLIGHT PROGRAM

The main objective of this part of the program was to obtain Omega signal and phase data in the Wallops area to provide preliminary technical information and experience in the same geographic area where NASA plans to evaluate the performance of a Differential Omega system (Reference 3).

A 30-hour flight program was conducted to obtain preliminary Omega signal and phase data in the vicinity of the NASA Wallops Flight Center. The tests provided both quantitative and qualitative Omega technical information and flight experience to be used in preparation of a more comprehensive joint NASA/FAA flight test program to evaluate the performance of a Differential Omega system. Factors investigated in Part One were:

- Altitude Effects
- Phase Anomalies Along Coastlines
- Various Station Pair Combinations

- Performance in Flights Parallel and Perpendicular to LOPs
- Diurnal Effects
- Precipitation Effects
- Interference (60 Hz, RFI) Effects
- Influence of Maneuvers (Steep Turns, Spirals, etc.)
- Accuracy (With Radar Tracking)

The routes flown were especially designed to test Omega performance under the conditions listed above. Several short flights were conducted in the Boston area prior to deployment to the Wallops area to verify operation of the avionics system and recording devices and to review flight crew duties and procedures. Portions of the Part One flight paths were monitored by the Wallops tracking radar to provide an indication of position accuracies.

3.2 PART TWO: NORTHEAST CORRIDOR FLIGHT PROGRAM

Part Two was a 30-hour flight program designed to examine Omega performance on the low-altitude VTOL RNAV routes developed by ASI in Reference 1 for the Boston-New York-Washington corridor. The Omega equipment was used to repeat the same Zulu routes that were previously flown with the VOR/DME RNAV equipment. This provided a means for comparison of Omega performance with the previous VOR/DME RNAV results in order to give preliminary operational indications on the suitability of Omega navigation for city-center to city-center commercial VTOL operations. Primary emphasis was placed on determining suitability and accuracy, but evaluation of signal and phase information as in Part One was continued. Other factors investigated were:

- Suitability for VTOL Operations
- Performance at Various Altitudes Over and Near Cities
- Terrain Effects
- Performance During Operational Maneuvers

Because a range instrumentation system was not available over the proposed VTOL test routes, it was not possible to measure the absolute position accuracy of the Omega system. Consequently, accuracy was checked by comparing Omega indications of position with those obtained by visual sightings of known landmarks and/or VOR/DME waypoints.

SECTION 4

FLIGHT PROGRAM EQUIPMENT AND FACILITIES

The equipment and facilities used to conduct the Flight Evaluation of Omega Navigation included the following:

- Piper Cherokee 180 aircraft
- Omega Mark III Navigation System
- Custom Interface Unit (CIU) and data recorder
- Voice recorder
- Wallops Island tracking radar.

Each of the above items is described in this section.

4.1 PIPER CHEROKEE 180 AIRCRAFT

The 60-hour flight evaluation program was conducted in a leased Piper Cherokee 180 aircraft based at Hanscom Field, Bedford, Massachusetts. This is the same aircraft used previously by MIT to conduct the NASA-sponsored research program to investigate Omega navigation for general aviation. The Cherokee is a four-place general aviation aircraft powered by a 180 HP Lycoming engine. The electrical system includes a 60-amp alternator and a 12-volt, 25-amp battery. The aircraft has a standard instrument panel and avionics including dual VHF transceivers, automatic direction finder, glideslope receiver, transponder, single-axis autopilot and the Omega Mark III Navigation System used in the flight evaluation. The aircraft specifications and performance details are presented in Table 1.

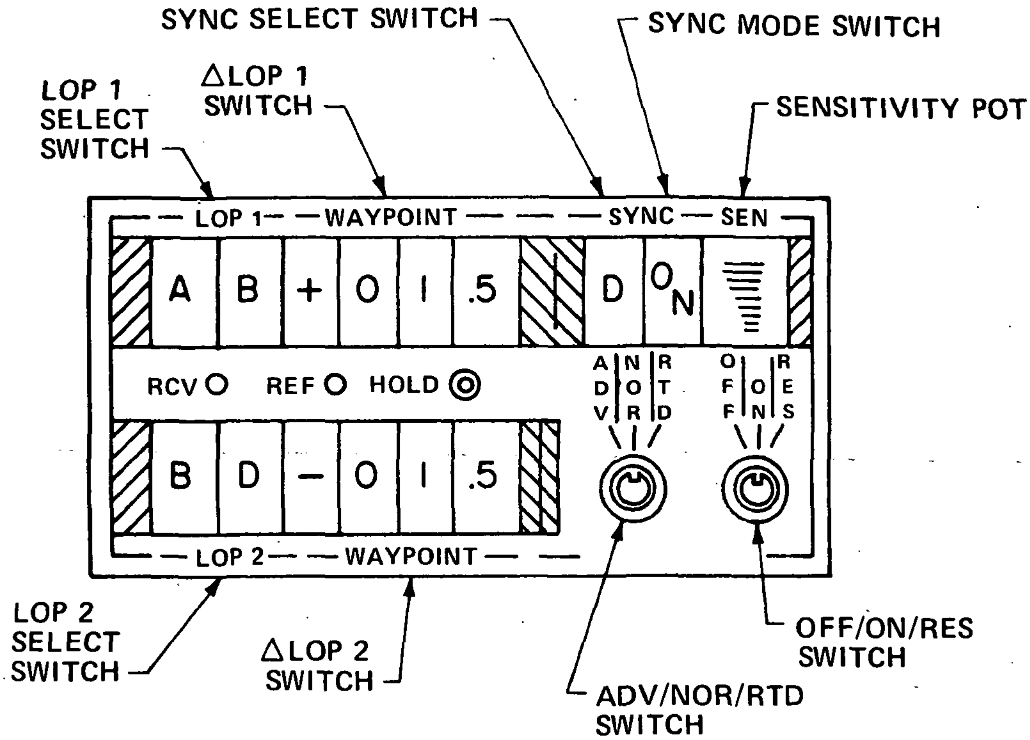
4.2 OMEGA MARK III NAVIGATION SYSTEM

The Omega avionics system used in the program is the Omega Mark III Navigation System manufactured by the Dynell Electronics Corporation in Melville, New York. This avionics system described in Reference 4 transforms Omega phase

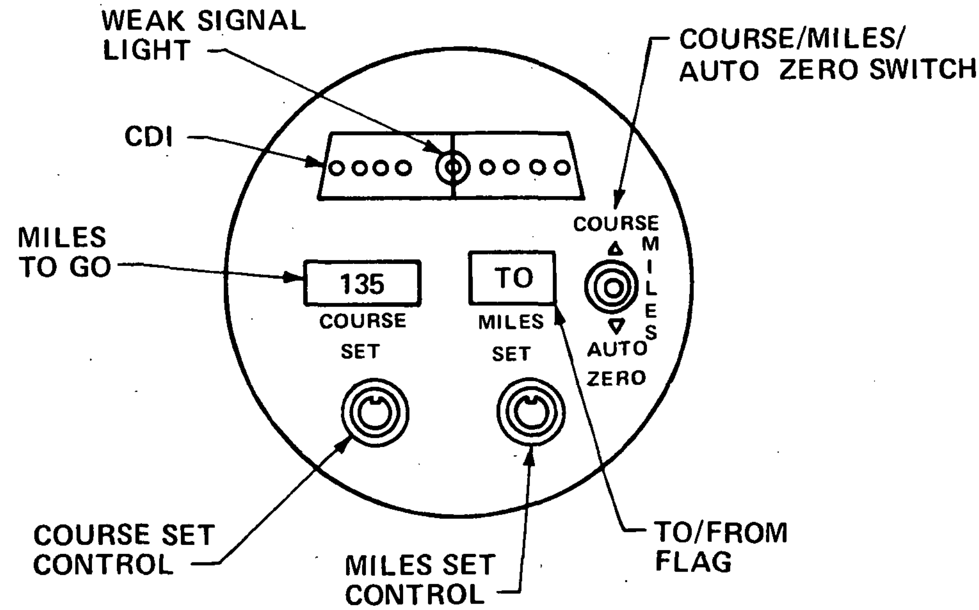
Table 1. Piper Cherokee Dimensions and Performance Characteristics.

Dimensions, External:	
Wing span	30 ft 0 in
Wing chord (constant)	5 ft 3 in
Length overall	23 ft 6 in
Height overall	7 ft 3-1/2 in
Areas:	
Wings, gross	160 sq ft
Trailing-edge flaps (total)	14.60 sq ft
Fin	7.50 sq ft
Tailplane	24.40 sq ft
Weights and Loadings:	
Weight empty (standard)	1,330 lb
Max gross weight	2,400 lb
Performance:	
Max level speed at S/L:	132 knots
Max cruising speed (75% power) at 7,000 ft (2,130 m)	124 knots
Stalling speed, flaps down	50 knots
Rate of climb at S/L	750 ft/min
Service ceiling	13,000 ft
T-O run	720 ft
Landing run	600 ft
Range (75% power at 7,000 ft)	629 nm

data into crosstrack deviation and miles-to-go displays familiar to pilots. The system consists of the two units shown in Figure 6, plus the antenna coupler shown in Figure 7. The DR-30 Receiver houses the majority of the electronics, and the front panel contains the switches to set the circuits for navigation. The DI-30 Indicator provides the readouts used during flight as well as switches for setting miles-to-go (MTG) and course number (a parameter describing flight course in terms of lines of position). Power requirement is 1 amp at 12 V DC. An antenna coupler is provided so that the standard ADF sense antenna may be used without affecting other equipment. A functional block diagram for the Mark III set (Receiver and Indicator) is shown in Figure 8. The basic system specifications are shown in Table 2.



DR-30 RECEIVER UNIT



DI-30 INDICATOR UNIT

Figure 6. Mark III Omega Navigation System Components.

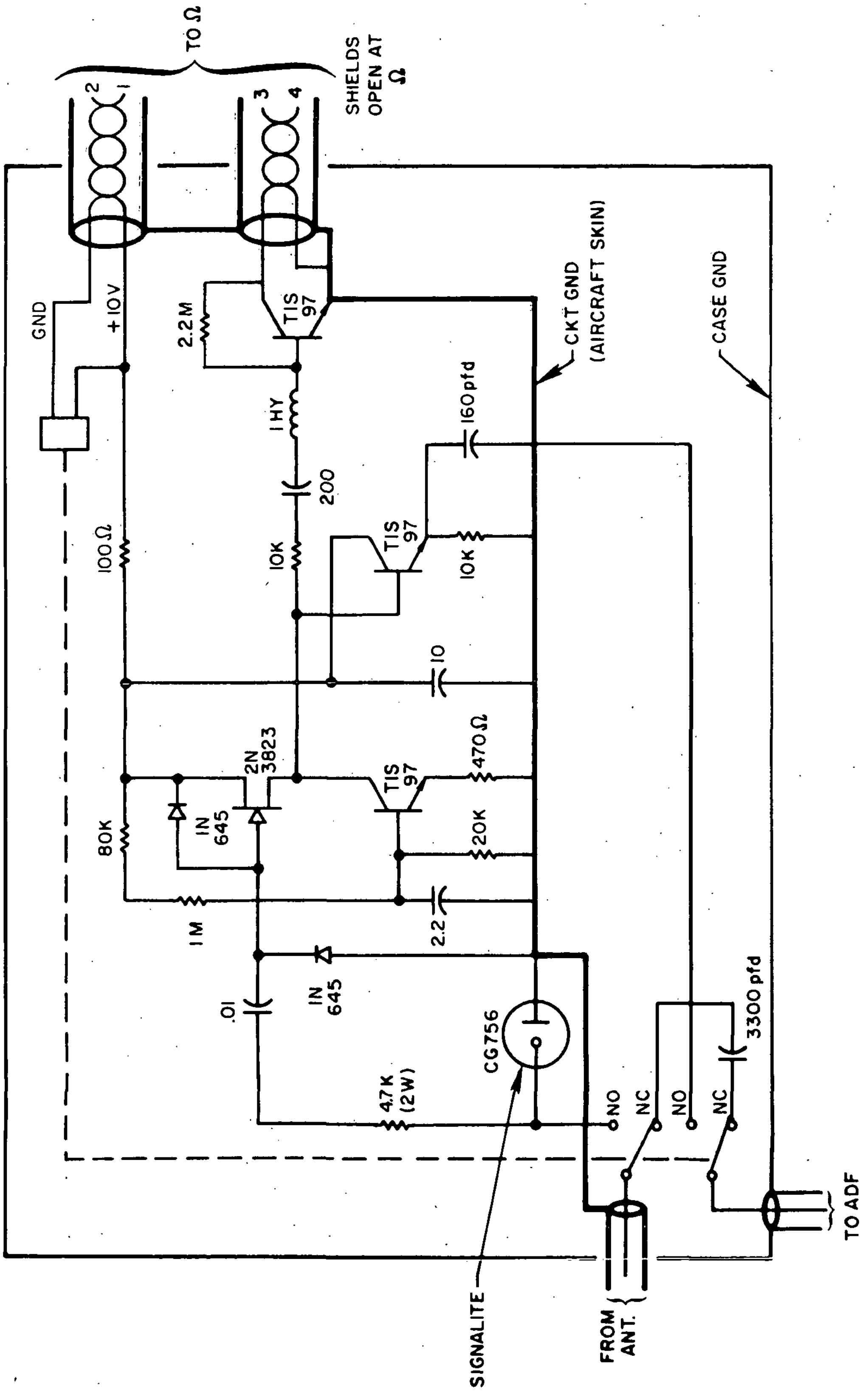


Figure 7. Dynell Mark III Antenna Coupler.

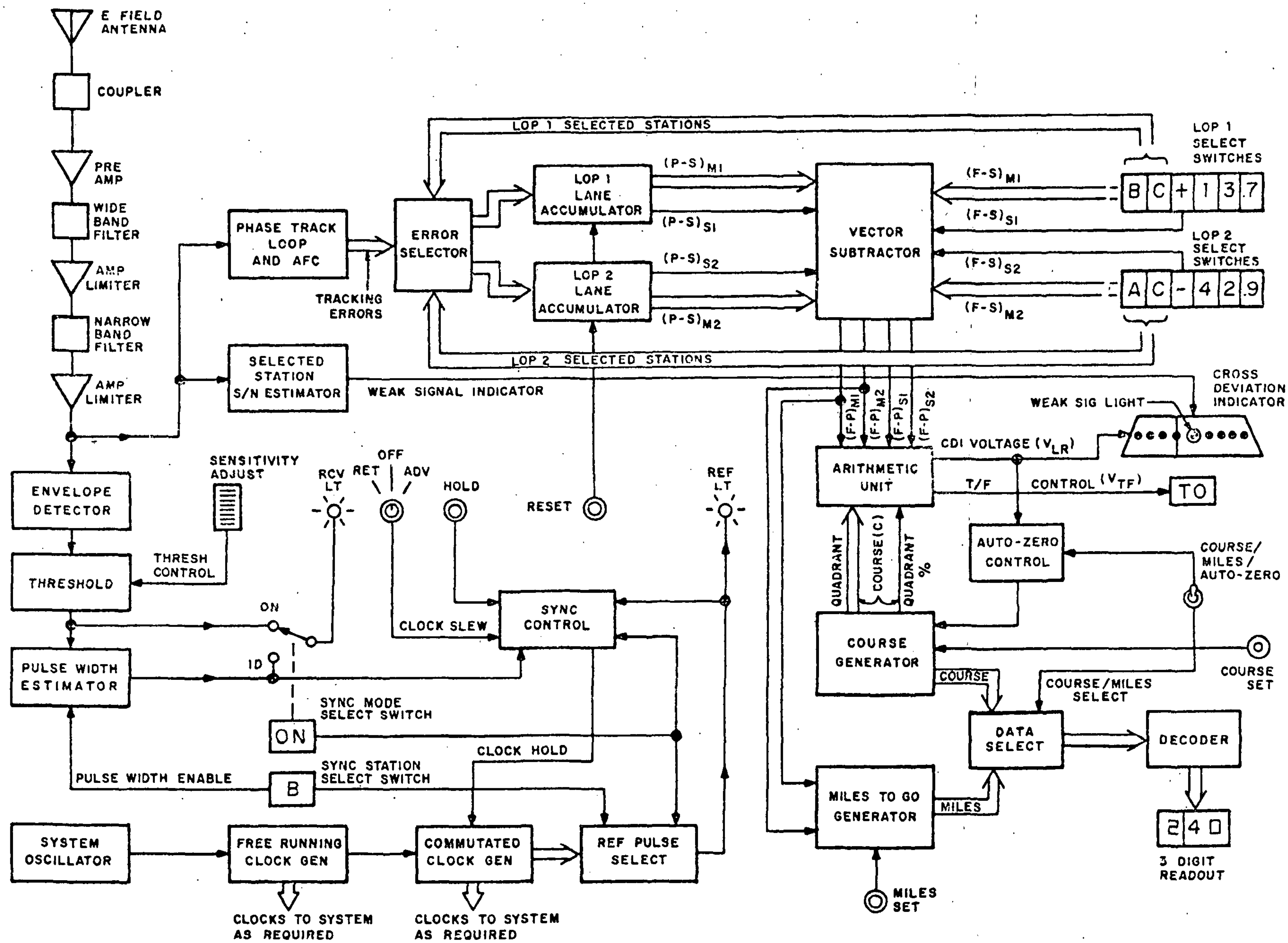


Figure 8. Functional Block Diagram of Mark III Omega Navigation System.

Table 2 . Mark III Omega Navigation System Specifications.

Dimensions	
Receiver Unit (DR-30)	6" W x 3" H x 13" D
Indicator Unit (DI-30)	3.5" Dia. x 5" D
Weight	
Receiver Unit	4.5 lbs
Indicator Unit	1.5 lbs
Power Requirement	12 V DC, 1A
Operating Temperature	$-20^{o}C$ to $+60^{o}C$
Maximum Aircraft Speed	Approximately 400 knots
Navigation Range	
Single Leg Flight	Approximately 1,000 miles
Multi-Waypoint Flight	Unlimited
Navigation Readouts	
CDI	Sensitivity nominally $\pm$ 4 miles full scale
Miles to Go	3-digit display to 999 miles
To/From Flag	Indicates destination arrival
On Ground Setup Time	Approximately 2 minutes with destination number predetermined

The range of the navigator is in excess of 1,000 miles for a single flight leg, but is unlimited if multiple waypoints are used. Basic system accuracy is independent of length of the flight. Should a course deviation be encountered, simply re-zeroing the CDI will provide the pilot with a new direct course to the original destination. Flight plan changes may be made at any time by inserting the new destination and re-zeroing the CDI. The Mark III System is provided with a standard autopilot output which can be used in the same manner as that from a VOR system.

The receiver unit contains three distinct subsystems. These include clock generation and synchronization, phase tracking, and processing to compute cross-track errors and distance-to-go. These three subsystems plus the installation of the Omega Mark III navigation system are briefly discussed below.

4.2.1 CLOCK GENERATION AND SYNCHRONIZATION

The clock generation subsystem includes a stable oscillator from which the reference signal is derived for the phase tracking loop and a commutator clock which matches the Omega transmission sequence. Synchronization of the receiver involves the aligning of this commutator clock with the received Omega signals which are detected and which operate the RCVR light on the receiver front panel. The SENSE GAIN potentiometer adjusts the threshold for this light. The REF light is illuminated by the internal clock gate while the RCVR light responds to signals from Omega stations. Manual synchronization is accomplished by depressing the HOLD button on the front panel when the REF light comes on and releasing it when the desired station illuminates the RCVR light. The alignment of the two lights can be refined by use of the ADV/RTD (advance/retard) control on the receiver panel. Synchronization is complete when the REF and RCVR lights are illuminated simultaneously.

4.2.2 PHASE TRACKING

Once the receiver is synchronized, phase tracking of the 10.2-kHz transmissions from the Omega stations begins automatically. A single phase tracking loop time multiplexed between all the stations is used. By the use of this single loop, differential instrumentation errors between stations are eliminated and the tracking system error is reduced. Auxiliary features include an AFC loop to correct small errors in the system master oscillator and a S/N (signal-to-noise) ratio estimator.

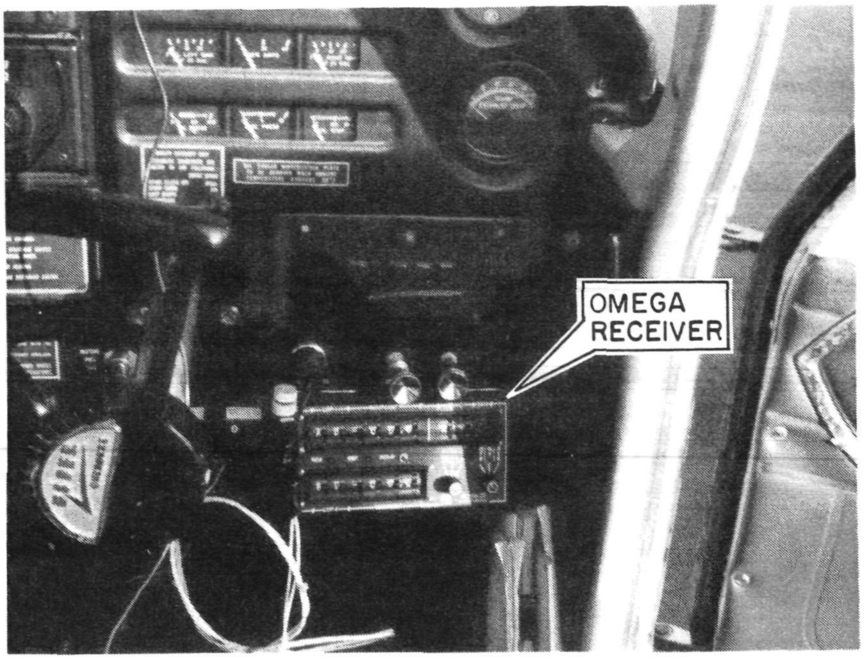
The S/N ratio estimator is thresholded to drive a warning light if the S/N ratio of a station selected for navigation is insufficient.

4.2.3 POSITION CALCULATION

The position calculation circuitry is essentially a special-purpose computer which calculates various parameters based upon position vectors in the Omega coordinate system whose origin is the position of the receiver when last reset (usually at the start of the flight). The present position of the aircraft is computed from the outputs of the phase tracking loops and is stored as a vector from the origin to the aircraft position. The position of the desired waypoint is supplied to the computer as a vector from the origin to that waypoint. The computer subtracts these two vectors to generate a vector from the position of the aircraft to the desired waypoint. The crosstrack component of this vector is displayed on the CDI, and the length of this vector is scaled and displayed on the miles-to-go readout. By flying to keep the CDI centered, a great circle path from the present position to the desired waypoint is achieved.

4.2.4 INSTALLATION

The Omega receiver was hard-mounted in the test aircraft under the instrument panel on the right side of the aircraft so it would be easily accessible by the co-pilot/Omega operator. Figure 9(a) shows this installation. The indicator was installed in the instrument panel among the flight instruments, directly in front of the pilot. In Figure 9(b) the Omega indicator is visible below the artificial horizon between the turn coordinator and the lower VOR indicator.



(a) Receiver Mounted Under Instrument Panel on Right Side.

(b) Omega Indicator Below Artificial Horizon on Instrument Panel.

Figure 9. Receiver and Indicator Locations in Test Aircraft.

The antenna coupler was mounted behind the instrument panel near the ADF. The lead from the existing ADF sense antenna was connected to the coupler which supplied signals to both the ADF and the Omega receiver, but kept the two electrically isolated. Proper grounding of the sense antenna was found to be critical for good performance of the Omega receiver. Power for the Omega receiver was supplied by the aircraft 12-volt electrical system.

Operation of the Mark III was straightforward in that two pairs of Omega stations were chosen and selected on the front panel thumbwheels. The differences between the first waypoint (or destination) and the starting point in terms of changes in "lanes" (Δ LOPs) generated by the selected station pairs were read from a computer output and entered using the other thumbwheels. The receiver was synchronized, the CDI (Course Deviation Indicator) was zeroed, and the miles-to-go counter was set to the known distance from the starting point to the first waypoint. The receiver then displayed crosstrack deviation and miles-to-go during the flight along with a to/from flag and a weak signal light which warned of excessively low signal-to-noise (S/N) ratios.

4.3 CUSTOM INTERFACE UNIT (CIU) AND DATA RECORDER

A custom interface unit (CIU) was fabricated by Dynell Electronics to assist data recording and reduction. The unit was portable to facilitate its use in two separate functions: in the air, for converting (digital) parameters from the receiver to frequency-shift-keyed (FSK) signals for recording on a standard cassette tape recorder; and on the ground, for demodulating the FSK signal to standard teletype format (RS232C) for post flight computer processing of the data. A functional diagram of the airborne equipment used in the flight program is shown in Figure 10. The CIU received power from the Omega receiver, and it supplied power to the data recorder.

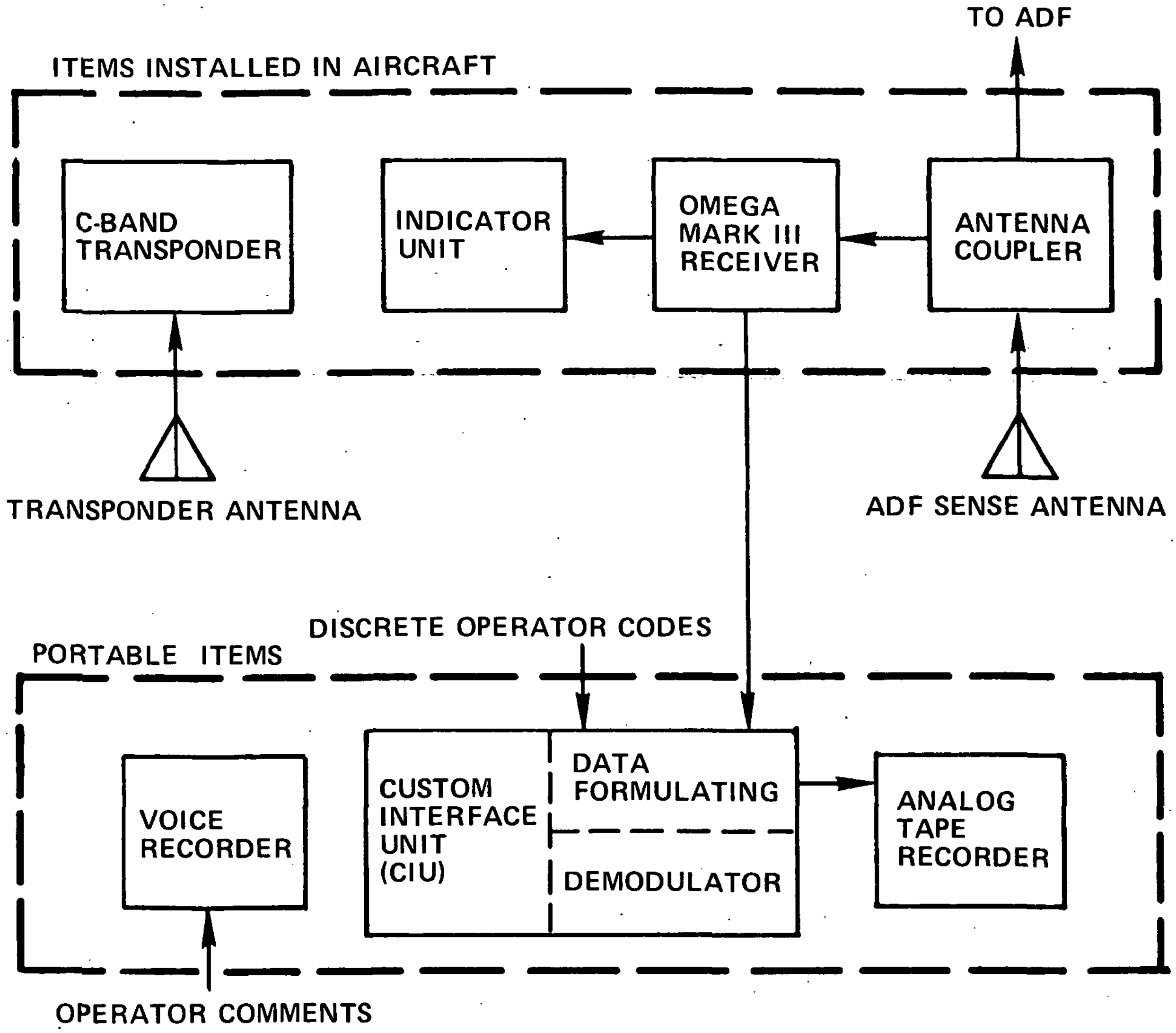


Figure 10. Airborne Equipment Functional Diagram.

The CIU was housed in an aluminum chassis approximately 3.25" x 14" x 10". On the front of the unit were switches for power on/off, circuit enable/disable, and operator discrete code selection. On the back panel were two input plugs, wired in parallel, and four BNC plugs: to tape recorder, from tape recorder, 6V power output, and teletype output. Internally, the circuitry consisted of CMOS integrated circuits on a wire wrap board with power supply components mounted separately.

The Mark III Omega receiver was modified to supply the following parameters to the CIU after each 10-second Omega cycle:

- LOP 1: present position relative to origin
- LOP 2: present position relative to origin
- Crosstrack deviation
- Miles-to-go readout
- Signal-to-noise ratio of each station (8)
- Weak signal indicator
- Auto-zero activation
- Reset indication
- To-from flag indication
- Operator discrete code selection.

These parameters were all present inside the Mark III in digital form, and no A/D conversion was required. (The analog CDI was driven by a D/A converter.) Details of the CIU Data Format are contained in Appendix D.

The various parameters, timing signals, and DC power were fed to the CIU by a cable connected to the Mark III. The timing signals selected which parameter or part of a parameter was to be put onto an internal data bus which fed the FSK converter. The CIU output was routed to the microphone input of a portable cassette recorder.

Unlike the Omega receiver itself, the CIU was not hard mounted in the aircraft. Instead, it usually was placed on the back seat or on the floor of the aircraft. When data was to be recorded, the unit was turned on, and the enable/disable switch was placed in the "disable" position. This caused a high frequency tone to be written on the cassette tape as a "header." After approximately 30 seconds the switch was placed in the "enable" position allowing data to be written on the tape.

One difficulty encountered with the CIU was the failure of the chip supplying the four most significant bits of the fractional part of the LOP 1 lane accumulator.

This failure was detected after the first set of flights at Wallops. Since the chip was unavailable locally, it was replaced by the chip supplying the least significant four bits of the fractional part of LOP 1, leaving an empty socket on the board. This caused the least significant LOP 1 byte to be duplicated in the data string as the preceding signal-to-noise ratio byte. This known error was not judged significant as the maximum error this could induce was less than 0.0625 lanes, much smaller than the observed noise in the LOP counters.

4.4 VOICE RECORDER

A portable battery powered cassette recorder was used for recording inflight notes. The recorder had several attributes making it extremely useful for this purpose: small size, no external power requirements, and easy control. The small size of the recorder allowed it to be placed under the co-pilot/Omega operator's seat. Because no external power was required, there were no superfluous wires to be attached and checked before flight. With the primary recorder controls preset, the recorder was started and stopped using a remote switch on the microphone. The tape recorder was activated only when recording was desired so voice records were sequential on the tape with no intervening dead time. This provided tape economy and freed the operator from inflight tape changing requirements on this recorder.

4.5 WALLOPS ISLAND TRACKING RADAR

Four of the first set of flights at Wallops (Flights 1-1, 1-3, 1-8, 1-9), were tracked by the Wallops FPS-16 tracking radar. For this purpose, a C-band transponder was installed in the test aircraft. The transponder was supplied by NASA and consisted of a battery pack, an antenna, and the transponder itself. The battery pack was carried in the luggage compartment of the test aircraft and supplied power to the transponder. The transponder antenna was hard-mounted on the underside of the aft fuselage of the test aircraft. Due to short battery life, the transponder was normally used only for radar identification of the test aircraft. After the aircraft was identified, tracking was accomplished by skin track mode.

The tracking provided two types of data. The first were real-time plot board tracks of each flight. The second were reduced digital readouts as shown in Figure 11. These data were originally to be processed with the Omega receiver estimates of position in order to generate comprehensive statistics on Omega accuracy. However, with the above mentioned failure of a CIU chip, the Omega position readouts were not available (see Section 4.3).

TIME GMT	SLANT RANGE ALTITUDE TOTAL VELOCITY LOOK RANGE	AZIMUTH LATITUDE EAST WEST VELOCITY LOOK AZIMUTH	ELEVATION LONGITUDE NORTH SOUTH VELOCITY LOOK ELEVATION	HORIZONTAL RANGE ALTITUDE VELOCITY TRACKING MODE	NORTH SOUTH FLIGHT ELEV.	EAST WEST FLIGHT A_Z.	V. AZ. DOPPLER
12.00	24095.	221.6865	3.4062	24033.	-17946.	-15986.	221.6941
	1500.	37.7823	-75.6457				
15-34-22.00	65.	53.	36.	-0.	0.	0.	0
	24095.	221.6865	3.4062	1			
22.00	23453.	221.3249	3.4937	23400.	-17571.	-15454.	221.3327
	1496.	37.7857	-75.6396				
15-34-32.00	66.	53.	39.	-1.	0.	0.	0
	23453.	221.3249	3.4937	1			
32.00	22805.	220.9744	3.5706	22752.	-17176.	-14921.	220.9823
	1465.	37.7892	-75.6336				
15-34-42.00	67.	53.	40.	-0.	0.	0.	0
	22805.	220.9744	3.5706	1			
42.00	22156.	220.5815	3.6733	22102.	-16784.	-14380.	220.5896
	1482.	37.7928	-75.6275				
15-34-52.00	67.	56.	37.	-1.	0.	0.	0
	22156.	220.5815	3.6733	1			
52.00	21528.	219.9641	3.7784	21472.	-16459.	-13794.	219.9723
	1472.	37.7957	-75.6208				
15-35-02.00	67.	59.	32.	-1.	0.	0.	0
	21528.	219.9641	3.7784	1			
62.00	20905.	219.2833	3.8653	20849.	-16136.	-13203.	219.2915
	1457.	37.7986	-75.6141				
15-35-12.00	68.	59.	32.	-1.	0.	0.	0
	20905.	219.2833	3.8653	1			
72.00	20278.	218.5826	3.9526	20222.	-15806.	-12614.	218.5909
	1454.	37.8016	-75.6074				
15-35-22.00	67.	58.	34.	-2.	0.	0.	0
	20278.	218.5826	3.9526	1			

Figure 11. Wallops Tracking Radar Data.

SECTION 5

FLIGHT PROGRAM PROCEDURES

This section describes the planning and procedures used in the Omega flight evaluation program. The importance of safety in flight operations was stressed throughout the program, and all operations were conducted in accordance with the ASI Flight Safety and Procedures Handbook which includes pertinent Federal Air Regulations (FARs). Flight objectives were secondary to considerations of flight safety. The following subsections include brief discussions of flight planning and check lists, data recording procedures, and navigational techniques employed.

5.1 FLIGHT PLANNING AND CHECKLISTS

Extensive flight planning was conducted throughout the program to take maximum advantage of each flight hour. This planning ranged from the broader aspects that included standardization of documentation, formats, procedures and check lists for the flight program to the detailed aspects that involved determination of specific flight paths, airspeeds, altitudes, etc. for each flight.

5.1.1 FLIGHT PLANNING DOCUMENTS

For each flight a standardized information packet was made for each flight crew member. This packet included a Flight Evaluation Sheet as shown in Figure 12, a Flight Plan as shown in Figure 13, and a Flight Map as shown in Figure 14.

The Flight Evaluation Sheet (Figure 12) was designed to provide identification and general information for a given flight. The flight number and objectives were entered at the top of the sheet with operational data in the box at the center of the page. Operational data included such parameters as time and date, a general description of flight route and duration, participants, and summary weather information. On the bottom of the sheet were data recording requirements, contingency

Flight No.: 1-20 Test Description

Test Objective: Provide S/N data in the vicinity of SWL VOR enroute to WAL, and along power lines.

Item	Planned	Actual
Date	3-6-75	3-7-75
Departure	1 p.m.	1:55 p.m.
Duration	.4	.6
Area/Route	SBY-WAL	Same
Pilot	W. C. Hoffman	Same
Omega Operator	P. V. Hwoschinsky	Same
Other Participants	J. D. Howell	Same
Weather	VFR	Same
Winds at Cruise	10 N	10 S

Data Recording Procedures: CIU on tape.
Voice tape log.

Contingency Plans: Non precision approach to WAL if IFR.

If Omega or CIU inoperative, pick up radar plots, return SBY.

Special Requirements: Above minimums for WAL approach.

Figure 12. Sample Flight Evaluation Sheet.

FLIGHT NO.: 1-20 DATE: 3/7/75

CHECK-POINT	HDG CN / MH	ΔLOP STATION A-B / B-D	ΔLOP STATION A-D / B-C	LEG DIST / GROUND SPD	TIME PT-PT / ALT	TIME ETA / ATA
0		0				
SBY		0				
1	096	+1.8	+0.2	18	9	
SWL	181	-1.8	-1.4		1500	
2	086	+2.6	+0.4	8	4	
WAL	193	-2.4	-1.9		1500	

Figure 13. Omega Flight Plan.

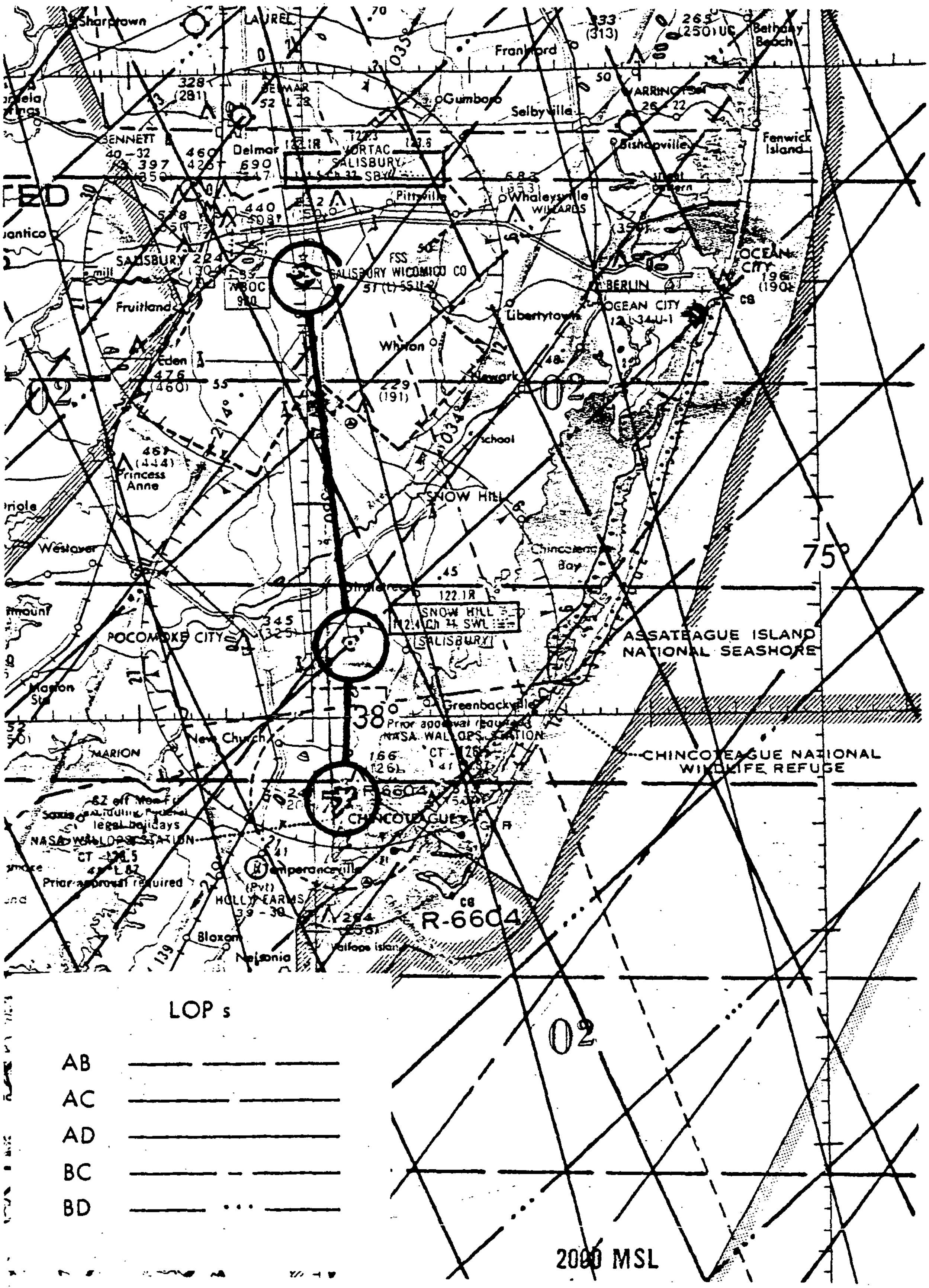


Figure 14. Sample Flight Map.

plans, and special requirements. These three provided information to make a go/no go decision based on flight test objectives.

The Flight Plan (Figure 13) was in a standard format for pilot usage, and it completely specified the test flight profile. Distances, headings, times, and Omega receiver settings were all included. In addition, Omega receiver settings for additional LOP selections were included so that station outage would not require termination of data collection.

A map of the proposed flight (Figure 14) was included in the flight test information packet with the desired flight path marked. This provided a quick-look at the desired profile and was helpful in aircraft orientation on the charts actually used for navigation. In addition it provided a convenient chart for clipboard use by observers.

5.1.2 OPERATIONS CHECKLISTS

A complete set of operations checklists was made to reduce errors in the flight program. The checklists are largely self-explanatory and typical examples are included as Figures 15 through 20.

1. Aircraft Keys
2. Standard Instrument Charts
3. Clipboard
4. Information Packets
5. Custom Interface Unit
6. Two Tape Recorders Plus Cassettes
7. Connecting Cables
8. MIC and PWR Cable
9. Tool Kit

Figure 15. Flight Equipment Checklist.

1. Connect BNC-Mini cable from TO REC on CIU to MIC on recorder.
2. Connect BNC-Power cable from PWR on CIU to 6V on recorder.
3. Recorder Volume - set at 3.
4. 50 pin harness from receiver - plugged into either 50 pin socket.
5. Front PWR switch - up for DC power.
6. Enable/Disable switch - DISABLE for count of 30 on tape counter; then ENABLE.
7. Event Marker - initialize.
8. Note completion of this checklist on voice tape recorder.

Figure 16. Checklist for Connection and In-Flight Recording with CIU.

1. T/B circuit breaker - OFF.
2. A/C master - ON.
3. PWR-ON.
4. SYNC sw - ON.
5. Adj SENS as required.
6. Chk format; record sta strength as Str, Mod, Wk on voice tape.

Figure 17. Omega Turn-On Checklist.

AUTO SYNC

1. SYNC sw-ID.
2. SYNC-select D (or other).
3. Depress HOLD momentarily.
4. SYNC when REF light on and off (w/in 30 sec).
5. SYNC-sw-ON.
6. Check sync.

MANUAL SYNC

1. SYNC sw-ON.
2. SYNC select-D (or other).
3. Depress HOLD when REF light goes off.
4. Release HOLD when proper RCV light goes off.
5. Adj of ADV/RTD sw.
6. Insert LOP letters.
7. Insert LOP #s for WPT.
8. Reset lane accumulators.
9. Display MTG, flag on FROM.
10. Adj MILES SET for distance.

Figure 18. Receiver Synchronization Checklists.

START ENGINE

1. T/B circuit breaker - ON.

TAXI

1. Check sync (SYN sw ON).
2. Check weak signal light not flashing.
3. Reset vector at airport ref. pt. during E through H slots.
4. Start recorder.
5. Record checklist completion on voice tape.

Figure 19. Ground Operations Checklists.

AFTER TAKEOFF

1. Auto zero indicator during E through H slots.
2. Verify course number.
3. Check CDI centered.
4. Record on voice tape.

AT WAYPOINT

1. Set in new LOP #'s from reset point.
2. Auto zero ind. on E through H slots.
3. Adjust distance scaler.
4. Record on voice tape.

Figure 20. In-Flight Operations Checklists.

5.2 DATA RECORDING

Data were recorded in the aircraft on two airborne tape recorders and on maps. Ground data consisted of FPS-16 radar tracking at Wallops Island when available. Tape recorded data included the digital output of the CIU and voice records. Map records and radar data were used for position plotting.

5.2.1 OMEGA DATA

As described in Section 4.3, various Omega receiver parameters were recorded on a portable cassette recorder. During data reduction it was discovered that the Omega/CIU/recorder system also had recorded transmissions from the aircraft VHF transceivers. Consequently, most Omega data flights were made with the radios off, and transmissions were minimized when the radios were on. Thus, little data were lost.

Tapes used for the recording were standard audio quality tapes. Because of memory limitations in the processor the standard tape length was 30 minutes per side. However, some recordings were made on 45-minute tapes, which were processed in two parts. Performance of standard tapes was adequate, and there was no requirement for any high fidelity tapes, such as CrO_2 tapes, or high fidelity recorders incorporating high-frequency noise reduction circuitry.

Time synchronization on the Omega data tapes was achieved by setting a new operator discrete code on the CIU at a known time. With this reference the times of both previous and subsequent data strings could be determined unless severely garbled data from radio transmissions intervened. Few such problems were encountered.

5.2.2 VOICE RECORDER

During the flight evaluation program pertinent information was verbally recorded on a cassette recorder. This provided the capability to process data later with extensive and complete notes of the events of the flight. The voice recorder was usually operated by the Omega receiver operator.

Figures 21, 22, and 23 show three checklists associated with voice recorder operation. The first was used to insure that the recorder itself was operating properly and proper identification of the flight data was accomplished. The second and third were used to insure that entries on the tape were complete and appropriate. It was standard procedure for the person making the voice recording to do his own

CHECK BEFORE FLIGHT

1. Battery level in the green.
2. Proper operation.
   a. Remote control.
   b. Playback.

FOR EACH VOICE TAPE

1. Flight number.
2. Date.
3. Participants.
4. Weather.
   a. Surface winds.
   b. Winds aloft.
   c. Clouds.
   d. Precipitation.
   e. Visibility.
   f. Temperature.
   g. Turbulence.
5. Type of synch used.
6. Reset position.

Figure 21. Voice Recorder Checklist: Initial Record on Tape.

transcription. When this was done shortly after a flight, it was often possible to recall more information than what was recorded on the tape. A sample transcript is shown in Figure 24.

OMEGA RECEIVER CHANGES
1. LOPs.
2. Synch used.
a. Type.
b. When.
3. CIU discrete code.
4. Course number.

Figure 22. Voice Recorder Checklist: Receiver Setting Changes.

GENERAL
1. Time.
2. Actual position.
3. Altitude (MSL).
4. CIU discrete code.
5. Waypoint in use.
6. Course number.
7. CDI.
8. MTG.
9. Weather.

Figure 23. Voice Recorder Checklist: General.

OMEGA FLIGHT O-2-Z1 NOTES (December 20, 1974)

Route Z1 NYC-BOS (with Farmingdale and Bedford connectors)

Time	Discrete Code	Location	Description
3:30	0	T-O roll FRG	Weak A and weak BC, strong D
3:35		1 mi E FRG	Switched on tape, CDI centered MTG 11 CN 489
3:36			Enable CIU
3:37	1	3 NNE FRG	On direct course for WPT 2 CDI 3-1/2 L MTG 11 ALT 5500
3:41	2		Tape drive erratic; reseated tape on spindles
3:43	3	WPT 2	Set in WPT 3
3:45			CDI 4-1/2 L MTG 38 counting down
3:53	4	Bridgeport Apt.	CDI 3L MTG 16
3:58	5	3S N. Haven Apt.	CDI 1/2R MTG 2 "FROM"
4:05	6	Griswold Apt. (WPT 3)	CDI 1R MTG 7 "FR" Good ABCD signals, set in WPT 4
4:15	7	4 lane Hwy	CDI 1/2R MTG 24
4:18	8	3 W Norwich, Hwy	CDI centered MTG 18 Switched tape sides
4:20	9		Enabled CIU
4:25	10	Moosup, WPT4	CDI centered MTG 8
4:30	11	S. of Lake 7 mi @ 166° from PUT	(41°50'/71°45'W) CDI centered MTG 0 "TO" → "FR" PUT 166° PVD 040°
4:35	12	5W Woonsocket	PVD-WOS HWY PUT 071° CDI 2R MTG 10

Figure 24. Sample Voice Transcript.

Standard length audio cassettes were used in the recorder. By using the remote microphone switch described in Section 4.4, it was possible to record many flights on one side of the cassette. The time compression of the flights facilitated later transcription because it was not necessary to search the tape for voice records. A special tape recorder designed for transcription was used to play back the cassettes.

5.2.3 POSITION PLOTTING

Aircraft position was plotted manually on maps in the cockpit when possible. In addition, position plots were available from the tracking radar during the first set of Wallops flights, and position plots were made from CIU recorded data for the second set of Wallops flights. Radar and Omega plots are discussed in Sections 4.5 and 6.4.4.

On the early NE corridor flights position plots were drawn by hand in order to estimate necessary corridor widths for VTOL service. An example of such a plot is shown in Figure 25. In the Wallops area flights, position plots were occasionally drawn as a crosscheck. These plots proved invaluable in the analysis of shore effects. Once, position plots were available following an unknown failure of the voice recorder. This salvaged flight data otherwise could not have been correlated with the recorded Omega data.

5.3 NAVIGATION TECHNIQUES

A variety of navigation techniques were employed during the flight program so that comparisons could be made with a wide range of other test data and to assure reliability of measured accuracy. In both the Wallops area and the Northeast Corridor, all the tested forms of navigation were used in different flights over the same regions to provide corroborative data. The most common technique was navigation using Omega with visual position checks for confirmation. Occasionally this was reversed

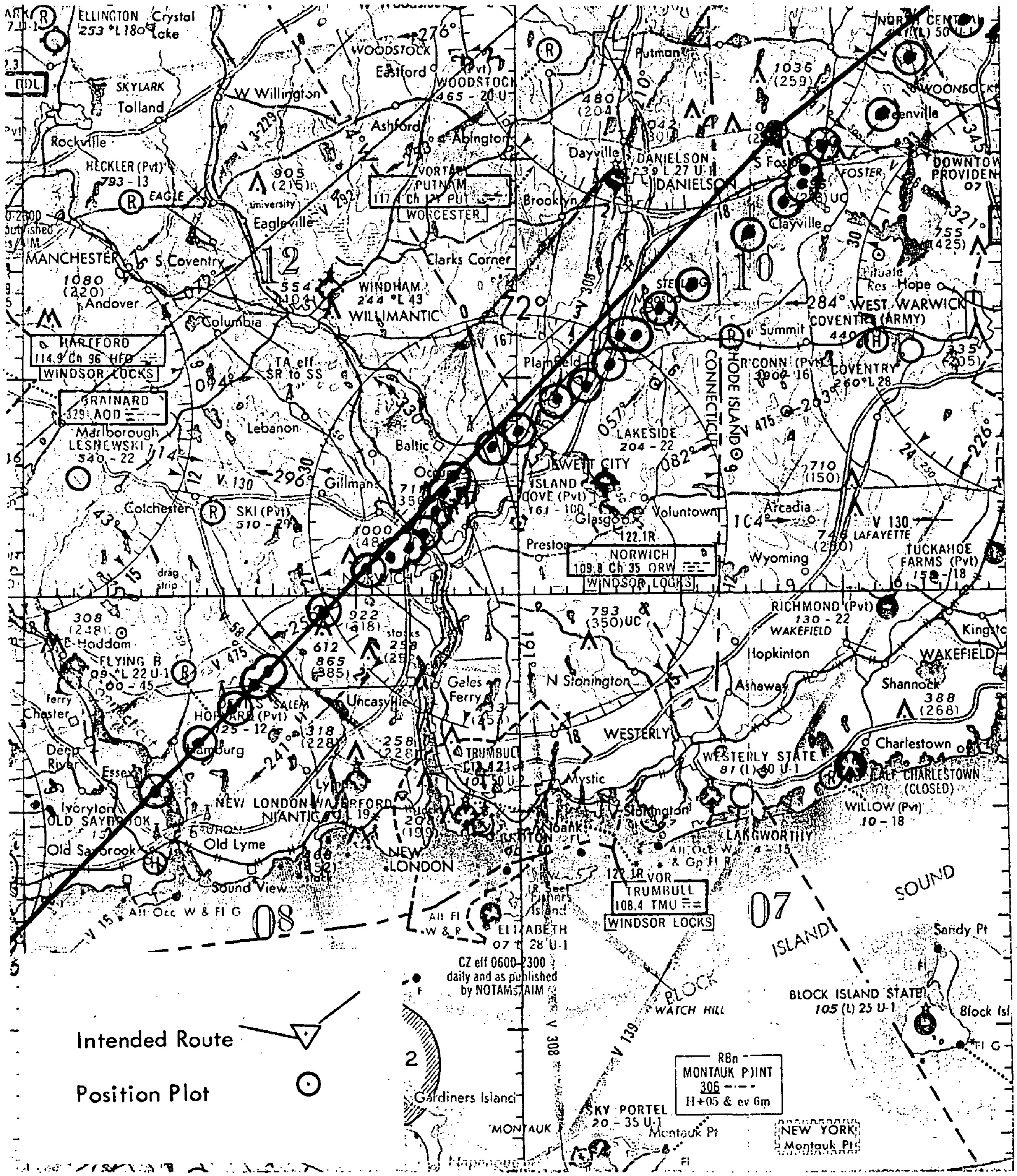


Figure 25. Typical Manual Position Plot.

by flying visually and recording Omega position information. Additionally, VOR radials and ILS localizers were used for navigation with the Omega position recorded for comparison. Finally, Omega routes were flown under radar tracking with some radar position information supplied later for comparison.

5.3.1 VISUAL NAVIGATION

The visual navigation mode consisted of contact flying with voice reports at regular intervals to record actual position relative to known landmarks. This information was then used for verification and comparison with the Omega indication of position. Examples of flight segments where visual navigation was the preferred mode included: flying under the New York TCA along the Hudson River, flying along a straight section of railroad on the Delmarva peninsula, and crossing expanses of water at low altitude. Another advantage of contact flying was the ability to navigate without the VOR receivers, the power inverters of which were found to be major sources of interference for the Omega receiver.

5.3.2 VOR/ILS NAVIGATION

Many flights were conducted using VOR as the primary navigation source with the Omega recorded position used for comparisons with a known ground track. In the Northeast Corridor VOR was used for enroute navigation; and in the Wallops area VOR was used to provide navigation for flying precise patterns in the Snow Hill area. Omega was used to navigate the aircraft to an ILS approach path, and the Omega was monitored during the approach.

On most of the Northeast Corridor flights the Omega receiver was used as the primary navigation source. However, IFR operations and some Boston area local flights used VOR for primary navigation, and the position recorded by the Omega set was analyzed for comparison.

At Wallops the Snow Hill VOR was used for primary navigation on many flights. The VOR was used to define radials along which the Omega data was recorded. By comparing the Omega indicated position to the known path, anomalies such as the shoreline effect were studies, and navigation information was provided through areas where Omega interference was suspected.

ILS paths were followed on two flights; the Omega set was adjusted to correspond to the ILS readout, but the ILS was used for primary navigation. Again, the Omega position was later compared with the assumed aircraft path.

5.3.3 OMEGA NAVIGATION

On many flights, including most of the Northeast Corridor flights, the aircraft was flown using the Omega receiver as the primary navigation device. This provided data on how well the pilot was able to follow the Omega needle deflections, and also gave data on pilot reactions to the needle and required techniques. Position reports were entered on the voice tape for statistical analysis of the errors. One advantage of this mode of navigation was that it allowed a significant noise source in the flight evaluation program, i.e., the aircraft VHF radios, to be removed.

SECTION 6

POST-FLIGHT DATA PROCESSING

A very large volume of data was recorded during the 60-hour flight evaluation program. Thus it was essential that an efficient computerized data processing and plotting system be developed to provide reduction of the data for subsequent analysis. This section includes brief descriptions of the post-flight data reduction system including the data processing equipment, the data reduction software (see Appendix C), and plotting routines.

6.1 DATA PROCESSING EQUIPMENT

A functional block diagram of the post-flight data processing system is shown in Figure 26. As shown in the figure, the data processing equipment consisted of a Wang 2200 minicomputer with peripherals including an output typewriter, an analog plotter, a cassette tape, and a teletype interface board. The elements of the ASI Wang 2200 minicomputer installation are indicated in Table 3.

The 2200 is programmed entirely in BASIC, thus simplifying program writing and debugging. Arithmetic operations are easily handled, and standard system routines include natural log, sine, cosine, tangent (and their inverses), square root function, absolute value, greatest integer function, signum function, and a random number generator. The logical functions and character string manipulation functions available were particularly useful for the Omega data reduction and processing tasks.

Using the small processor offered several advantages for processing the type of data obtained on the Omega flight program. First, it was easily dedicated solely to data reduction, thereby eliminating waiting time for some other processor availability. Second, with the small, easy to use machine, program errors were easily detected and corrected. Finally, the use of the small machine allowed data processing at low cost.

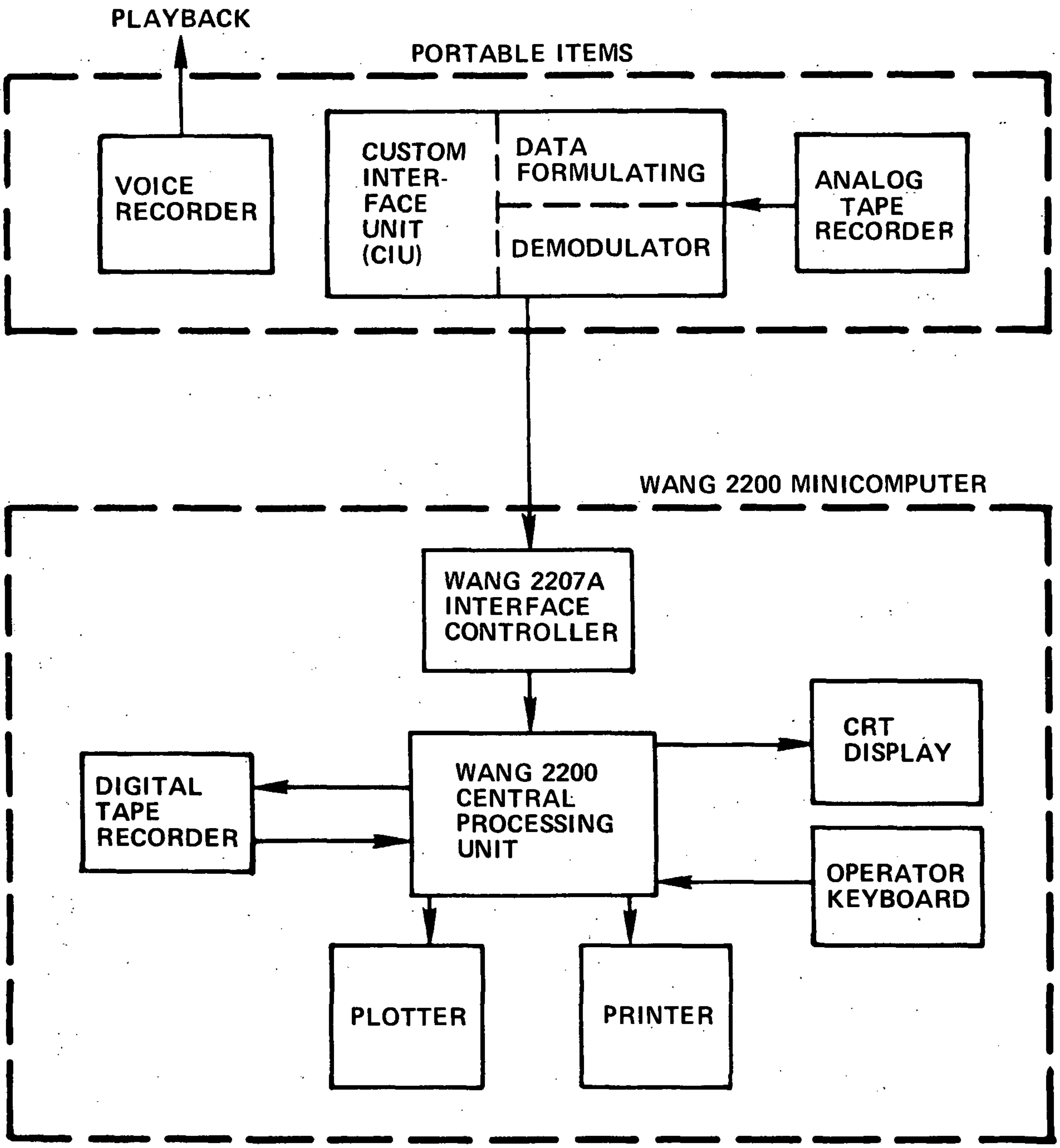


Figure 26. Post-Flight Data Processing Functional Diagram.

Table 3. ASI Wang 2200 Minicomputer System.

2200B-1 Central Processor
2216/2217 Combined Display/Cassette Drive
2222 Keyboard
2201 Output Writer
2290 CPU Stand
2212 Analog Flatbed Plotter
2207A I/O Interface Controller
4096 Step Memory Option
OP-1 Option 1 - Matrix ROM
OP-3 Option 3 - Character Edit ROM

With this processor, flight test data was rewritten onto the processor's cassettes, reduced, and plotted at the rate of three hours of processing per hour of recorded data, with no time lost accessing a distant machine or waiting for plots. Thus, it was possible to perform the data reduction well within the allotted time and also to perform additional services that facilitated data interpretation and presentation.

Error detection was easily performed with the small machine. Because each data string was displayed on the CRT as it was read in, errors caused by faulty tape recorders and interference between the CIU and VHF radios were detected and eliminated before time was wasted processing bad data. In addition programming bugs were also easily detected and corrected, and program optimization for speed was simplified.

6.2 DATA TRANSCRIPTION

In the air, data were recorded on the portable cassette recorder by the custom interface unit as described in Section 4.3. On the ground the cassette recorder was played back through the CIU to generate RS232C teletype data for input to the Wang processor through a teletype interface board. The data at this point consisted of a string of 33 ASCII characters followed by a carriage return (hex 0D) and a line feed (hex 0A). The format of the recorded data for each 10-second Omega cycle are described in Appendix D.

Two anomalies were observed during the transcription. One anomaly was the presence of illegal character strings, i.e., strings containing characters not in the repertoire of the CIU. Another type of anomaly caused execution of the transcription program to stop, but this one occurred rather infrequently.

The CIU expressed data as four-bit bytes, preceded by high order and parity bits so that the data were presented as the ASCII characters 0, 1, ..., 9, :, ;, [, =,], and ?. Occasionally, garbled data appeared, recognizable as characters not in this 16 character set. It was quickly discovered that transmissions from the aircraft VHF transceivers were also recorded on the cassette recorder along with the flight data, and this overlay was the source of most of the garbled data.

The second type of error was harder to discover because processing stopped. It was discovered that the Wang "reset" instruction used to stop processing is an ASCII character (hex 03), and it was hypothesized that the data garbled by the voice overlay monitored above resulted in the reset instruction.

The actual program used for reading the data was "TRNSFR7+". This program read new data into memory in real time, performed simple validity checks, and later stored the data on the processor cassette in digital format. Because almost all of the memory of the processor was used for data storage, no processing of the raw data was undertaken in this program. File statistics were generated and printed for the various data logs maintained.

6.3 DATA CHECKING

Even though the character strings were displayed on the CRT as they were read into the processor, it was decided to obtain the capability to check unprocessed data as stored on the processor cassette tapes. This allowed several functions: checking for anomalies in other than real time, confirmation of data transfer, checking of log parameters, detection of errors in tape management, and checking for anomalies not easily discernible in real time. Two programs, TRNSCHK and DATACHK, were written for data verification.

6.3.1 TRNSCHK

TRNSCHK read individual records from the data tapes with each record containing seven character strings. These strings were then printed on the processor CRT. With the strings so displayed, those containing illegal characters could be observed and eliminated, as could strings which were over- or under-length. With practice seven character strings could be verified in less than three seconds.

6.3.2 DATACHK

In order to detect hardware failures, DATACHK observed the eventual occurrence of a "1" and a "0" in each bit of the character strings. DATACHK took each character string in a data file, checked that only strings of proper length and character content were processed, and "ANDed" and "ORed" each string with strings initially set to all zeroes and all ones, respectively. Thus, any bit which had failed and was identically either one or zero was detected. Further, the program had the capability to combine the results of more than one data file so as to provide a larger sample set. Unfortunately DATACHK was written after a chip failure had gone undetected until some final data processing.

Using DATACHK the failure of four bits of the LOP 1 readout was confirmed. In addition, it was discovered that the least significant bit of the S/N counter had failed, but this error was determined to be insignificant and was not corrected. One other known anomaly detectable even with TRNSCHK was the result of removing a defective chip on the CIU data bus. Because the CIU circuitry on the data bus was CMOS, the capacitance of the bus receiver duplicated the preceding byte of data during the time slot of the removed chip.

6.4 PLOTTING ROUTINES

The recorded data were processed to yield several different types of plots. These included:

- Miles to go (MTG: 0 - 75)
- Status flags (FLAGS: tf a r w)
- Needle deflection (Right/Left)
- Map plots (Omega position)

6.4.1 MILES-TO-GO PLOTS

The miles-to-go (MTG) was plotted on a linear scale of 0 to 75 miles, with tick marks on the x axis representing 25 mile steps. No filtering or special processing of any kind was done. Not all character strings were processed for MTG, however. Any string which was over- or under-length or which contained illegal characters was rejected. A blank space was left on the plot, however, indicating deleted data. In addition, space was left to indicate the lack of data acquisition while a cassette was being changed in the aircraft.

6.4.2 STATUS FLAG PLOTS

Four status flags were recorded by the CIU: to/from flag, autozero, lane accumulator reset, and weak signal (tf a r w) for any station used for navigation. With the exception of the to/from flag, which was plotted as a line, each flag was plotted as a tick mark above the x axis when it occurred. Labels for these flags are shown on the plots presented in Sections 7 and 8. Invalid character strings were omitted as in the MTG plots.

6.4.3 NEEDLE DEFLECTION PLOTS

Needle deflection plots recorded the deviation of the needle sampled every 10 seconds. These deflections were calculated from the phase measurements at the end of each 10-second Omega transmission sequence. In practice, the needle was prone to oscillations at frequencies higher than those recordable by the sampler. These oscillations were apparent to the pilot and required the pilot to manually filter the CDI readout. As in the miles-to-go plotting routine, breaks in the data resulted in discontinuous plots of needle deflection.

The needle deflection plotting routine also plotted S/N ratios as a user selectable option. S/N was recorded as an 8-bit S/N count number between 0 and 255, which gave an estimate of the S/N ratio according to the formula

$$\text{Count number} = 128 + 100 \times (\text{broadcast time of Omega station}) \times \text{ERF}\left(\sqrt{\text{S/N power}}\right)$$

The plotting routine used code to limit the S/N ratios to a minimum of −30 dB. The maximum was based upon the transmission time of the station. Invalid strings were omitted as was the case with the MTG plots.

6.4.4 MAP PLOTS

The lane accumulators were used by the internal Omega receiver processor to generate navigation information for display to the pilot. These accumulators were recorded by the CIU and were used for generating map plots. The map plot routine converted the accumulated lane change between last reset point and present position, with eight bits per lane of LOP 1 and LOP 2. Due to a failed integrated circuit in the CIU during the first half of the flight program, the four low-order bits of LOP 1 were invalid.

The LOP accumulators were read out and converted to numerical form. A linearization based on a circular earth model was then used to determine change of latitude and longitude from the last reset point, and thus the present estimate of latitude and longitude was derived. These points were then plotted as a continuous line with breaks occurring when data were not consecutive, as was the case with invalid character strings. Most plots were made on Mercator projection maps, but a capability to plot on Lambert conformal projection maps was also developed.

SECTION 7

WALLOPS AREA FLIGHT PROGRAM RESULTS

As detailed in Section 3.1, the objectives of the Wallops area flight tests were to investigate the various effects due to altitude, shoreline, station pairs, LOP geometry, diurnal variations, precipitation, radio frequency interference, maneuvers, and to gather some information on accuracy through the use of radar tracking. These results were then analyzed to provide initial information and flight experience for the differential Omega flight test and evaluation program.

Flight planning for the Wallops area included preparation of LOP versus position tabulations, LOPs for the local area plotted on aeronautical sectional charts, and detailed flight descriptions as discussed in Section 5.1 to ensure adequate coverage of the test objectives. Various contingency plans were formulated for precipitation, IFR weather, and lack of radar coverage. A table of the various effects to be investigated was prepared to provide a rapid comparison of objectives completed with those yet to be examined (Table 4).

The sixteen flight tests, described in Table 5, were made in two groups; the first from February 19 through 22, and the second from March 7 through 9. The first group of eleven included four flights with radar tracking. These were in two pairs, the first pair being a comparison of low and high altitude routes at five and ten thousand feet, respectively. The second pair compared the same altitude and route before and after local sunset. Three of the remaining flights were refueling trips to and from Salisbury conducted at varying altitudes past Snow Hill VOR. The remaining four flights compared different types of navigation including: contact flying along the peninsula railroad; airport to airport flying using VORs, NDBs and flashing beacons;

Table 4. Wallops Area Flight Test Objectives.

Flight	Date (1975)	Flight hours	Altitude	Coast.	Station pairs	LOP direction	Diurnal	Precipitation	Interference	Maneuvers	Radar	Hours data recorded
1-0	2/19	0.4							X			0.4
1-1	2/20	2.6	X	X					X		X	2.5
1-2	2/20	0.3							X			0.3
1-3	2/20	2.5	X	X					X		X	2.5
1-4	2/20	0.9		X			X		X			0.8
1-5	2/20	1.4		X			X		X			1.4
1-6	2/21	3.0		X		X			X			3.0
1-7	2/21	0.4							X			0.1
1-8	2/21	1.7		X		X	X		X	X	X	1.6
1-9	2/21	1.8		X		X	X		X		X	1.7
1-10	2/22	1.3	X	X					X			1.3
1-20	3/7	0.6			X	X			X			0.3
1-21	3/7	1.3			X			X	X			1.2
1-22	3/8	2.7	X	X	X	X			X	X		2.6
1-23	3/8	2.1		X					X			2.1
1-24	3/9	3.0		X	X	X			X	X		2.8

Table 5. Wallops Area Omega Flights.

Flight Number	Flight Description
1-0	Ferry Flight SBY - WAL (1000')
1-1	Low Altitude Star Route (5000', 4000', 3000', 2000') with Radar
1-2	Ferry Flight WAL - SBY (1000')
1-3	High Altitude Star Route (10,000') with Radar
1-4	Ferry Flight WAL - ORF (1000')
1-5	Night Beacon and VOR Flight, ORF - SBY - WAL (3000')
1-6	Modified Snake Route (2000') WAL - MFV - SBY
1-7	Ferry Flight SBY - WAL (1500')
1-8	Day Race Track Route with Radar (3000')
1-9	Night Race Track Route with Radar (3000')
1-10	SWL VOR Constant Radial Flight (6000', 5000', 4000', 3000', 2000') WAL - SBY
1-20	Ferry Flight SBY - WAL using AC, BD, LOPs at 2000'
1-21	Railroad Flight to Kellam in Heavy Rain at 1000', AB/BD, AC/BD, WAL - SBY
1-22	Constant LOP Octopus using AD, AC, AB, BD, BC LOP s, SBY - SWL - SBY (2000', 7000')
1-23	VOR Cloverleaf 30° Cardinal Hdgs (3000'), SBY - SWL - SBY
1-24	VOR Cloverleaf 30° Card plus 15° (3500'), Constant CD LOP AB/BC, CD/BD, AB/BD

flying with Omega navigation along constant East-West LOPs through the Wallops area; and VOR radial flying perpendicular to the coastline on Assateague Island.

The second group of five flights was conducted without radar tracking and included: airport to airport navigation using Omega alone; a repeat of the railroad flight using alternate LOP pairs and accompanied by moderate rain; Omega navigation along various LOPs from the Snow Hill VOR; and two VOR radial flights comparing afternoon and morning signals in a flower petal pattern.

The following discussions contain selected excerpts from the recorded and processed Omega data for illustrations of specific points. A complete presentation of all the flight data, and their interpretation, is contained in Appendix A.

7.1 ALTITUDE EFFECTS

All the Wallops area flights were concerned with the effects of altitude to some degree, but as can be seen in Table 4, only four specifically addressed this phenomenon in that various altitudes were flown during the flight.

7.1.1 EXPECTED RESULTS

Proximity to local noise sources on the ground led to the expectation of higher signal to noise ratios at greater altitudes. Also, modal interference was expected to be greatest at the edge of the waveguide (the ground or reflecting ionospheric layer), and again more stable signals were expected at higher altitudes. The same reasoning also applied to the local terrain and coastline effects. Diurnal effects were expected to be independent of altitude due to the macroscopic shifting of lanes caused by diurnal changes of the ionosphere. Precipitation effects were also expected to be independent of altitude because of the extremely local nature of precipitation static and its independence of altitude. Finally, a number of previous tests had indicated an improvement in signal to noise ratio after takeoff, indicating a strong ground effect.

7.1.2 TAKEOFF PHENOMENON

The takeoff phenomenon was an improvement in S/N ratio as the aircraft left the ground and climbed above the local treetops. A signal masking effect by trees and local terrain was investigated by NASA Langley Research Center (Reference 4) and was believed to be the cause of this phenomenon. The effect was first noticed during Northeast Corridor flight tests without the CIU. By observing the weak signal light on the indicator and the receiver reference light, a fair knowledge of individual station S/N ratio was obtained. During some flights where Station A (Norway) appeared weak during ground runup of the aircraft, the number of weak signal lights reduced dramatically after takeoff.

A reverse effect - decreasing S/N values - was observable in the data for landings. Both of these low altitude effects can be seen in the S/N plots for Stations A and B in Figure 27. These same variations were discernible in the Northeast Corridor flight data as discussed in Section 8.2.1. This effect was not a particularly strong one, and was easily masked by other effects such as inverter noise change (discussed in Section 7.6.2).

7.2 SHORE EFFECTS

Eleven of the sixteen Wallops flights encountered some coastal crossings and of those, seven were specifically intended to provide information for the determination of the magnitude and direction of the effect on the LOPs.

7.2.1 EXPECTED RESULTS

Early Omega literature and flight experience with LORAN indicated that there may be anomalies in the Omega navigation system associated with overflight of shore lines. It was expected from the nature of electromagnetic waves traveling over areas of different conductivity that the waves would be retarded slightly when passing into a region

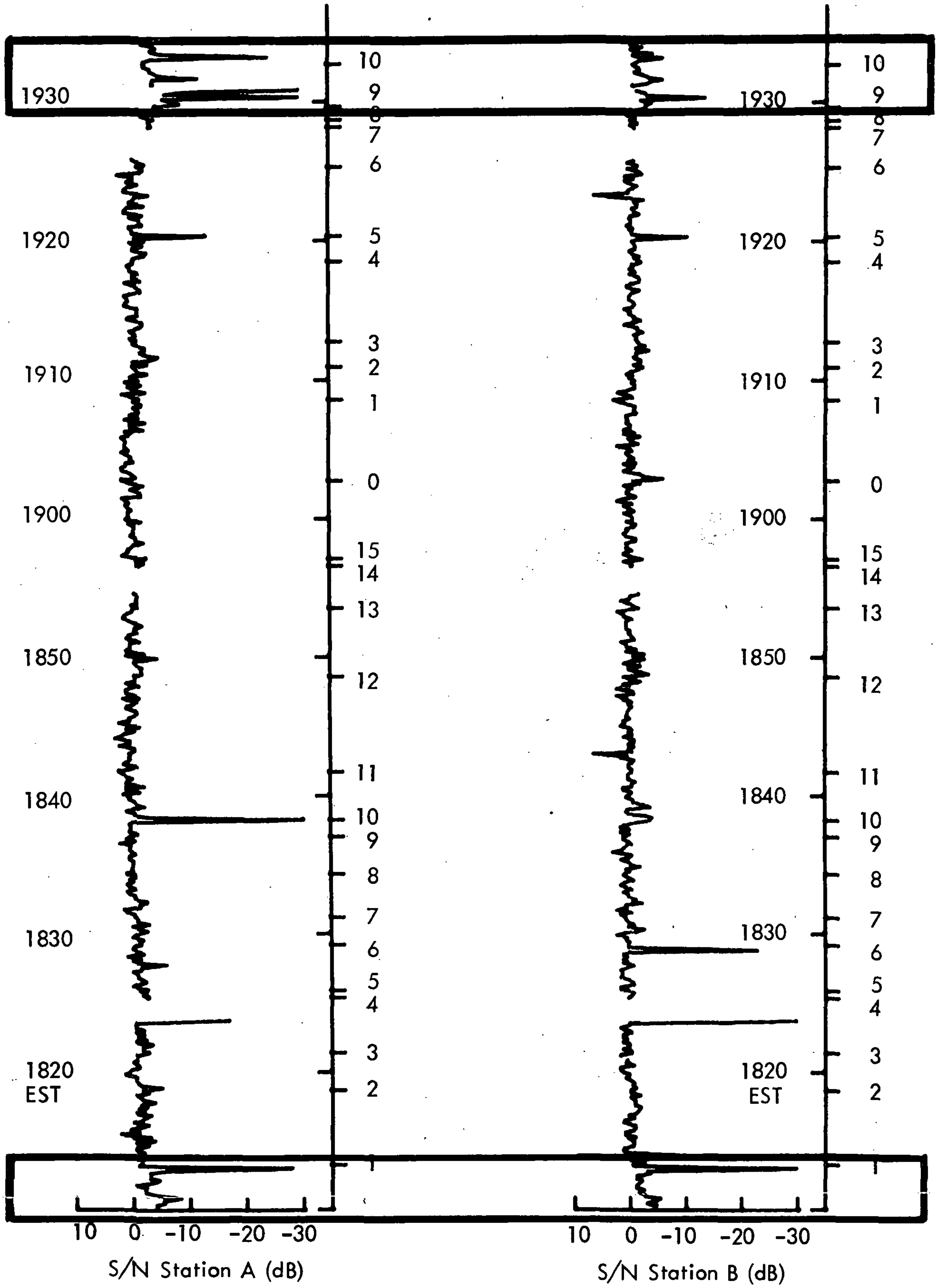


Figure 27. Flight 1-9, S/N Station A and B;
WAL-racetrack (night, radar), 2/21/75, 3000', 1810-1935 EST, 2310-0035 GMT.

of lower conductivity and that this would cause kinks in the LOPs that would result in course bending. These shore effects were expected to be greater at lower altitude due to proximity of the shoreline. A rather simplified approach to the expected geometry of the affected LOPs near a coastline was obtained by plotting wave fronts (lines of constant propagation time) from two stations to an observer on the coast and comparing phase differences. This exercise led to the realization that, due to the long transmission paths and the relatively long wave lengths, several hundreds of miles of propagation anomalies would be required to make even a small shift in the local phase measurement. Consequently, the extremely small changes in conductivity due to a shoreline should have a miniscule effect on Omega LOP shape.

7.2.2 COURSE DEVIATIONS OBSERVED

In the flights over shorelines it appeared to the cockpit observers that there were needle deflections which represented some course bending. This was particularly true for the Delmarva Peninsula where there is an inner and outer shore with a tidal flat in between. In addition there are many irregularities in both coasts such as the Crisfield Peninsula and the bend in Assateague Island around Toms Cove. The observations of these course needle deflections were noted on the voice tape as "course bending" since some fluctuations had been anticipated.

Subsequent analysis of the plots of needle deflection on the CDI when flying over a coast in the Wallops area revealed that there was little correlation with subsequent passes over the same or similar spots either in direction or magnitude of the needle deflection. This can be seen in Figure 28 which shows passes over the coastal region in question along the 120° radial of the Snow Hill VOR. The greatest magnitude of the fluctuations corresponded to roughly 0.5 nm which was less than the phase noise of the Norway signal. Some CDI fluctuations were also observed along the Connecticut coast

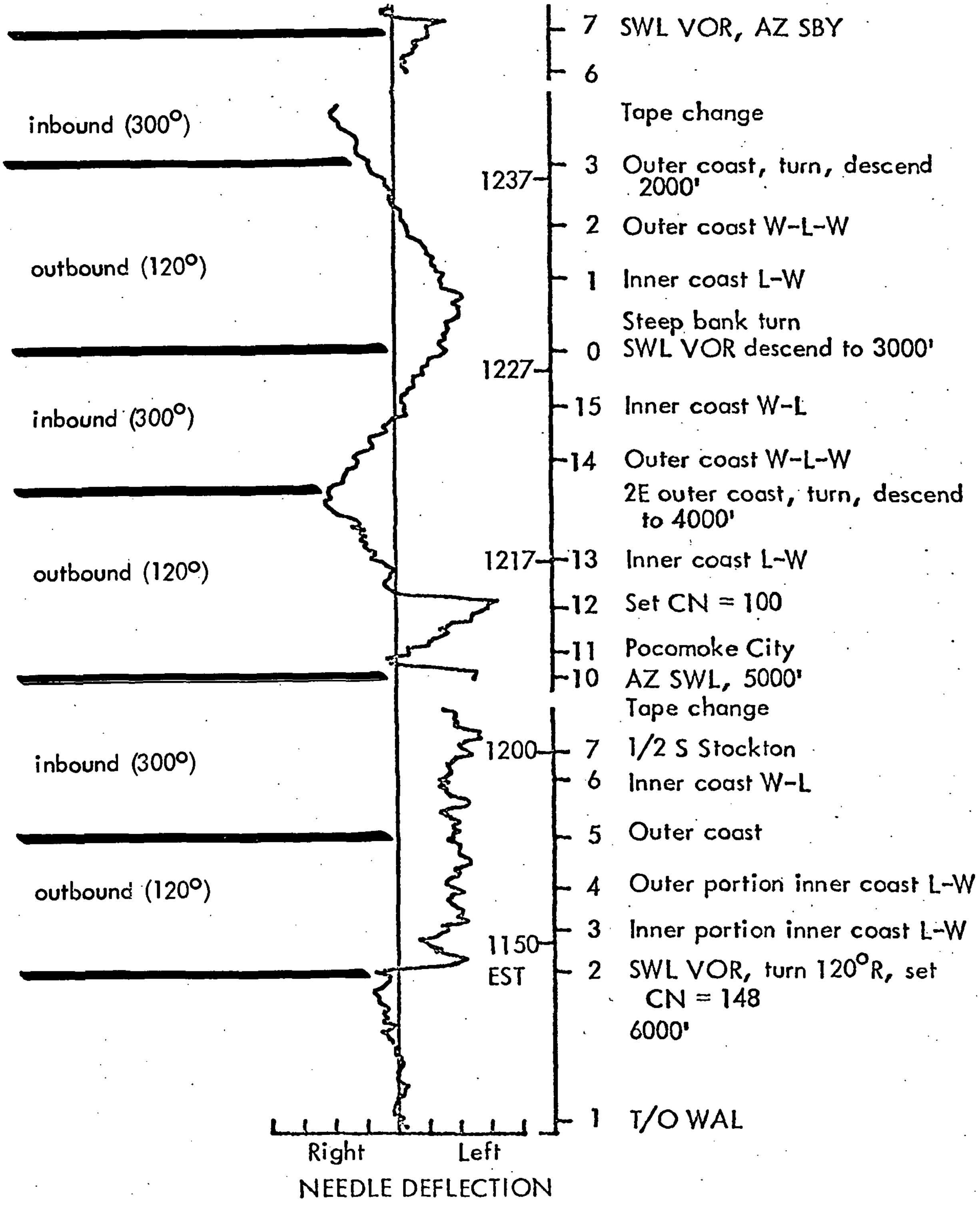


Figure 28. Flight 1-10, Needle Deflection Over Coastal Region Along a Fixed VOR Radial.

near the Madison VOR, but this was in the vicinity of a significant amount of HF and VHF energy. Flights over the Maine and Massachusetts coasts showed no shore effects at all (Section 8.3.2).

7.2.3 VARIATIONS WITH S/N

Most of the needle fluctuations near the shores in the Wallops Area were attributed to reduced S/N for Station B. Some reduced S/N values for stations A and H could also be seen, but H was not used for navigation. The decreasing S/N values in the Delmarva area may have been due to local HF marine radio broadcast energy leaking into the Omega receiver via the ADF antenna from a concentration of such equipment in the dwellings along the coast.

Another indication that such observed needle deflections were not directly associated with course bending near shorelines was obtained from records of Flight 1-22. This flight was flown along a constant LOP and the plotted output should have a straight line. The track flown was noted on a map during flight and needle deflection corrections were subsequently overlaid. The result was, indeed, a fairly straight path.

7.2.4 ALTITUDE EFFECTS

Flight 1-10 (Figure 28) was conducted with each successive leg 1000' lower than the preceding leg along the Snow Hill VOR 120° radial. There was a noticeable increase in the needle fluctuations with decreasing altitudes, but the VOR scallops were also becoming more pronounced which produced a strong background bias for the Omega comparisons.

7.3 STATION PAIRS AND LOP DIRECTIONS

In the Wallops area only stations A, B, C and D were used for navigation. H was not used because of the very low S/N ratios (see Volume II). Characteristics of the Omega system dictated that from these four stations the usable combinations were A-B, A-C, A-D, B-C, B-D, and C-D. The geographic situation was such that the Wallops area was nearly on the extended centerline of C-D behind Station D. Consequently, C-D had a 43 mile spacing between LOPs, was very difficult to track, and was virtually unusable in the Wallops area.

Several flights were made parallel and perpendicular to LOPs generated by the five usable station combinations. In flights along constant LOPs (listed in Table 6) the CDI deflection was assumed to depend on only one LOP and, hence, to incorporate the anomalies peculiar to only the two stations generating that LOP. These anamalies are discussed throughout this section, and are listed to reflect station correlation with anomalies. In addition, flights along LOPs reflected the effective increase in navigation error due to poor geometry of the LOPs.

Table 6. Flights Along LOPs.

Flight	LOPs
1-6	A-B
1-8	A-B, B-D
1-9	A-B, B-D
1-22	A-D, A-C, A-B, B-D, B-C
1-23	A-B, B-D
1-24	A-B, B-C, C-D

7.3.1 EXPECTED RESULTS

Variations were expected in CDI noise observed flying along the different LOPs due to the different noise characteristics of each station and due to different shoreline effects with each LOP choice. Because of the wide spacing of the C-D LOPs in the Wallops area, difficulty was expected in flying the C-D LOP.

7.3.2 OBSERVED RESULTS

Station A S/N ratios were often not good; consequently, the flights along LOPs partially generated by Station A confirmed that Station A was responsible for noise in the CDI and MTG readouts. The C-D LOP was predictably hard to fly. Otherwise there were no unusual phenomena observed with various station combinations, indicating that a judicious selection of stations based on station power and geometry could lead to successful navigation.

As discussed in Section 7.6, navigation with Station A encountered various local noise phenomena and was also prone to background noise effects. On Flight 1-22, turbulent air made the pilot's job of filtering the Omega data more difficult, as is evident from Figures 29 and 30. The apparent improvement in needle following in the second part of the flight was partly due to an increase in Station A S/N ratio as the VHF radio power supplies warmed up, and partly due to an LOP switch so that Station A signals were processed for only one LOP after 1139 EDT. The LOP switch resulted in smoothing of the CDI, but the MTG readout, heavily dependent upon the A-B LOP, was still noisy.

As discussed in Section 7-2, observed shoreline effects also seemed to be dependent upon LOP selection. For example on Flight 1-24 a slow CDI drift to the left which was not correctable with aircraft maneuvering was observed when flying

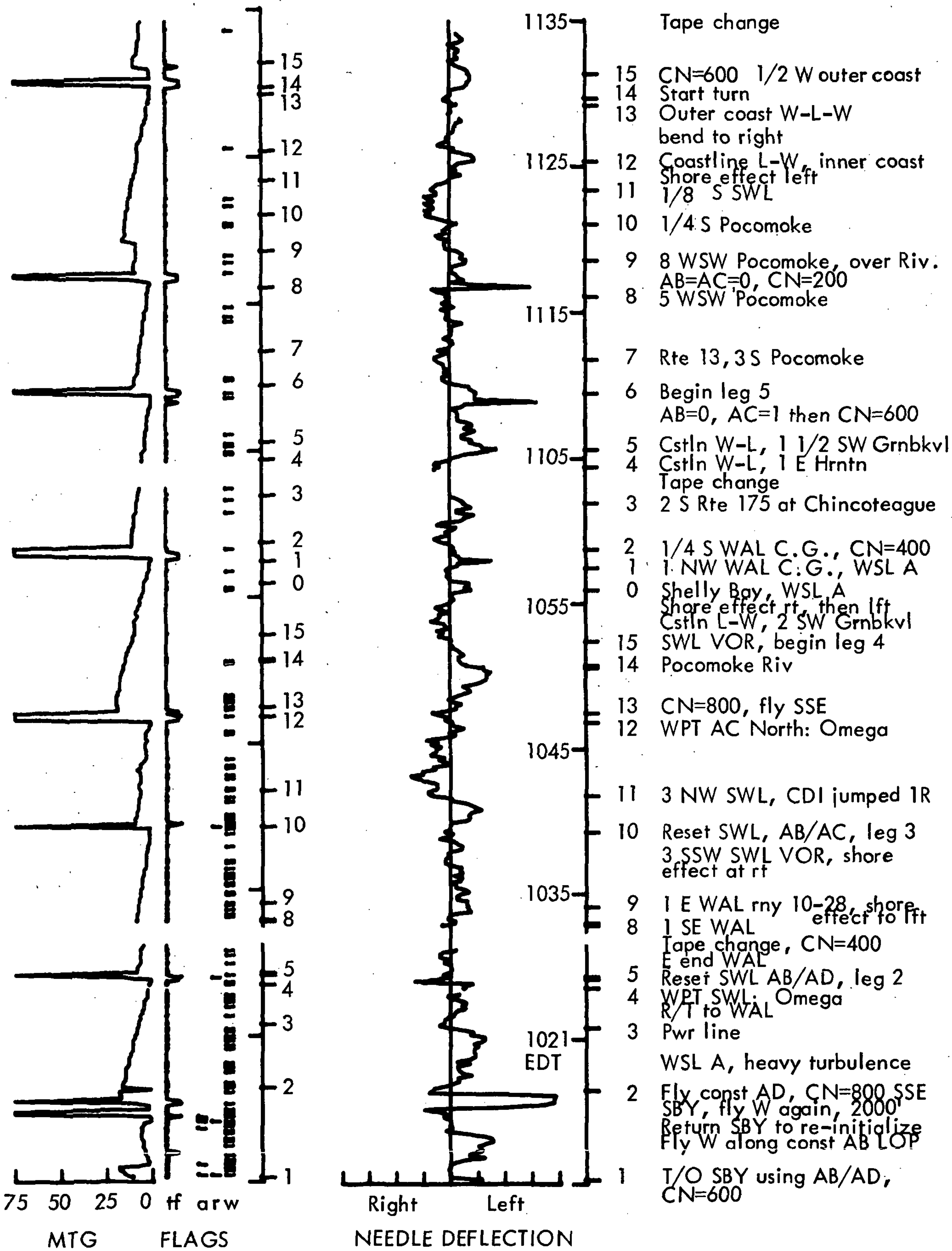


Figure 29. Flight 1-22 (First 81 min.), Miles to Go and Needle Deflection; SBY-SWL-LOP's, 3/8/75, 3500', 1000-1256 EDT, 1400-1656 GMT.

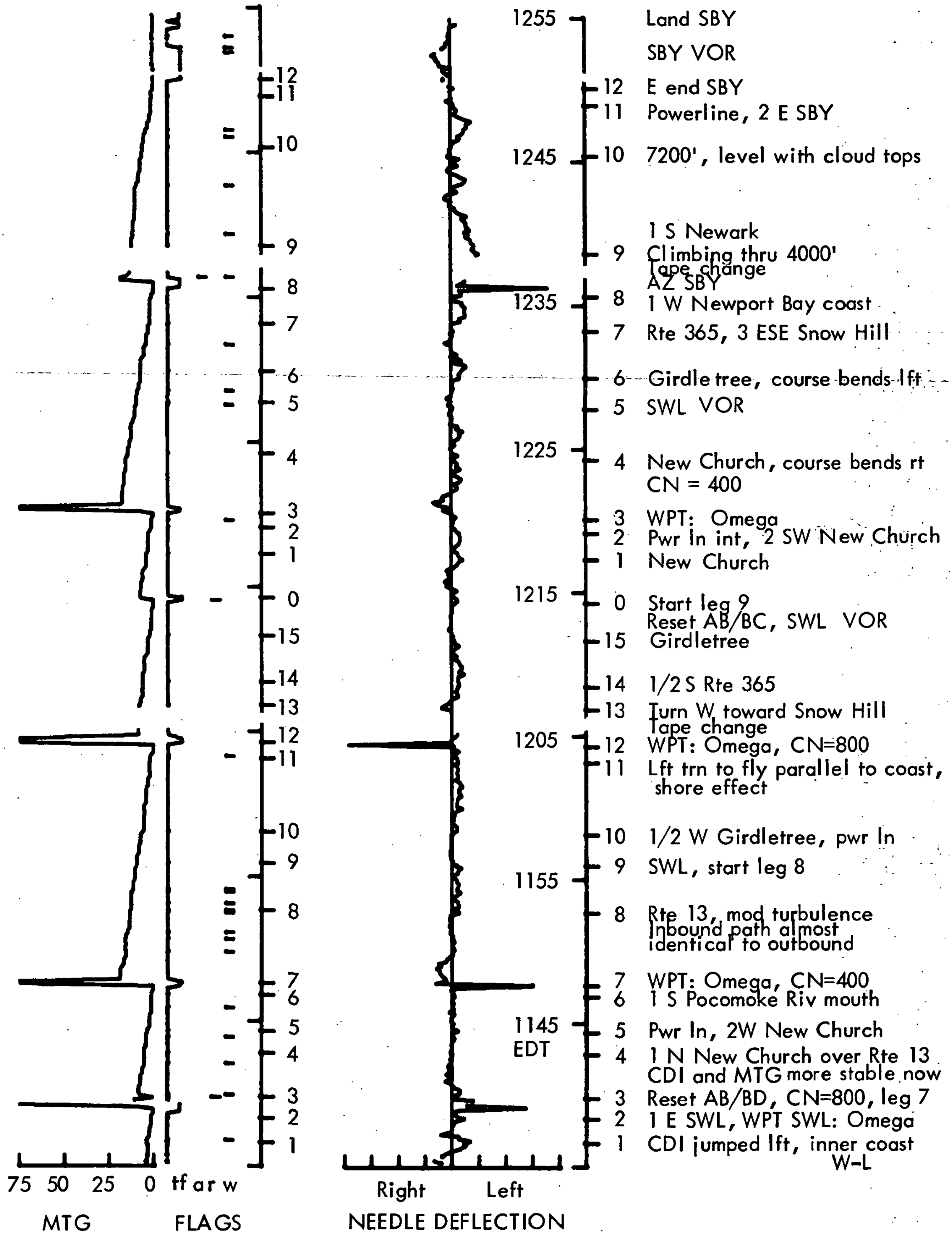


Figure 30. Flight 1-22 (Second 80 min.), Miles to Go and Needle Deflection; SBY-SWL-LOP's, 3/8/75, 3500', 1000-1256 EDT, 1400-1656 GMT.

the C-D LOP over the shore. This was partially attributable to the poor S/N ratio of station C, and partially due to the 43 mile spacing of the C-D LOPs.

7.4 DIURNAL EFFECTS

The flights in the Wallops area were staggered throughout the day to determine the extent of errors attributable due to the different diurnal shifts in the Omega LOPs (see Figure 31).

7.4.1 EXPECTED RESULTS

For any Omega signal there were three basic propagation paths: entirely sunlit (day), entirely dark (night) and mixed illumination (transition). As is described in the Omega Propagation Correction Tables, wave propagation had a tendency toward greater long-term stability during the day, but with varying short-term conditions. Wave propagation at night had a lesser degree of long-term stability, but more nearly smooth short-term conditions. The transition periods caused most difficulty because the changes were of intermediate stability and occurred nonlinearly.

As the flight schedule shows, the transition periods for Stations A and C (Norway and Hawaii) were the longest, due to their great longitude displacement which presented the greatest possibility for diurnal errors. In the Wallops area the expected periods of inaccuracy due to diurnal effects occurred at:

Station	Transition Occurrence at Wallops (GMT)	
A-Norway	1647 - 2242 (sunset)	0556 - 1151 (sunrise)
B-Trinidad	2147 - 2242	1056 - 1151
C-Hawaii	2242 - 0411	1151 - 1720
D-North Dakota	2242 - 0012	1151 - 1322

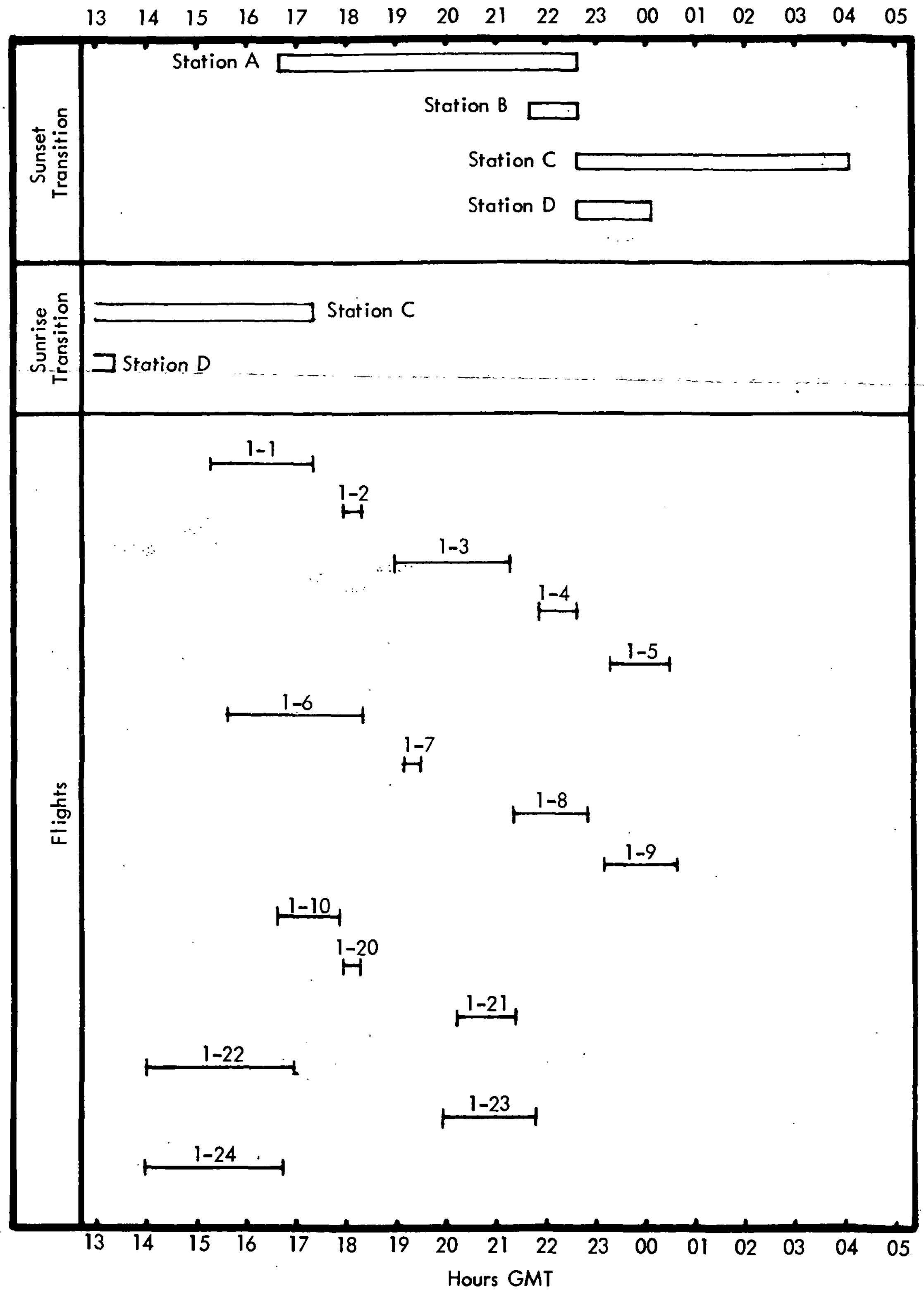


Figure 31. Station Transition Times and Wallops Area Flight Schedule.

7.4.2 ERRORS OBSERVED DURING TRANSITION

Figure 32 shows propagation corrections and rates of change of corrections for the Wallops area, and from this it can be seen that LOP changes occurred in a non-uniform manner for each station. On Flights 1-22 and 1-24 Omega navigation employed Station C during its sunrise period, with no great loss of accuracy even though this was the period and station with the greatest change. Figures 33 and 34 show two Omega and VOR waypoints as occurring simultaneously at 1007 and 1025 EST, but about half a minute apart at 1040, only 15 minutes later, and a mile north of the waypoint. By 1103 the Omega and VOR waypoints occurred at the same time again, but the CDI indicated one and one half miles to the right of course (Northeast), and the MTG nonzero indication confirmed this. This illustrates the accuracy degradation due to diurnal shifts, but not to the expected degree. That is, over the period from 0856 - 1003 EST the expected change in C from Figure 32 would be about 25 centicycles or a quarter of a lane (about two miles).

The flights during the transition of Station A seemed less affected by diurnal shifts than by low S/N ratios and sudden phase anomalies or local interference even during high S/N ratio periods. The short periods of transition for Stations B and D seemed to have little detectable effect probably because their greatest change was at sunrise and not during these flights. From the propagation correction at sunset for Station C, it is seen that the change is regular and fairly gradual so that an hour long flight might accrue an error of about one tenth of a lane or a mile at most. On Flight 1-4 both A and B transition occurred, and it required an additional 0.3 A-B lanes and -0.1 B-D lanes to center the needle and zero the miles after landing at Norfolk. Flight 1-5 required no correction for B-D, but -0.3 A-B lanes, so that the same A-B input was required during and after the A and B transitions. This may be partly attributable to LOP calculation errors.

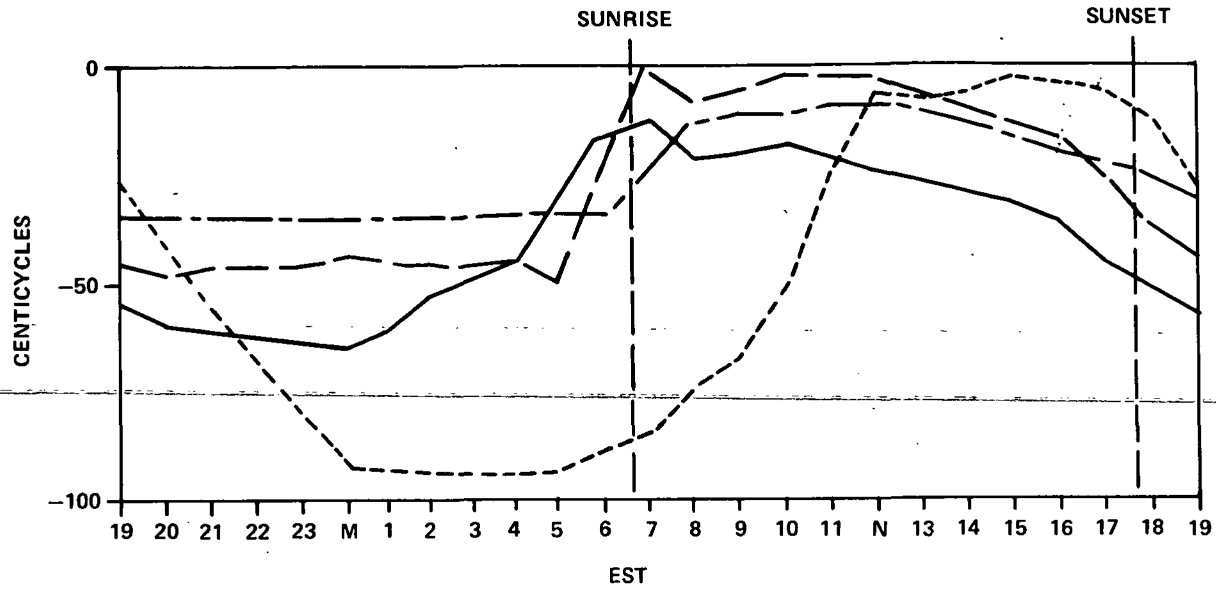


Figure 32(a). Wallops Area Omega Propagation Corrections for 10.2 kHz, Stations A, B, C and D for the Period 15-29 February 1975 (40.0 N, 76.0 W).

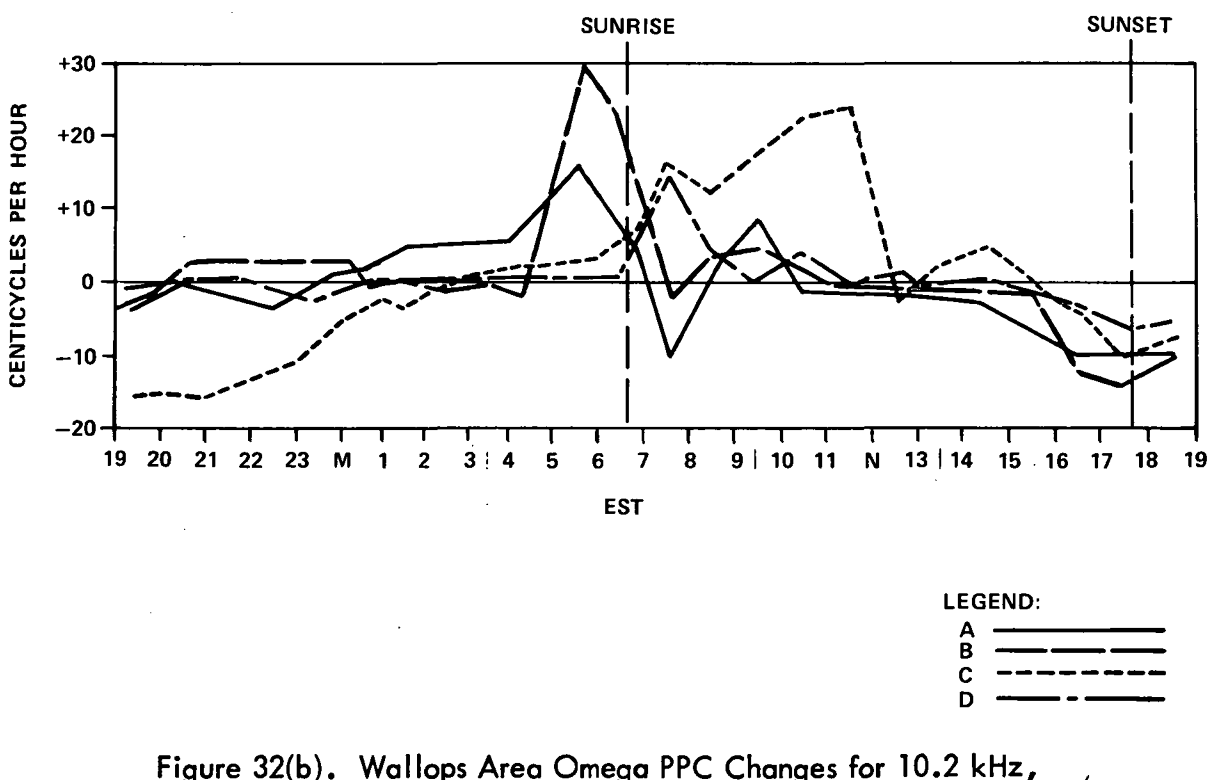


Figure 32(b). Wallops Area Omega PPC Changes for 10.2 kHz, Stations A, B, C and D for the Period 15-29 February 1975 (40.0 N, 76.0 W).

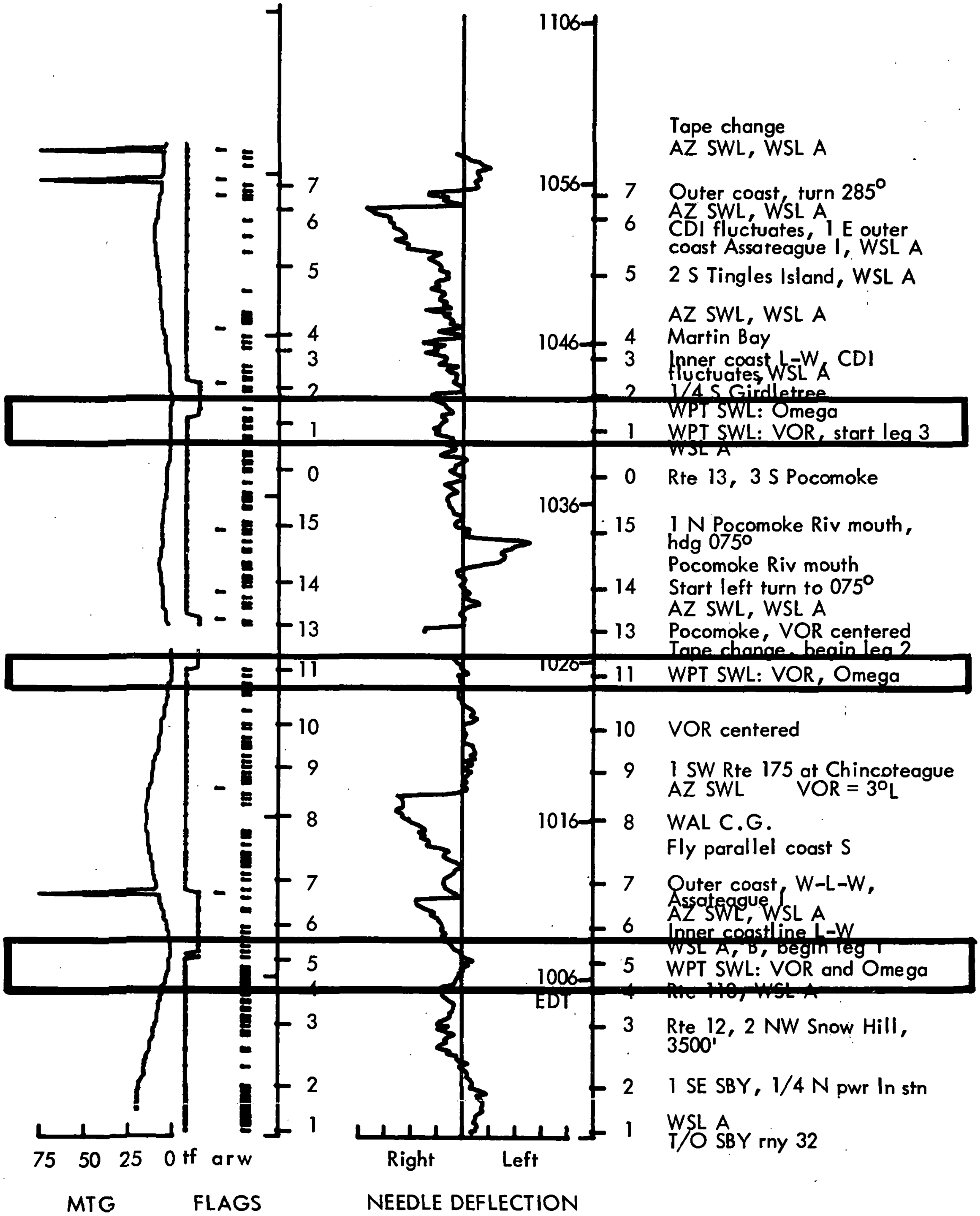


Figure 33. Flight 1-24 (First 63 min), Miles to Go and Needle Deflection; SWL VOR Cloverleaf, 3/9/75, 3500', 0956-1245 EDT, 1356-1645 GMT.

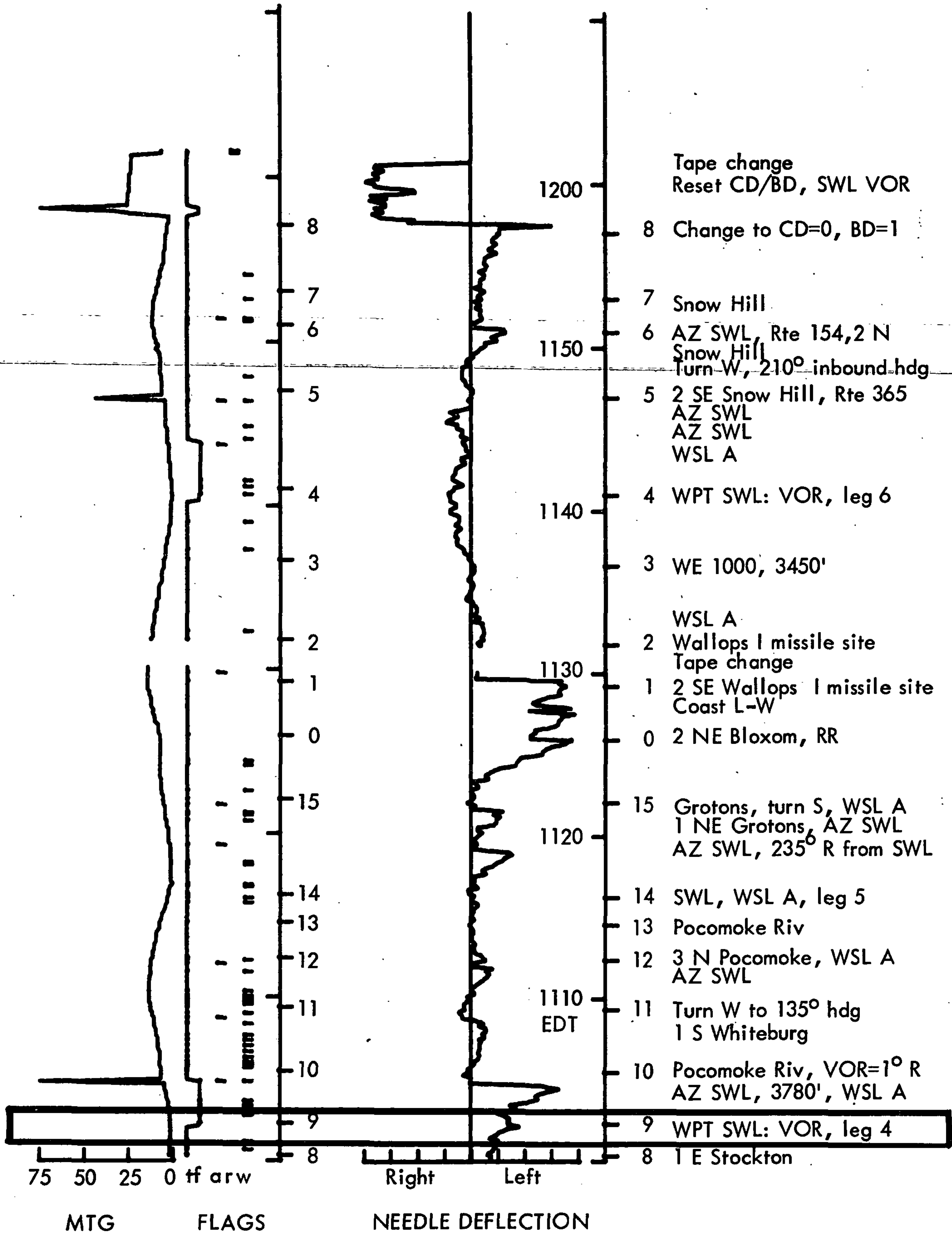


Figure 34. Flight 1-24, (Second 62 min.), Miles to Go and Needle Deflection; SWL VOR Cloverleaf, 3/9/75, 3500', 0956-1245 EDT, 1356-1645 GMT.

7.4.3 S/N RESULTS

The most significant noise effect during the diurnal tests in the Wallops area was the occurrence of fluctuations of the CDI needle. This may have been due to many causes: sudden phase anomaly, instability of phase during transition, or most likely local interference. This fluctuation occurred most frequently during the transition of Station D,which is strongest and least noisy in the Wallops area. An analysis of weak S/N for Station A as shown in Figure 35 shows little diurnal noise repeatability.

7.5 PRECIPITATION STATIC EFFECTS

Two flights were conducted during periods of precipitation near Wallops. One was flown during light to heavy rain; the other during light snow showers.

7.5.1 EXPECTED RESULTS

Owing to the nature of VLF transmission and reception, precipitation static is to be expected with an E-field antenna in rain or heavy snow. As the vehicle flies through the precipitation, the particles making and breaking contact with the aircraft skin can cause changes in the aircraft's E-field stronger than the Omega signal detected between the E-field antenna and aircraft skin. The relatively slow speed of the aircraft (120 kts) was expected to limit the extent of precipitation static.

7.5.2 DESCRIPTION OF CIRCUMSTANCES

Flight through a light snow shower lasted no more than five minutes. This was during leg four of Flight 1-23 (see Figures 36 and 37) to the northwest of the Snow Hill VOR. Rain was encountered during Flight 1-21 (see Figures 38 and 39). Alternating moderate to heavy rain occurred during the first twenty-five minutes

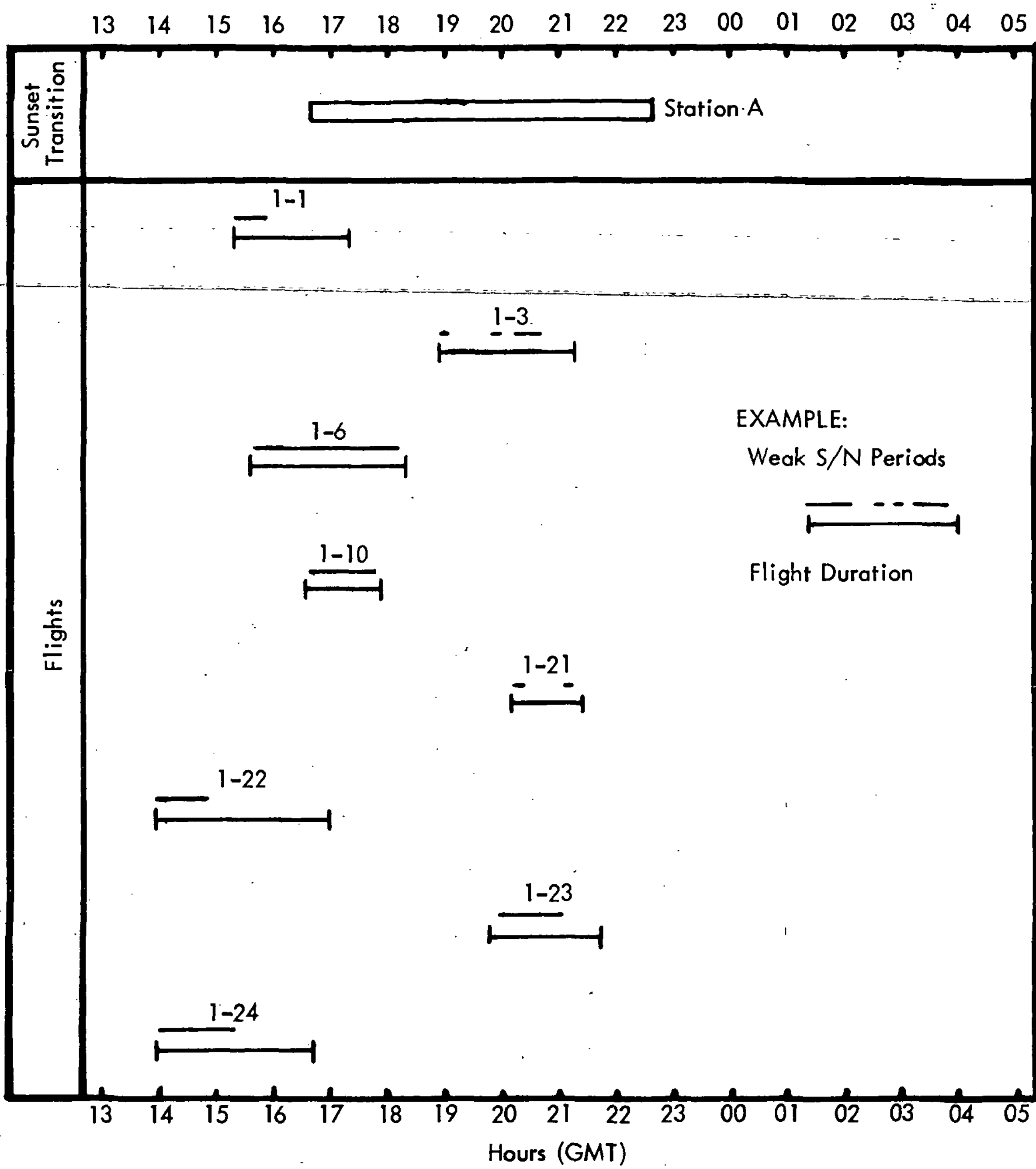


Figure 35. Weak S/N Periods for Station A in the Wallops Area.

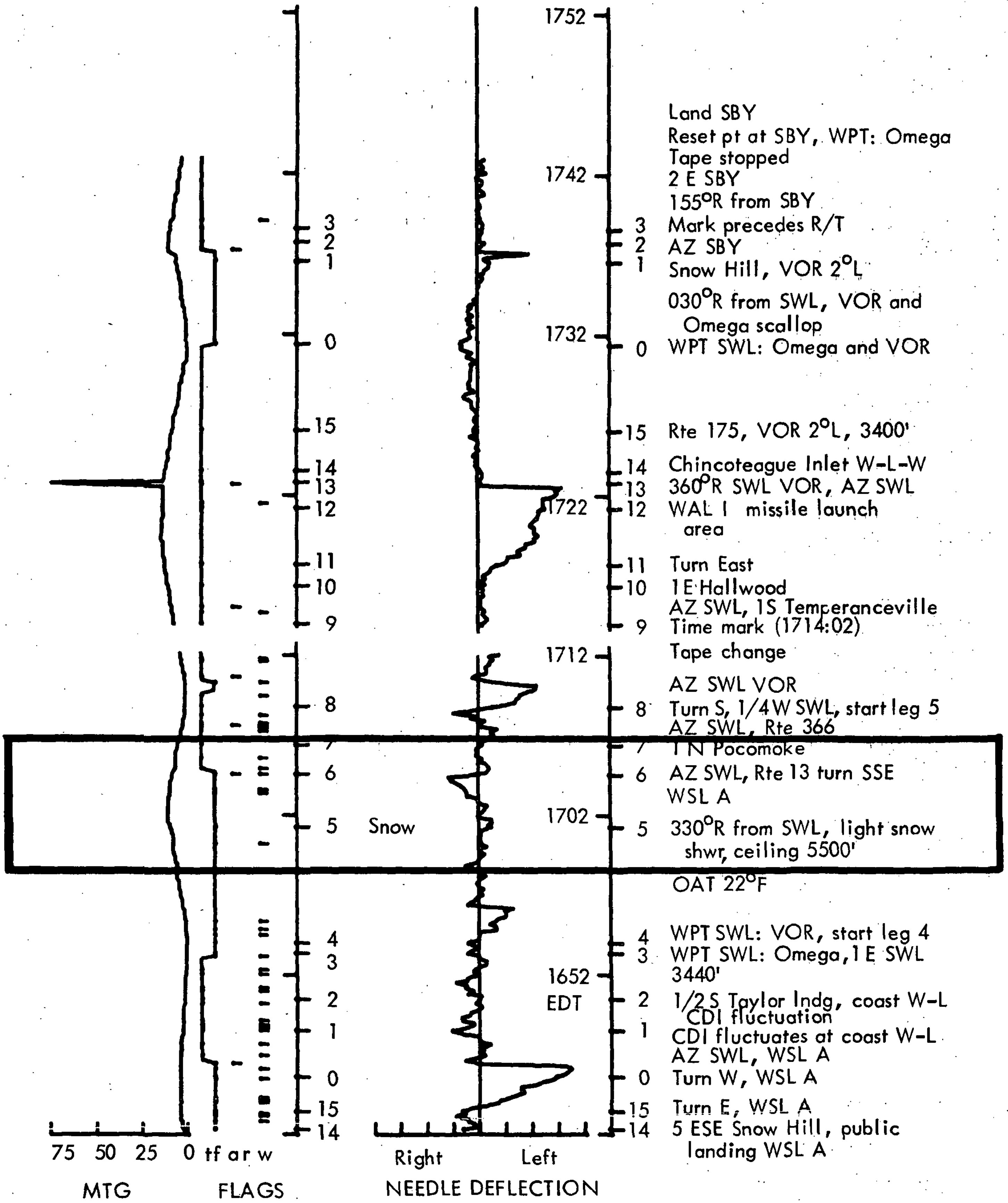


Figure 36. Flight 1-23 (Second 61 Min), Miles to Go and Needle Deflection; SWL VOR Cloverleaf, 3/8/75, 3300', 1556-1747 EDT, 1956-2147 GMT.

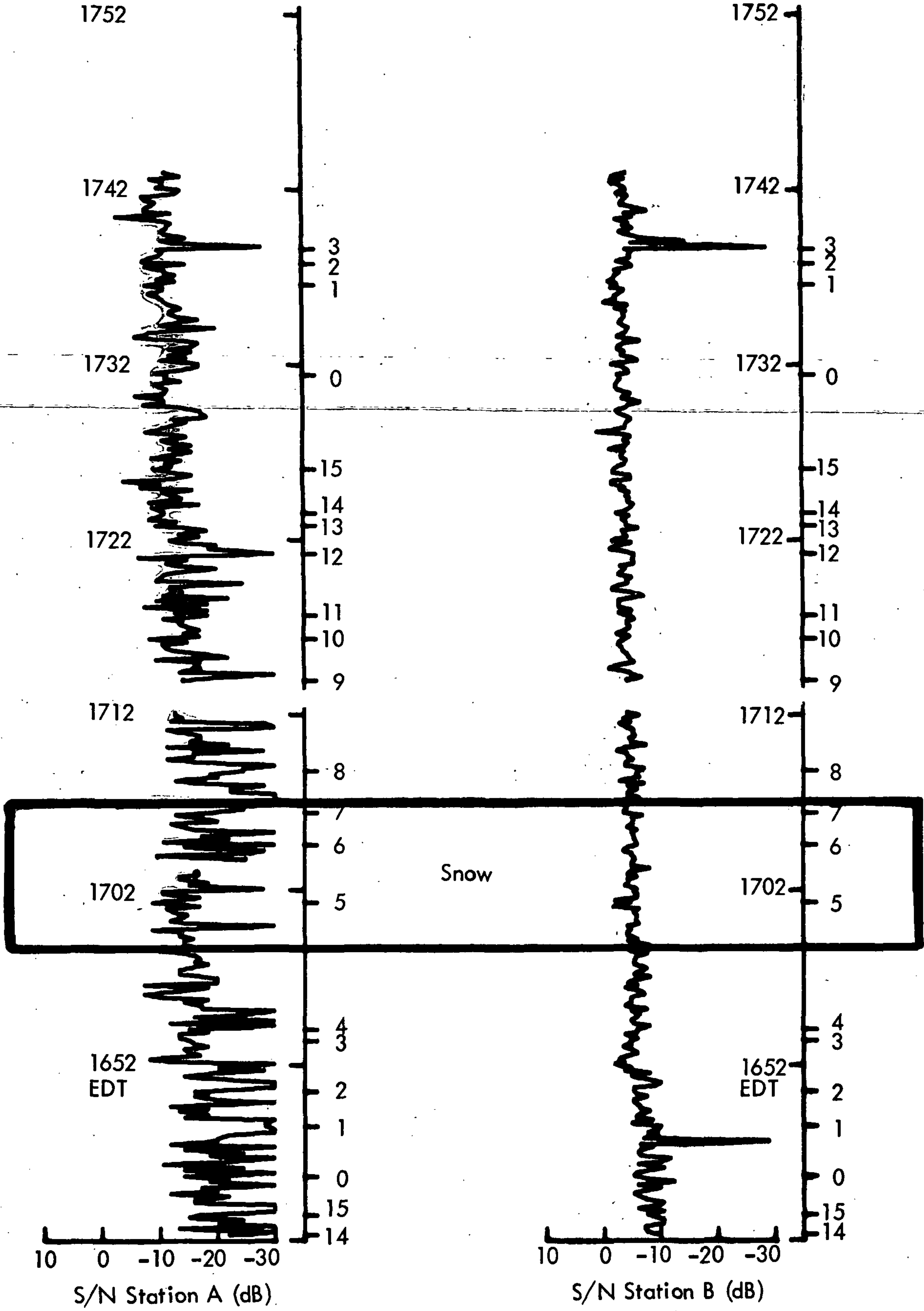


Figure 37. Flight 1-23 (Second 61 Min), S/N Station A and B; SWL VOR Cloverleaf, 3/8/75, 3300', 1556-1747 EDT, 1956-2147 GMT.

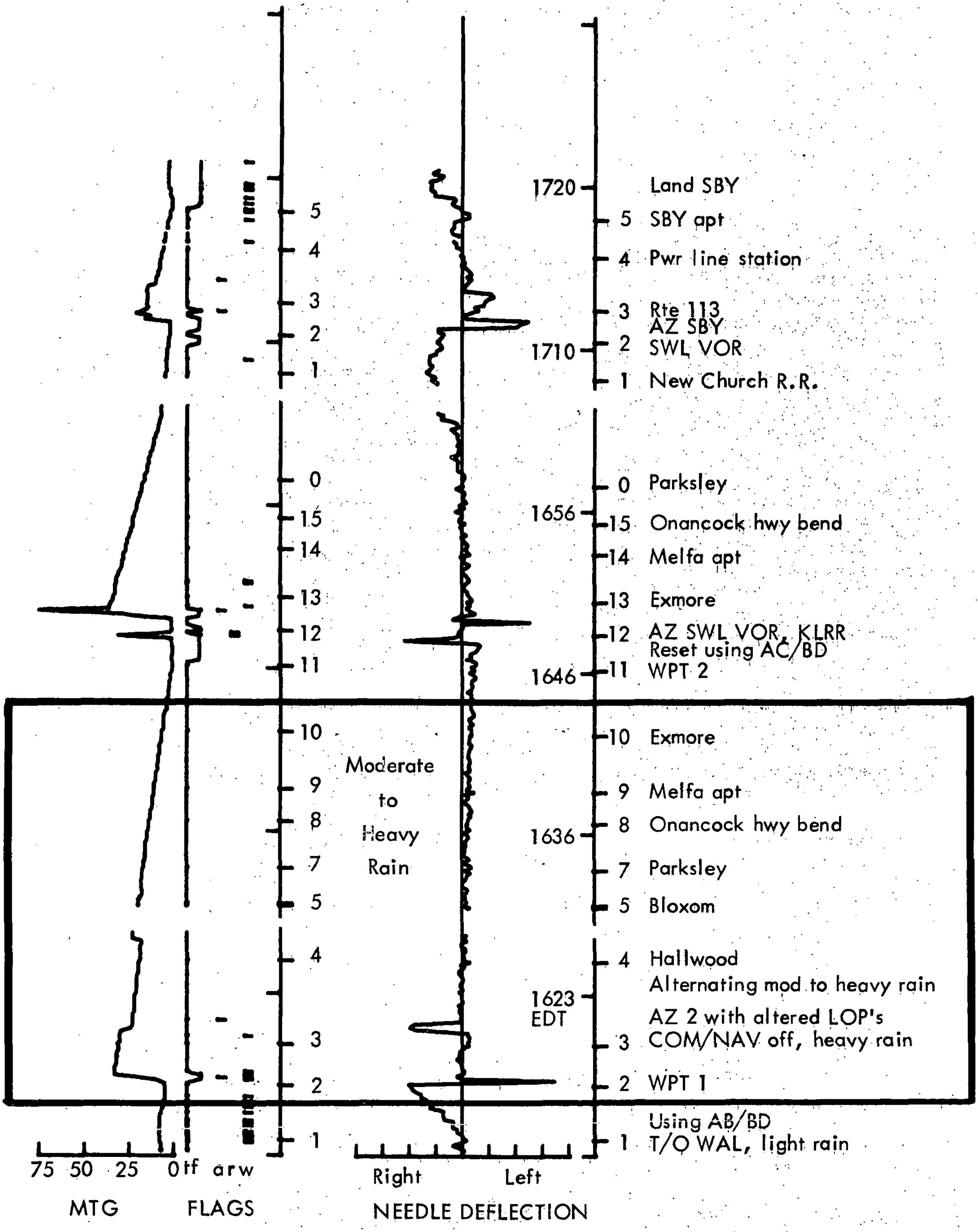


Figure 38. Flight 1-21, Miles to Go and Needle Deflection; WAL-R.R.-SBY (Rain), 3/7/75, 1000', 1613-1722 EDT, 2013-2122 GMT.

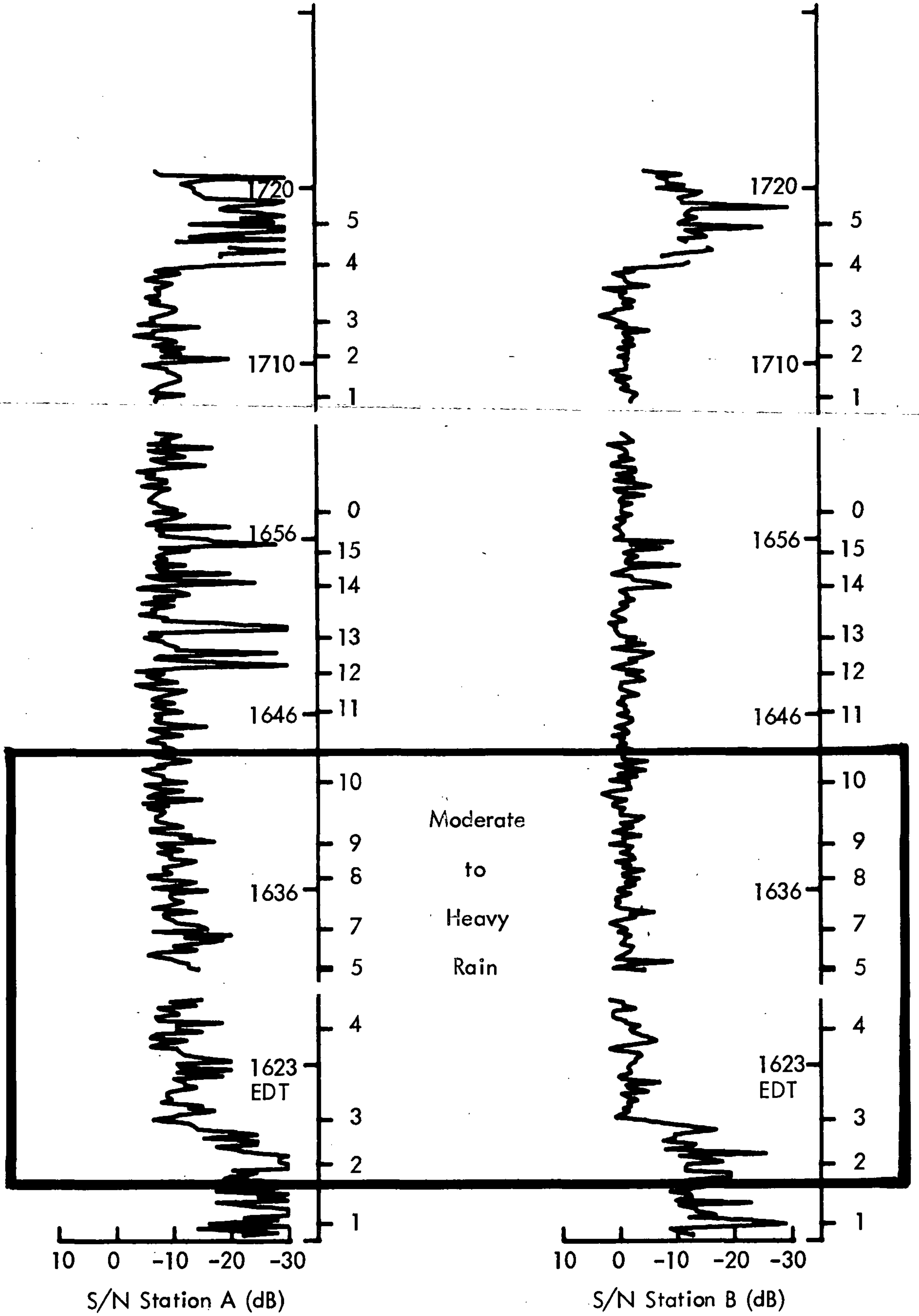


Figure 39. Flight 1-21, S/N Station A and B;
WAL-R.R.-SBY (Rain), 3/7/75, 1000', 1613-1722 EDT, 2013-2122 GMT.

followed by intermittent light rain; the second half of the flight employed different stations to determine any effects on navigation.

7.5.3 S/N RESULTS

There seemed to have been no noticeable effect from the snow shower, since, during the encounter, only Station A appeared even slightly degraded whereas the precipitation static should have had an impairing effect on all stations. During this period also the VHF invertor was still warming up and the overall Station A signal to noise ratio was improving.

On the other hand, Flight 1-21 shows S/N ratios decreased during the rain from the values expected with the radios turned off. In addition, the S/N plots show irregular levels over short periods, indicating that the precipitation effect varied rapidly but had only a minor overall influence, especially when compared to the effect of turning the radios off at the beginning of the flight and on at the end.

7.5.4 ACCURACY AND PILOT TRACKING

During precipitation in the Wallops area there was no degradation of indicator information, although there was a CDI fluctuation ten minutes prior to entering the light snow shower. The position, waypoint and final destination accuracy was about average for the Wallops area.

7.6 INTERFERENCE AND SIGNAL STRENGTH VARIATIONS

All the flights in the Wallops and Snow Hill VOR areas were directed toward determining the effects and levels of interference to Omega navigation for use during the upcoming differential Omega studies.

7.6.1 EXPECTED RESULTS

Preliminary discussions with FAA NAFEC personnel indicated an Omega interference anomaly in the Snow Hill VOR area that was detected at altitudes from (3000' to 10,000'). Further discussions with Dynell indicated that the VOR itself might have been the source of interference, and that similar effects had been noted on Long Island and in southern Connecticut. The Coast Guard Omega Project Office revealed that some difficulty in Station A reception had been observed as far south as their Norfolk, Virginia monitor station. This was attributed to low station power output and the Greenland icecap shadow effect.

7.6.2 INTERFERENCE OBSERVATIONS AND PROBABLE SOURCES

Interference can be classified into three sources: internal to the test aircraft, near field (local anomaly), and far field (lightning). In addition, signal strength can be reduced by polar cap absorption events and low station power output.

The most obvious interference source was the aircraft inverters that powered the VHF radios. A 20 dB increase or decrease occurred in the observed S/N ratio whenever the radios were turned off or on, as can be seen in Figure 40 at 18:31 (event 3) and 18:34 (event 4). In addition, when the radios were left on for a long period of time, the S/N ratio improved at a rate of about 15 dB per hour for the first hour which is also shown in Figure 40 from 18:34 to 19:30 EST. The C-band transponder installed for radar tracking had no effect on S/N ratios and did not appear to generate any interference.

Near field interference sources were not so easy to distinguish. These effects were manifested by a series of CDI oscillations when flying along an A-B LOP. These CDI oscillations were of a two-mile magnitude and continued for several minutes. This made it more difficult for the pilot to derive heading change information

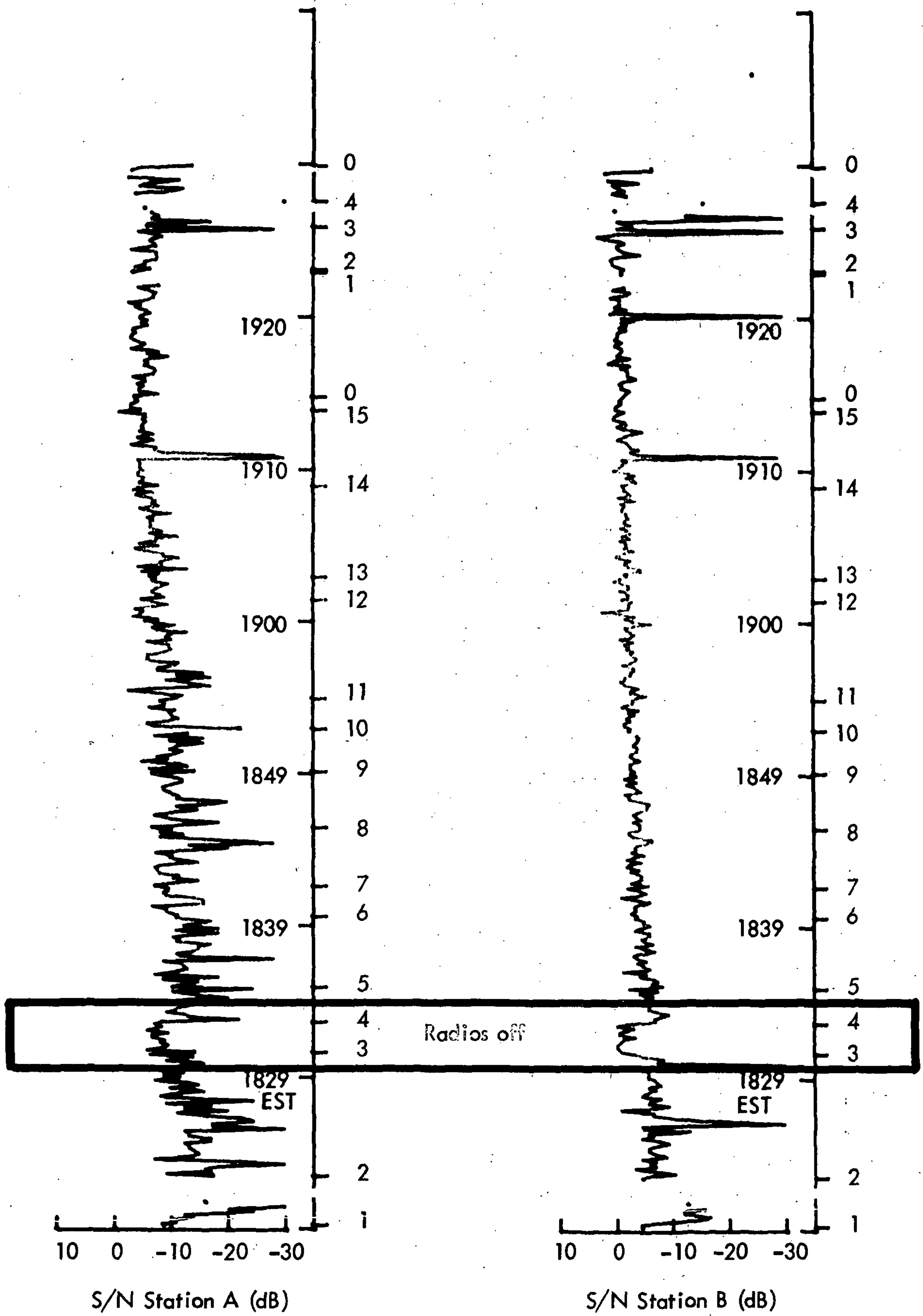


Figure 40. Flight 1-5, S/N Station A and B;
ORF-WAL (night), 2/20/75, 3000', 1818-1932 EST, 2319-0032 GMT.

from the display. When the CDI did settle down, it did so for only a few seconds before again fluctuating. For example, in Figure 41, each CDI spike in a group represents a minute or two of constant fluctuation. This effect was most often noted near the Wallops Airport which was found to be the center of the disturbance pattern. This effect was most probably not due to poor station reception since the S/N ratio for Station A was 0 dB and there was a noticeable lack of weak signal lights. It was most likely due to the FPS-16 tracking radar.

7.6.3 INTERFERENCE EFFECTS AND ALTITUDE

Two types of interference were tested for altitude effects: powerline noise and Wallops local interference. Although no powerline noise was found at any altitude, the Wallops interference showed an interesting altitude correlation.

All flights over the Snow Hill VOR were in the vicinity of powerlines. In addition, powerline crossings were noted on other flights as they occurred. Surprisingly, no powerline interference was detected, either as S/N degradation or as position indication error.

Wallops interference was observed on Flights 1-8 and 1-9 at 3000', weakly on Flight 1-1 at 5000', and not at all on Flight 1-3 at 10,000'. On all of these flights, the aircraft was being tracked by the FPS-16 radar. Transponder operation was apparently not a contributing factor, because the interference was observed at 3000' with the transponder both on and off.

7.6.4 ACCURACY AND PILOT TRACKING DURING INTERFERENCE

Two particular types of CDI fluctuations were observed on Wallops flights. On Flights 1-8 and 1-9, considerable CDI fluctuations were observed, apparently due to local noise most pronounced in the immediate vicinity of Wallops (Figure 41).

On Flight 1-6, fluctuations in the CDI were observed, apparently due to weak signals from Station A (Figure 42). Flight 1-22 displayed indicator noise attributable to Station A. These three phenomena are discussed below.

Flights 1-8 and 1-9 encountered considerable CDI oscillations for periods as long as five minutes, with one second stable needle indications occurring only two or three times in the course of the oscillations. These oscillations were of approximately half full scale to either side of center of the CDI. This oscillatory condition was worst on Flight 1-9, which surprisingly was the most accurate flight observed. When the aircraft was flown over the initial reset point after an eighty minute night flight, the Omega indication of return to the reset point and the visual observation coincided as closely as could be measured at 1000' altitude.

On Flight 1-6 the Station A S/N ratio was extremely poor as shown in Figure 43. This led to fluctuations in both the CDI and the MTG display, presumably because phase lock was poorly maintained and the indicators displayed processed noise. The weak signal light did indicate the lack of adequate S/N ratio. However, even on flights with such noisy data, the pilot could navigate by flying a constant heading and waiting for the Omega indications to settle before taking a position fix. Manual data filtering was difficult during periods of turbulence and maneuvering. However, few Wallops flights were beset with such noisy data.

Flight 1-22 displayed fluctuations on the CDI and MTG which were noted on many other flights. These fluctuations were regular, and approximately a mile in magnitude. From flights parallel to LOPs, it was determined that these jumps are caused by the Station A signal. These fluctuations, which do not show up well on the plots, were observed on most flights.

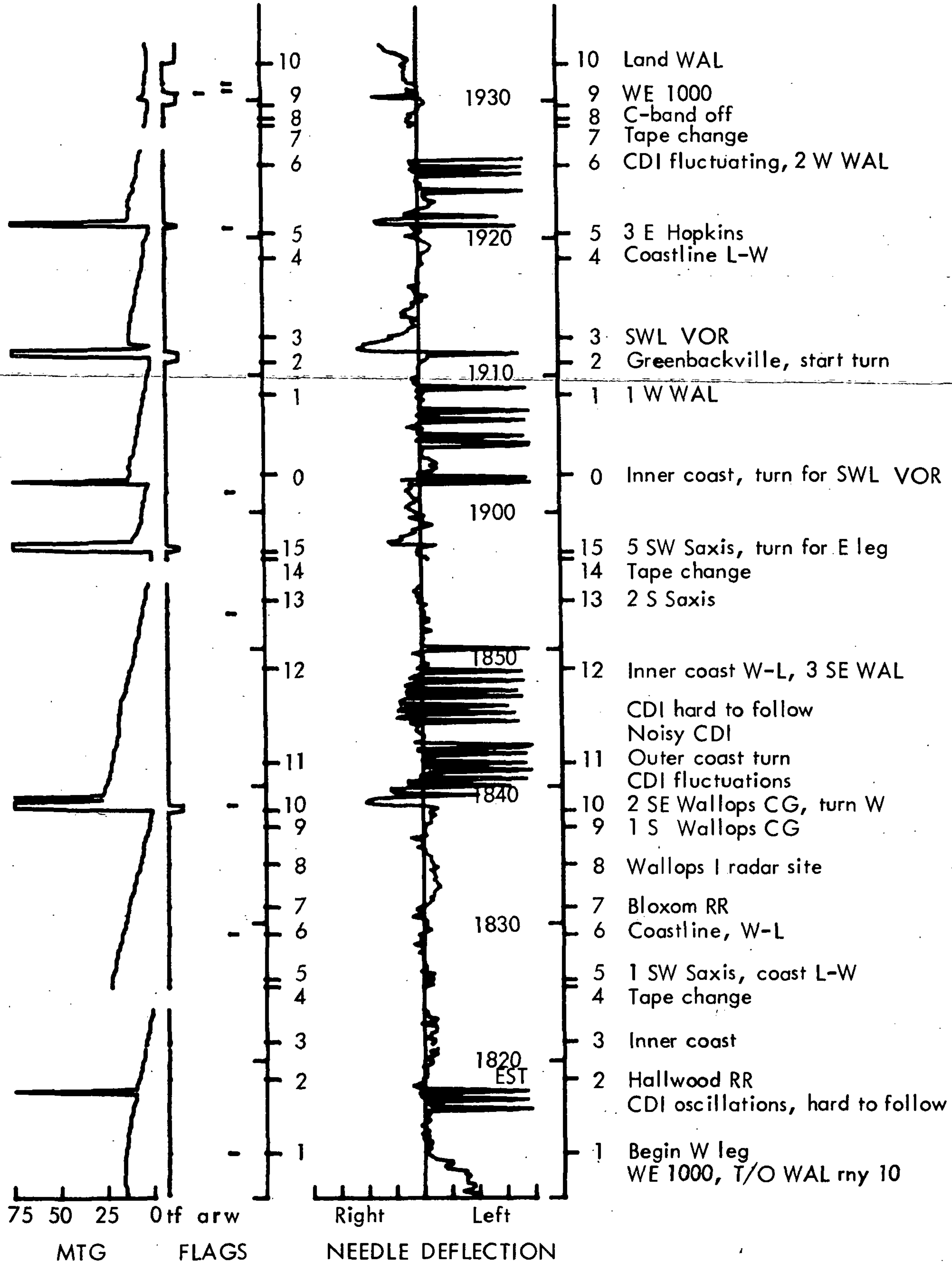


Figure 41. Flight 1-9, Miles to Go and Needle Deflection;
WAL-racetrack (night, radar), 2/21/75, 3000', 1810-1935 EST, 2310-0035 GMT.

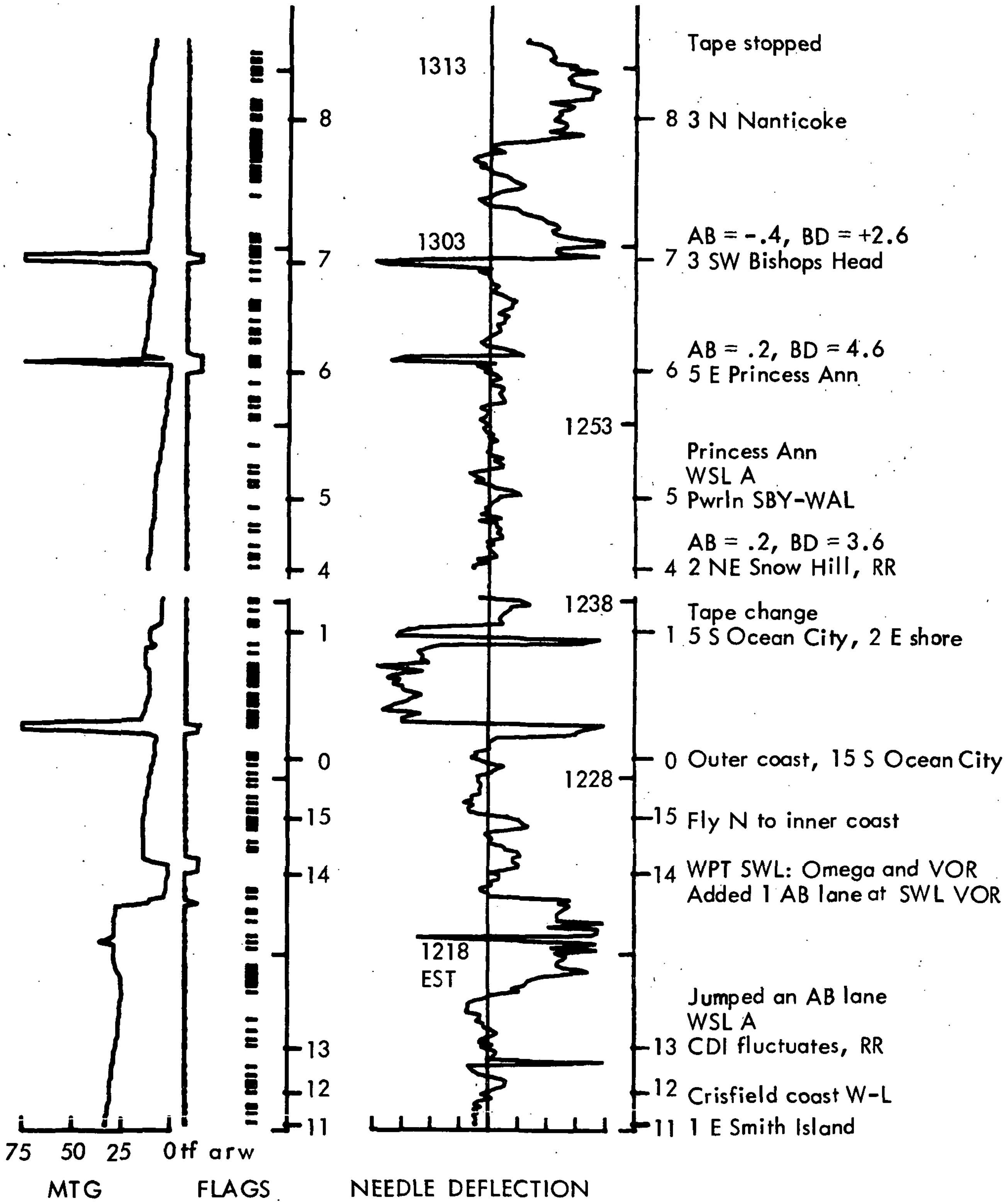


Figure 42. Flight 1-6 (Second 66 min.), Miles to Go and Needle Deflection; WAL-SBY snake, 2/21/75, 2000', 1038-1320 EST, 1538-1820 GMT.

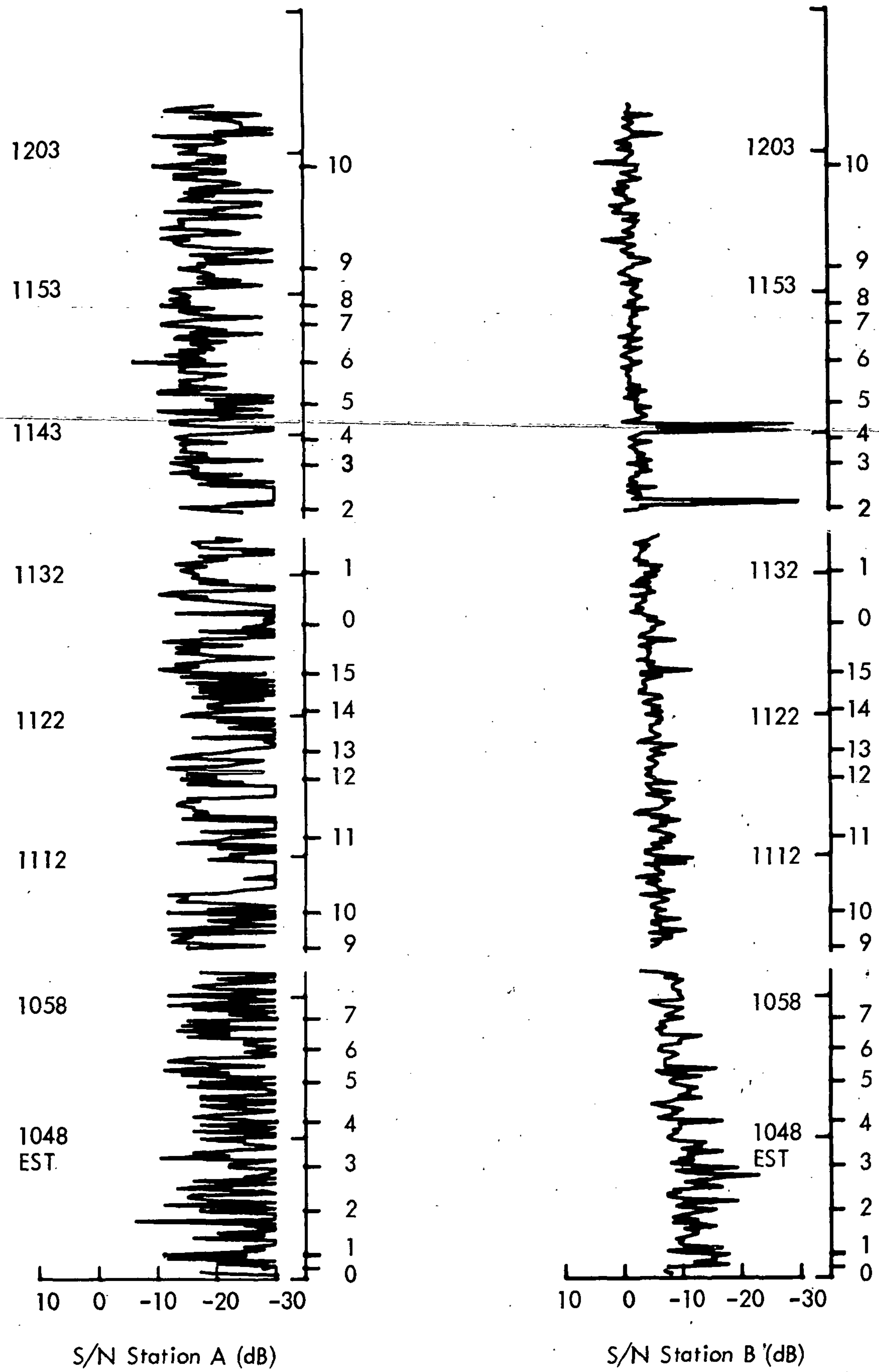


Figure 43. Flight 1-6 (First 89 min.), S/N Station A and B; WAL-SBY snake, 2/21/75, 2000', 1038-1320 EST, 1538-1820 GMT.

7.6.5 SIGNAL STRENGTH VARIATIONS

As mentioned above, the greatest variations in S/N ratios occurred with the turning on and off of the VHF radios onboard the aircraft. However, significant variations did occur in the Station A S/N ratio.

Deterioration in Station A S/N ratio could come from two sources: deterioration of signal strength, and increase in background noise. If background noise were the cause of poor S/N ratio for Station A, degradation of other S/N ratios would also be expected. Since this was not the case, it was concluded that the occasional low S/N ratios for Station A were the result of low signal strength.

Polar cap absorption (PCA) can cause an occasional decrease in signal strength of VLF waves travelling over the northern polar cap. PCAs are caused by solar proton events. During several flights, PCAs caused poor Station A S/N which resulted in weak signal lights and poor phase tracking, which in turn resulted in lane jumps, CDI drifts, and MTG jumps or failures to count. Flights 1-6, 1-10, 1-23, and many others exhibited these symptoms and the poor Station A S/N ratio.

7.7 MANEUVERS

In nearly all flights some maneuvering was completed with no effect on the performance of the Omega navigation system. Course reversals, steep turns, and gliding descents on approaches did not unlock the tracking in any instance. Other maneuvers were accomplished in the Northeast Corridor Flights and the results are reported in Section 8. These maneuvers, even though somewhat more abrupt than those in the Wallops series, also had no effect.

7.8 RADAR AND ACCURACY

As reported in Section 4.5 four of the first set of flights at Wallops (Flights 1-1, 1-3, 1-8, and 1-9) were tracked by the Wallops FPS-16 tracking radar. The data were to be processed with the Omega receiver estimates of position in order to generate comprehensive statistics on Omega accuracy. However, due to an internal failure in the CIU the Omega position readouts were not recorded. Furthermore, after the CIU was repaired, the FPS radar was not available for Omega tracking. Therefore, no radar-derived accuracy data were obtained, but accuracy data were acquired in the Northeast Corridor test flights. This is reported in Section 8.1.2.

SECTION 8

NORTHEAST CORRIDOR FLIGHT PROGRAM RESULTS

As detailed in Section 3.2, the objectives of the Northeast Corridor flight program were to repeat previously flown low-altitude Zulu routes to compare Omega performance and VOR/DME results. Factors investigated included: suitability of Omega navigation for city center VTOL operation, performance at several altitudes over various terrain (urban, industrial, forests, mountains, water), and effects of maneuvers (holding patterns, simulated approach, missed approach).

Flight planning for the Northeast Corridor investigation included plotting Omega LOPs on aeronautical sectional and terminal control area charts (Figure 44), preparation of LOP versus position tabulations, and detailed flight descriptions as discussed in Section 5 to ensure complete coverage of test objectives. Contingency plans were formulated for IFR weather and for periods when particular Omega stations were off the air. A flight status table was prepared to provide comparison of the various objectives completed with those yet to be examined (Table 7).

The 19 flights were accomplished during the period from November 22, 1974, to March 9, 1975, with the majority of flights held during the latter half of January and middle of February. Four flights were conducted in the local Boston area for equipment operation verification and calibration. One flight was conducted during heavy rain with very poor S/N ratio for Station A. Five flights occurred entirely at night and two more before and after sunset. Table 8 shows a description of the NE corridor flights. Appendix B contains all of the flight data and their interpretation. Selected excerpts are included here for illustrations of specific points.

8.1 OMEGA SUITABILITY FOR COMMERCIAL VTOL OPERATIONS

Two important considerations in the application of Omega navigation systems to commercial VTOL operations are (1) signal availability down to very low altitudes and (2) accuracy. This section includes a brief discussion of each of these considerations.

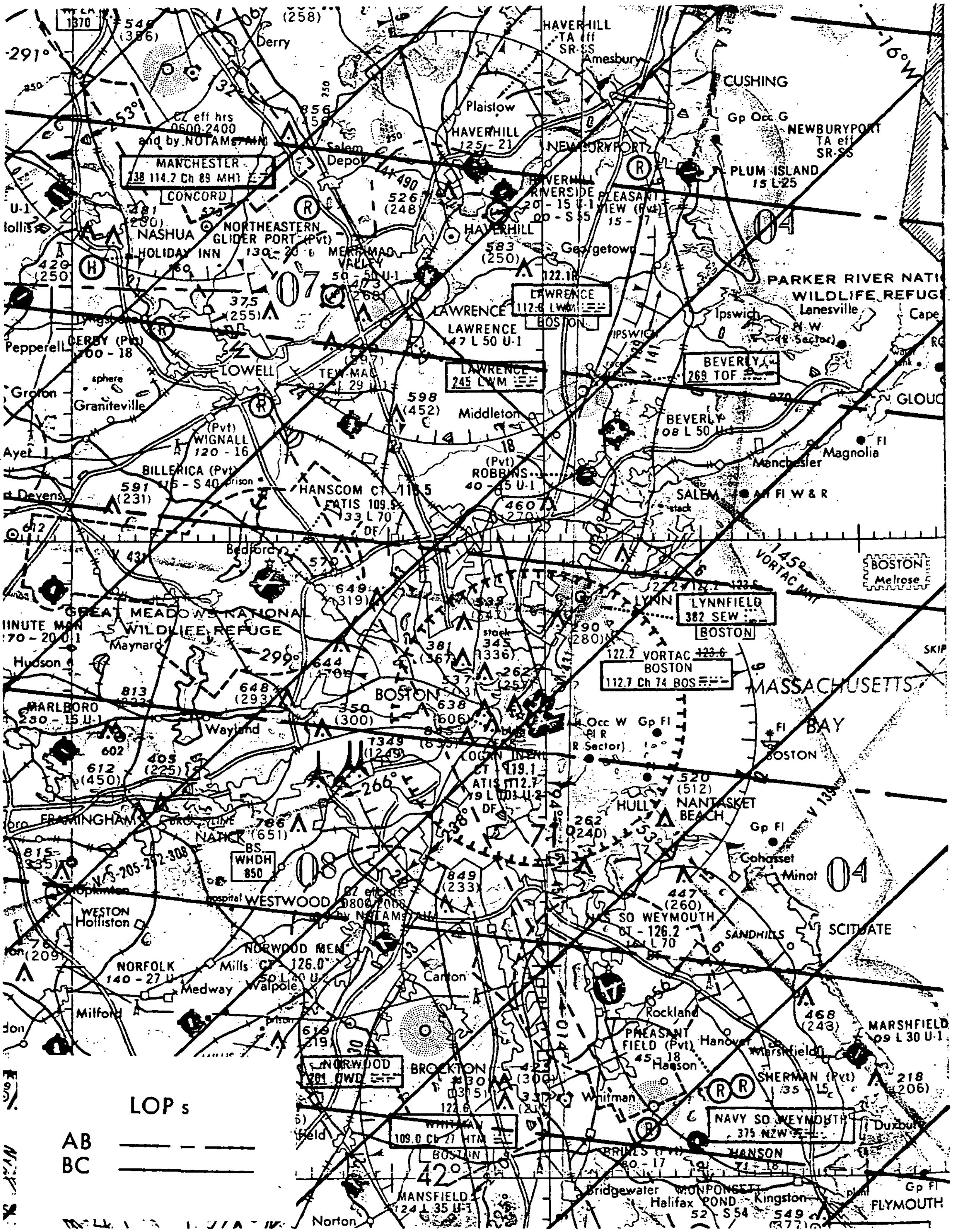


Figure 44. Omega LOPs Plotted on Aeronautical Chart.

Table 7. NE Corridor Flight Test Objectives.

Flight	Date	Flight Hours	Suitability	Altitude Effects	Terrain Effects	Maneuver Effects	Hours Data Recorded
	(1974)						
2-1	11/22	0.8		X		X	0
2-2	11/23	2.1	X	X	X		0
2-3	12/3	3.6	X		X		1.5
2-Z1-1	12/20	2.2	X		X		1.5
	(1975)						
2-Z1-2	1/24	2.0	X	X	X		1.6
2-4	1/27	0.9		X		X	1.0
2-5	1/30	1.7	X	X	X		1.0
2-6	1/31	1.6	X	X	X		1.5
2-7	2/7	1.9	X	X	X	X	*
2-8	2/10	2.3	X	X	X	X	1.0
2-9	2/10	1.7	X	X	X		*
2-10	2/14	3.7	X	X			3.0
2-11	2/17	3.5	X	X			3.4
2-12	2/19	3.5	X	X	X		3.4
2-13	2/22	3.1	X	X	X		3.0
2-21	2/27	1.3	X	X	X	X	1.0
2-31	3/5	0.7	X	X			0.5
2-41	3/9	3.2	X	X	X		3.2
2-44	3/9	3.5	X	X	X		3.1

* Recorded data was lost in software transfer.

Table 8: NE Corridor Omega Flights.

Flight Number	Flight Description
2-1	Local check flight (BED→ LWM→ BED)
2-2	Zulu ferry flight to FRG for mating CIU (BED→FRG)
2-3	CIU pickup and 4721L dropoff (FRG→ BED)
2-Z1-1	4721L pickup and Zulu 1 flight (FRG→ BED)
2-Z1-2	Omega pickup after repair (FRG→ BED)
2-4	Local airport night flight, LOP #2 sign chip bad
2-5	Drop off enroute to Princeton (BED→FRG)
2-6	Pickup on return from Princeton, direct flight (FRG→ BED)
2-7	Local noise sensitivity check (BED-TWR-FRM-GDM-HST-BED)
2-8	Zulu attempt to D.C., D lost enroute over statue (BED→FLU)
2-9	Return from Flushing using A, B, C (BDR→ BED)
2-10	Zulu to D.C. (North route; BED→ CLP)
2-11	IFR return from D.C. (DUL→ ARP→ LHV→ BED)
2-12	Zulu to D.C. with divert to SBY enroute to WAL (BED→ SBY)
2-13	Zulu return from WAL (SBY→ BED)
2-21	Night repeat of 0-2-7 to test system with chip exchange
2-31	Haverhill ferry flight
(2-32)	(Day-time ground test of CIU at BED)
2-41	Zulu 1, South divert to SBY via Airports
2-44	Airports to Zulu 1, at high altitude (5500' and 7500'; SBY→ BED)

8.1.1 SIGNAL AVAILABILITY

With the broad coverage of Omega, navigation signals should be available at least at all altitudes providing terrain clearance. Local interference, however, may reduce signal reliability.

As discussed in Section 2, Omega signals were available with no shadowing of stations due to terrain effects. For VTOL operations this meant continuous signal availability at least while the aircraft was airborne. However, as observed on Flight 2-41 and others, signal availability was not as good on the ground as it was in the air. By comparison with the Madison VOR, as shown in Figure 45 (Reference 2), Omega signal availability should have been greater, with no radio horizon effects. Although this may be insignificant for enroute navigation, the greater signal availability of Omega would be advantageous for low-altitude maneuvering for approaches to sites where VOR coverage is masked.

Local interference effects may adversely affect Omega accuracy, however. Any strong source of interference could possibly result in a local decrease in S/N ratios, with corresponding difficulties in maintaining phase lock. Although several occurrences of local interference were suspected, none could be verified by the S/N ratio plots. Sufficient experience was not obtained in this low-cost program to confirm or deny local interference effects which may, in fact, be manifestations of the current experimental status of the Omega system.

8.1.2 OBSERVED ACCURACY

The observed accuracy of the Omega system for the NE Corridor and Wallops area flights was quite satisfactory for enroute RNAV and most likely satisfactory for terminal operations. Approach capability was not investigated in the flight program.

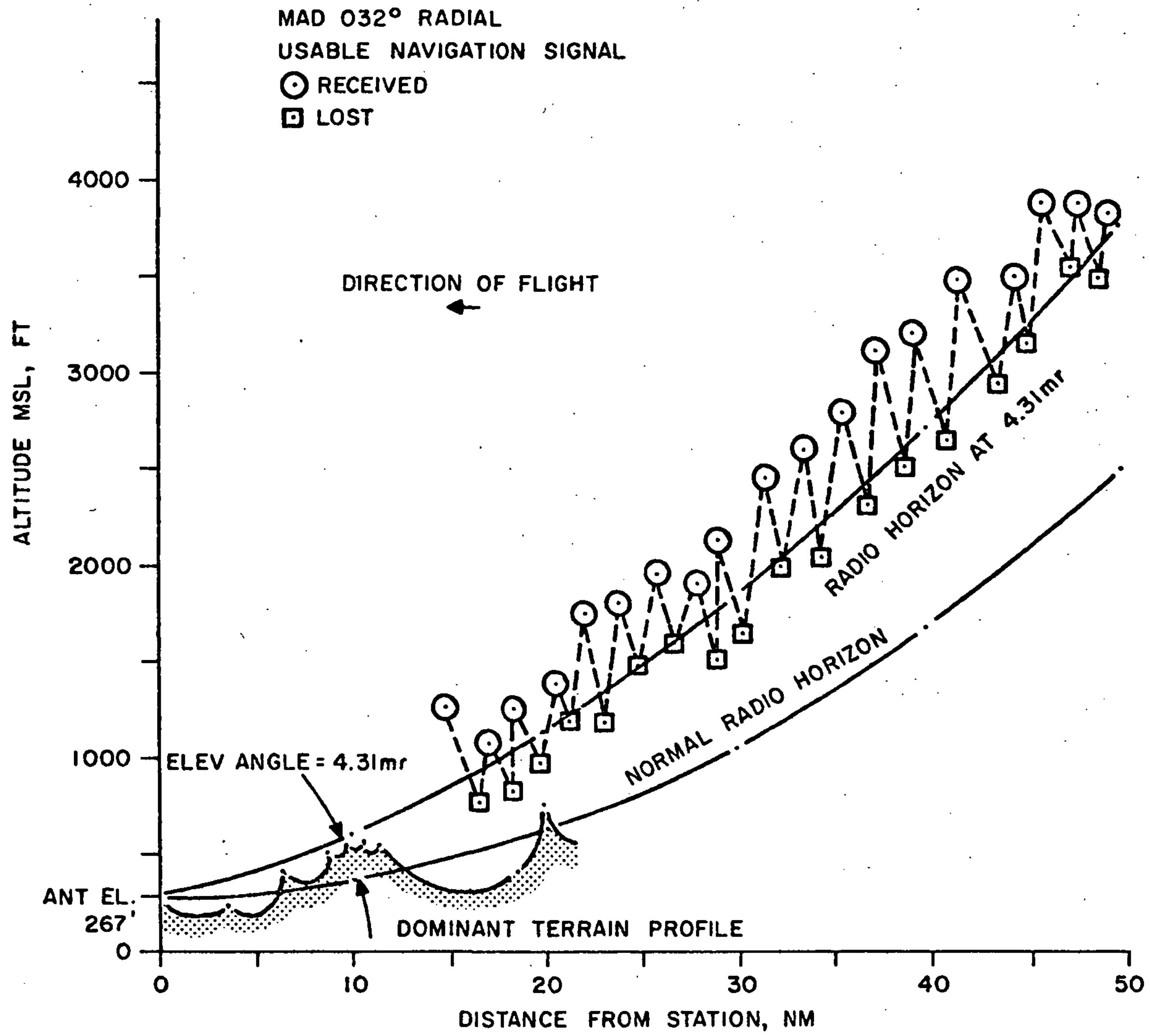


Figure 45. Sample VORTAC Coverage, Madison VOR (Reference 2).

All but two errors observed in the Omega system readouts were less than two miles, and most errors were less than one mile. This does not, of course, consider circumstances in which equipment failures were detected. Overall Omega accuracy, however, could be a strong function of receiver design and local interference.

As observed in Section 7, the plots of raw Omega data position estimates were exceedingly noisy. Filtering, by the pilot or by the receiver, was required for navigation. Greater accuracy, i.e., less susceptibility to short-term noise, could be expected from filters with time constants on the order of two minutes. The lack of such a filter, however, would necessitate incorporation of air data to provide lead for a usable display.

To compare Omega accuracies achieved in this program and Omega accuracies which would ultimately be available, three noise sources peculiar to the receiver used in this program are discussed. These noise sources are lack of filtering, reset random bias, and coarseness of waypoint selection.

As mentioned above, data filtering is important for Omega navigation. The particular receiver used in these flight tests had no filtering except the RF filtering in the front end of the receiver and the filtering provided by the phase lock loops. This lack of filtering meant that any bias introduced when the lane accumulators were reset remained in the system until the lane accumulators were again reset, yielding data with a constant random bias. Lastly, on the receiver used, waypoints could only be inserted with a resolution of a tenth of a lane. Thus, the results achieved in this flight test can be considered a worst case for commercial VTOL Omega receivers.

Reference 2 gives results for VOR/DME-based RNAV observed accuracy for flights along the same proposed low-altitude VTOL routes flown in this Omega program. That study concluded that a path width for VTOL airways of $\pm$ 2 miles, with a 1 mile secondary area on each side, would be sufficient. This structure is shown in Figure 46. A comparison of flight test statistics from the Omega data was made with the VOR/DME statistics. This is shown in Table 9 where the VOR/DME statistics are given in range and bearing error and the Omega statistics are in radial position error. Based on this comparison, it appears that Omega is not accurate enough to meet these requirements for airway dimensions, but Omega does have a strong potential to augment the VHF/UHF navigation systems by virtue of its excellent coverage. This is its greatest appeal for general aviation use.

Table 9. Comparison of VOR/DME and Omega Waypoint Position Errors.

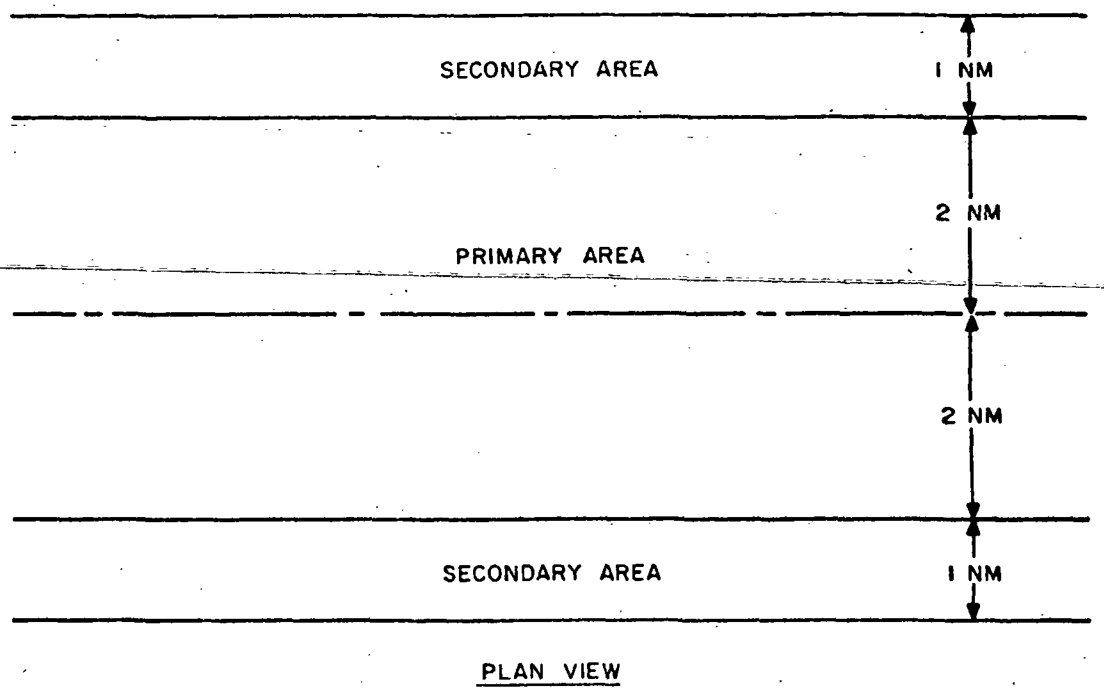
	VOR/DME		Omega
	Bearing (deg)	Range (nm)	Radial (nm)
Mean	0.1	-0.1	.74
Standard Diviation	2.7	0.7	.77

8.1.3 REQUIRED PILOT TECHNIQUE

For commercial VTOL operations, sophisticated filtering techniques using Omega and air data, and possibly low-cost inertial system data can be presumed. At this level of sophistication, no special piloting techniques would be required.

8.2 ALTITUDE EFFECTS

On Northeast corridor flights, S/N variations with altitude, S/N variations at takeoff, and ease of needle following at various altitudes were investigated. The



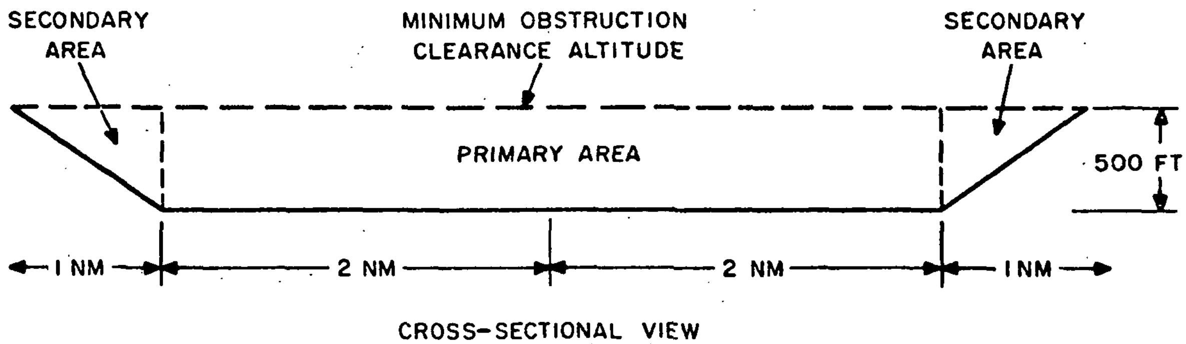


Figure 46. Proposed Helicopter Airway (Reference 2).

majority of these flights were flown at a nominal 2000 ft MSL. As Table 10 shows, however, these flights ranged from 500 ft MSL to 7500 ft MSL, getting to within 200 ft of the surface in some areas in order to detect S/N variations with altitude. Similar to the Wallops altitude effects described in Section 7.1, altitude effects appeared to be limited to locally generated noise (e.g., the ITT low-frequency communication transmitter in Commack, N. Y., on Long Island). Changes in station signal strength at takeoff were first noted during the early Zulu route tests. The ease of following the CDI was directly correlated with Station A S/N ratio, but uncorrelated with altitude.

Table 10. NE Corridor Flight Altitudes.

Flight	Altitude
2-1	3000' MSL
2-2	2000' then under NY TCA at 1100' and 500'
2-3	2000' MSL
2-Z1-1	2000' MSL
2-Z1-2	3500' MSL
2-4	3000' AGL
2-5	2500' MSL
2-6	5500' MSL
2-7	2000' AGL with 200' portion over powerline
2-8	2000' MSL then 1100' through NY TCA
2-9	3000' MSL
2-10	2000' except 1100' through TCA
2-11	7000' (IFR)
2-12	2000' except 1100' through TCA
2-13	2000' except 500' through TCA
2-21	2000' AGL
2-31	1500' MSL
2-41	2000' MSL except 500' through TCA
2-44	5500' MSL except 7500' over TCA

8.2.1 S/N ON TAKEOFF - GROUND VERSUS AIRBORNE EFFECTS

As discussed in Section 7.1.2, the takeoff phenomenon is an improvement in S/N ratio at takeoff when the aircraft climbs above the masking effect of the trees and local terrain. This phenomenon was first noted on Flight 2-2 even before the CIU was available for data recording. It can best be seen in the recorded data on the Station A S/N ratio plot for Flight 2-Z1-1 (see Figure 47). The opposite effect during landing can be seen for Station B in the S/N plot for Flight 2-44 (Figure 48). Flight 2-12 (Figure 49) illustrates the much larger effect of the radios being turned off at 1218 EST. A comparison of observations made with the Omega receiver in the test aircraft and at a ground test site indicates that the receiver was less affected by small disturbances in phase at the ground site, but more affected by the drifting of 60 Hz powerline noise. Additionally, weak signal-to-noise due to PCA's appeared more deleterious to the ground site reception.

8.2.2 PILOT TRACKING

As detailed in Section 7.6.4, three problems occurred affecting the CDI presentation: irregular jumps of about one mile due to lack of Station A received phase stability; drift due to weak Station A S/N ratio; and lane jumps due either to interference or weak S/N ratios on stations other than A. The first two of these effects were not altitude dependent, while interference due to local anomalies decrease with altitude. When strong S/N ratios were being received, the pilot was required to make only small heading corrections to maintain a centered CDI, but poor S/N ratios often resulted in noisy CDI presentations. Under these circumstances the preferred flying method was to maintain a constant heading with long-term CDI changes corrected and short-term variations ignored. This filtering increased pilot workload over those levels required during quiet periods.

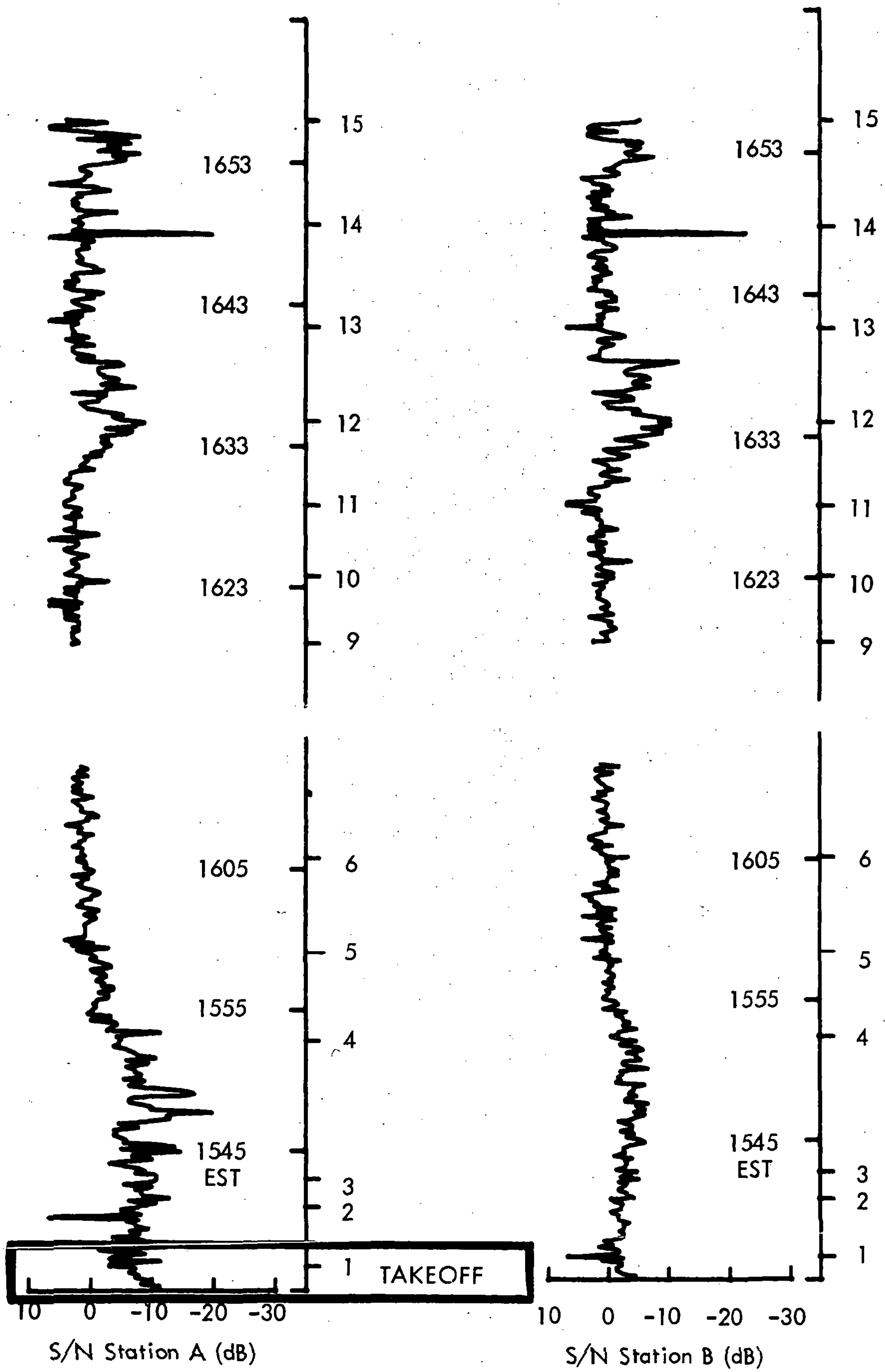


Figure 47. Flight 2-Z1-1, S/N Station A and B;
FRG-BED, 12/20/74, 5500', 1530-1700 EST, 2030-2200 GMT.

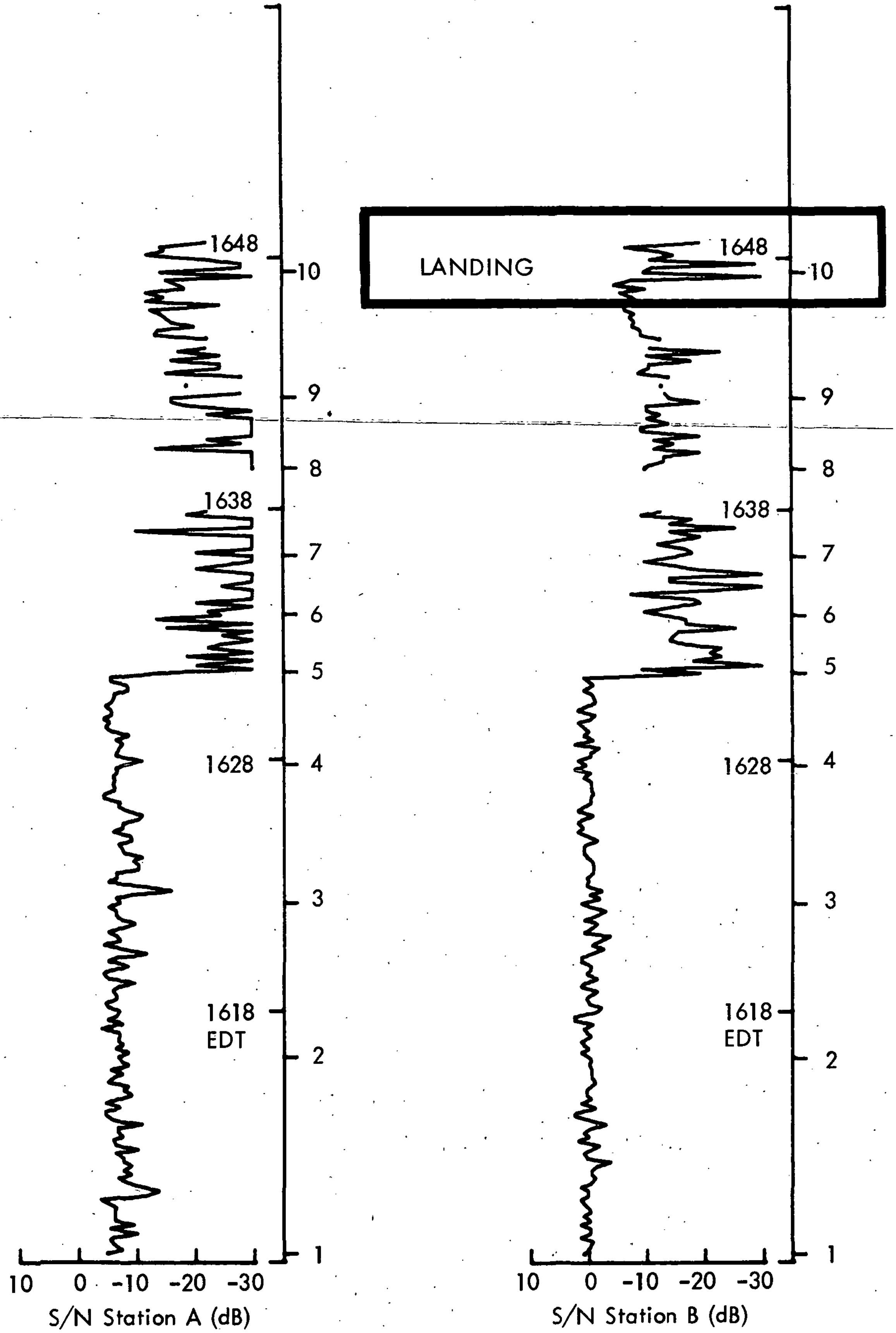


Figure 48. Flight 2-44 (Third 41 Min), S/N Station A and B; SBY-BED (Z1), 3/9/75, 5500' (Over TCA), 1330-1646 EDT, 1730-2046 GMT.

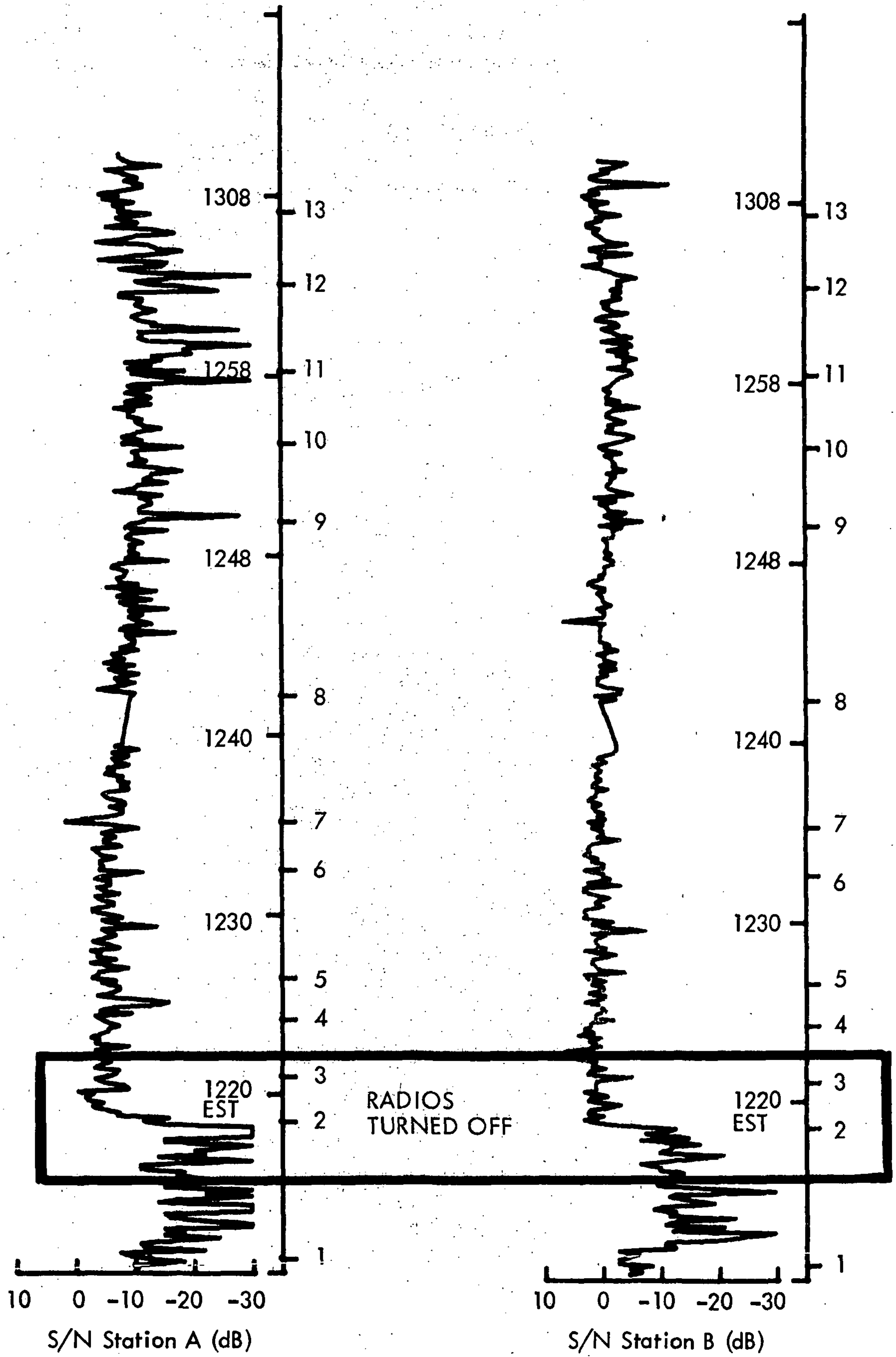


Figure 49. Flight 2-12 (First 61 Min), S/N Station A and B; BED-SBY (Z2, ZS) 2/19/75, 2000', 1210-1530 EST, 1710-2030 GMT.

8.3 TERRAIN EFFECTS

Flights over urban areas, bodies of water, mountains and forests were made to see whether varied terrain affected Omega performance and whether such effects were altitude variant.

8.3.1 CITIES

It was anticipated that flying over cities would adversely affect S/N ratios and, in general, degrade the navigation performance due to local interference from many sources. In the actual tests, however, no degradation was encountered with the exception of low-altitude flying along the Hudson River under the New York TCA. The masking effect of buildings at the same or higher altitudes than the aircraft caused an increase in weak signal lights and a decrease in S/N ratio, as shown in Figures 50, 51, and 52. Additional expected urban noise sources were television transmitting towers and power lines which proved to have no observable effect.

Another interesting effect was observed over central Connecticut. From Eastford to Middleton along the selected Z-routes a region of lowered S/N ratios was observed on all flights. This region, shown in Figure 53, along with a typical S/N decline had a well-defined northern boundary, but the southern boundary was less well-defined and subject to variations from flight to flight. Although this is not a large city area, it is thickly settled with some concentrated industrial centers and at least one large university.

Consequently, it is assumed that there are sources of near field interference as discussed in Section 7.6.2. This phenomenon should be verified and studied further.

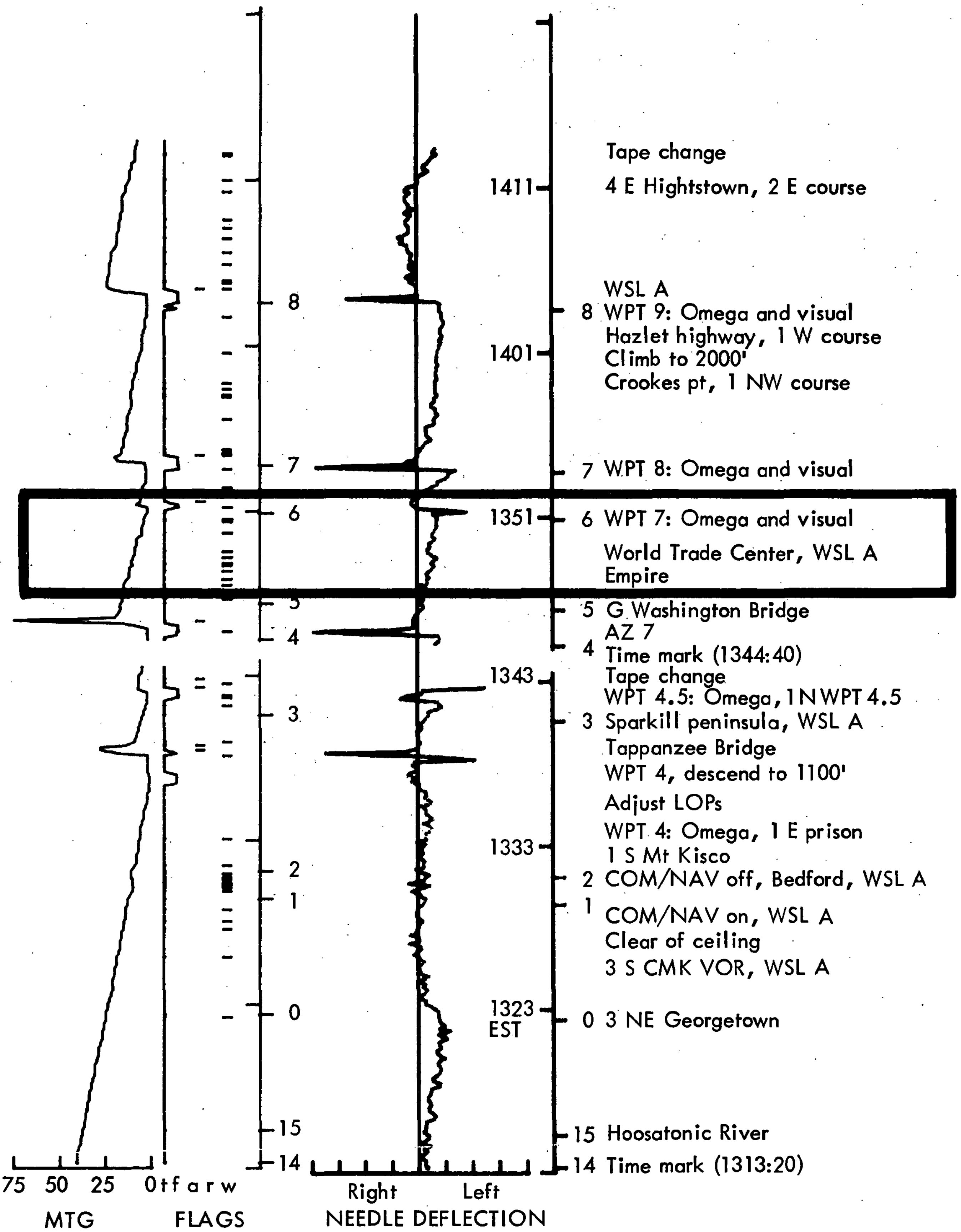


Figure 50. Flight 2-12 (Second 60 Min), Miles to Go and Needle Deflection; BED-SBY (Z2, ZS) 2/19/75, 2000', 1210-1530 EST, 1710-2030 GMT.

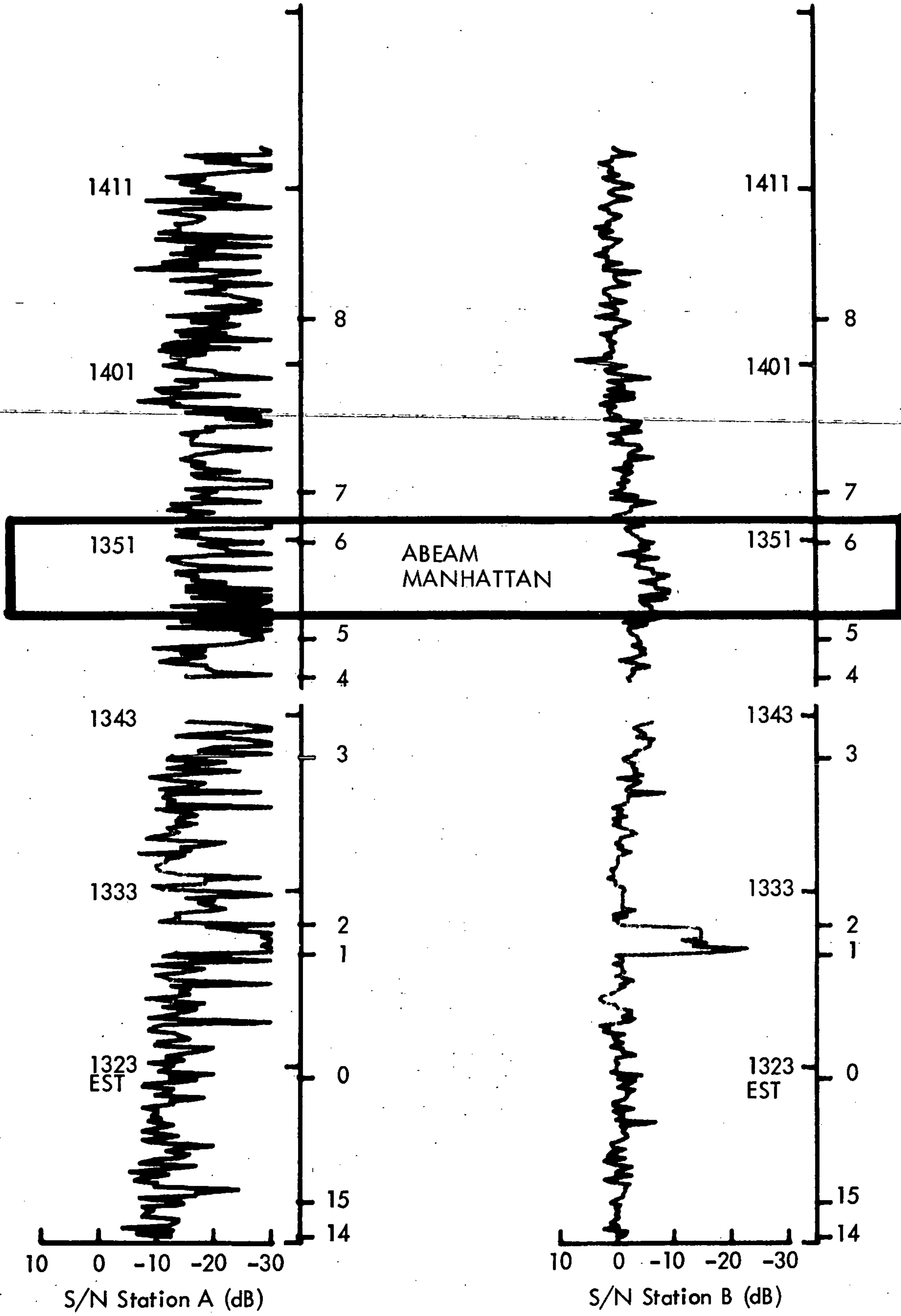


Figure 51. Flight 2-12 (Second 60 Min), S/N Station A and B; BED-SBY (Z2, ZS) 2/19/75, 2000', 1210-1530 EST, 1710-2030 GMT.

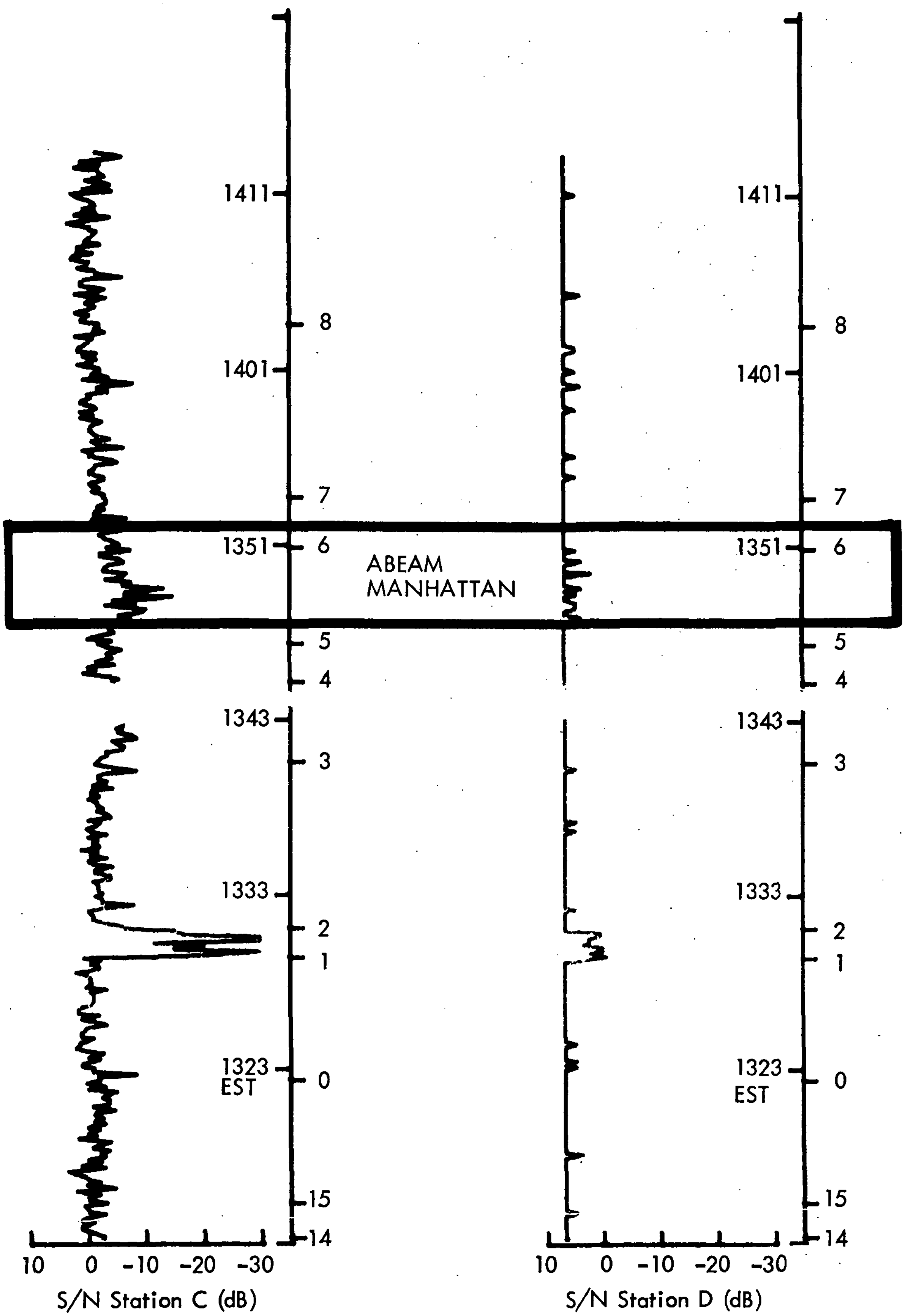


Figure 52. Flight 2-12 (Second 60 Min), S/N Station C and D;
BED-SBY (Z2, ZS) 2/19/75, 2000', 1210-1530 EST, 1710-2030 GMT.

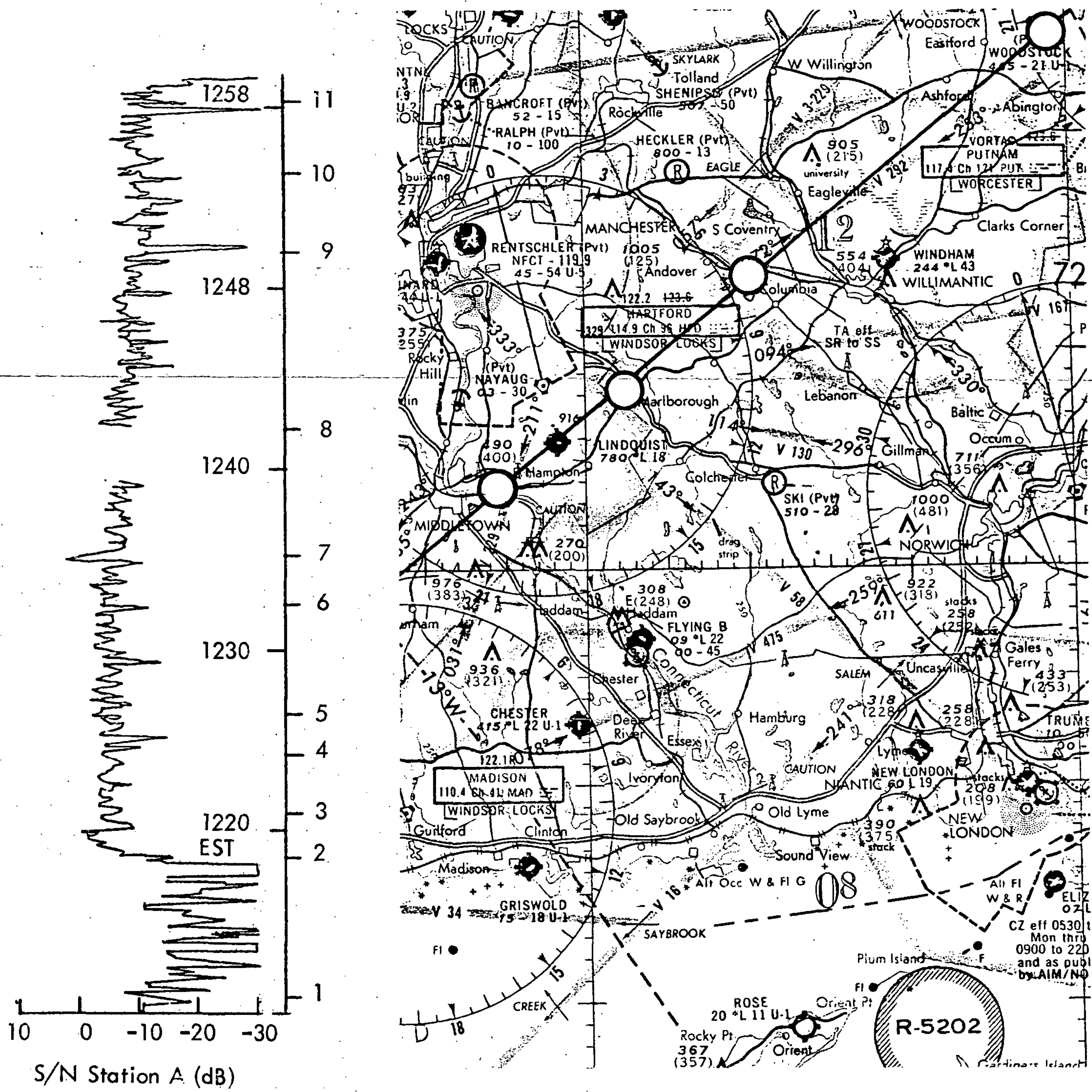


Figure 53. Central Connecticut S/N Degradation (Flight 2-12).

8.3.2 WATER

There were no noted irregularities or changes in S/N ratio during flights over water except for some coastline effects along the Connecticut coast of Long Island Sound. Other bodies of water overflown during this set of flights included the Atlantic Ocean at the Main and Massachusetts coasts and the New York Lower Bay between New Jersey and Long Island.

8.3.3 EFFECTS

Three flights in the Northeast Corridor were flown in the vicinity of mountainous areas. Flights 2-7 and 2-21 were flown at low altitude around Mt. Wachusett, which rises abruptly to an elevation of about 2000 ft MSL from the prevailing terrain elevation of 1000 ft. Flight 2-11 was flown at 7000 ft over mountainous terrain rising to 2300 ft MSL during a flight from Dulles airport to Bedford via the Lake Henry VOR. This route was flown in IFR conditions including moderate to heavy rain, with extremely low Station A S/N ratio resulting in loss of phase lock. There were no observable terrain effects during any of these flights.

8.3.4 FORESTS

Approximately one fifth of the Northeast Corridor flying was over unpopulated forest areas. There were no observable changes in navigation ability of the receiver attributable to forest areas.

8.4 MANEUVER EFFECTS

Flights 2-7 and 2-21 were specifically designed to determine what effect various maneuvers would have on Omega receiver performance. A series of stalls, spirals, steep and medium banked turns, and slow speed descents were accomplished at various altitudes, with no apparent effect on Omega presentation or S/N ratios.

SECTION 9

CONCLUSIONS

A 60-hour flight test program collecting data on the OMEGA navigation system was conducted. This data has been plotted and documented in detail in this report. Conclusions relating to Omega signal and phase characteristics as well as the accuracy and suitability of Omega navigation for city-center to city-center VTOL operations are contained in the following subsections, but additional analysis would be productive. Such analysis would be facilitated by the large volume of data and the extensive documentation.

9.1 OMEGA SIGNAL AND PHASE CHARACTERISTICS

The signal-to-noise ratio of each station was plotted as a function of time. Station D (North Dakota) consistently had the strongest signal-to-noise ratio, and Station A (Norway) consistently had the weakest signal-to-noise ratio of those stations on the air. The typical consequence of a weak signal-to-noise ratio was a lane jump in the coordinate associated with the weak signal. This typically caused the indicated position to jump by about 8 miles. A weak signal light normally preceded the lane jump, but weak signal lights on Station A were more common than not. Lane jumps due to low signal-to-noise ratio from Station A were the primary cause of poor Omega navigation reliability in this test program.

Factors which affected the signal-to-noise ratios most appreciably were associated with the aircraft installation of the navigation set. Proper grounding of the antenna was found to be critical. Furthermore, throughout the program there was a 20 dB increase in the signal-to-noise ratio whenever the VHF radios were turned off. This noise source was determined to be the inverters for the VHF radios. VHF transmissions always obliterated recording of the Omega data; however, this occurred because the audio recorder was sensitive to the high transmitted power level and demodulated the VHF carrier onto the recording.

There were two geographic areas where markedly reduced signal-to-noise ratios were recorded. One was in the NASA Wallops area and was thought to have been associated with the Wallops radar facilities. The second area was in Central Connecticut, but the reason was not precisely determined in the scope of this effort. In all flights the signal-to-noise ratio consistently improved after takeoff. Furthermore, test observations indicated no problems due to altitude variations, coastal overflight, precipitation, close proximity to power lines, in-flight maneuvers, or terrain features.

9.2 SUITABILITY AND ACCURACY FOR VTOL OPERATIONS

Coverage by Omega signals is quite good, which makes the system especially attractive for low altitude VTOL and remote area applications. Tall buildings in city center areas can reduce signal-to-noise ratios somewhat by shadowing; however, this does not prevent navigation.

Workload associated with Omega navigation is a problem, particularly in terminal areas. Waypoint definition and selection are complicated. The fact that hyperbolic coordinates are not orthogonal is a continual source of potential confusion to pilots. The conversion process between the latitude/longitude system and Omega LOPs is also a potential source for error. Consequently, Omega input should be in terms of latitude and longitude, and it is very desirable to have the capability for stored way-points as inertial navigation experience has shown. The alternative is to have pre-calculated waypoint LOPs, but this drastically reduces the flexibility of the system. It is desirable for course information to be relative to North, but all these features necessitate an additional computation capability in the Omega equipment. Also, the pilot has to compare the Omega course needle indications against his compass heading, and this is taxing when low signal-to-noise ratios cause needle fluctuations. Without filtering, the ten-second Omega update rate is just too slow to preclude mental averaging of needle displacement and compass heading. Lastly, there is no crosscheck available to verify proper waypoint insertion, such as the identification feature provides for a VOR pilot. In fact, the Omega system does not have a crosscheck to verify that it is working properly. At present the major check is the weak signal light which, unfortunately, is illuminated for Station A much of the time.

The main problem with using Omega for navigation at the present time is reliability. Omega cannot be used in the Northeast Corridor without both Norway and Trinidad, primarily because of the station geometry. Hawaii can be interchanged with North Dakota, but both together give little additional information, because their extended baseline passes through the Northeast. Norway is marginal at the present transmitted power which leads to lane jumps and loss of reliability.

The overall absolute accuracy observed was on the order of one nautical mile. The equipment used for all the tests measured position relative to the Omega coordinates established during the initial alignment. The error sources for this configuration consist of:

1. The random error associated with the Omega phase measurement made during each ten second signal format. This error has been found to be normally distributed with zero mean and a standard deviation of 0.4 lanes. The error is uncorrelated with adjacent ten second phase measurements. This is a significant observation for the design of flight filters of Omega measurements.

2. The error at initial alignment is a random sample from the error distribution described in #1. After alignment, this error becomes a bias error on all further phase measurements. The error is peculiar to systems which navigate with phase change from initial alignment instead of absolute phase measurement.

3. The change in skywave correction after initial alignment is an error when not accounted for by the Omega navigator. The data shown in this report has the skywave correction entered naturally through the initial alignment. The skywave correction is not changed with time until subsequent alignments. Consequently, the small change in skywave correction between alignments is a source of error in this configuration. Since the time is seldom more than a few hours, the error is normally small. The error is actually deterministic, being found by using standard skywave correction tables.

The distribution of the Omega position error is Gaussian with zero mean in each coordinate. The combined range error was found to satisfy a Weibull distribution with the parameter C equal to two. This is equivalent to a Raleigh distribution which would be the analytic result of normally distributed errors in each of two orthogonal coordinate directions.

REFERENCES

1. Hoffman, W. C., Hollister, W. M., and Howell, J. D.: Navigation and Guidance Requirements for Commercial VTOL Operations. NASA CR 132423, January 1974.

2. Pierce, J. A., Palmer, W., Watt, A. D., and Woodward, R. H.: Omega – A World Wide Navigational System (System Specifications and Implementation). Pickard and Burns Publication No. 886B, 2nd Edition, Waltham, Mass., N66-31152, May 1966.

3. Walcott, H. R.: Omega Plus Differential Omega. ICAO Bulletin, August 1974, pp. 22-25.

4. Anon.: Omega Mark III Navigation System Description and Operation Manual. Dynell Electronics Corporation, Melville, New York, 1974.