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FLIGHT TEST AND EVALUATION OF OMEGA NAVIGATION FOR GENERAL AVIATION

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ABSTRACT

A seventy hour flight test program was accomplished to determine the suitability and accuracy of a low cost Omega navigation receiver in a general aviation aircraft. An analysis was made of signal availability in two widely separated geographic areas. Comparison was made of the results of these flights with previous work focused on VOR/DME. Conclusions are drawn from the test experience that indicate developmental system improvement is necessary before a competent fail safe or fail soft area navigation system is offered to general aviation.

Thesis Supervisor: Walter M. Hollister
Title: Associate Professor

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GLOSSARY

a	Autozero flag
A	Station A (Norway)
A/D	Analog to digital
adj	Adjust
AGL	Above ground level
Altrn	Alternate
Apr	Approach
apt	Airport
AZ	Autozero
B	Station B (trinidad)
BED	Bedford, Massachusetts
C	Station C (Hawaii)
CDI	Course deviation indicator
CG	Coast Guard
Chinctge	Chincoteague
CIU	Custom interface unit
CMK	Carmel VOR
CN	Course number
COL	Colts Neck VOR
const	Constant
Crdkvl	Craddackville
CYN	Coyle VOR
D	Station D (North Dakota)
D/A	Digital to analog
dB	Decibel
EDT	Eastern daylight time
EST	Eastern standard time
F	Fahrenheit
FSK	Frequency shift keying
ft	Feet

Grnbk	Greenbackville
H	Station H (Japan)
hdg	Heading
hwy	Highway
IAD	Dulles Airport, Washington, D. C.
IFR	Instrument flight rules
ILS	Instrument landing system
int	Intersection
Is	Island
kts	Knots
LHY	Lake Henry VOR
LOP	Line of position
LRP	Lancaster VOR
lt	Left
L-W	Land-to-water flight path coverage
MM	Middle marker
mod	Moderate
MPH	Miles per hour
MSL	Mean sea level
MTG	Miles to go
NAFEC	National Aeronautical Flight Experimental Center
NDB	Nondirectional radio beacon
NEC	Northeast Corridor
N, E, S, W	North, east, south, and west and any logical combination thereof
NY	New York City
OAT	Outside air temperature
OM	Outer marker
ORF	Norfolk, Virginia
plt	Plant
PWL	Pawling VOR
r	Reset switch flag
R	Radial

RCVR	Receiver
REF	Reference light
RNAV	Area navigation
rny	Runway
RNZ	Barnes VOR
rr	Railroad
rt	Right
R/T	Radio transmission
Rte	Route
SBY	Salisbury
SENS	Receiver signal sensitivity control
S/N	Signal to noise ratio
subt	Subtract
SWL	Snow Hill VOR
TAS	True air speed
TCA	Terminal control area
tf	To/from indicator flag
T/O	Take off
twr	Tower
V39	Victor airway 39
V93	Victor airway 93
VFR	Visual flight rules
VOR	Very high frequency omnidirectional radio range
VTOL	Vertical take off and landing
w	Weak signal light flag
WAL	Wallops
WE1000	Wallops radar zero refernce, 1000 ft from west end of runway 10-28
W-L	Water-to-land flight path coverage
W-L-W	Water-to-land-to-water flight path
Wpt	Waypoint
Wsl	Weak signal light

Z1	Bedford to New York Zulu route
Z2	New York to Bedford Zulu route
ZS	Washington, D. C. to New York Zulu route
ZW	New York to Washington, D. C. Zulu route

Section 1

INTRODUCTION

As the airspace becomes increasingly more congested in the next few decades, Omega navigation will provide a low cost means for general aviation to upgrade to area navigation capability. In this analysis and evaluation, a commercially built low cost receiver was flight tested and compared with VORTAC results. Various observations, conclusions, and recommendations were then made upon the Omega system and low cost general aviation receiver use.

General aviation, as a portion of United States civil aviation, accounts for 98% of the civil aircraft fleet. Some 95% of civil pilots are general aviation airmen, and 96% of the airports are used primarily by general aviation. In addition, general aviation accounts for 37% of intercity air passengers, and virtually 100% of local passengers, (for a total of 90 million annual passengers), industrial aid flying, agricultural and forestry flying. It contributes to the economy through export sales of $150 million and domestic sales of $1.5 billion annually (Reference: Flight Transportation Laboratory Report R73-5A).

The importance of general aviation has been demonstrated. As the air traffic environment becomes more heavily populated, the importance of the development of low cost area navigation becomes critical for general aviation. Area navigation allows much more freedom in routing than the airway beacon system since it allows direct and offset course routing. There is a strong potential for Omega navigation to provide low cost area navigation for general aviation. Omega can enhance the VOR system by providing navigation coverage capability (since Omega is not light of sight limited) to areas where it is not cost effective to install VOR transmitters such as mountainous regions, remote inland areas and offshore fishing or drilling sites.

The implementation of any new navigation system requires real world tests during a complete range of environmental conditions. This thesis has made that evaluation and found the candidate Omega RNAV potential to be real but with certain practical problems which can be solved with continued development.

Section 2

TEST OBJECTIVES AND SCOPE

The objectives of this test program were to determine the suitability of low cost Omega for General Aviation use through analysis and evaluation of flight tests designed to cover a broad spectrum of possible navigation effects and differing flight environments. The scope of these effects investigated during both VFR and IFR conditions included: noise and interference measurements at various altitudes; use of various station pair combinations and flights parallel to LOPs; detection of phase shifts due to diurnal ionospheric height variations, local coastline, terrain, maneuvers or local noise sources; and evaluation of ground versus airborne performance.

2.1 MIT/ASI Joint Test Effort

The MIT Flight Transportation Laboratory and Aerospace Systems, Inc. (ASI) have completed a flight evaluation of a low cost Omega navigation receiver in a General Aviation aircraft. The results of the program provide both qualitative and quantitative data on the Omega Navigation System under actual operating conditions (Ref. 1). These data directly support current NASA/FAA research programs.

The joint flight evaluation program consisted of two major parts corresponding to the ultimate application of the information obtained in each of two geographic areas. The Wallops flight program obtained 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. The Northeast Corridor flight program examined Omega operational suitability and performance on the VTOL RNAV routes developed by ASI (Ref. 2) for city-center to city-center VTOL commercial operations in the Boston-New York-Washington corridor.

2.2 Flight Test Locations and Environments

All the flight tests were conducted in three general areas: the Wallops area and Northeast Corridor as mentioned above in the joint MIT/ASI test program, and also in the local Boston and northern New England areas. The flight environment included: day, night and transition period operation; VFR and IFR operation; clear air, hazy, rain and snow shower operation; and with and without VHF radios in use.

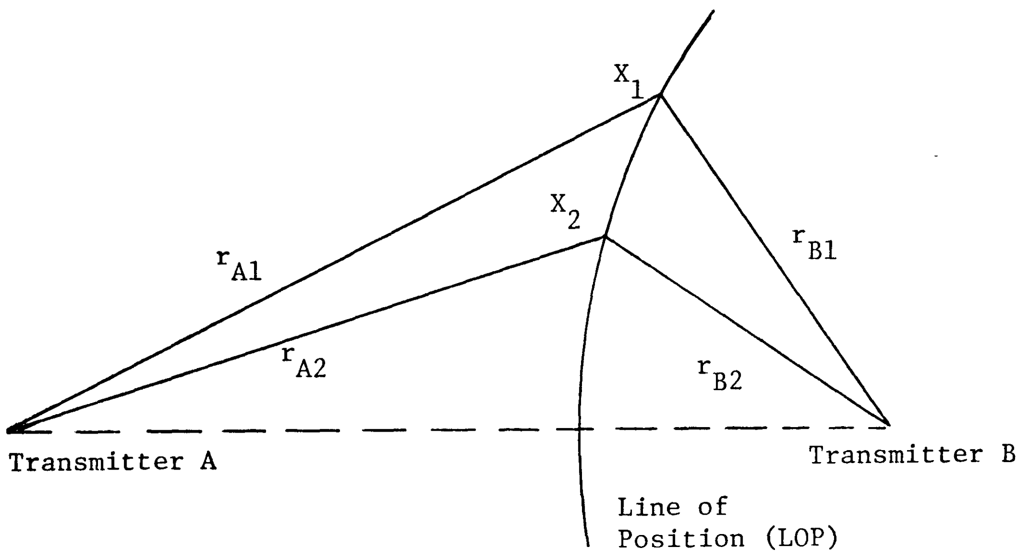
Section 3

OMEGA NAVIGATION SYSTEM

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

3.1 Principles of Hyperbolic Navigation

Hyperbolic navigation is a radio navigation technique used by the Omega, Loran, and Decca navigation system. It is based on a distance difference measurement whereby the navigation receiver determines one or more lines of position along which the receiver is assumed to be located (Ref. 3). The intersection of two such lines of position is then the location of the receiver. The term "hyperbolic" refers to the locus of possible receiver locations having a constant distance difference between two transmitter sites. In Figure 3-1, from any point X, on the line of position, the difference between the distances to transmitter A and to transmitter B is constant.



$$r_{A2} - r_{B2} = r_{A1} - r_{B1} = \text{Constant}$$

Figure 3-1 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 sets of hyperbolae or Lines of Position (LOPs) are required as shown in Figure 3-2. Figure 3-3 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 intersecting hyperbolae are at angles of less than 50° (Ref. 4). Such a condition drastically reduces the precision of position measurement.

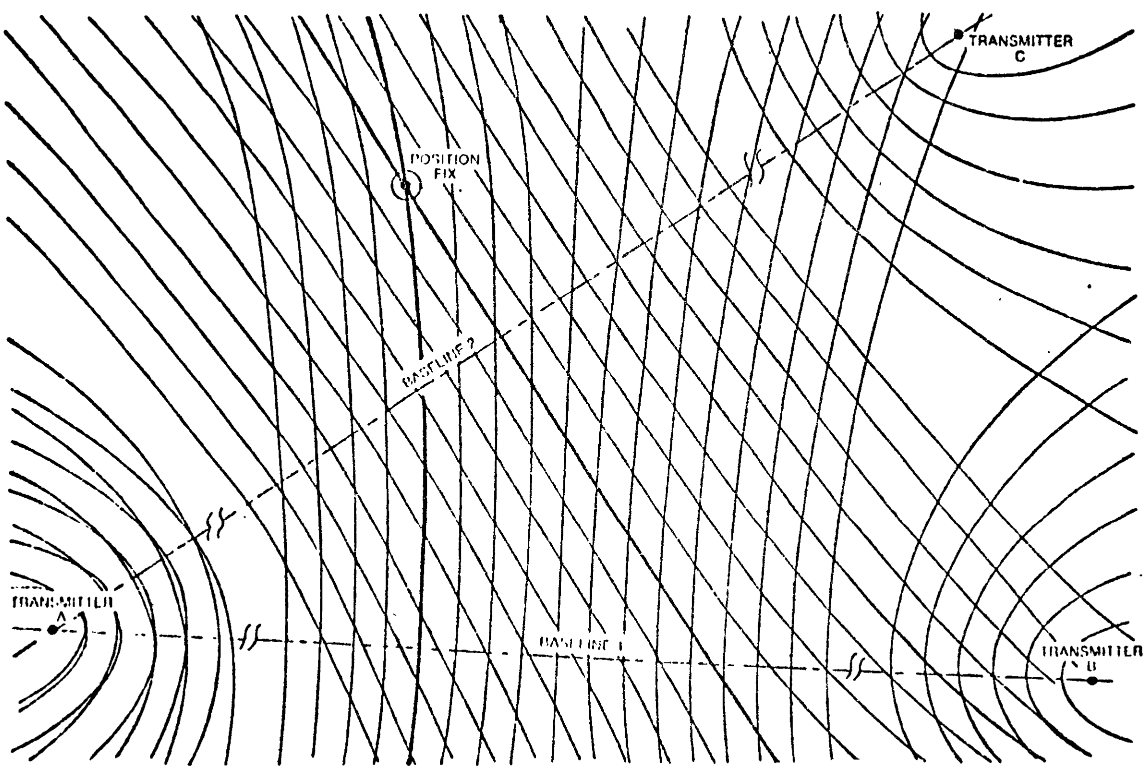


Figure 3-2 Three Omega Transmissions are Needed to Determine a Position Fix

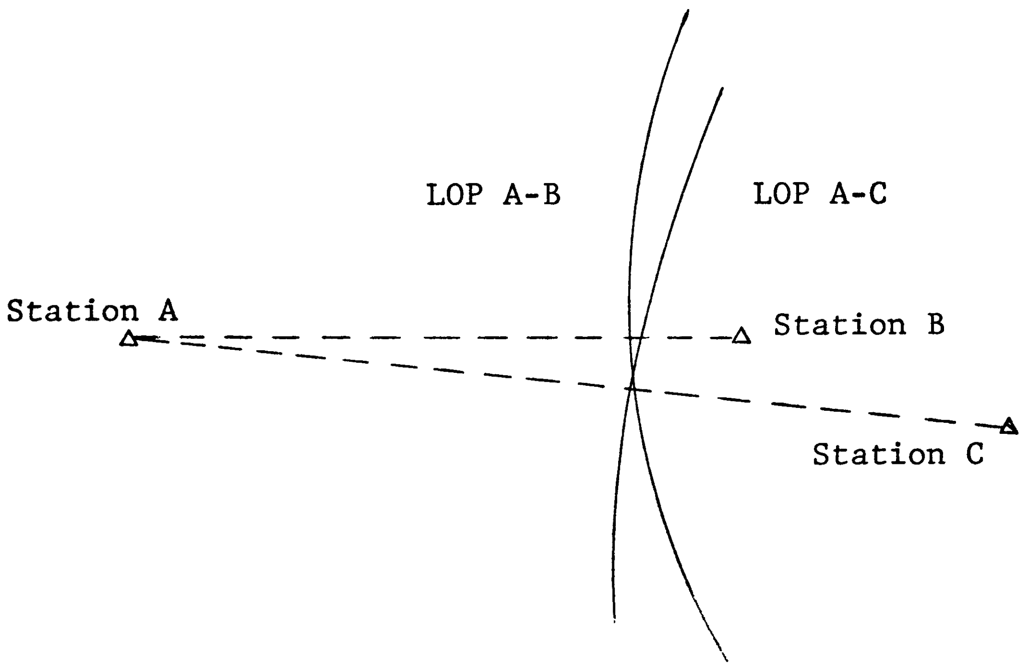


Figure 3-3 Example of Poor LOP Geometry for Position Fix

3.2 International 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 difference lines of position (LOPs). Accuracies of one to two miles are achievable, but with position ambiguities occurring in multiples of lane width. However, these ambiguities are largely resolved by the use of multiple frequency receivers.

Eight stations are planned, each with 10 kw power. These stations, listed in Figure 3-4, transmit on frequencies of 10.2, 11.33, 13.6 kHz and a unique communication frequency alternately. The transmitted signals are sinusoidal with tight phase tolerances maintained by quadruple cesium standards. The only modulation is the cycling of the transmitter between frequencies. The signals travel in the waveguide formed by the earth's surface and the ionosphere, with attendant waveguide phenomena as illustrated by Figure 3-5. As the height of the ionosphere varies diurnally, the speed of propagation varies, and so does the phase of the signal at the receiver as in Figure 3-6. 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 seven hundred miles of the transmitter (Refs. 5 and 6).

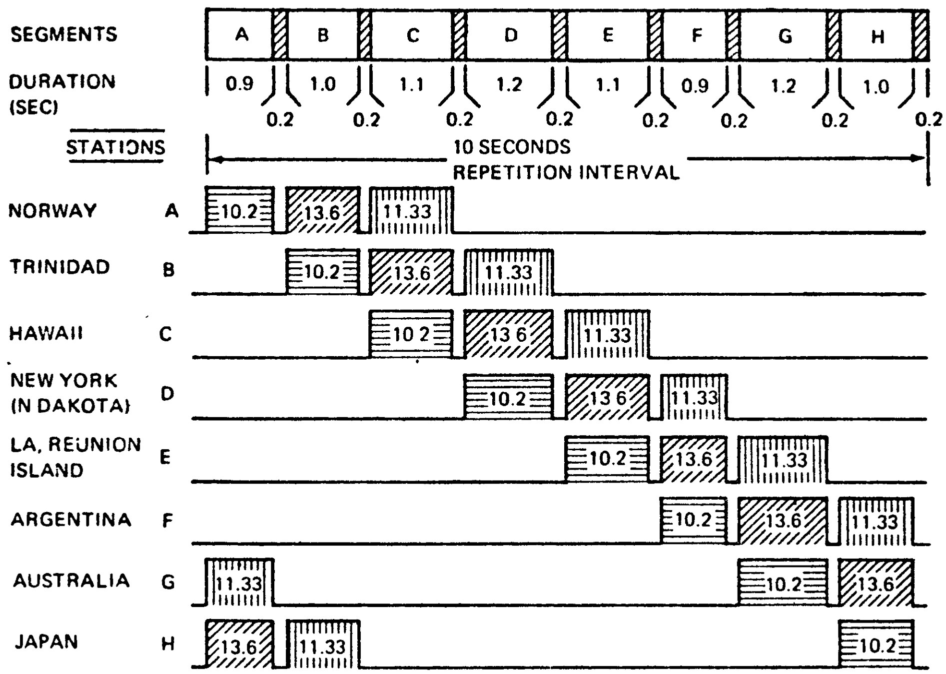


Figure 3-4 Omega Transmission Format

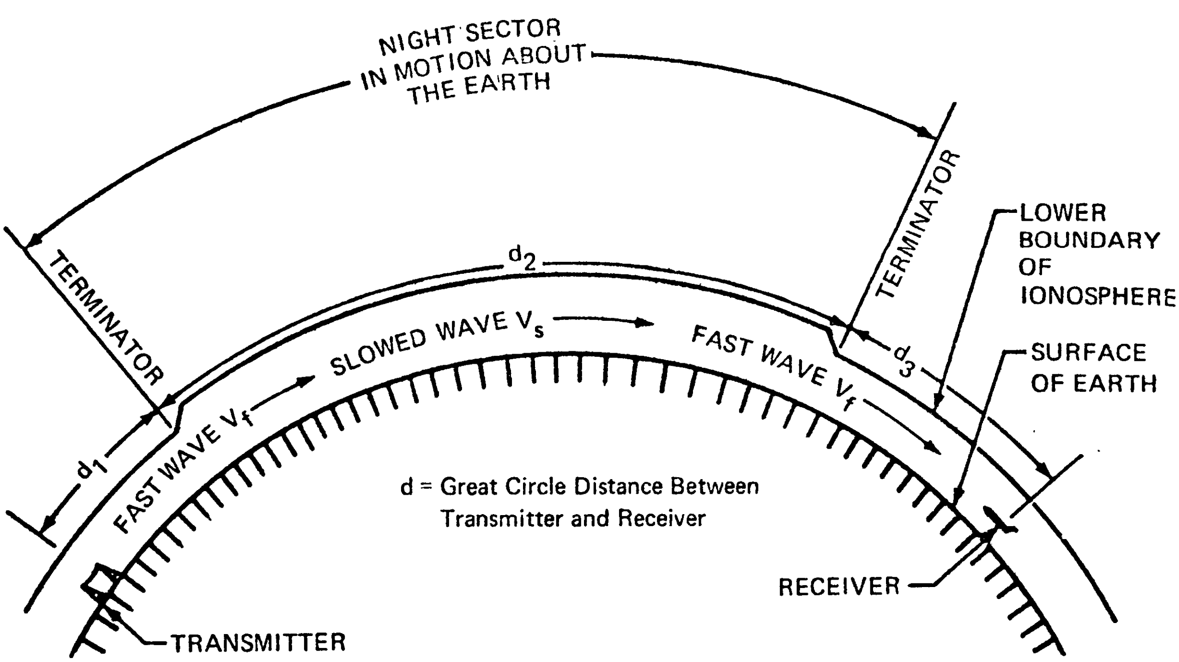


Figure 3-5 Earth-Ionosphere Waveguide

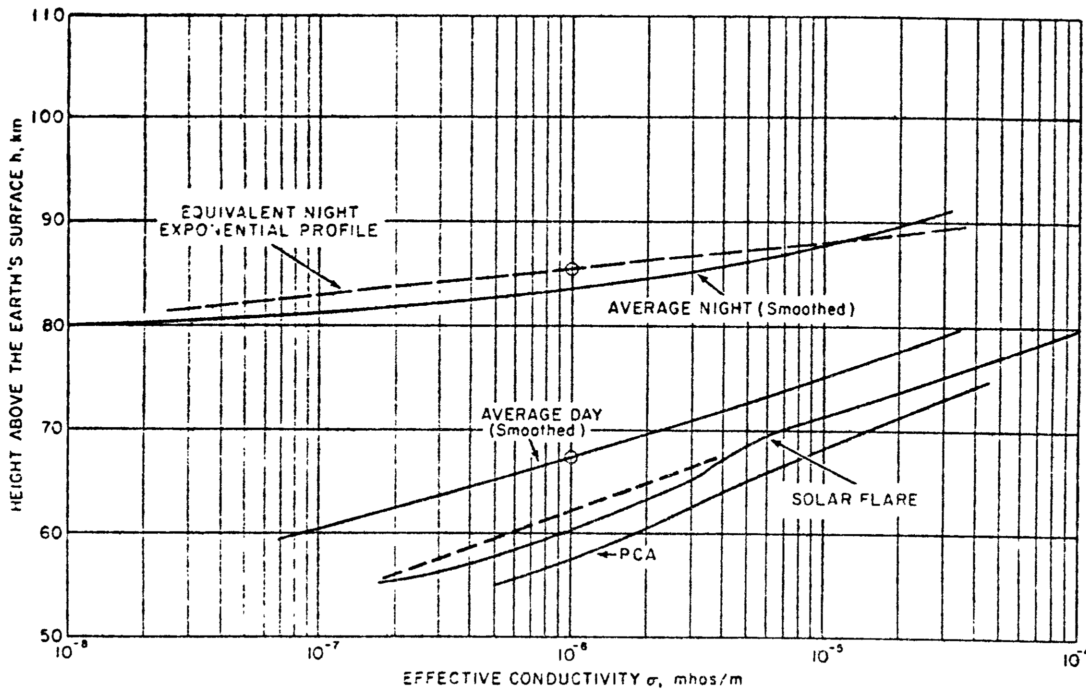


Figure 3-6 Effective Ionospheric Conductivity Profiles

Distances are derived from differential phase measurements, which have an ambiguity of one cycle. Thus, when obtaining a position fix, the position estimate will be accurate to one or two miles but with an ambiguity of some multiple of eight miles. That is, the receiver cannot absolutely specify position over a distance greater than eight 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 frequencies 10.2 and 11.33 kHz observe ambiguities spaced approximately 72 miles apart. This is accomplished by comparing 10.2 kHz with 11.33 kHz zero phase crossings, i.e., every nine 10.2 kHz lanes or ten 11.33 kHz lanes, the zero crossings will coincide, as shown in Figure 3-7.

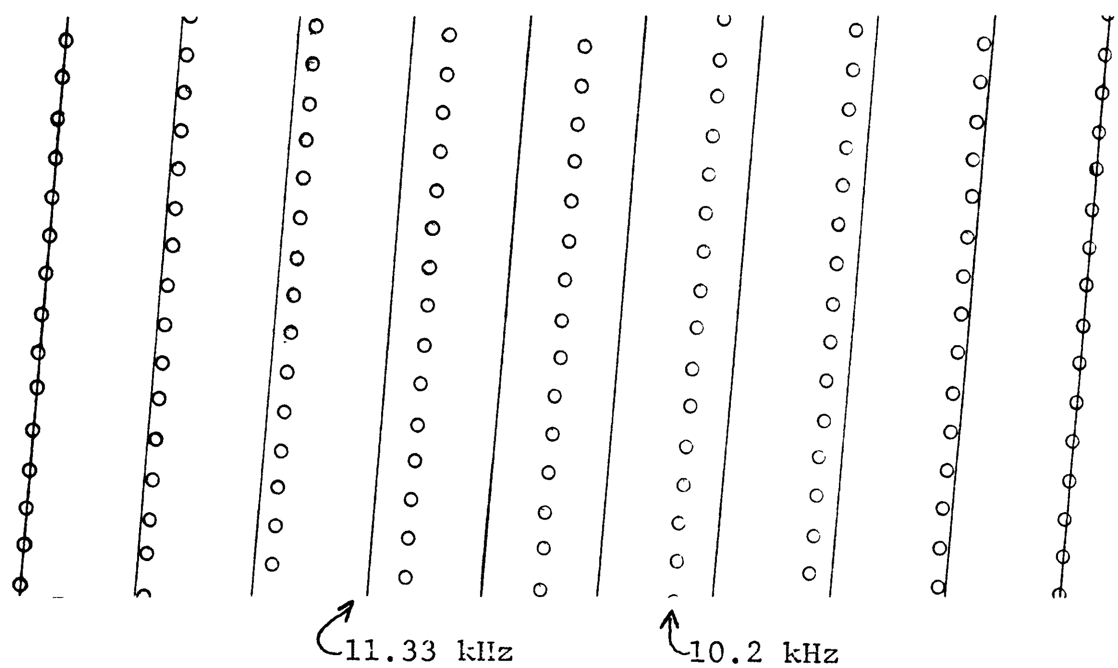


Figure 3-7 Ambiguity Resolution to 72 nm by Use of 10.2 kHz and 11.33 kHz Lanes

3.3 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 economic, 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 a standard for Omega evaluation. VOR signals provide bearing from the station sometimes augmented by Distance Measuring Equipment (DME) to supply sufficient information to drive an RNAV computer. The accuracy of VOR and DME is roughly 3° and .1 mile, respectively. However, the VOR/DME system is strictly line of sight, which limits its low altitude coverage area as seen in Figure 3-8 (Ref. 2). 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 the nature of the signals. Furthermore, Omega requires only eight stations for worldwide coverage, versus more than 600 operating VOR stations in the United

States alone which provide only partial coverage.

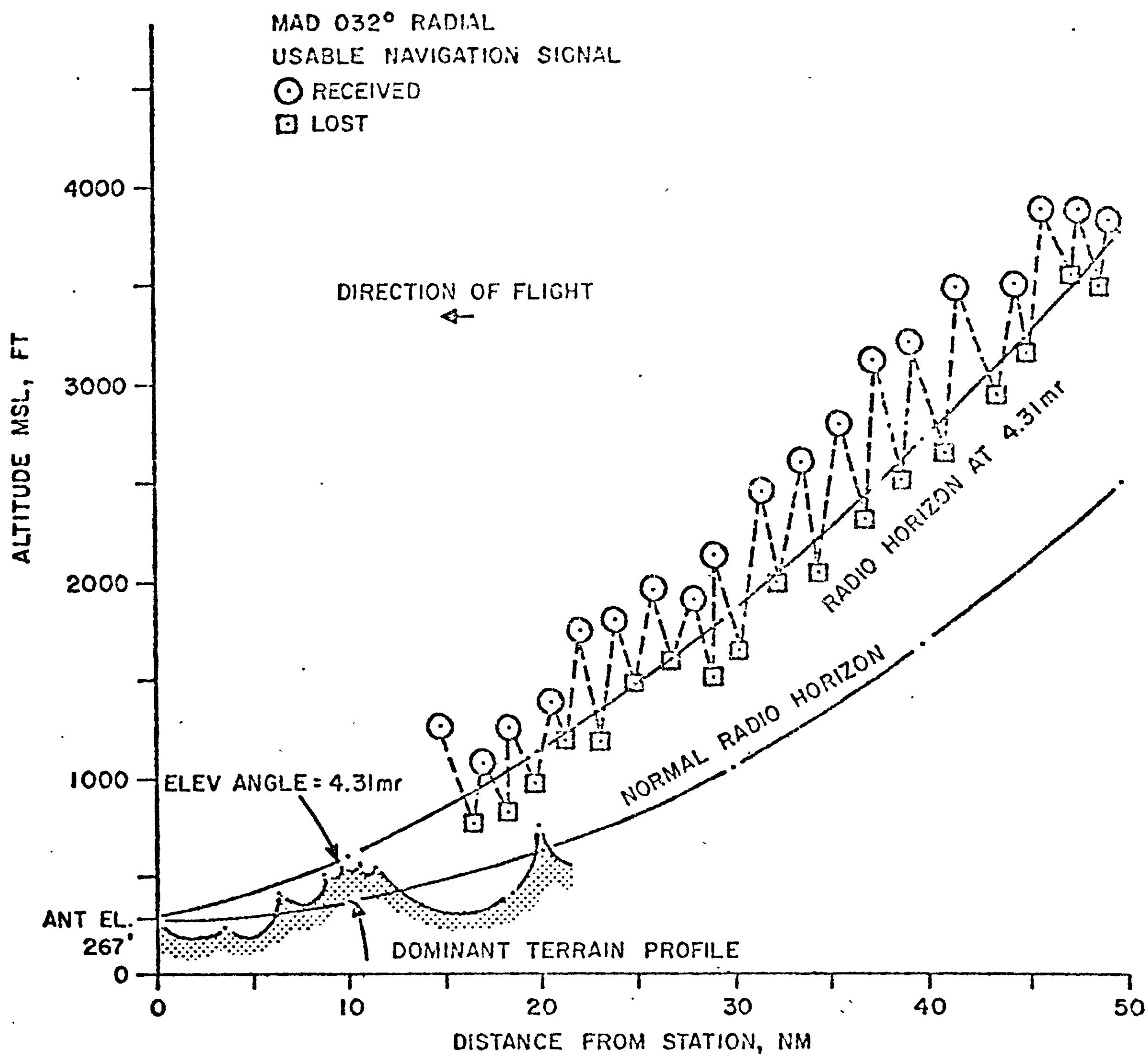


Figure 3-8 Sample VORTAC Coverage, Madison VOR

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), processors utilizing air data (rate aiding), sophisticated filtering techniques, and improved antennae (H field crossed loop instead of E field wire or rod) (Refs. 7 and 8). In addition to improving accuracy via differential Omega, micro Omega and alpha Omega which broadcast localized correction information to the receiver, there are also composite and difference frequency Omega which use the different frequencies from the transmitter to cancel out any phase anomalies which may occur along the propagation path (Refs. 9 and 10).

Other advantages of the Omega system include its simple signal format, relatively simple handling of the signal permitting a usable CDI display and thus its potential for low cost airborne equipment. Due to the ranges from which transmitters are received and the nearly linear nature of the LOPs, the CDI has a constant deviation sensitivity regardless of range to the user's origin or destination (Ref. 11).

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 operation (non precision approaches and enroute navigation). Omega is also susceptible to atmospheric and locally-generated noise. Moreover, at the present time, station reliability is not sufficient for aviation use, although it is expected to improve steadily.

Diurnal propagation effects cause apparent shifts in the reference grid. Noise effects can become critical in heavy precipitation. A standard for resolution of lane ambiguity must be determined. Precipitation static and high frequency break through are problems common to the use of E-field wire antennas (Ref. 12).

A definite user warning system is needed to indicate periods of Polar Cap Absorption (PCA), Sudden Ionospheric Disturbance (SID), and station outage (Ref. 11). PCAs are caused by solar proton showers usually only in the higher lattitudes (55° to 90°). They are predictable a short time in advance but the severity and length of activity are not. SIDs, sometimes called sudden phase anomalies (SPA), are caused by x-ray bursts (from solar flares) bombarding the ionosphere on the sunlit hemisphere. During both PCAs and SIDs the received phase delay is decreased changing the calculated position by up to 4 nm and at the same time signal strength is enhanced (Ref. 13). An interim plan is given in Appendix C for the temporary information system while an international standard is being chosen.

3.4 Future of Omega System and Uses

The future of the Omega Navigation System looks optimistic in the light of the above advantages and disadvantages. For every drawback there is at least one feasible proposed solution. Although Omega will not replace the VORTAC or Loran C systems, it will provide navigation capability where these other systems cannot; for example, over the North Atlantic and unpopulated regions where it isn't cost effective to deploy LF or VHF systems. It was recently concluded that Omega has a definite role in the fourth generation ATC system (Refs. 5, 14) by providing general aviation and other low altitude airspace users with a continuous inexpensive RNAV capability. Other uses for which Omega has been studied other than marine and submarine (for which it was originally designed) include: global rescue network (GRAN), windfinding using balloon radio sondes, positioning systems for mass transit (OPLE), guidance navigation for mini RPVs, as well as a variety of uses in hybrid form (Refs. 5, 8 and 15).

Section 4

GENERAL AVIATION NAVIGATION REQUIREMENTS

The term general aviation is an umbrella phrase which usually includes all aviation which is not military or airline, and this can be anything from a Piper Cub to a Gulfstream business jet or from a traffic helicopter to an agricultural spray plane.

Reference 16 indicates that in spite of a recent slowdown in general aviation itinerant operations, the number of general aviation IFR aircraft handled has continued to increase, and they are forecast to grow substantially throughout the next ten years. There has been an ever-increasing acceptance as well as requirement for general aviation pilots to file IFR flight plans and use the FAA en route traffic control system. More pilots are becoming IFR qualified and more aircraft are being equipped with the necessary navigation and communication gear. The industry anticipates these trends will continue and by fiscal year 1983 the volume of general aviation IFR aircraft handled is expected to reach 20.7 million. This if over five and a half times the present volume.

4.1 Variety of Types and Requirements of General Aviation Aircraft

General aviation avionics navigation equipment requirements vary from nil to the latest in automated RNAV capability. General aviation is by far the greatest user of domestic airspace. Statistics show that 98 percent of registered aircraft come under this category and they conduct more than 80 percent of all domestic United States flights (Ref. 17). General aviation aircraft, not including business aircraft, are almost exclusively piston powered light planes, slow moving with severe payload and performance limitations (usually below 10,000 ft and slower than 250 kts). Weight, the cost of equipment and ease of operation are all important.

The navigation environment falls into two distinct areas, terminal and enroute. The terminal area acts as the collecting hub for all the different types of aircraft which greatly increases the risk of midair collisions. The enroute portion is where RNAV has its greatest impact in increasing user freedom, safety and economy by allowing direct routing (rather than via beacons) and offset paths parallel to congested airways. The ideal requirements for general aviation are:

a. World-wide coverage

b. Unsaturable service

c. Accuracy sufficient to satisfy the horizontal separation minima suitable for smoothly joining the landing guidance system to be used for airfield approach

d. All altitude service unaffected by terrain

e. Nonsusceptibility to propagation anomalies

f. Unambiguous position fixes

g. Redundant position fix data available

h. Economical to all user categories

It is not likely that any one aid will meet all specified requirements, but with suitable airborne elements combined with the external navigation service in a complementary manner, a complete navigation "system" will achieve most if not all the requirements (Ref. 5).

It must be emphasized that the overwhelming system requirement is low cost. It was pointed out early in its development that Omega had the potential of being very low cost (Ref. 18), and more recent estimates of receiver processor costs are very encouraging (Ref. 19) for unit prices around $1000. The current prototypes cost about $4000 for simple Omega receivers and from $25,000 to $40,000 for "automatic" receivers with lattitude and longitude read-out and built in skywave corrections. There is also a good probability of the appearance of low cost automatic receivers derived from the current Air Force low cost competition (Refs. 20 and 21). Relatively good accuracy (.2 - 2.0 nm) also may soon be available at low cost through composite Omega application (Ref. 22).

4.2 Comparison of VOR, Loran, and Omega

There are four basic types of position-fixing methods used by ground-based radio systems. These are intersecting lines of position determined by distance/bearing (rho-theta), bearing/bearing (theta-theta), distance/distance (rho-rho) and hyperbolic line of position measurements.

All four of the techniques are used in modern radio aids, but their performance characteristics differ considerably. The four important types of errors are propagation, geometry, instrument, and dynamic. The propagation errors, are strongly dependent on operating frequency. Ground waves are primarily used at low frequencies and long ranges, because they tend to follow the earth's curvature. These waves are, however, susceptible to significant propagation anomalies because of changes in surface conductivity and dielectric constant, as well as diurnal ionospheric effects. The line-of-sight waves are used in the VHF, UHF, and microwave regions and primarily for short-range use. In the lower of the bands, site errors due to reflections are a serious problem (Ref. 5).

The three primary performance parameters for comparison are accuracy, coverage, and signal availability. Of the candidate systems, Loran-C offers the highest performance with respect to accuracy. The signal coverage and availability of the VORTAC system are primarily affected by signal propagation characteristics. The line-of-sight limitations of the VHF/UHF signals of the VORTAC system can significantly decrease the signal availability in certain areas. The low frequency and very low frequency transmissions of Loran-C and Omega respectively are not limited by line-of-sight propagation; consequently, they can provide navigation signals over a wider area and serve more diverse customers than the VORTAC system. In a cost-effectiveness assessment covering twenty years, the operations and maintenance costs predominate over those of the initial facilities and equipment expenditures. The Omega system requires the smallest number of ground station facilities followed by Loran-C, Differential Omega, and the various configurations of the VORTAC system. The Differential Omega system requires the lowest expenditure for facilities and equipment and also for the operations and maintenance functions. Loran-C and the various configurations of the VORTAC system follow in their respective order. (Ref. 23).

In comparing user equipment, the Loran and Omega systems consist of an antenna, coupler, receiver-processor and indicator versus the VORTAC system of dual antennae, couplers, raw data displays, course line computer and RNAV display. The latter system quite obviously becomes more expensive for comparable enroute accuracy. In addition, pilot workload for Loran or Omega systems can be reduced by at least 50% over VORTAC systems by eliminating the continuous changing of VHF channels and three dimensional references associated with each VORTAC station. For single pilot operation, which is the case for the large majority of general aviation, this is of importance in alleviating fatigue and maintaining pilot awareness (Refs. 24 and 25).

4.3 Comparison of VLF and Omega

The International Omega System occupies the VLF spectrum between 10 kHz and 15 kHz, with synchronized pulsed continuous wave transmissions and communication. The U. S. Navy also operates an additional set of VLF transmitters around the earth for communication and time dissemination between 15 kHz and 25 kHz. The latter group are authorized to transmit at power levels up to 1,000 kw, and the received signal strength of the communications stations is between 25 μv and 10 mv varying with transmitter distances of 9,000 nm and 400 nm respectively. Omega power output, however, is authorized at only 10 kw and only North Dakota is currently near full power as shown in Table 4-1. The received signal strength of the Omega stations varies from 15 μv to 400 μv for transmitter distances of 3,000 nm and 1,200 nm respectively.

Because strong VLF signals are normally available, clear-cut signal drop-out criteria are easily established, with the result that high confidence can be placed in the correctness of an acquired signal and data smoothing is unnecessary. Because the communication signals are continuous wave there is a statistically higher probability of obtaining a correct fix once per lane than with the time sequenced Omega signals.

Station	Location	Frequency (kHz)		Radiated Power (kw) (Nominal)	Radiated Power (kw) (Authorized)
NAA	Cutler, Maine	17.80		890	1,000
NBA	Balboa, Panama Canal Zone	24.00		150	1,000
NLK	Jim Breek, Washington State	18.60		250	1,000
NPH	Hawaii	23.40		140 to 630	1,000
NWC	North West Cape, Australia	22.30		1,260	1,000
GBR	Rugby, Great Britain	16.00		250	300
NDT	Yosami, Japan	17.4		125	500
JXN	Nelgeland, Norway	16.4		150	350
HSS	Annapolis	21.4		500	1,000
NAU	Puerto Rico	28.5		50	100
ΩA	Norway	12.30		7	10
ΩB	Trinidad	12.00	10.2	2	10
ΩC	Hawaii	12.20	+ 11.33	5	10
ΩD	North Dakota	12.85	13.6	9 to 10	10
ΩH	Japan	13.10		5	10

Table 4-1 Omega and VLF Communication Stations Available for Navigation

Omega navigation, on the other hand, is still in its development stage and can be expected to improve in signal strength, coverage, and number of selectable stations. VLF and Omega are affected similarly by diurnal variations but only Omega has published skywave correction tables. Finally, Omega is a dedicated navigation system and planned station outages for maintenance are published in Notices to Mariners, whereas the Navy has not formulated any definite operating policy that guarantees continuous station operation (Ref. 26).

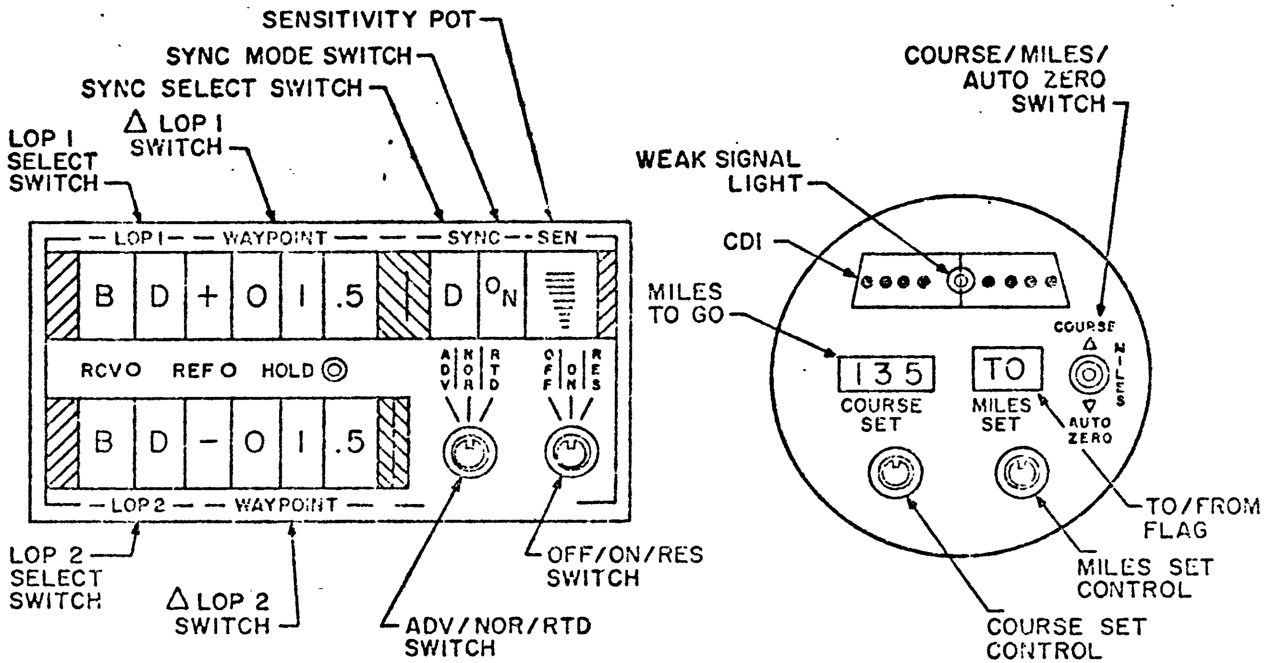
Section 5

FLIGHT EQUIPMENT AND FACILITIES

The equipment and facilities used to conduct the Flight Evaluation of Omega Navigation included a Mark III Omega Navigation System, a Mark III Custom Interface Unit (CIU) and data recorder, an external filter with course deviation indicator and strip chart recorder, a voice data recorder, and the Piper Cherokee 180 test aircraft equipped with a C-band transponder.

5.1 Omega Mark III Navigation System

The Omega avionics system used in the flight test program was the Omega Mark III Navigation System manufactured by the Dynell Electronics Corporation of Melville, New York. This avionics system described in Reference 27 transforms Omega phase data into crosstrack deviation and miles-to-go displays familiar to pilots. The system consists of the two units shown in Figure 5-1, plus an antenna coupler. 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 (CN) (a parameter describing



RECEIVER INDICATOR

Figure 5-1 Omega Mark III Navigation System Components flight course relative to the Omega LOPs. The peak power requirement is 1 amp at 12 V DC. An antenna coupler is provided so that the standard ADF sense antenna may be used simultaneously for Omega and ADF. A functional block diagram for the Mark III set (receiver and indicator) is shown in Figure 5-2. The basic system specifications are shown in Table 5-1.

The range of the navigator is in excess of 1,000 miles for a single flight leg, but is unlimited if multiple way-points are used. The basic system accuracy is independent of the length of flight except when flying during transition without skywave corrections. 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 essentially three separable and distinct subsystems. These include clock generation and synchronization, phase tracking, and processing to compute crosstrack errors and distance-to-go. These three subsystems

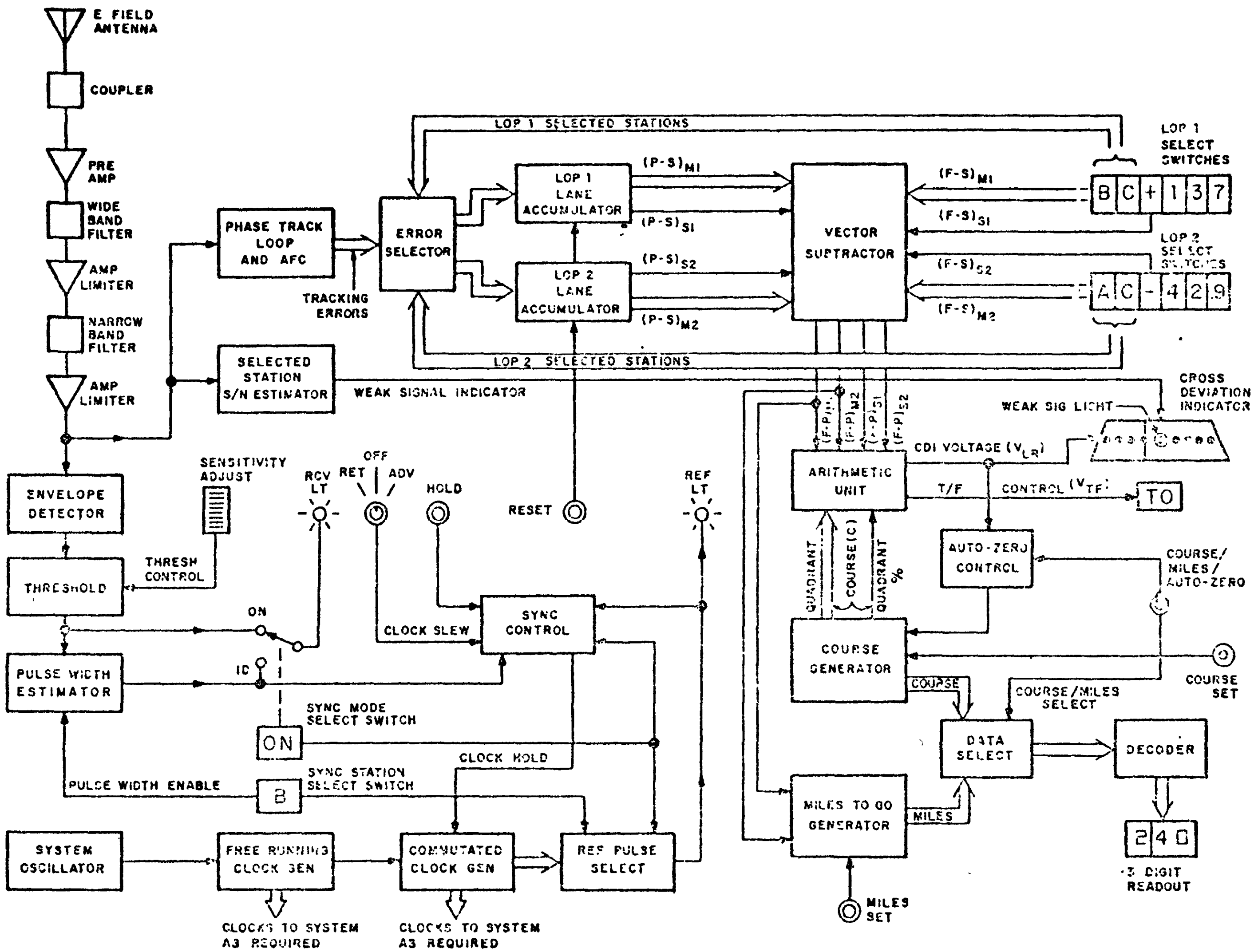


Figure 5-2 Omega Mark III Navigation System Functional Block Diagram

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°C to +60°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 ± 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 numbers predetermined

Table 5-1 Omega Mark III Navigation System Specifications

are briefly discussed below.

5.1.1 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 and the pulse width gate. 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 goes off and releasing it when the desired station has illuminated 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 for a selected station.

5.1.2 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.

5.1.3 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 track 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.

The Omega receiver was hard-mounted in the test aircraft to facilitate operation of the unit and to decrease the number of separate test items in the aircraft. It was fixed under the instrument panel on the right side of the aircraft, easily accessible to the co-pilot/Omega operator. The indicator was installed in a spare opening in the instrument panel among the flight instruments; directly in front of the pilot below the artificial horizon, between the turn coordinator and the lower VOR indicator.

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 necessary for good performance of the Omega receiver. Power for the Omega receiver was supplied by the aircraft 12 volt electrical system via the cigar lighter.

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 acquired from a computer program and entered using additional thumbwheels. The receiver was synchronized, the CDI (Course Deviation Indicator) zeroed, and the miles-to-go counter 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 indicating waypoint passage and a weak signal light which warned of excessively low signal-to-noise (S/N) ratios.

5.2 Custom Interface Unit (CIU) and Data Recorder

The 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 and post flight data processing equipment used in the flight program is shown in Figure 5-3. The CIU received power from the Omega receiver, and it supplied power to the data recorder.

The CIU is housed in an aluminum box approximately 3.25" x 14" x 10". On the front of the box are switches for power on/off, circuit enable/disable, and operator discrete code select. In addition, there are three fuses on the front panel to ensure the necessary isolation in the event of power surge. On the back panel are two input plugs, wired in parallel, and four BNC plugs: to tape recorder, from tape recorder, 6 vDC power output, and teletype output. Internally, the circuitry consists 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:

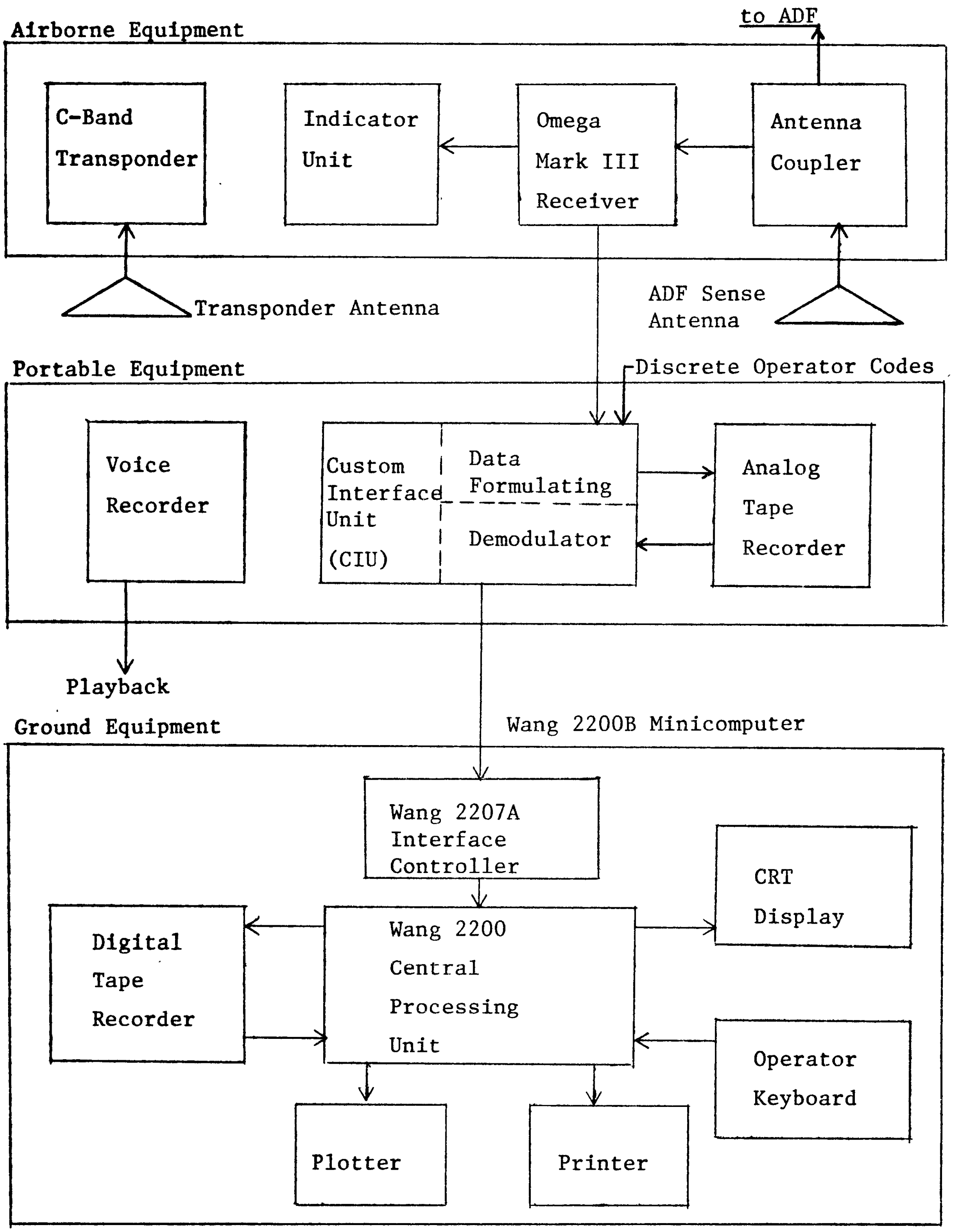


Figure 5-3 Airborne and Post Flight Data Processing Equipment Functional Diagram

a. LOP 1: present position relative to origin

b. LOP 2: present position relative to origin

c. Crosstrack deviation

d. Miles-to-go readout

e. Signal-to-noise ratio of each station (8)

f. Weak signal indicator

g. Auto-zero activation

h. Reset indication

i. To-from flag indication

j. Operator discrete code selection

These parameters are all present inside the Mark III in digital form, and no A/D conversion is required. (The analog CDI is driven by a D/A converter.)

The various parameters, timing signals, and DC power are fed to the CIU by a cable connected to the Mark III. The timing signals select which parameter or part of a parameter is put onto an internal data bus which feeds the FSK converter. The CIU output is routed to the microphone input of a standard 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 in the Wallops area. 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.

5.3 External Filter, Course Deviation Indicator and Strip Chart Recorder

A portable 12 vDC Rustak strip chart recorder was used on some of the early flights to record the CDI information as displayed to the pilot.

An additional CDI movement was prepared to be mounted on the dashboard hand hold in the event the Mark III indicator could not be hard mounted. This CDI used the Omega autopilot output to drive a standard movement.

An external analog filter was designed (Refs. 28 and 30) and built in order to provide external adjustment of the CDI sensitivity and to damp out some of the fluctuations noted when the first test flight was made. The input to the filter is the same Omega autopilot output used to drive either the auxilliary CDI or recorder pen. The outputs of the filter are independent circuits driving both the auxilliary CDI and recorder.

The filter was employed on only one test flight during which the Omega receiver drifted.

5.4 Voice Recorder

A portable battery powered cassetted recorder was used for recording inflight notes. Use of a voice recorder obviated the need for knee-pad notes and allowed a much higher volume of data to be noted. The recorder has 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.

5.5 Piper Cherokee 180 Aircraft

The flight evaluation program was conducted in a leased Piper Cherokee 180 aircraft (N4721L) based at Hanscom Field, Bedford, Massachusetts. 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 5-2.

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 lbs
Max gross weight	2,400 lbs
Performance:	
Max level speed at S/L:	132 kts
Max cruising speed (75% power) at 7,000 ft (2,130 m)	124 kts
Stalling speed, flaps down	50 kts
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

Table 5-2 Piper Cherokee Dimensions and Performance Characteristics

Section 6

GROUND EQUIPMENT AND FACILITIES

Flight planning and data processing necessitated considerable computation capability and extensive use was made of the MIT IBM 370-65 computer and the ASI Wang 2200B and its related hardware. Arrangements were made to take advantage of the FPS-16 tracking radar at Wallops and the DABS radar at Lincoln Laboratory to obtain precise position information. Fixed position bench test sites were constructed at MIT and ASI to provide a ground base for comparison.

6.1 MIT IBM 370-65 Computer

The MIT computer was used in flight planning by calculating the necessary navigation input parameters used during mulitple waypoint flight tests. The parameters included LOP changes and distance between waypoints, magnetic heading and course number (vehicle course in hyperbolic reference system) to the next waypoint. Additionally the computer was used to prepare tables of course number vs magnetic heading for use in enroute variation of flight plan such as encountered when receiving radar vectors or making full approaches with procedure turns. Preliminary statistics were computed and printed on calcomp using data from the strip charts.

6.2 ASI Wang 2200B Computer System

The ASI computer system was employed during the joint MIT/ASI portion of the flight test program to reduce some 60 hours of cassette recorded data for post flight data analysis. A block diagram of the post flight data processing is shown in Figure 5-3. The elements of the Wang 2200B system are listed in Table 6-1.

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

Table 6-1 ASI Wang 2200B Computer System

The flatbed plotter was used to prepare the figures in Appendices A and B.

6.3 Wallops FPS-16 Tracking Radar and Lincoln Laboratory DABS Radar

Four of the first set of flights (Flights 1-1, 1-3, 1-8, and 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 carried in the back seat. 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 maintained by skin track mode. During the night flight 1-9, the transponder was left on to ensure against track loss.

Flight plans were prepared to employ the highly accurate position determination of the DABS radar by flying both enroute segments and RNAV approaches to Hanscom Airport.

Scheduling irregularities precluded the use of the Lincoln Lab. faciltities.

6.4 Fixed Position Bench Test Sites

Bench sites were prepared at MIT and ASI to provide a low cost preliminary view of the actual received signals and receiver indications as well as to provide background data to corroborate airborne indications. The bench sites consisted of a roof mounted 8 foot whip antenna and co-located antenna coupler with coupler lead long enough to extend to a convenient indoor location, and a well filtered 12 v DC power supply.

Section 7

FLIGHT TEST 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. The following subsections include brief discussions of flight planning and check lists, data recording procedures and navigational techniques employed.

7.1 Omega LOP Versus LAT/LON Algorithms

A series of computer programs were written in Fortran to convert position information from latitude and longitude coordinates to Omega LOP coordinates by use of gradient vectors (H-vectors) linearized to a local area (Ref. 3). For example, a transformation from the relative change in lat/lon to the corresponding change in A-B and B-D LOP between two points would be:

$$\begin{Bmatrix} \Delta AB \\ \Delta BD \end{Bmatrix} = \begin{bmatrix} H_1 & H_2 \\ H_3 & H_4 \end{bmatrix} \begin{Bmatrix} \Delta lat \\ -\Delta lon \times \cos(lat) \end{Bmatrix}$$

where H_4 would be the change in the B-D LOP for a given change in miles east (see Appendix C.2). This algorithm was refined in programming to produce the necessary waypoint input parameters used with the Mark III receiver. A sample output for the Wallops area is shown in Figure 7-1. These programs were also converted to BASIC for use with the Wang 2200B computer. It was found that to remain within acceptable accuracy limits (the LOP changes are entered into the DR-30 receiver in tenths of lane increments) the linearization was limited to a fifty mile radius of the H-vector calculation point.

7.2 Preparation of Omega Aeronautical Charts

A series of Aeronautical Sectional and Terminal Control Area charts were overlaid with Omega LOPs as the only other Omega charts available were not intended for or usable by general aviation pilots. This was done for both the Wallops area and the New England Region, and provided a very useful cross check to ensure waypoints had been computed correctly and LOPs properly entered in the receivers. Occasional waypoint blunders were found and corrected enroute through reference to these charts. These charts were also used for preliminary flight planning for determining optimal routing

TO		AWAL	ADLM	AWRG	ASBY	AOCN	ACRF	TBER	TSBY
	LAT	37.94	38.47	38.47	38.33	38.32	38.02	38.33	38.34
	LON	75.47	75.57	75.18	75.52	75.12	75.83	75.22	75.60
FROM									
AWAL	DAB	0.0	-3.5	-3.5	-2.6	-2.5	-0.5	-2.6	-2.7
	DBD	0.0	3.3	1.8	2.3	0.7	1.8	1.2	2.7
	DR	0.0	32.1	34.6	23.8	28.3	17.8	26.3	24.8
	CN	0.	496.	467.	494.	443.	556.	462.	500.
	HM	0.	7.	38.	10.	51.	301.	41.	1.
ADLM	DAB	3.5	0.0	-0.0	0.9	1.0	3.0	0.9	0.9
	DBD	-3.3	0.0	-1.5	-0.9	-2.6	-1.4	-2.1	-0.6
	DR	32.1	0.0	18.2	8.5	23.1	29.8	18.3	7.9
	CN	96.	0.	202.	102.	145.	64.	140.	81.
	HM	187.	0.	105.	178.	128.	220.	132.	205.
AWRG	DAB	3.5	0.0	0.0	0.9	1.0	3.0	0.9	0.9
	DBD	-1.8	1.5	0.0	0.6	-1.1	0.1	-0.6	0.9
	DR	34.6	18.2	0.0	17.7	9.5	40.9	8.4	21.0
	CN	67.	602.	0.	724.	104.	795.	79.	698.
	HM	218.	285.	0.	258.	176.	244.	208.	263.
ASBY	DAB	2.6	-0.9	-0.9	0.0	0.1	2.1	-0.0	-0.0
	DBD	-2.3	0.9	-0.6	0.0	-1.6	-0.5	-1.2	0.3
	DR	23.8	8.5	17.7	0.0	18.9	24.1	13.9	3.8
	CN	94.	502.	324.	0.	191.	37.	200.	581.
	HM	190.	358.	78.	0.	108.	233.	105.	290.

Legend:

DAB = AB LOP lane change
DBD = BD LOP lane change
DR = point to point distance
CN = hyperbolic course reference
HM = magnetic heading

AWAL = Wallops airport
ADLM = Delmar
AWRG = Warrington
ASBY = Salisbury
AOCN = Ocean City
ACRF = Crisfield
TBER = Town of Berlin
TSBY = Town of Salisbury

Figure 7-1 Computer Generated Waypoint Input Parameters for the Mark III Receiver in the Wallops Area when flying along LOPs in various directions. Finally, it was determined to be possible to derive the proper LOP changes to within .15 lane by observation of the charts alone without reference to precomputed programs or accurate measures, making it possible for VFR enroute route changes with only slightly degraded accuracy.

7.3 Flight Planning

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.

7.3.1 Test Description

For each flight, a standardized information packet was made for each flight crew member. This packet included a Flight Evaluation Sheet, shown in Figure 7-2, a Flight Plan, Figure 7-3, and a flight map, Figure 7-4.

Flight No.: 1-1 Test Description

Low altitude star route

Test Objective: Provide initial area survey of Wallops and mid Delmarva Peninsula at 5000' and selected lower altitudes with radar tracking

ITEM	PLANNED	ACTUAL
Date:	2/19/75	2/20/75
Departure:	9 a.m.	10 a.m.
Duration (hrs):	1 hr	2.6 hrs
Area/route:	Low altitude star	same
Pilot:	W. C. Hoffman	same
Omega operator:	P. V. Hwoschinsky	same
Other participants:	None	same
Weather:	VFR	same
Winds at cruise:	Calm	5 kts, N

Data recording procedures: CIU on tape, voice log tape

Contingency plans: no go if IFR

Special requirements: Radar availability not required but useful. Fly lower altitudes until radar track lock is lost.

Figure 7-2 Sample Flight Evaluation Sheet

FLIGHT NO.: 1-1 DATE: 2/20/75 AM

CHECK-POINT	HDG CN / MH	ΔLOP STATION A-B	ΔLOP STATION A-D	LEG DIST / GROUND SPD	TIME PT-PT	TIME ETA
		B-D	B-C		ALT	ATA
0 Wallops						
1 Parksley	026 / 231°	1.1	.9	15 / 115	8	8
		-.1	.1		5000	
2 Wallops C. G.	300 / 077°	.5	-.3	15 / 115	8	16
		-.9	-.8		5000	
3 Pocomoke	519 / 328°	-.8	.2	15 / 115	8	24
		1.0	.9		5000	
4 Metomkin Island	093 / 185°	1.4	.6	21 / 115	11	35
		-.8	-.5		5000	
5 Saxis	517 / 331°	.1	1.0	15 / 115	8	43
		.9	1.0		5000	
6 N. Refuge	278 / 082°	-.6	-1.0	25 / 115	13	56
		-.4	-.6		5000	
7 Snow Hill VOR	573 / 287°	-.8	-.2	10 / 115	5	1:01
		.6	.5		5000	
8 Wallops	087 / 193°	0	0	7 / 115	4	1:05
		0	0		5000	

Figure 7-3 Omega Flight Plan

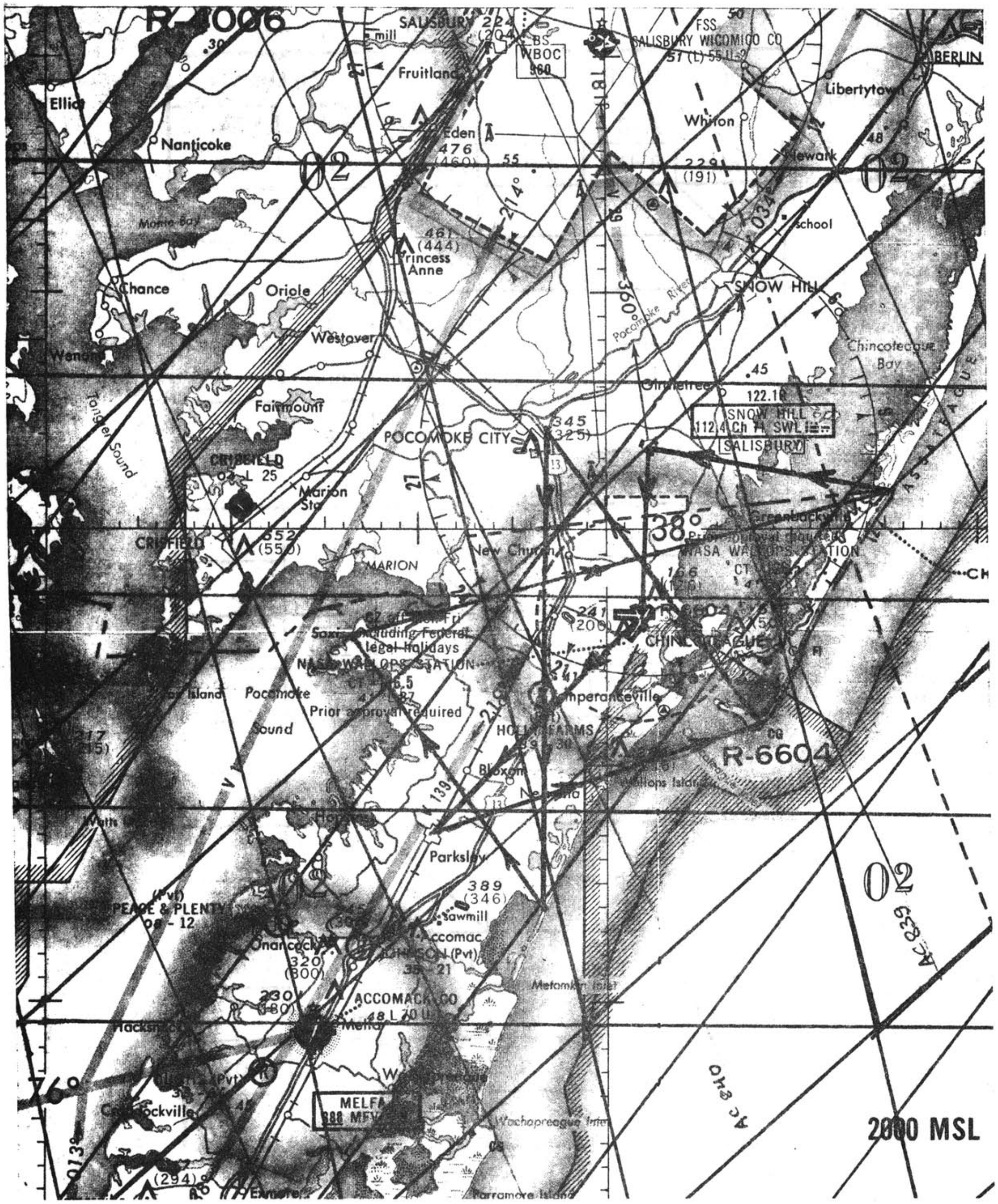


Figure 7-4 Sample Flight Map

The flight evaluation sheet, shown in Figure 7-2, was designed to provide identification of and general information about the flight. The flight number and objectives were supplied at the top of the sheet, with operational data in the box at the center of the page. Operational data includes 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 plans, and special requirements. These three provided information to make a go/no go decision based on flight test objectives.

The flight plan is shown in Figure 7-3. This sheet was in a format standard for pilot usage and 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 7-4) was included in the flight test packet with the desired 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.

7.3.2 Checklists

A comprehensive set of operational check lists was made to reduce errors in the flight test program and during ground transfer of data. Table 7-1 shows a list of checklist titles and Figures 7-5 and 7-6 are given as examples (Ref. 1).

Flight Equipment Checklist
Flight Recording CIU Checklist
Omega Warm Up Checklist
Receiver Synchronization Checklists
Ground Operations Checklist
Inflight Operations Checklists
Initial Voice Recorder Checklist
Waypoint Voice Recorder Checklist
Enroute Voice Recorder Checklist

Table 7-1 Checklist Titles

AUTO SYNC

1. SYNC sw-ID
2. SYNC-select D (or other)
3. Depress HOLD momentarily
4. SYNC when REF light on and off (within 30 seconds)
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 numbers for Waypoint
8. Reset lane accumulators
9. Display MTG, flag on FROM
10. Adj MILES SET for distance

Figure 7-5 Receiver Synchronization Checklists

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 7-6 Enroute Voice Recorder Checklist

7.3.3 Scheduling

Over the period of study and performance of the flight tests, the experimental work was composed of four phases. First, fixed position ground tests were conducted to determine the stability of the indicator outputs. These locations included the MIT bench test site, the top floor of a sixteen story building and in an automobile both parked and moving.

The second phase included experimental design teamwork on a method of filtering the CDI presentation to a more acceptable indication of crosstrack error without losing information necessary for accurate course following. Considerable effort and consultation was made in the design, redesign, and construction of a light weight, compact, low power filter.

The third phase spanned the period of initial flight tests and hardware mounting decisions to the shakedown flights with the CIU on board and receiver and indicator hard mounted. This period also included a majority of the actual flight planning and data standardization.

The fourth and final phase encompassed the bulk of the data flight tests, data reduction, analysis and evaluation of results. A last series of flights was made after the bulk of the data analysis to confirm partially resolved conclusions.

7.4 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.

7.4.1 Omega Data

As described in Section 5.4 and 7.3.2, various Omega receiver parameters were recorded on a portable cassette recorder. During data reduction, it was discovered that the Omega/CIU/recorder system also recorded transmissions from the aircraft VHF transceivers. Most Omega data flights were made with radios off, however, and very few transmissions were made on flights with the radios on. Thus, little data was lost.

The 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, 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 intervened. Few such problems were encountered.

7.4.2 Tape Log

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.

Figure 7-7 shows a pocket size check list used for recorder operation. The first section was used to insure that the recorder itself was operating, the second section of the check list was used to insure that entries on the tape were complete and appropriate. Transcription of voice tapes was accomplished as soon after each flight as possibe to ensure optimum accuracy and detail. A sample transcript is shown in Figure 7-8.

Check before Flight:

All wires properly connected

Voice recorder working

Voice recorder battery level in green

CIU recorder working

Voice Log Entry

Update CIU on C, check enabled:

Time: (hour) min, sec

(Waypoint change)

(T/F)

MTG

CDI

Event

(CN)

(Wsl ID)

Location and Action

Figure 7-7 Pocket Size Checklist for Voice Recorder

7.4.3 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 series of

Omega Flight 1-1 Notes (20 February 1975) Low Altitude Star Route

Time	Wpt	T/F	MTG	CDI	Event	CN	Wsl	Location and Action
10:33:30		T/F	1	½ lt				1/2 lt of course to Parksley
10:34:12	2	T	15	C	2		A	Over Parksley, radar mark, toward Wpt 2
10:37							A	
10:38:12					3		A	Over coastline
10:40:52			2	¼ rt	4			1 NW Wpt 2
10:42:12		T/F	0	C	5		A	3 NE Wpt 2
10:44:02	3	T	15	C	6	515	A	Autozero over Wallops Coast Guard
10:48:12			7	¼ lt	7			Over inner coast toward Pocomoke, 1 mile rt of course
10:50:22								Abeam SWL VOR
10:51:02			2	C	8			Crossing powerline from SBY to WAL, 2 SW Pocomoke City

Figure 7-8 Sample Voice Transcript

Figure 7-9 Typical Manual Position Plot

Wallops area flights, and position plots were made from CIU recorded data for the second set of Wallops flights.

On the early Northeast 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 7-9. In the Wallops area flights, position plots were occasionally drawn as a crosscheck. Finally, position plots were made following a failure of the voice recorder. This salvaged flight data which otherwise could not have been correlated with encountered phenomena.

7.5 Navigation Techniques

A variety of different 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 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 the radar position information supplied later for comparison.

7.5.1 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 generated needle deflections, and also gave data on pilot reactions to the position information and required techniques. Position reports were entered on the voice tape for statistical analysis of the errors. One major advantage of this mode of navigation was that it allowed the major noise source in the flight evaluation program, the aircraft VHF radios, to be turned off. Several nonprecision approaches were flown with the Omega along with final waypoints usually within the airport boundaries, but at least within one nautical mile when corrections were made within a hundred mile radius.

7.5.2 VHF Navigation

Many flights were conducted using VOR as the primary navigation source, with the Omega recorded position used for comparison 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 at Salisbury Md., 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 aircraft was flown. By comparing the Omega indicated position to the known path, anomalies such as the coastline effect were investigated, and navigation information was provided through areas where Omega interference was suspected.

ILS paths were followed on flights 2-11 and 1-24 (discussed later). On these 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.

7.5.3 Visual Navigation

The visual navigation mode consisted of contact flying with voice reports at regular intervals recording actual position relative to known landmarks. This information was then reduced with CIU supplied information for verification and comparison with the Omega indication of position. Examples of flight segments where visual navigation was the preferred mode included: flying through the New York TCA along the Hudson River, flying along a straight section of a railroad on the Delmarva Peninsula, and crossing expanses of water at low altitude. The main advantage of contact flying was the ability to navigate without the VOR receivers on, which was the major source of interference for the Omega receiver.

Section 8

POST FLIGHT DATA PROCESSING

A very large volume of data was recorded during the flight evaluation program. Thus it was essential that an efficient computerized data processing and plotting system be developed to provide rapid reduction of the data for subsequent analysis. This section includes a brief description of the post-flight data reduction system including the data processing equipment, the data reduction software, and plotting capability. A majority of the software generation and data reduction was accomplished by an ASI/MIT team (Refs. 1 and 28).

8.1 Data Processing Equipment

A functional block diagram of the post flight data processing system is shown in Figure 5-3. As shown in the figure, the data processing equipment consisted of a Wang 2200B minicomputer with peripherals including an output typewriter, an analog plotter, a cassette tape and a teletype interface board. The elements of the ASI Wang 2200B minicomputer installation are indicated in Table 6.1. The 2200B is programmed entirely in BASIC.

8.2 Data Transcription and Checking

In the air, data was recorded on the portable cassette recorder by the custom interface unit as described in Section 7.4.1. 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. It was discovered that some transmissions from the aircraft VHF transceivers were recorded on the cassette recorder along with the data, resulting in garbling of data.

8.3 Plotting Capability

The recorded data were processed to yield several different types of plots. These plots included S/N ratios, Omega estimates of aircraft position, miles to go (MTG), various status flags, and needle deflection. These are discussed in the following sections.

8.3.1 Miles-to-Go Plotting

The miles-to-go (MTG) was plotted on a linear scale of 0 to 75 miles, with tic marks on the y axis representing 25 mile steps. No filtering or special processing of any kind was done. A blank space was left on the plot, indicating deleted data. In addition, space was left to indicate the lack of data acquisition while a cassette was being changed in the aircraft.

8.3.2 Status Flag Plots

Four status flags were recorded by the CIU: to/from flag, autozero, lane accumulator reset, and weak signal on any station used for navigation. With the exception of the to/from flag, which was plotted as a continuous bistable position line, each flag was plotted as a tic mark above the x axis when it occurred. Labels for these flags are shown on the plots presented in Appendices A and B.

8.3.3 Needle Deflection Plotting

Needle deflection plots recorded the deviation of the needle deflection calculated from the phase meausrements at the end of a 10 second Omega transmission sequence. In practice, the needle was prone to oscillations at frequencies higher than those recorded 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 result in discontinuous plots of needle deflection.

8.3.4 S/N Ratio Plots

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 signal-to-noise ratios to a minimum of -30 dB. The maximum was based upon the transmission time of the station.

Section 9

FLIGHT TEST PROGRAM RESULTS

As detailed in Section 2, the objectives of the Wallops area flight tests were to investigate the various effects due to altitude, coastline, station pairs, LOP geometry, diurnal variations, precipitation, radio frequency interference, maneuvers, and geographic location. These effects were then to be analyzed to provide initial information and flight experience for the differential Omega flight test and evaluation program. The objectives of the Northeast Corridor and New England Region flight program were to repeat previously flown low altitude Zulu routes to compare Omega performance with VOR/DME results. Factors investigated included: suitability and accuracy of Omega navigation for city center VTOL operation, performance at various altitudes over various terrain (urban, industrial, forests, mountains, water), effects of maneuvers (holding patterns, simulated approach, missed approach), and ground versus airborne performance.

Flight planning included plotting Omega LOPs on aeronautical sectional and terminal control area charts, preparation of LOP versus position tabulations and detailed flight descriptions as discussed in Section 7.3 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.

Flight status and summary tables were prepared to provide rapid comparison of the various objectives completed with those yet to be examined, these are shown in Table 9-1 through 9-4. As can be seen in the tables, the sixteen Wallops area flight tests were made in two groups; the first from February 19 through 22, and the second 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 through the Wallops area; and VOR radial flying perpendicular to the coastline on Assateague Island.

Flight Number	Date (1975)	Flight hours	Coast	Altitude	Station pairs	LOP direction	Diurnal	Precipitation	Interference	Maneuvers	Accuracy	Terrain	Radar	Hours data recorded
1-0	2/19	0.4							X		X			0.4
1-1	2/20	2.6	X	X					X	X	X		X	2.5
1-2	2/20	0.3							X		X			0.3
1-3	2/20	2.5	X	X					X				X	2.5
1-4	2/20	0.9	X	X			X		X		X			0.8
1-5	2/20	1.4	X				X		X		X			1.4
1-6	2/21	3.0	X			X			X					3.0
1-7	2/21	0.4							X		X			0.4
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			X	X	X			1.3
1-20	3/7	0.6							X		X			0.3
1-21	3/7	1.3		X	X			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	X		X			2.1
1-24	3/9	3.0	X		X	X			X	X	X			2.8

Table 9-1 Wallops Area Flight Test Objectives

Flight Number	Flight Description
1-0	Ferry flight SBY-WAL (7500')
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 WAL-MFV-SBY (2000')
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 AB, 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 LOPs SBY-SWL-SBY (2000')
1-23	VOR cloverleaf 30° cardinal headings (3000'), SBY-SWL-SBY
1-24	VOR cloverleaf 30° cardinal headings plus or minus 15° (3500'), constant CD LOP, AB/BC, CD/BD, AB/BD

Table 9-2 Wallops Area Flight Summaries

Flight Number	Date	Flight hours	Coast	Altitude	Station pairs	LOP direction	Diurnal	Precipitation	Interference	Maneuvers	Accuracy	Terrain	Radar	Hours data recorded
(1974)														
2-1	11/22	.8		X						X				0
2-2	11/23	2.1		X							X			0
2-3	12/3	3.6	X				X							1.5
2-Z1-1	12/20	2.2	X			X	X							1.5
(1975)														
2-Z1-2	1/24	2.0	X	X			X		X					1.6
2-4	1/27	.9		X		X	X			X	X			1.7
2-5	1/30	1.7	X	X							X			1.0
2-6	1/31	1.6	X	X			X		X		X			1.5
2-7	3/7	1.9		X		X	X	X	X	X	X	X		1.0
2-8	2/10	2.3		X							X	X		1.5
2-9	2/10	1.7			X	X			X		X			1.5
2-10	2/14	3.7			X				X		X			3.0
2-11	2/17	3.5		X			X	X	X			X		3.4
2-12	2/19	3.5	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	X	X		1.0
2-31	3/5	0.7								X	X			0.5
2-41	3/9	3.2	X								X			3.2
2-44	3/9	3.5	X	X	X	X			X					3.1
2-51	4/22	3.6	X	X					X	X	X	X		3.5

Table 9-3 Northeast Corridor Flight Test Objectives

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 Washington D. C., D lost enroute over Statue of Liberty BED-FLU
2-9	Return from Flushing using A, B, C, BDR-BED
2-10	Zulu to Washington D. C., north route, BED-College Park
2-11	IFR return from Washington D.C., IAD-ARP-LHY-BED
2-12	Zulu to Washington D. C. with divert to SBY enroute to WAL, BED-SBY
2-13	Zulu return from WAL, SBY-BED
2-21	Night repeat of 2-7 to test system with chip exchange
2-31	Haverhill-BED ferry flight
2-32	Day 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
2-51	Mountain flight near Mt. Washington (2500' and 7000')

Table 9-4 Northeast Corridor Region Flight Summaries

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 heavy 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 twenty Northeast Corridor region 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. (Five of these flights had data lost in transfer.) 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.

9.1 Altitude Effects

All the Wallops area flights were concerned with the effects of altitude to some degree, but as can be seen in Table 9-1, only six were specifically addressed to this phenomenon.

On the Northeast Corridor flights, S/N varations with altitude, S/N variations at takeoff, and ease of needle following at various altitudes were investigated. The majority of these flights were flown at a nominal 2000 ft MSL. As Table 9-5 shows, however, these flights ranged from 500 ft MSL to 7500 ft MSL, getting to within 200 ft of the surface in order to detect S/N variations with altitude, both in general and in specific areas. Altitude effects appeared to be limited to locally generated noise (e. g., the ITT low-frequency communication transmitter in Commack, New York, 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.

9.1.1 Expected Results

Proximity to local noise sources on the ground led to the expectation of higher signal to noise ratios at greater altitude. 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

Flight	
2-1	3000 ft MSL
2-2	2000 ft then under NY TCA at 1100 and 500 ft
2-3	2000 ft MSL
2-Z1-1	2000 ft MSL
2-z1-2	3500 ft MSL
2-4	3000 ft AGL
2-5	2500 ft MSL
2-6	5500 ft MSL
2-7	2000 ft AGL with 200 ft portion over power-line
2-8	2000 ft MSL then 1100 through NY TCA
2-9	3000 ft MSL
2-10	2000 ft except 1100 ft through NY TCA
2-11	7000 ft (IFR)
2-12	2000 ft except 1100 ft through NY TCA
2-13	2000 ft except 500 ft through NY TCA
2-21	2000 ft AGL
2-31	1500 ft MSL
2-41	2000 ft MSL except 500 ft through NY TCA
2-44	5500 ft MSL except 7500 ft over NY TCA
2-51	2500 ft and 7000 ft MSL

Table 9-5 Northeast Corridor Flight Altitudes

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.

9.1.2 Takeoff Phenomenon

The takeoff phenomenon is described as an improvement in S/N ration as the aircraft leaves the ground and climbs above the local treetops. A signal masking effect by trees and local terrain was investigated by Mr. Caroll Lytle of the NASA Langley Research Center (Ref. 29) and is 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. This effect was observed on a few of the Wallops area flights (e. g., Flight 1-9, Figure A.4-2), but was more obvious in the Northeast Corridor flights where the phenomenon of S/N decreasing during landing could be observed, see Figure B.3-2 and B.5-8. This effect is not a particularly strong one, and is easily masked by other effects such as inverter noise change (discussed in Section 9.4).

A comparison of observations made with the Omega receiver in the test aircraft and at the ground test site indicates that the receiver is less affected by small disturbances in phase at the ground site, but more affected by the drifting of 60 Hz powerline noise.

9.1.3 Accuracy

Accuracy was not so much a function of altitude as was the level of difficulty obtaining position information accurately as altitude increased. It has been reported that there is no significant change in signal strength noticed with altitude. However, less noise was sometimes present at higher altitudes (Ref. 30).

9.2 Coastline Effects

Eleven of the sixteen Wallops flights encountered some coastal crossings and for those, seven were designed to determine the magnitude and direction of the effects on the LOPs.

9.2.1 Expected Results

It was expected from the nature of electromagnetic waves traveling over areas of different surface conductivity that the waves would be retarded slightly when passing into a region of lower conductivity (Figure 9-1, Ref. 31). A rather simplified approach to the expected geometry of hyperbolic 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 the phase differences. Figure 9-2 shows typical coastal path geometry (Ref. 6). These coast effects were expected to be greater at lower altitudes due to proximity of the coastline. Finally, due to the long transmission paths and relatively long wave lengths, several hundreds of miles of propagation anomalies are required to make even a small shift in the local phase measurement, such that extremely small local coast changes would have a miniscule effect (Ref. 6).

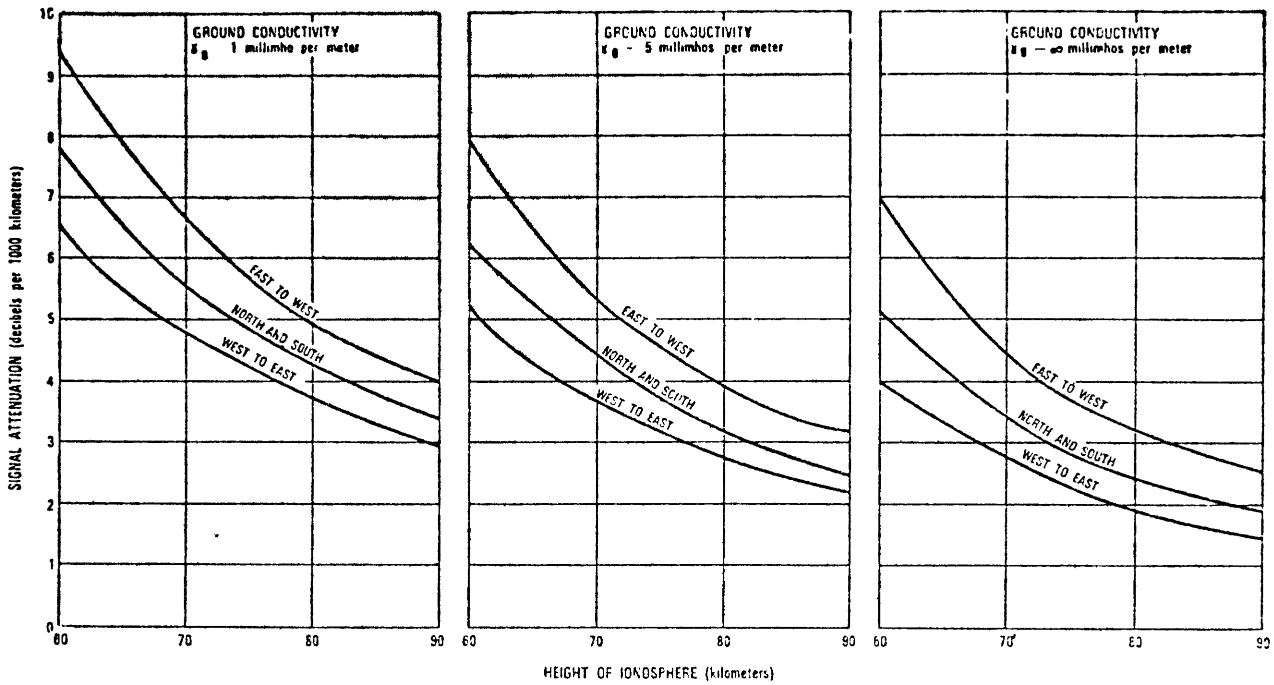


Figure 9-1 Attenuation of the 10.2 kHz Omega signal as a function of ionosphere height for different ground conductivities. The conductivities given are typically those for sea-water paths (infinite), good-conductivity land paths (5 millimhos per meter), and poor-conductivity land paths as found in the Arctic (1 millimho per meter). (Ref. 31)

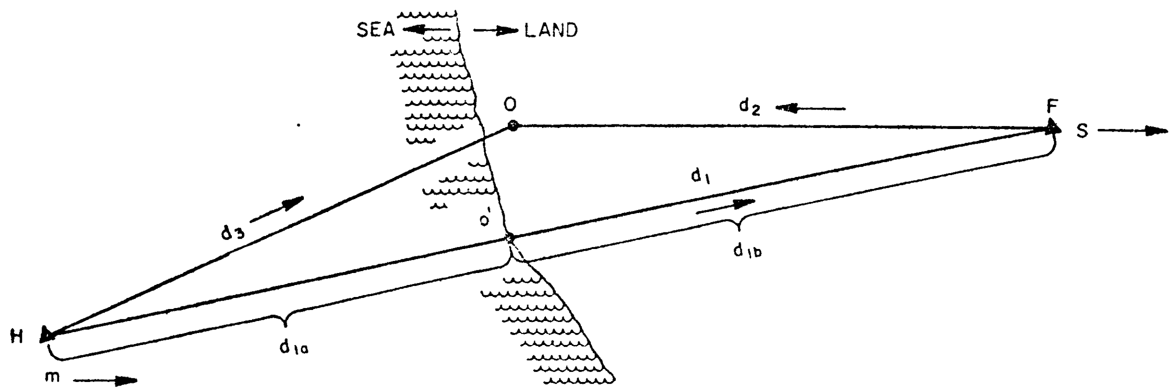


Figure 9-2 Typical path geometry showing master, slave and observer positions for propagation including both sea and land paths (Ref. 6).

9.2.2 Observed Course Bending

The actual path change commands observed on the CDI when passing over a coast in the Wallops area appear to have little correlation with subsequent passes over the same or similar spots either in direction or magnitude. The magnitude of the bends was on the order of .5 nm (Ref. 1); which is less than the phase noise in the Norway signal, and understandable in view of the level of difficulty of holding a constant heading over an irregular coastal area in moderate air turbulence. Some course bending has been observed along the Connecticut coast near the Madison VOR, but it was in proximity with a significant amount of HF and VHF energy.

Flights over the Massachusetts and Maine coasts show no path bending at all.

9.2.3 Variation with S/N

Some of the path bending is due to random noise in the Station A signal, as mentioned above; and may be partially due to local HF marine radio broadcast energy leaking into the receiver via the ADF antenna (Refs. 12 and 30). Flight 1-22 was flown along a constant LOP and the plotted output should have indicated a straight line. An airborne sketch was made of the visual track over the ground and needle deflection corrections were overlaid. The result was a fairly straight path.

9.2.4 Variation with Altitude

As mentioned in Section 9.1.3, the inaccuracy of position measurements increases with altitude. There was no increase in noticeable path bending at higher altitudes. Close comparison of the VOR heading information with Omega in the Snow Hill coastal area showed no more than internal receiver position uncertainty (Ref. 1).

9.3 Diurnal Effects

The flights in the Wallops area were staggered throughout the day to determine the extend of errors accruable due to the different diurnal shifts in the Omega LOPs (See Figure 9-3). Selected flights in the Northeast Corridor region investigated diurnal effect errors (Table 9-3).

9.3.1 Expected Results

There are three basic propagation paths: entirely sunlit (day), entirely dark (night) and mixed illumination (transition). As is mentioned in the Omega Propagation Correction Tables (Ref. 32), wave propagation has a tendency toward greater stability during the day, but with slowly varying conditions. Night propagation conditions are less stable but more constant than during the day. The transition periods caused the most difficulty because the changes are of intermediate stability and occur nonlinearly.

As the flight schedule shows, the transition periods for Station A and C (Norway and Hawaii) are the longest, due to their great longitudinal displacement, and present the greatest possiblity for diurnal errors. Table 9-6 shows expected periods of inaccuracy due to diurnal effects.

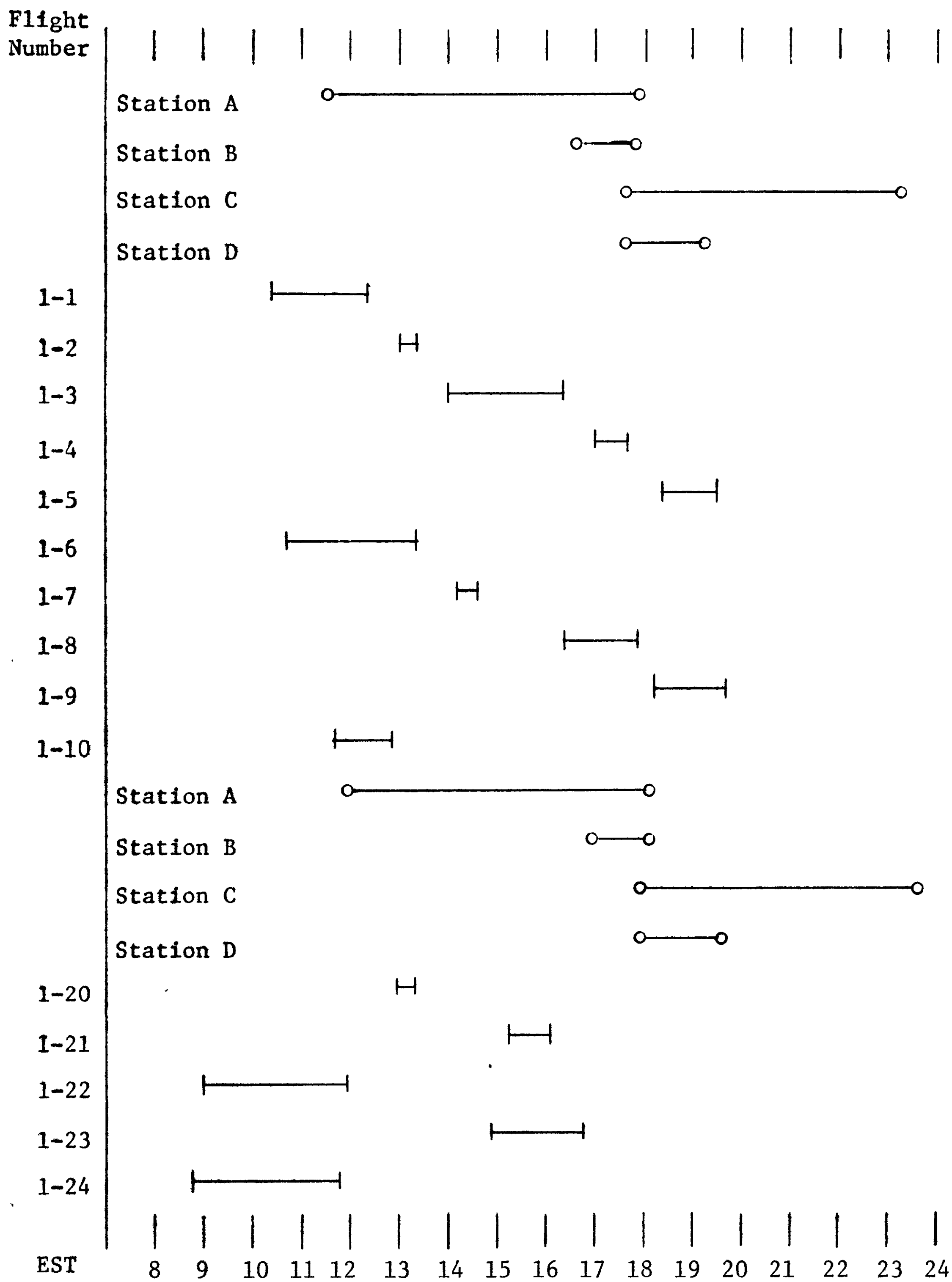


Figure 9-3 Wallops Area Flight Schedule and Station Transition Times

Station	Transition Occurrence at Wallops (EST)	
A - Norway	1147 - 1742 (sunset)	0056 - 0651 (sunrise)
B - Trinidad	1647 - 1742	0556 - 0651
C - Hawaii	1742 - 2311	0651 - 1220
D - North Dakota	1742 - 1912	0651 - 0822

Table 9-6 Station Transition Periods for the Wallops Area (February 21, 1975)

The operation of the Mark III receiver as explained in Section 5.1.3 removed some of the effect of the diurnal changes by employing only the relative changes in LOP waypoints. This essentially provided the navigation with a differential Omega fix at beginning of each flight or after the last reset time.

9.3.2 Errors Accrued During Transition Periods

Two Wallops area flights occurred during the sunrise shift, eight during the early sunset shift, two during the late sunset shift and five occur during mixed transition and daylight conditions. Figures 9-4 and 9-5 show propagation corrections and rates of change of corrections respectively for the Wallops area, and from this it can be seen that LOP changes occur in a non-uniform manner for each station. On

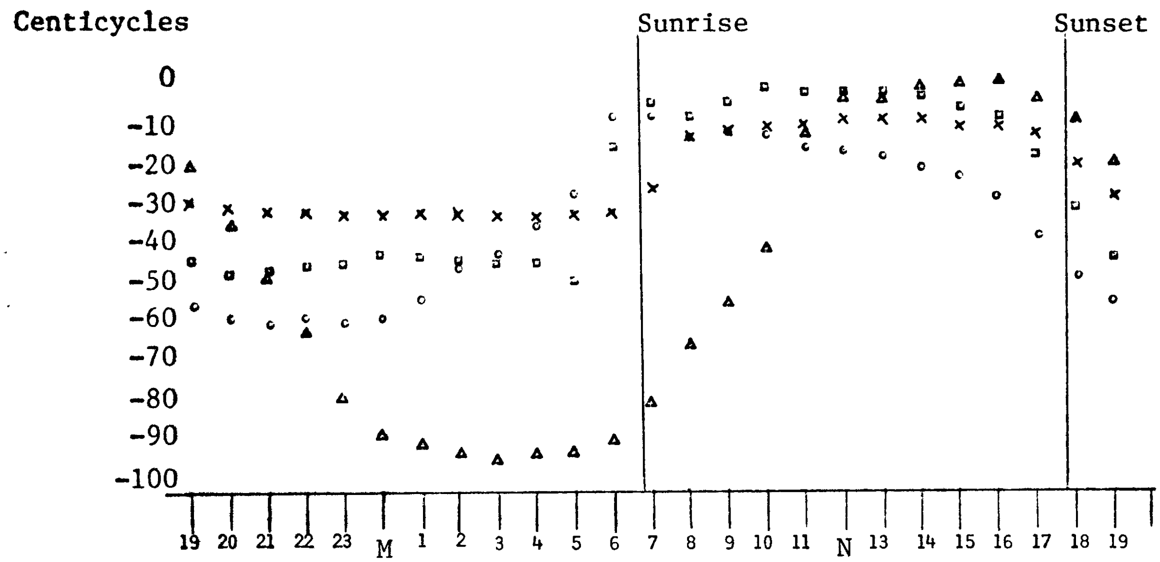


Figure 9-4 Wallops Area Omega Propagation Corrections for 10.2 kHz, Stations A, B, C, and D for the Period February 15-29, 1975 (40.0N, 74.0W)

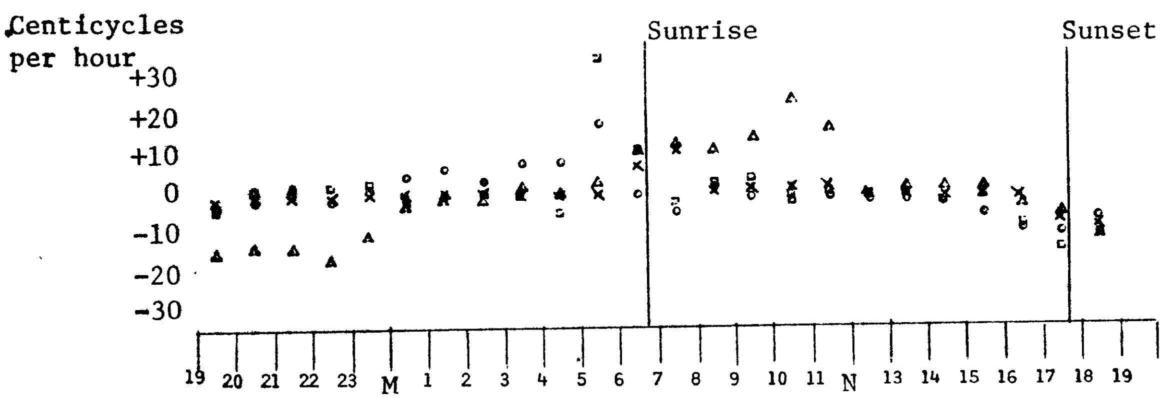


Figure 9-5 Wallops Area Omega PPC Changes for 10.2 kHz, Stations A, B, C, and D for the Period February 15-29, 1975 (40.0N, 76.0W)

Legend: Station A ∘ , Station B ▫ , Station C △ , Station D ×

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. During the first two hours of Flight 1-24, which employed LOP pairs AB and BC concurrent with the sunrise transition for Station C the Omega waypoints were compared with the VOR waypoints. Although there was a 1-1/2 nm accuracy degradation, it was less than half the magnitude expected from Figure 9.4 of some 40 centicycles or 3-1/2 nm. As shown in Figure A.2-1, during Flight 1-5 after sunset, a 70 minute flight ended with a 2 nm error which is partly attributable to a waypoint setting error of 0.9 nm and partly to the shift in the B-D measurement.

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 since 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.

9.3.3 S/N Variation

The most significant noise effect during the diurnal tests in the Wallops area was occurrence of fluctation of the CDI needle. This may have been due to many causes, but most likely local interference. This fluctuation occurred during the transition of Station D, which is strongest and least noisy in the Wallops area. In addition, the weakest station (A) was very strong during the whole flight. An analysis of periods of weak S/N for the stations with special focus on Station A shows no indication of diurnal noise fluctuation.

9.4 Interference and S/N Variations

All the flights in the Wallops and Snow Hill VOR area were directed toward determining the effects and levels of interference to Omega navigation for use during the upcoming differential Omega studies. A series of flights investigated interference in the Boston area near transmitters, powerlines and plants.

9.4.1 Expected Results

Preliminary discussions with Mr. Robert Moore of the FAA Omega flight evaluation section indicated an Omega interference anomaly in the Snow Hill VOR area that was detected at altitudes from 3000 ft to 10,000 ft. Further discussions with Mr. Paul Rademacher of Dynell indicated that the VOR itself might be the source of interference, and that similar effects had been noted on Long Island and in southern Connecticut. Commander Herbert and Mr. Robert Willems of 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.

9.4.2 Interference Observed and Probable Causes

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 variations in the Greenland attenuation shadow effect and low station power output.

The most obvious interference source was the aircraft inverters powering the VHF radios. A 20 dB increase or decrease occurred in the observed S/N ratio whenever the radios were turned on or off, respectively, as can be seen in Figure A.2-2 at 18:31 (Event 3) and 18:34 (Event 4), and in Figure B.4-8 (Event 1). 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 as shown in Figure A.2-2 from 18:34 to 19:30 EST. The C-band transponder installed for radar tracking had no observable effect on S/N ratios and did not appear to generate any interference.

Near field interference sources were not so easy to distinguish. The effects of these were manifested by a series of CDI oscillations when flying along an A-B LOP. These rapid CDI oscillations were of two mile magnitude and continued for several minutes. This made it more difficult for the pilot to derive heading change information from the display. When the CDI did settle down, it did so for only a few seconds before again fluctuating. For example, in Figure A.4-1, 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 as Figure A.4-2 shows and there was a noticeable lack of weak signal lights. It was most likely the FPS-16 tracking radar energy being detected by the ADF sense antenna (Ref. 8).

Other regions where interference was encountered regularly included: a broad area in central Connecticut between Willimantic and Middletown where weak S/N and difficulties with track loss were observed, near the Madison VOR where the CDI and MTG would wander about, and along the north coast of Long Island near Smithtown Bay where course bending and track loss occurred. It has been suggested that as stated in Section 9.4.1 these disturbances may be caused by the local VOR stations or other high frequency transmitters.

9.4.3 Variation with Altitude

Two types of interference were tested for altitude effects: powerline noise and other local interference, and far field attenuation. Although no powerline noise was found at any altitude, the Wallops local interference showed a definite 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. Only the local interference effects mentioned above were correlated with altitude. A comparison of Station A S/N ratios on Flights 2-6 (Figure B.1-2) and 2-12 (Figure B.3-2) shows that the observed decrease in S/N ratio over central Connecticut was less noticeable with increased altitude. Further, there was an absence of weak signal lights and path bending over the north coast of Long Island at higher altitudes.

Wallops radar interference was observed on Flights 1-8 and 1-9 at 3000 ft, weakly on Flight 1-1 at 5000 ft, and not at all on Flight 1-3 at 10,000 ft (Figures A.1-1 and A.4-1). On all of these flights, the aircraft was being tracked by the FPS-16 radar. Transponder operation was apparently not a contributing factor, as the interference was observed at 3000 ft with the transponder both on and off.

9.4.4 Navigation Accuracy and Ease of Needle Following

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 A.4-1). On Flight 1-6, fluctuations in the CDI were observed, apparently due to weak signals from Station A (Figure A.3-4). Flight 1-22 displayed indicator noise attributable to weak Station A. In the Northeast, 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 land jumps due either to interference or weak S/N ratio. When strong S/N ratios were being received, the pilot was required to make only small heading corrections to maintain a centered CDI but poorer S/N ratios often resulted in noisy CDI presentations. Under these circumstances the perferred flying method was to maintain a constant heading, with long-term CDI changes corrected and short-term variations ignored. This filtering increased pilot workload considerably over those levels required during quiet periods.

Flights 1-8 and 1-9 encountered very frequent, rapid 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 determined at 1000 ft altitude, as shown in Figure A.4-1.

On Flight 1-6 the Station A S/N ratio was extremely poor as shown in Figure A.3-2. 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 combinations.

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

9.4.5 S/N Variations

As mentioned above, the greatest variation 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, denegration of other S/N ratios would also be expected. Since this was not always the case, it was concluded that the occasional low S/N ratios for Station A were the result of low signal strength at the transmitter, or greater than usual attenuation over the Greenland icecap. During several flights, attenuation presumably caused poor Station A S/N resulting in weak signal lights, poor phase tracking, which in turn resulted in lane jumps, CDI drifts, and MTG jumps or failure to count. Flights 1-6, 1-10, 1-23 and many others exhibited these symptoms coincident with poor Station A S/N ratio.

9.4.6 Ground Site S/N Comparison

An analysis made of strip chart CDI records for both the ground and airborne tests shows similar irregularities or needle jumps both in length and magnitude. The ground test data also showed a slowly shifting bias which was probably caused by interference from 60 Hz powerline frequency drift. The ground site S/N results compared well with the airborne data with the VHF radios off.

9.5 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. In the Northeast region, two flights encountered light snow storms and a third was under IFR in alternating moderate to heavy rain.

9.5.1 Expected Results

The nature of VLF reception with an E-field antenna, precipitation static can be expected in rain or snow and some types of smoke. 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 extent of the static is a function of particle charge density and the speed of penetration.

9.5.2 Description of Circumstances

Flights through light snow showers lasted no more than five minutes. Rain was encountered during Flight 1-21 (see Figures A.5-1 and A.5-2). Alternating moderate to heavy rain occurred during the first twenty-five minutes followed by intermittent light rain, with the second half of the flight employing different LOPs to determine any effects on navigation. It can be seen that there was no appreciable precipitation effect at Wallops.

However, during Flight 2-11, which was IFR in heavy rain, the first hour was essentially static free (Figure B.2-3) but the second hour encountered heavy precipitation static from 1725 to 1746 EST, during which phase tracking was lost. Figure B.2-6 shows even Station D S/N was completely masked by the static effects.

9.5.3 S/N Variation

There seems to have been no noticeable effect from the snow showers, since during the encounters, only Station A appeared even occasionally slightly degraded whereas the precipitation static should have had an impairing effect on all stations. Flight 1-21 shows S/N ratios decreased during the rain from the values expected with the radio turned off.

(Figure A.5-2). Moreover, 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 back on at the end. The S/N variation during heavy rain in the Northeast as noted above was a drop off in level of from 20 to 35 dB for Stations A and D respectively. The average S/N level was about 3 dB higher in the Northeast than in the Wallops area, but there was no observable difference in the ability of the receiver to navigate properly.

9.5.4 Accuracy and Ease of Following Needle

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 which most likely is unrelated to the precipitation. The position, waypoint and final destination accuracy was about average for the Wallops area. During the IFR flight in the Northeast, the first waypoint was indicated simultaneously by both VHF and Omega, some 50 minutes into the flight and through some areas of very heavy rain. However, 15 minutes later, the precipitation static completely obliterated the S/N for all stations resulting in track loss.

9.6 Flights Parallel to Lines of Position

A series of flights were made parallel to LOPs. In flights along constant LOPs (listed in Table 9-7) the CDI deflection was assumed to depend on only one LOP, and hence incorporate the anomalies peculiar to only the two stations generating the LOP. These anomalies have been discussed above. In addition, flights along certain LOPs reflect the effective increase in noise due to poor geometry of the LOPs.

Flights	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
2-13	B-D
2-31	A-B, B-D
2-44	B-D

Table 9-7 Flights Along LOPs

9.6.1 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 effects of local noise 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.

9.6.2 Observed Results

As discussed above, Station A S/N ratios were often not very good. The flights along and normal to LOPs employing 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.

As discussed in Section 9.4, navigation with Station A encountered various local noise phenomena strong enough to affect the phase measurements from Station A but not the others. Station A S/N was also prone to background noise effects. On Flight 1-22, turbulent air made the pilot's job of filtering the CDI fluctuations more difficult, as is evident from Figures A.6-1 and A.6-4. The apparent improvement in needle following in the second part of the flight after 1139 EDT 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 change so that Station A signals were employed in only one LOP determination. The LOP change resulted in smoothing of the CDI, but the MTG readout, heavily dependent upon the A-B LOP, was still noisy.

On Flight 1-24, a slow CDI drift to the left was observed when flying the C-D LOP which was not correctable with aircraft maneuvering through large heading changes and path offsets. This is attributable to the 43 mile spacing of the C-D LOPs due to poor hyperbolic geometry near the extended baseline as illustrated in Figure 3-3.

On flights over central New Jersey and central Connecticut when the Station A S/N was poor enough to cause indicator drift or lane jumps, it was found possible to fly along constant B-D LOPs. Earlier flight test programs, also indicated the relative ease of flying along constant LOPs (Ref. 29).

9.7 Terrain Effects

Aside from local disturbances near Wallops or the Madison VOR, only the central Connecticut and New Jersey areas produced any position correlated phase anomalies. Flights over hilly or mountainous areas, cities, forests or expanses of water revealed no additional phase anomalies or changes in S/N ratio.

9.7.1 Expected Results

Due to the nature of propagation of VLF signals it was expected that local effects on phase or S/N would simply be too small to observe, as explained in Section 9.2. This was substantiated in previous flight test programs investigating use of Omega signals in valleys where VOR signals were lost and the mountains produced no noticeable effect on Omega navigation information (Ref. 33).

9.7.2 Observations over Cities, Water, Mountains and Forests

It was anticipated that flying over cities could 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 which may not be correlated to location. The signal masking effect of local noise sources during flight below the New York skyline may have caused an increase in received local noise which increased the weak signal light and decreased the S/N ratio (Figure B.3-4). Expected urban noise sources were television towers and powerlines which proved to have no observable effect.

There were no noted irregularities or changes in S/N ratio during flights over water. The areas investigated were: Long Island Sound, Delaware Bay; the portions of Chesapeake Bay, Chincoteague Bay, aand Atlantic Ocean adjacent to the Wallops area, and the New York Lower Bay between New Jersey and Long Island.

Four 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. Washussett, 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 the 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 and precipitation static resulting in loss of phase lock. Flight 2-51 was flown at 2500 ft into the valleys surrounding Mt. Washington which rises to 6288 ft. A lane jump was encountered once clear of the narrows valleys and in open terrain north of the mountain. But flight within several hundred feet of cliffs towering 3000 ft overhead encountered no signal loss or increase in weak signal lights.

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.

9.8 Maneuver Effects

Flights 2-7, 2-21 and 2-51 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 rapid pitch up maneuvers were accomplished at various altitudes with no apparent effect on Omega presentation or S/N ratio.

Section 10

SUITABILITY OF LOW COST OMEGA FOR GENERAL AVIATION

In order for any new navigation system to be considered suitable for introduction into use by general aviation, two important considerations must be investigated: signal availability at all altitudes and weather conditions, and reliable accuracy. From the users' standpoint, two additional suitability requirements must be met: reduced pilot workload to maintain safe flying conditions, and current system status information as might be found in Notices to Airmen.

10.1 Signal Availability

With the broad coverage of Omega, navigation signals should be available at least at all altitudes providing terrain clearance.

With no radio horizon effects, the greater signal availability of Omega would be advantageous for low-altitude maneuvering for approaches at airports where VOR coverage is poor. 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 program to confirm local interference effects which may, in fact, be manifestations of the current experimental status of the Omega system.

The Station A S/N was sometimes too low along the Atlantic coast to be used for navigation. This is due to several causes: low station power output (Norway isn't expected to be at full power for some time), Greenland icecap attenuation (shadow effect), and anisotropy of atmospheric attenuation along east-west paths (the west traveling energy is attenuated 2.2 times more than the easterly, Ref. 6). Experience from this flight test program indicated that the antenna system (coupler and ground circuits) installation is critical to received signal strength.

Finally, precipitation static can adversely affect even strong signals if E-field antennas are employed. Therefore, H-field loop antennas would be a requirement for IFR Omega use.

10.2 Observed Accuracy

The observed accuracy of the Omega system for the Northeast Corridor and Wallops area flights was quite satisfactory for enroute RNAV and most likely satisfactory for terminal operations. Only nonprecision approach capability was investigated in the flight program.

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. These results compared well with predicted accuracies. Table 10-1 shows a comparison of different types of Omega navigation and their accuracies.

Mode	Expected Accuracy	Source
Simple Omega	0.5 - 2.0 nm	Swanson (Ref. 34)
Differential	0.25 - 0.5	Brogden (Ref. 35)
Composite	0.3 - 1.5	Pierce (Ref. 9)
Difference Frequency	0.75 - 3.0	Swanson (Ref. 36)

Table 10-1 Expected Omega Accuracy by Mode

Overall Omega accuracy, however, can be a strong function of receiver design and local interference. 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 base case for general aviation Omega receivers. But even the most expensive systems are not immune to lane jumps (Ref. 37)

A simple statistical analysis of radial errors was done on a sample of 81 waypoints in the Northeast and Wallops regions. The sample mean was $\bar{x}$ = .74 nm and the standard deviation was σ = .77 nm.

10.3 Required Pilot Technique and Pilot Reaction

As discussed in Section 9.4.2, two types of indicator fluctuations occurred, requiring the pilot to visually filter the output in order to navigate smoothly. In the instance of a short term phase instability the pilot would simply change heading slowly using half standard rate turns (1-1/2° bank). Indicator fluctuations in the Wallops area due to local interference were impossible to filter due to the rapidity and magnitude of fluctuations, and the pilot was required to hold a heading for several minutes until a stable CDI offset indication could be obtained. These latter fluctuations had a period of about one second and magnitude of $\pm$ 2 CDI dots ($\pm$ half scale or 2 nm). It has been shown that a pilot will tend to lose confidence in his navigation system if he continuously observes random meter fluctuations due to noise of greater than one fifth scale deflection (30 μa, one dot) (Ref. 30). Greater accuracy and less susceptibility to short-term noise, can 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.

Four pilots were employed in the course of these flight tests. Each filtered the CDI output at a different sensitivity with heading changes varying from 5° to 20° per dot on the CDI, and using from 1/2 to 1-1/2 standard rate turns. The lower change rates tended to produce a smoother course.

Pilot reaction varied depending on the stability of the indicator readings and waypoint accuracy. The range of reaction was from that of pure skepticism as to the ultimate use of Omega for general aviation, to a guarded optimism that indicated a need for more receiver filtering and a blunder protection system to avoid incorrect waypoints during IFR operations.

10.4 Need for Current System Status Information

Two forms of status information will be required by pilot users. One is a projection of station availability including output power levels and periods of outage published in Notices to Airmen for flight planning purposes. The other will be an augmentation of the weak signal light concept to include a steady light to indicate either a complete station outage, signal loss due to interference or computed LOP track loss.

Presently the only method of obtaining current detailed system status information is calling the Coast Guard Omega Navigation System Operations Detail (ONSOD). A reporting capability exists in the form of Notices to Mariners, but these reports are not very timely by mail. During a year's time of some 2600 notices, only 35 pertained to the Omega System, and only two system status and availability prognosis reports were made.

Various forms of improved status reporting systems have been proposed. A phase anomaly or station outage broadcast warning system for receivers has been proposed by Pierce (Ref. 6). It consists of changing an 11-1/3 Hz sideband modulation to 5-2/3 Hz on the 10.2 kHz carrier which would activate a warning circuit in the receiver. A more immediate interim voice system to be used with VHF receivers similar to Flight Service information is detailed in Appendix C.

10.5 Comparison of Omega Results with VOR/DME Results

The FAA has developed a VOR route width standard of ± 4 nm (up to 51 nm from the VOR, with a widening at ± 4.5° beyond 51 nm) based on system use accuracy data (Ref. 38). Recent NAFEC flight tests have shown VLF navigation to be an acceptable system that will operate well within the 4 nm tolerance (Ref. 39).

A nonprecision approach standard based on VLF with minimums down to 400 ft and one mile has been proposed by Litchford (Ref. 40). This would decentralize major hub airports and VOR beacon facilities allowing considerable growth in RNAV airways where the VOR airways can be come saturated.

A comparison of test flight statistics using Omega was made with previous data on the results of VOR/DME RNAV used for low altitude VTOL corridors in the Northeast Corridor (Ref. 2). The VTOL VORTAC statistics are given in range and bearing error and the Omega in radial position error as shown in Table 10-2

	VORTAC Bearing (deg)	VORTAC Range (nm)	Omega Radial (nm)
Mean	0.1	-0.1	.74
Standard Deviation	2.7	0.7	.77

Table 10-2 Comparison of VORTAC and Omega Waypoint Position Errors

It can be seen from the above Table that Omega navigation has a strong potential to augment VHF/UHF systems, and can increase at low cost the enroute and terminal area traffic density. But full system operational status and availability as well as flight information are prerequisites before complete adaptation for general aviation use.

Section 11

CONCLUSIONS

The conclusions derivable from this evaluation fall into four general categories. The categories that follow are interference and diurnal variation effects, transmitter difficulties, airborne equipment, and user considerations.

There was no measurable effect on navigation from flying very near coastlines, powerlines, television transmitters, over urban areas, between mountains or during extensive aircraft maneuvers. There was no diurnal repetition of S/N variation and diurnal phase shifts had only a minor effect on navigation accuracy.

Local noise sources can have a significant effect on navigation but have not been conclusively determined. Most likely VOR transmitters (e.g., the Madison VOR) and some radar sites such as at Wallops affect the measured phase in the receiver. There is a noticeable decrease in magnitude of this effect with altitude.

Day to day variations in S/N ratio were observed with all the Omega stations, but most predominantly with the

Norway station S/N in the Wallops area. The Station A S/N varied from very strong to unusably weak during a single day. Since station coverage is limited and only five stations are operating, Station A is critical to good LOP geometry in the northeast United States. A need for more frequent Notices to Mariners or inclusion of Omega information in Notices to Airmen has been demonstrated.

Receiver operation was satisfactory and provided high accuracy when S/N ratios were moderate to good. The cost and accuracy compare well with the VORTAC system. Currently, ground computation is necessary for flight planning, but new waypoints can be approximated enroute with little loss of accuracy if LOPs are plotted on charts beforehand. Waypoint blunders, however, are readily made and a need for some type of blunder detection in waypoint selection was determined. An extra LOP tracking loop would enhance the navigation reliability by allowing the pilot or an automatic circuit to switch when one of the currently used LOP pair stations fails, or becomes unusably weak.

Antenna and receiver installation are critical to good signal reception, especially if the aircraft is equipped with DC to AC invertors. For this reason the VHF transceivers had the greatest effect on the S/N ratios of any interference. For IFR operation it is probable that an H-field loop antenna will be necessary since the E-field wire is strongly susceptible to precipitation static.

The pilot's workload during long enroute waypoints was considerably reduced from the comparable VOR navigation, but with waypoints spaced closer than ten miles apart the workload become heavy. During periods of local interference the pilot was required to visually filter the CDI output and occasionally fly compass headings with infrequent CDI updates. Pilot reaction to the system's use ranged from strong pessimism to a guarded optimism with qualifications.

The Omega system as it exists is not one which allows the pilot to begin use enroute without an accurate position fix, and care must be taken in the choice of LOP pairs to maintain the optimum geometry for reliable navigation, However, it does provide increased user freedom, safety, and economy by allowing direct routing rather than beacon flying. Finally, the system will be found to be suitable for continuous coverage inexpensive area naivgation, especially where VHF coverage is not available.

Section 12

RECOMMENDATIONS

The following recommendations are given from insight gained during flight testing. They are grouped by additional flight testing, equipment modification, and system improvements.

Additional flight tests would be useful to determine areas of encountered VLF interference, and these could be charted as VLF warning areas on appropriate NOS publications for airmen. Further flight tests would determine position filtering parameters appropriate to enroute and approach portions of the flight profile.

Development of a dead reckoner or additional LOP tracking loop is needed for aviation users who might experience temporary signal loss. Automated filtering will be required for commercial low cost receivers, along with a blunder detection warning system and a receiver operational status feedback to the pilot.

Effort should be made to expedite implementation of an interim system status reporting system for aviation use.

Automated broadcast reporting techniques should be refined and implemented when available. Effort also should be made to expedite the full eight station operation at full power to provide the necessary coverage and signal redundancy. Area navigation enroute and terminal standards should be designed to minimize waypoint ambiguity and workload. Finally, it is highly desirable that the National Ocean Survey prepare aeronautical charts (enroute and sectional) with LOPs from three stations on a chart printed in one tenth lane increments (e.g., a New York sectional with A-B, B-D and A-D pairs, or A-B, B-C and A-C pairs) for ease in flight planning and enroute course changes.

Appendix A

WALLOPS AREA FLIGHT TESTS

Organization of Flight Test Appendices

A test description page is included for each flight in the Wallops area in Appendix A and each flight in the Northeast Region in Appendix B. In addition, for a selected sample of flights which are referred to in the text flight data pages are included.

The first flight data page includes the Omega indicator data which are readouts of miles to go (MTG) plotted on a scale of 0 to 75 miles, four status flags and the left right needle deflection (CDI) as described in Section 8.3 The four status flags are a bistable to/from indicator, autozero activation, reset of lane accumulators, and weak signal light activation in the past ten seconds. Event mark number changes are plotted along the x-axis. Time is labeled every ten minutes.

Following the Miles to Go and Needle Deflection page are two pages of S/N ratio for Stations A, B, C, and D which derive time axis and event markers from the same data as MTG and CDI. The location and description information on the MTG and CDI page are abbreviated for completeness and are encoded according to the Glossary and the following conventions:

Wsl A	Weak signal light observed during Station A transmission period
T/O WAL	Takeoff from Wallops airport
Wpt 1: Omega	Omega indication of waypoint 1 (from flag, needle centered and MTG zero).
Wpt 1: VOR	VOR indication of waypoint 1
Wpt 1	Visual indication of waypoint 1
AZ 2	CDI is autozeroed (symbol used only when more than two minutes elapse between waypoint and autozero)
Coast L-W	Crossing a coastline for land to water
7 SSE WAL	Visual position report of 7 nm to the south southeast of Wallops airport
1 NW twr 229	Visually 1 nm northwest of tower with charted height of 229 ft above MSL.

TEST DESCRIPTION

Flight No. 1-0

TEST OBJECTIVES:	Provide initial view of S/N ratios in the Snow Hill VOR area. First in a series of flights between Salisbury and Wallops past the Snow Hill VOR providing local interference data at various altitudes. Check point to point accuracy.
DATE:	19 Feburary 1975
TIME:	1546 - 1601 EST
ORIGIN:	Salisbury
DESTINATION:	Wallops
ROUTE:	Via Snow Hill VOR
ALTITUDE:	1500 ft.
WEATHER:	VFR, 15 kts, SW
SUMMARY:	First flight in the Snow Hill - Wallops area, initially along powerlines running south from Salisbury. Flew within one mile of the Snow Hill VOR. Recorded data not reproduced.

TEST DESCRIPTION

Flight No. 1-1

TEST OBJECTIVES:	Provide initial area survey of Wallops and mid Delmarva Peninsula at 5000 ft. and selected lower altitudes with radar tracking, to determine coast effect, level of accuracy achievable, and location and magnitude of interference.
DATE:	20 February 1975
TIME:	1020 - 1222 EST
ORIGIN:	Wallops
DESTINATION:	Wallops
ROUTE:	Low altitude star
ALTITUDE:	5000 ft. - 2000 ft.
WEATHER:	VFR, 15 kts, NW
SUMMARY:	Star route flown with radar tracking at 5000, 4000, 3000 and 2000 ft. Initial circuit flown at 5000 ft. was: Wallops, Parksley (Wpt 1), Wallops Coast Guard (Wpt 2), Pocomoke (Wpt 3), Metomkin Island (Wpt 4), Saxis (Wpt 5), Chincoteague

Flight No. 1-1 (con't)

SUMMARY: Refuge (Wpt 6), Snow Hill VOR (Wpt 7), and Wallops airport. Then on the second circuit each successive leg was flown 1000 ft. lower. The data is divided into the first 62 minutes and the last 58 minutes.

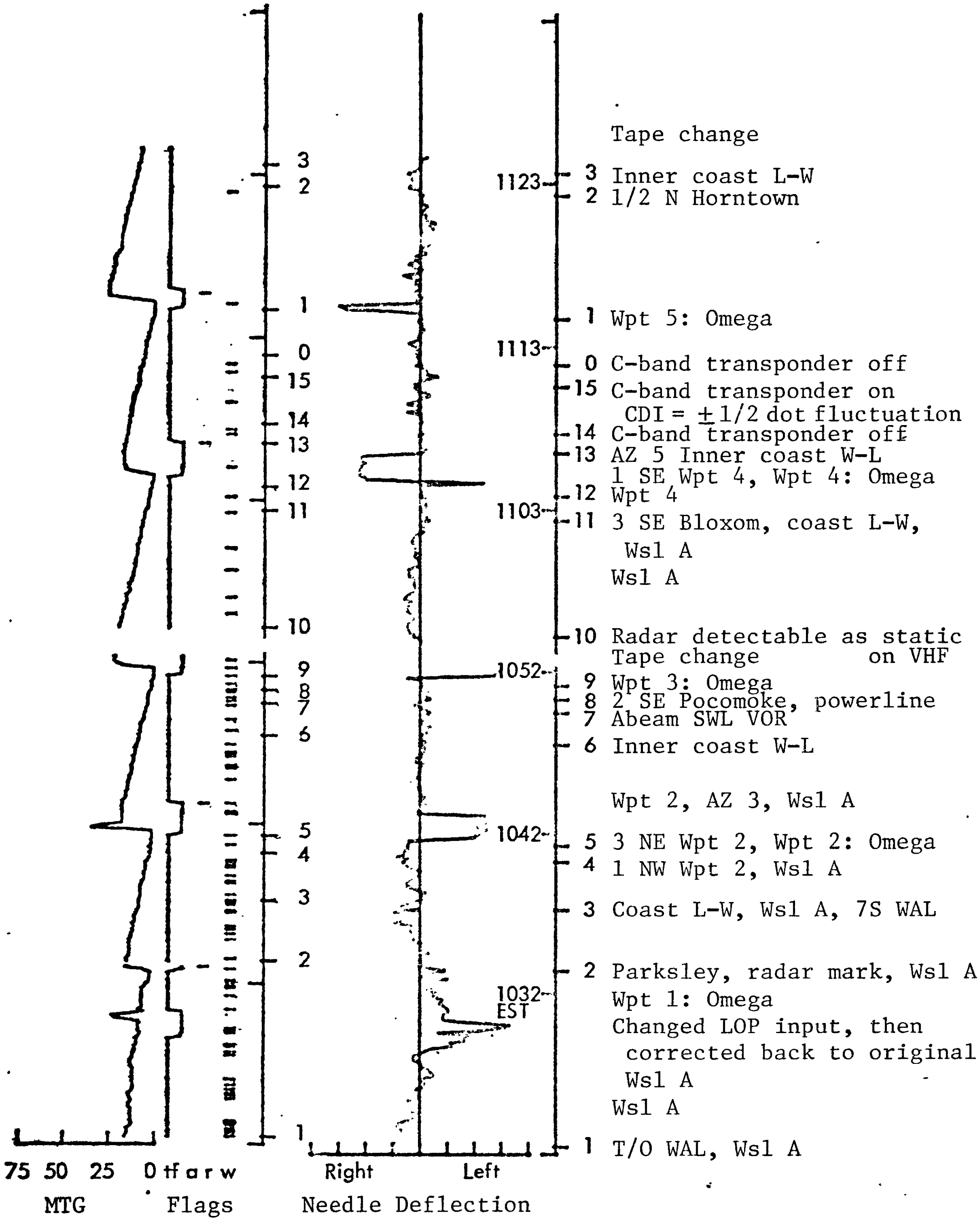


Figure A.1-1 Flight 1-1 (Part 1) Miles to Go and Needle Deflection

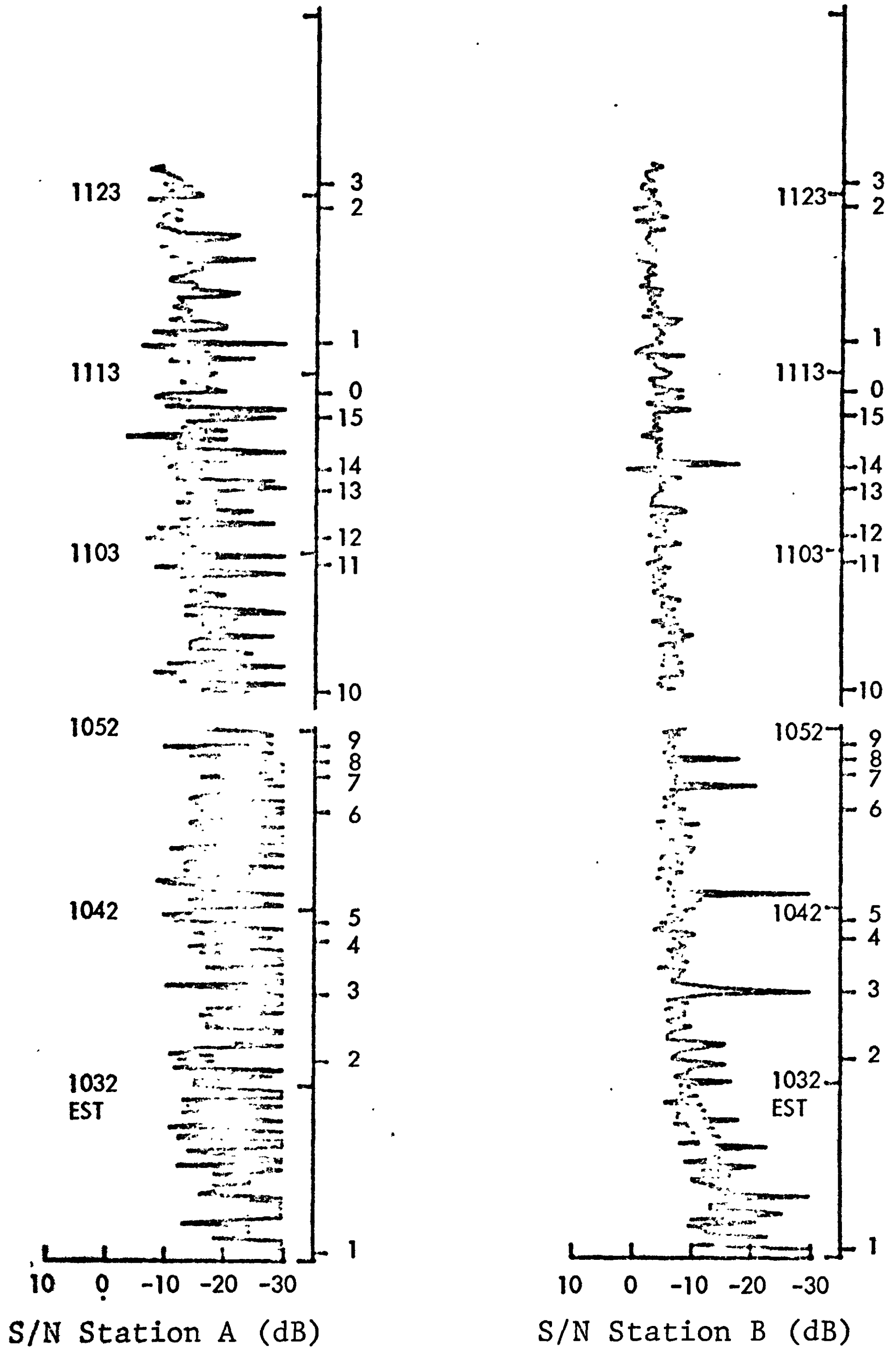


Figure A.1-2 Flight 1-1 (Part 1) S/N Stations A and B

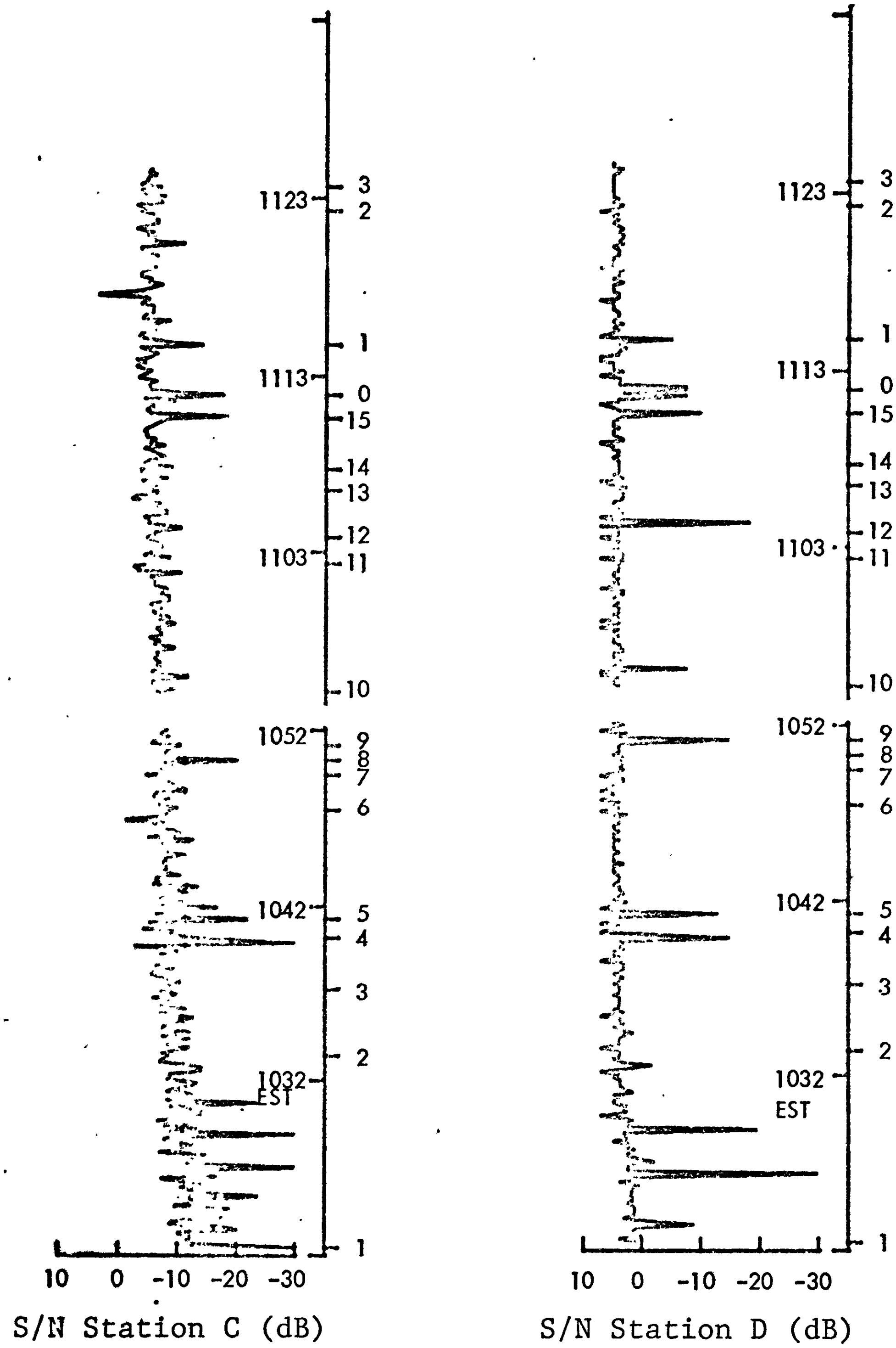


Figure A.1-3 Flight 1-1 (Part 1) S/N Stations C and D

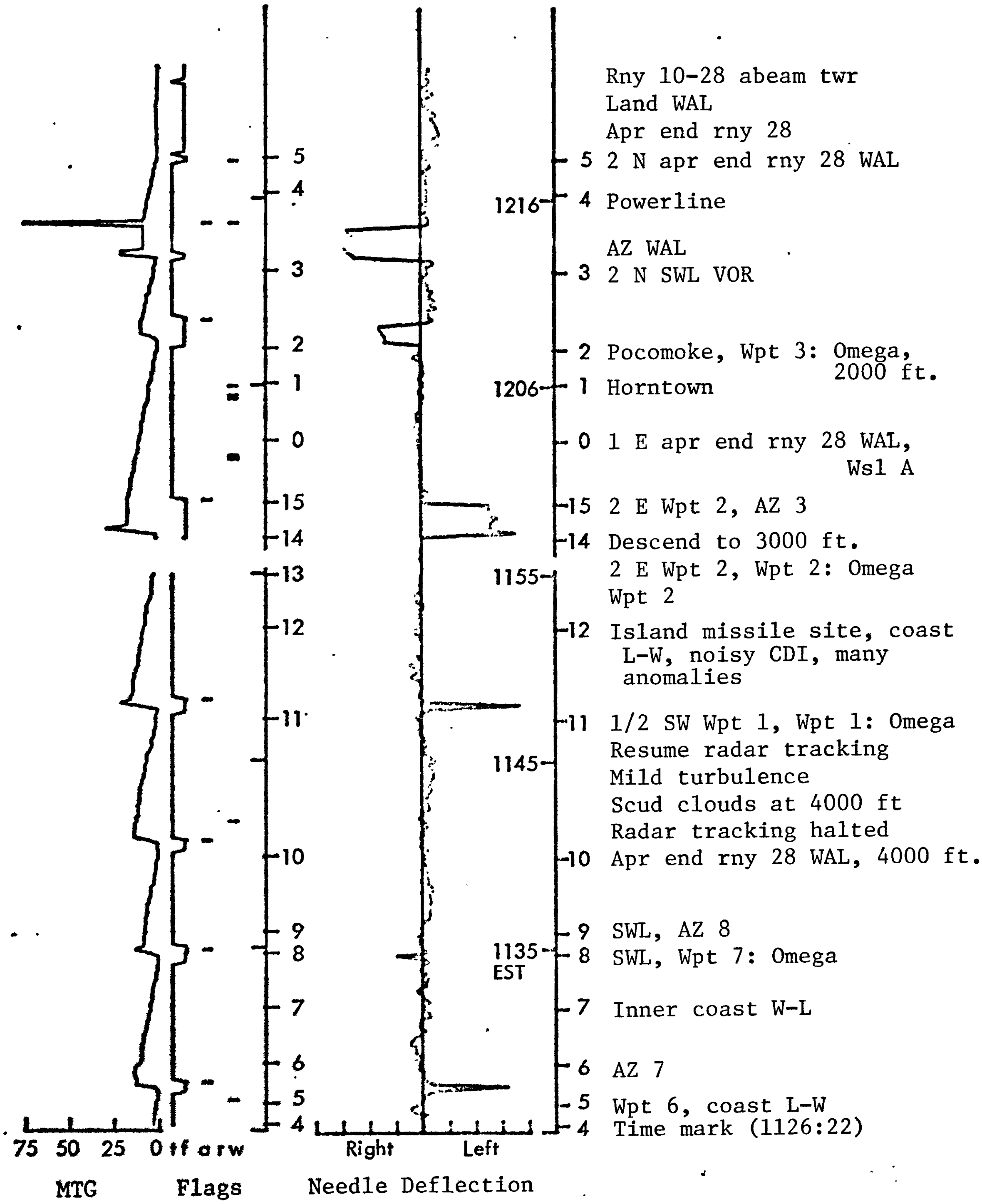


Figure A.1-4 Flight 1-1 (Part 2) Miles to Go and Needle Deflection

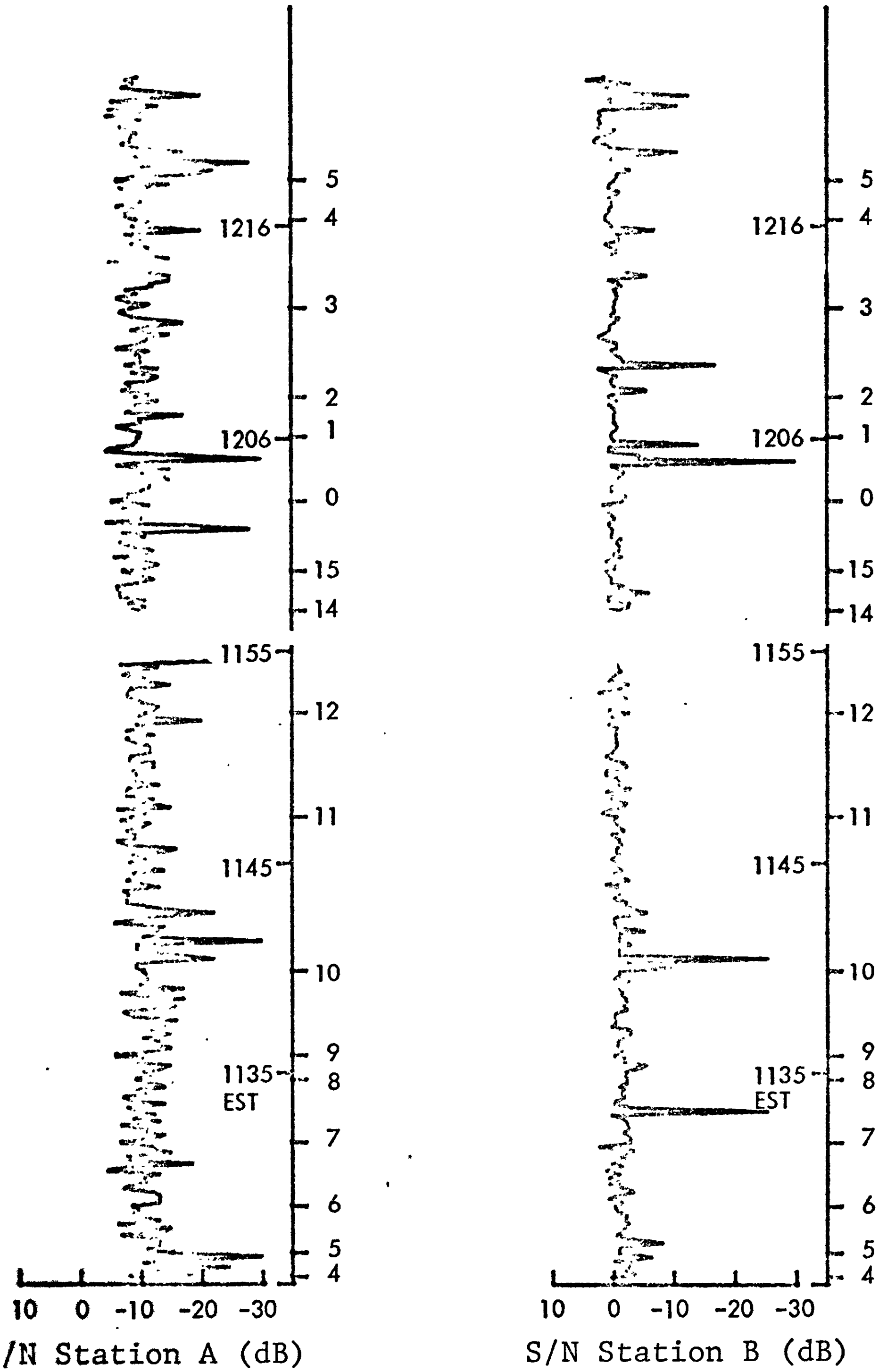


Figure A.1-5 Flight 1-1 (Part 2) S/N Stations A and B

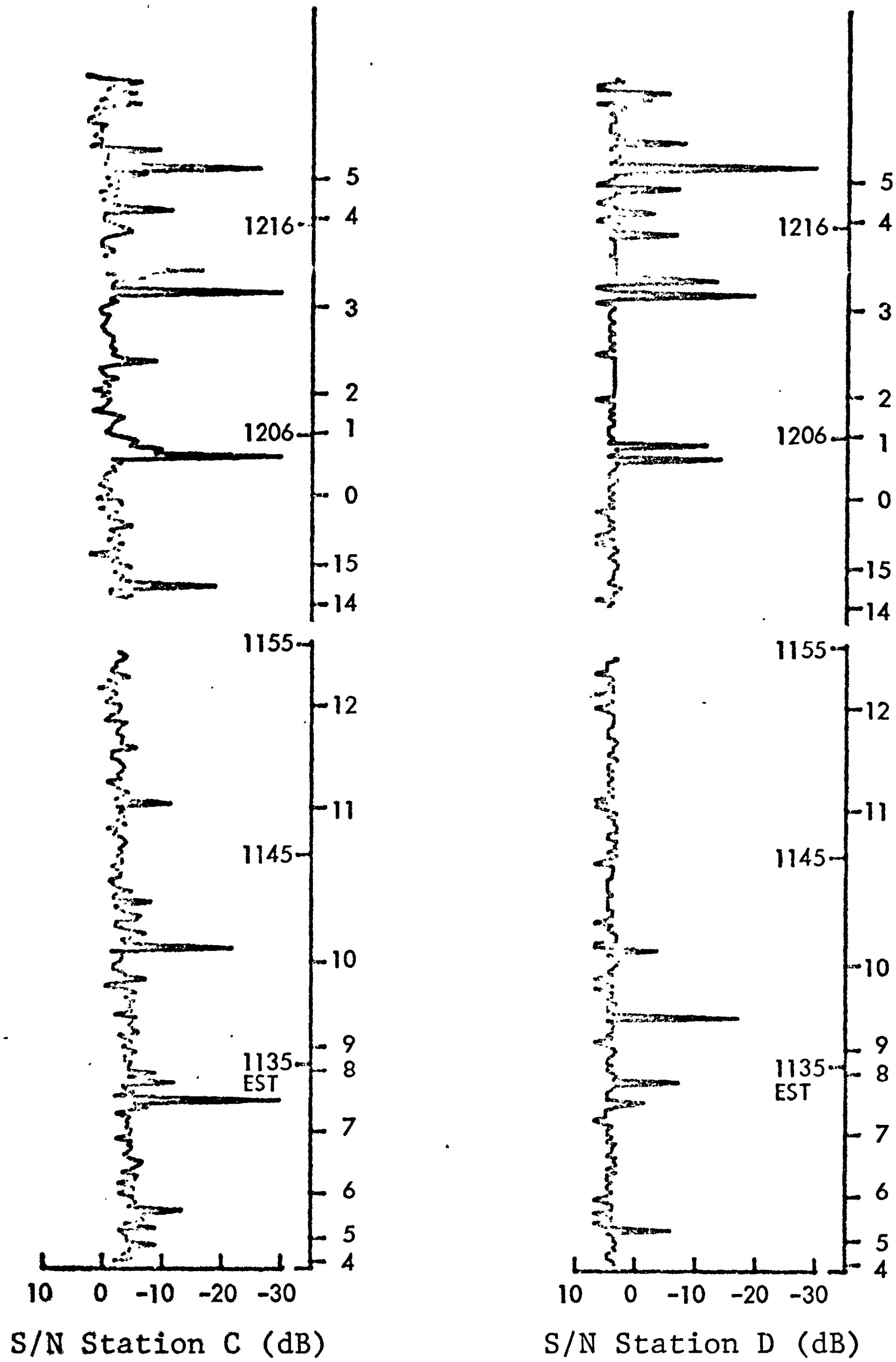


Figure A.1-6 Flight 1-1 (Part 2) S/N Stations C and D

TEST DESCRIPTION

Flight No. 1-2

TEST OBJECTIVES: Obtain additional S/N data near Snow Hill VOR. Second flight past the Snow Hill VOR and powerlines to Salisbury at low altitude to investigate interference and accuracy

DATE:	20 February 1975
TIME:	1259 - 1320 EST
ORIGIN	Wallops
DESTINATION:	Salisbury
ROUTE:	Via Snow Hill VOR
ALTITUDE:	1000 ft.
WEATHER:	VFR, 15 kts, NW

SUMMARY: Flight along powerlines from Wallops to Salisbury for refueling.

TEST DESCRIPTION

Flight 1-3

TEST OBJECTIVES:	Obtain S/N plot of Wallops area at 10,000 ft. with branches to decreasing altitude as radar coverage allows (includes return trip from Salisbury).
DATE:	20 Feburary 1975
TIME:	1359 - 1617 EST
ORIGIN:	Salisbury
DESTINATION:	Wallops
ROUTE:	High altitude star pattern
ALTITUDE:	10,000 ft.
WEATHER:	VFR with clouds at 4000 ft broken to scattered
SUMMARY:	Flight made at 10,000 ft detected coast effect. Route of flight was Salisbury, Ocean City (Wpt 1), Crisfield (Wpt 2), Hog Island (Wpt 4), Snow Hill VOR (Wpt 5), Watts Island (Wpt 7), Wallops (Wpt 8). Some noticeable effect of local interference on CDI.

TEST DESCRIPTION

Flight No. 1-4

TEST OBJECTIVES:	Check point to point accuracy during transition. Obtain additional S/N ratio data for the southern Delmarva Peninsula.
DATE:	20 February 1975
TIME:	1651 - 1740 EST
ORIGIN:	Wallops
DESTINATION:	Norfolk
ROUTE:	Via railroad to Kellam, along Bay Bridge to Norfolk
ALTITUDE:	1500 ft.
WEATHER:	VFR, 15 kts, SW
SUMMARY:	Incorrect waypoint set in to New Church. No interference from powerlines along railroad. Incorrect waypoint for Norfolk. Sunset after landing. Coast effect observed leaving Delmarva Peninsula and approaching Norfolk coast.

TEST DESCRIPTION

Flight No. 1-5

TEST OBJECTIVES:	Obtain S/N data, point to point accuracy at night, and attempt to detect coast effects, during Station D transition periods.
DATE:	20 February 1975
TIME:	1818 - 1932 EST
ORIGIN:	Norfolk
DESTINATION:	Wallops
ROUTE:	Via Melfa, Tangier Island and Salisbury
ALTITUDE:	3000 ft.
WEATHER:	Night VFR, 10 kts, S
SUMMARY:	Used radio and visual beacons for a check of night accuracy of Omega. Flight route was Norfolk direct to Cape Charles VOR (Wpt 1), direct Melfa NDB and beacon (Wpt 2), direct Tangier NDB and beacon (Wpt 3), direct Salisbury VOR and beacon (Wpt 4), direct Wallops (Wpt 5).

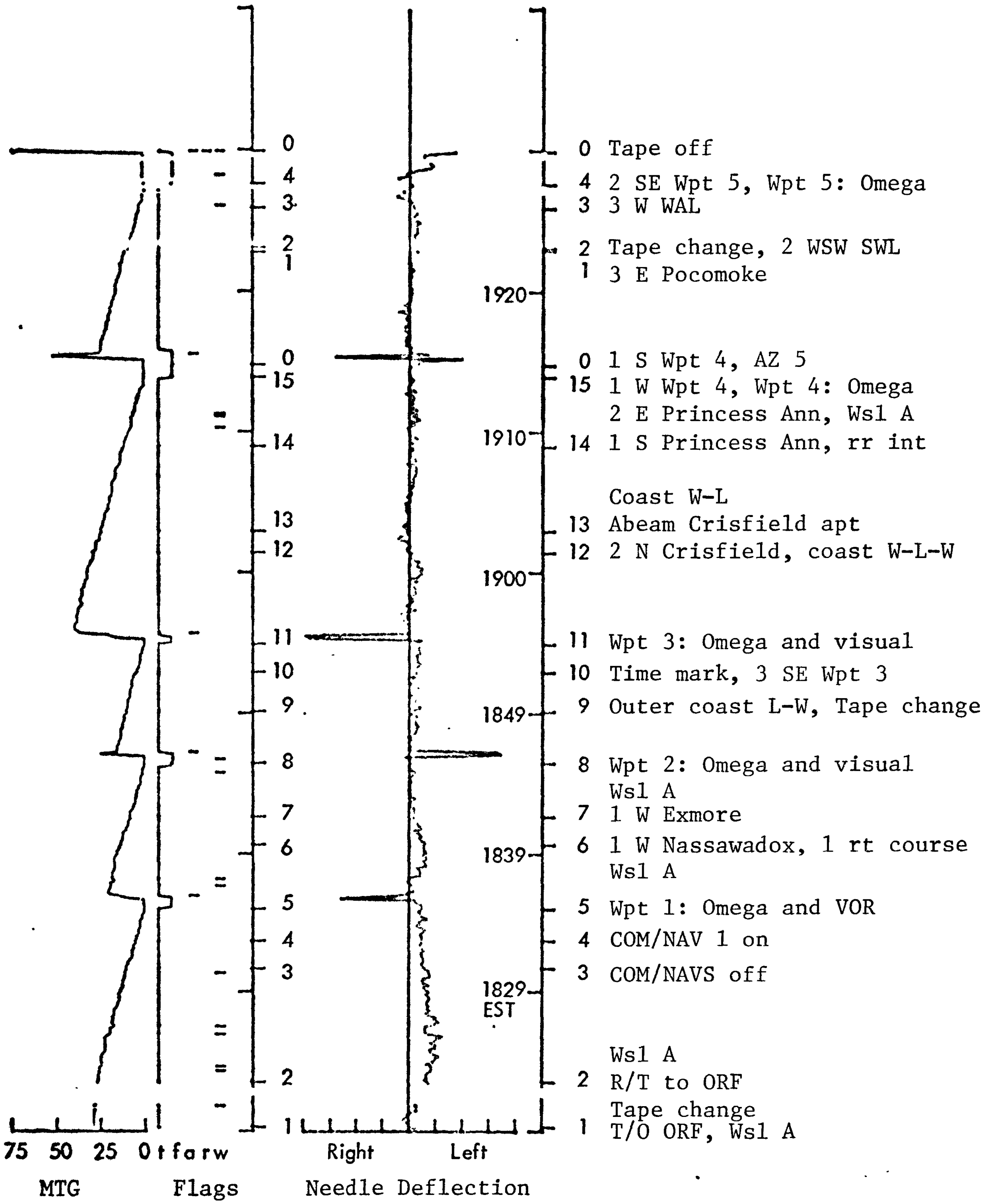


Figure A.2-1 Flight 1-5 Miles to Go and Needle Deflection

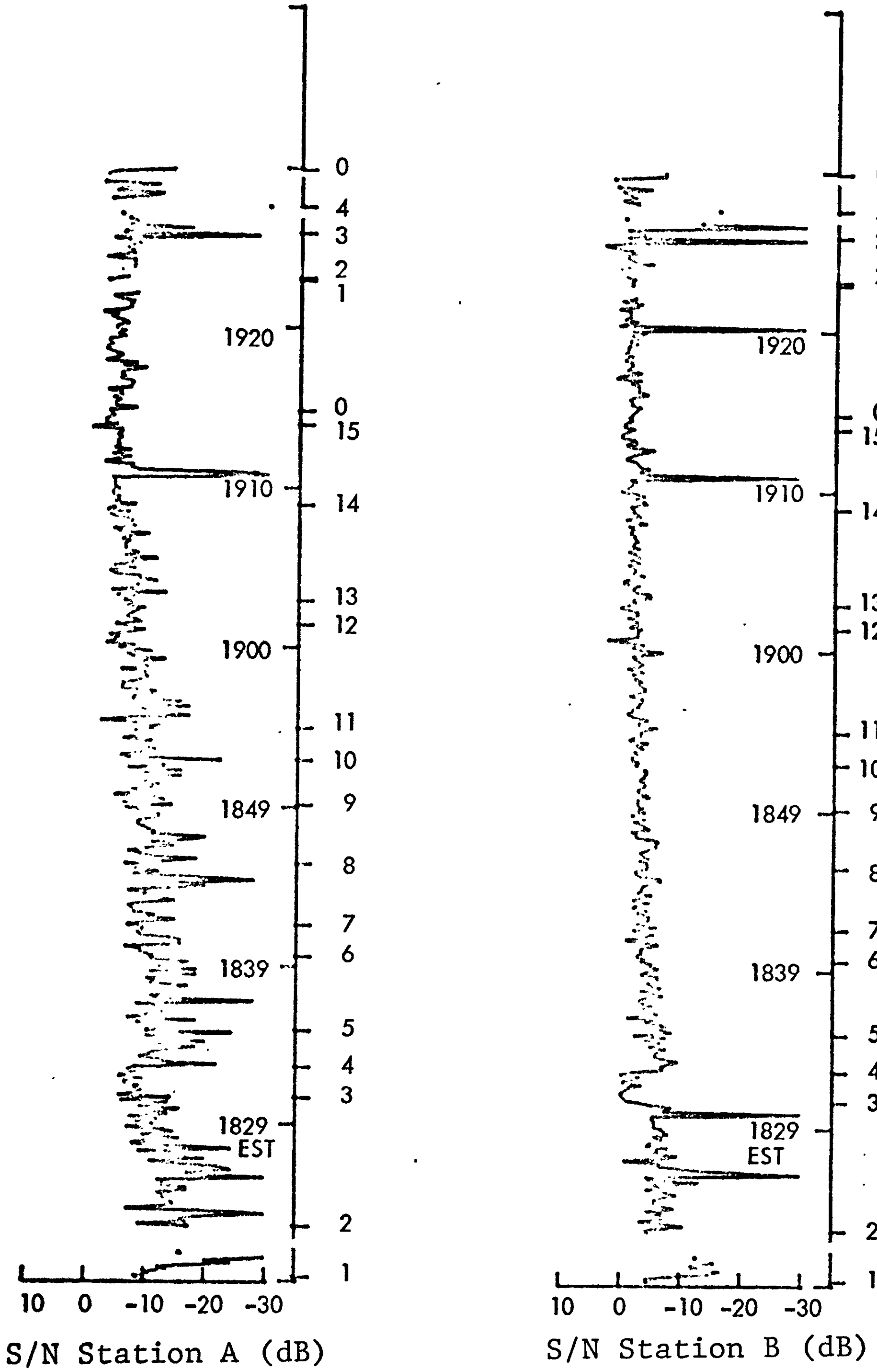


Figure A.2-2 Flight 1-5 S/N Stations A and B

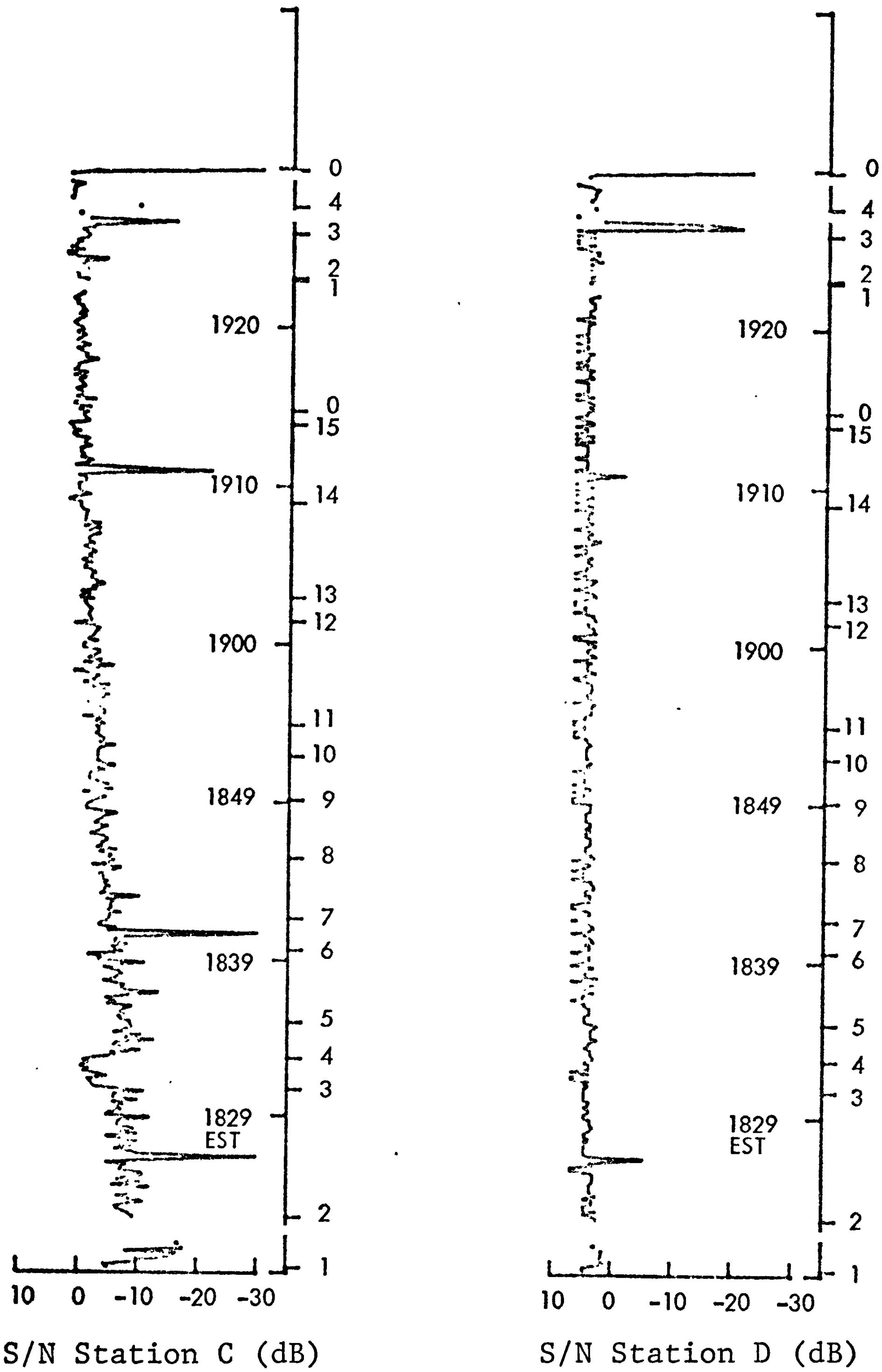


Figure A.2-3 Flight 1-5 S/N Stations C and D

TEST DESCRIPTION

Flight No. 1-6

TEST OBJECTIVES:	Provide initial mapping of S/N in Wallops area at low altitude by flying constant A-B lanes from 20 miles south of Wallops to 20 miles north. Test magnitude and direction of coast effects.
DATE:	21 February 1975
TIME:	1038 - 1320 EST
ORIGIN	Wallops
DESTINATION:	Salisbury
ROUTE:	Modified east-west snake route along the Delmarva Peninsula
ALTITUDE:	2000 ft.
WEATHER:	VFR, 15 kts, SW
SUMMARY:	Flight was modified enroute due to difficulty of obtaining station A signal. Lane count was lost 4 times. Various LOP input changes are indicated and course numbers parallel to the A-B LOP (200 and 600) were flown.

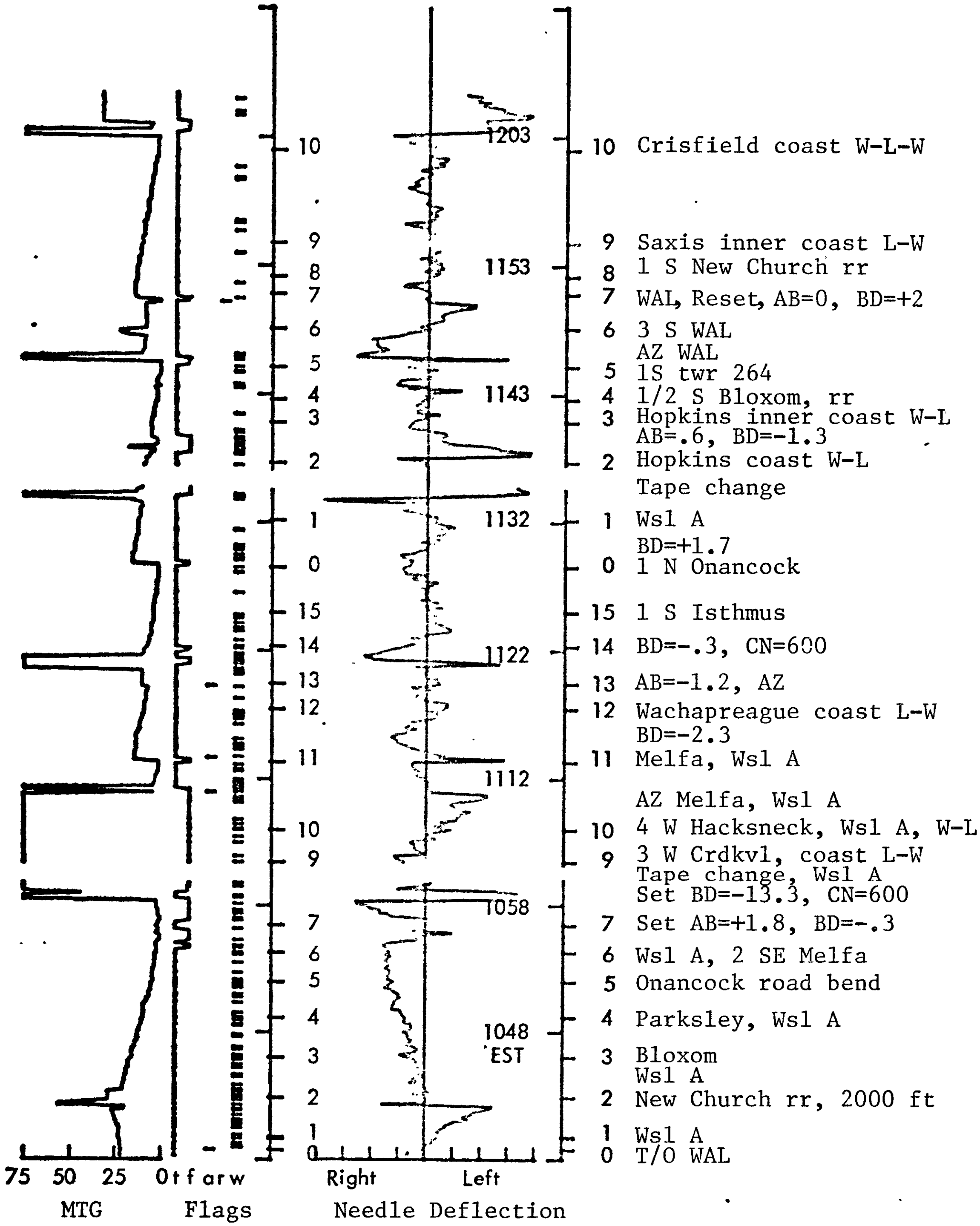


Figure A.3-1 Flight 1-6 (Part 1) Miles to Go and Needle Deflection

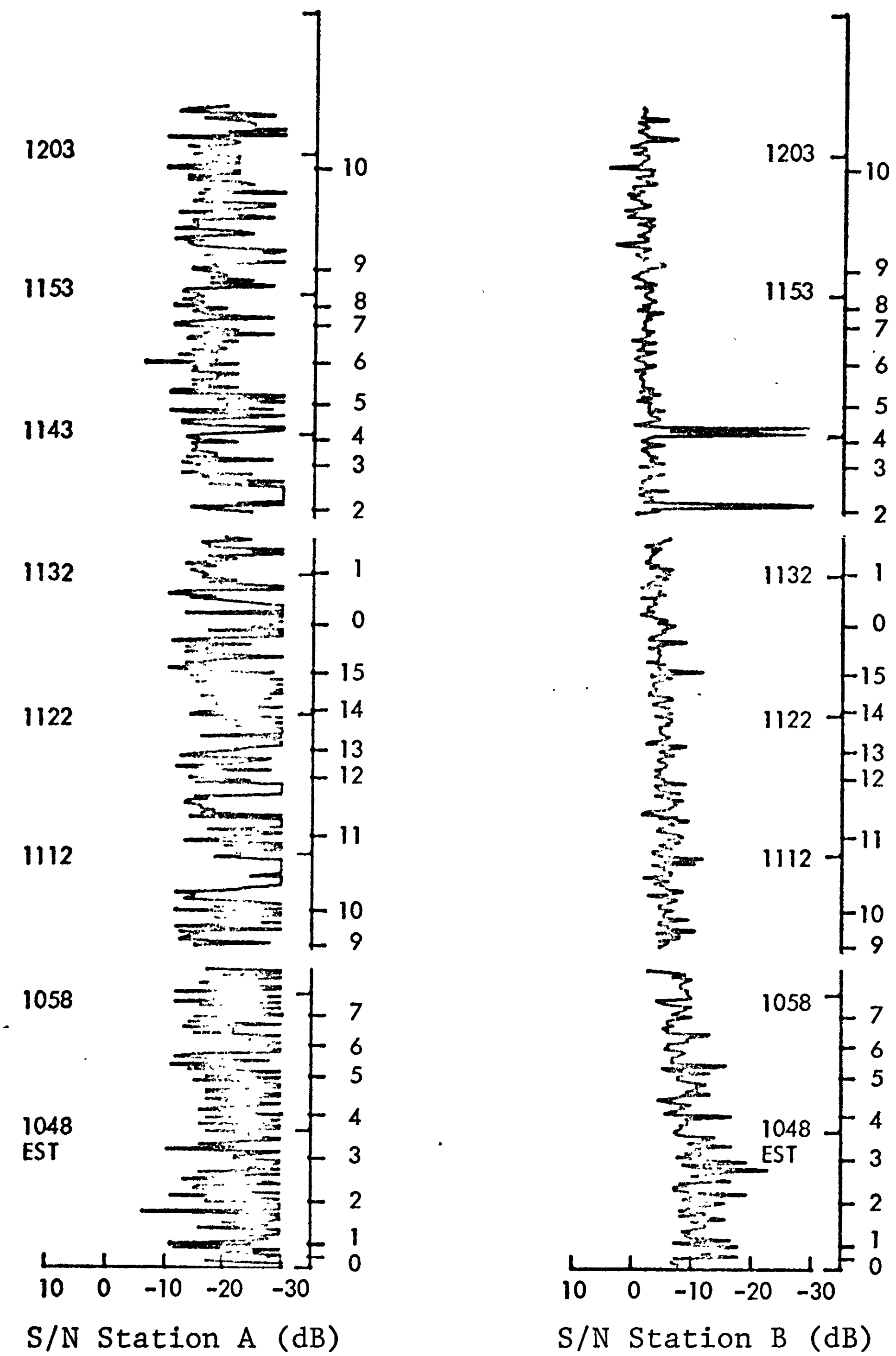


Figure A.3-2 Flight 1-6 (Part 1) S/N Stations A and B

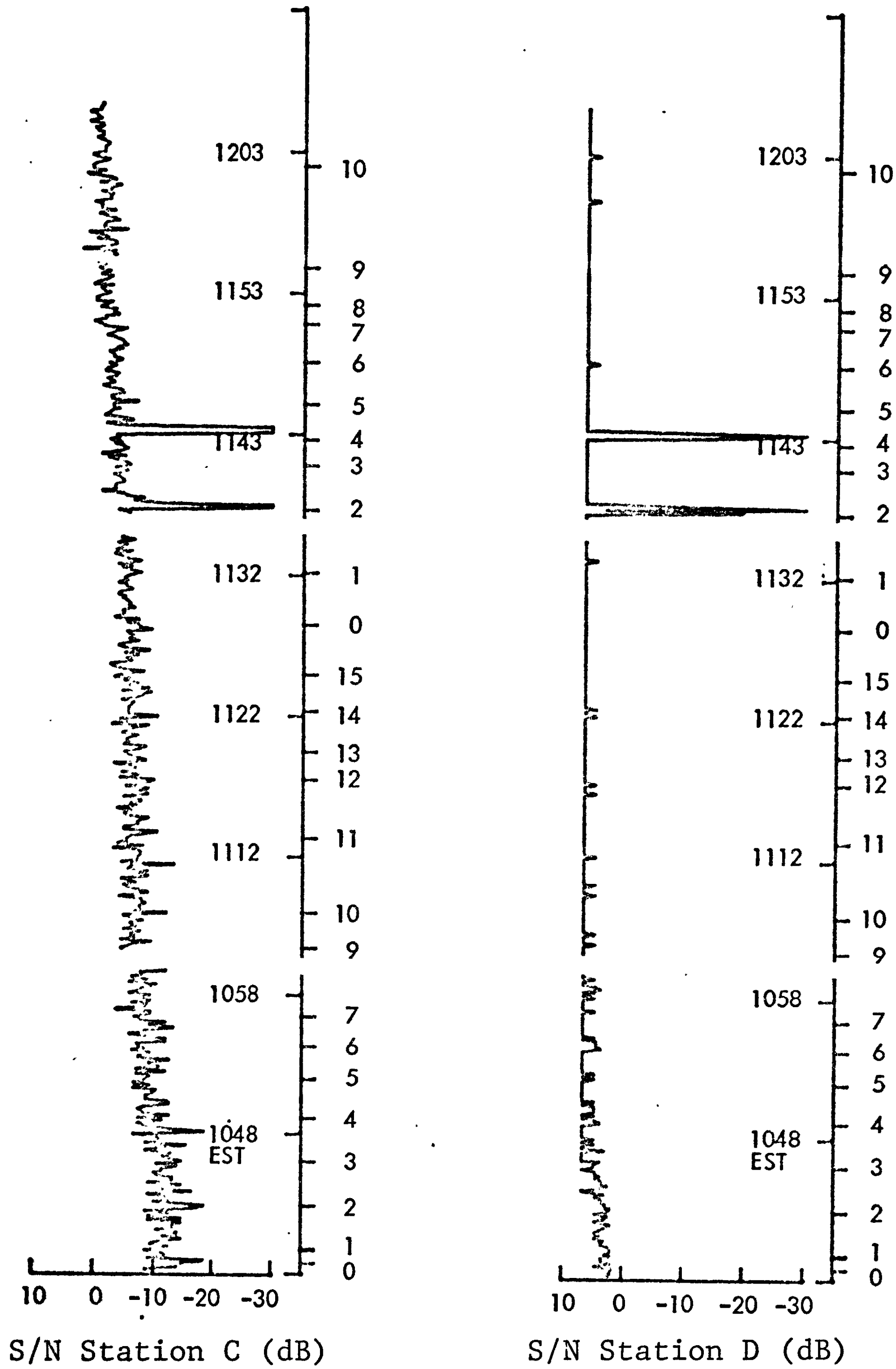


Figure A.3-3 Flight 1-6 (Part 1) S/N Stations C and D

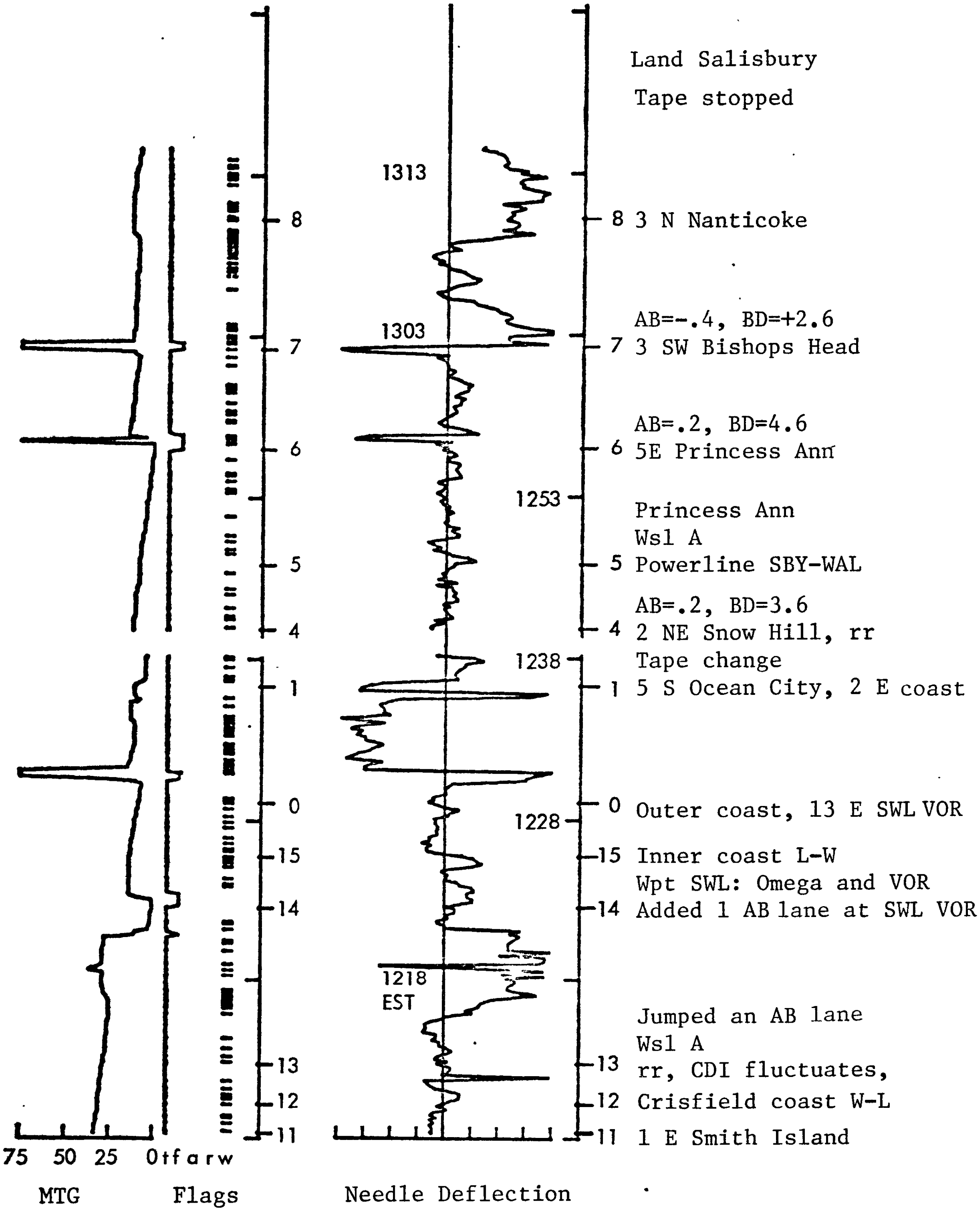


Figure A.3-4 Flight 1-6 (Part 2) Miles to Go and Needle Deflection

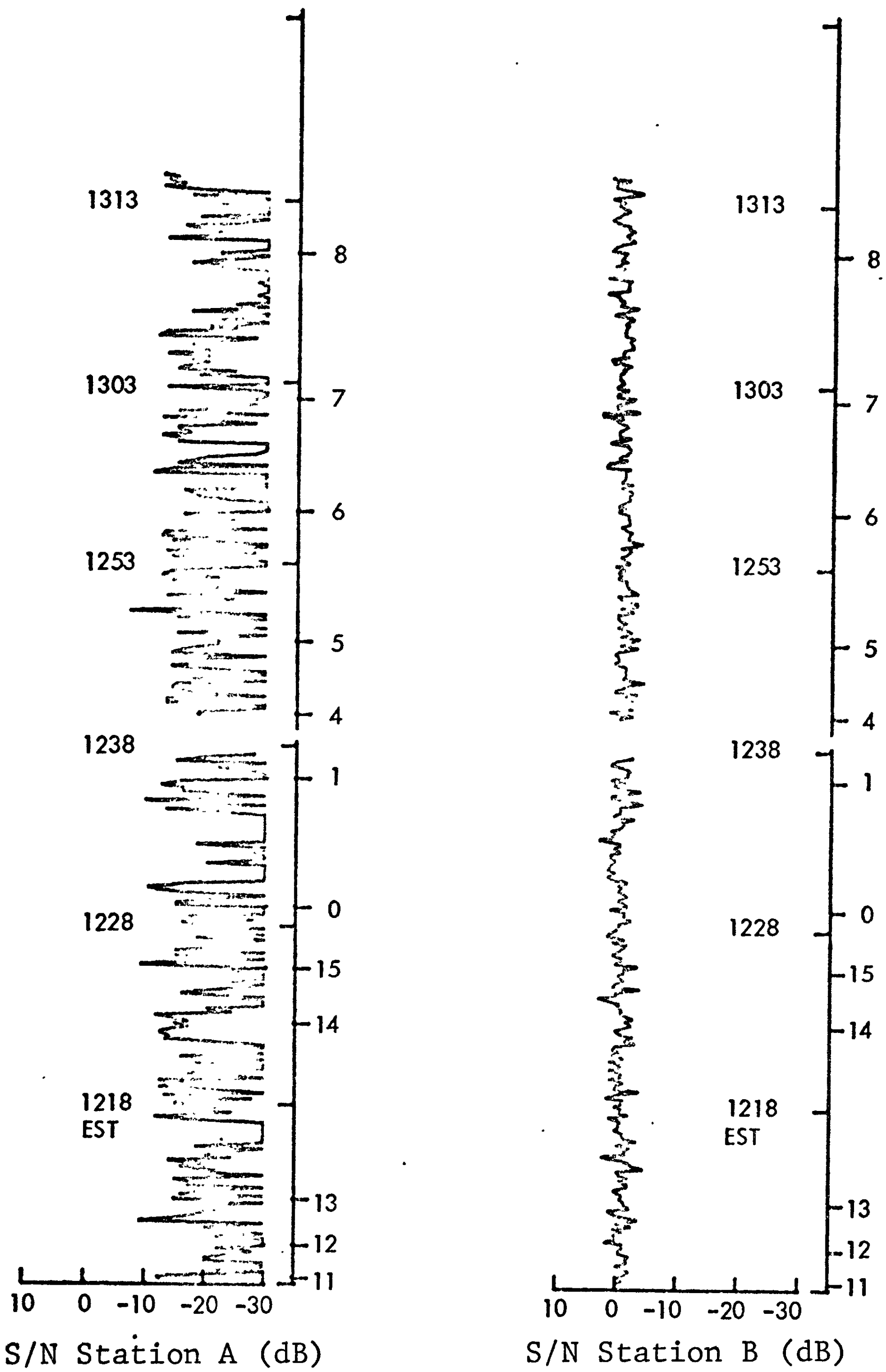


Figure A.3-5 Flight 1-6 (Part 2) S/N Stations A and B

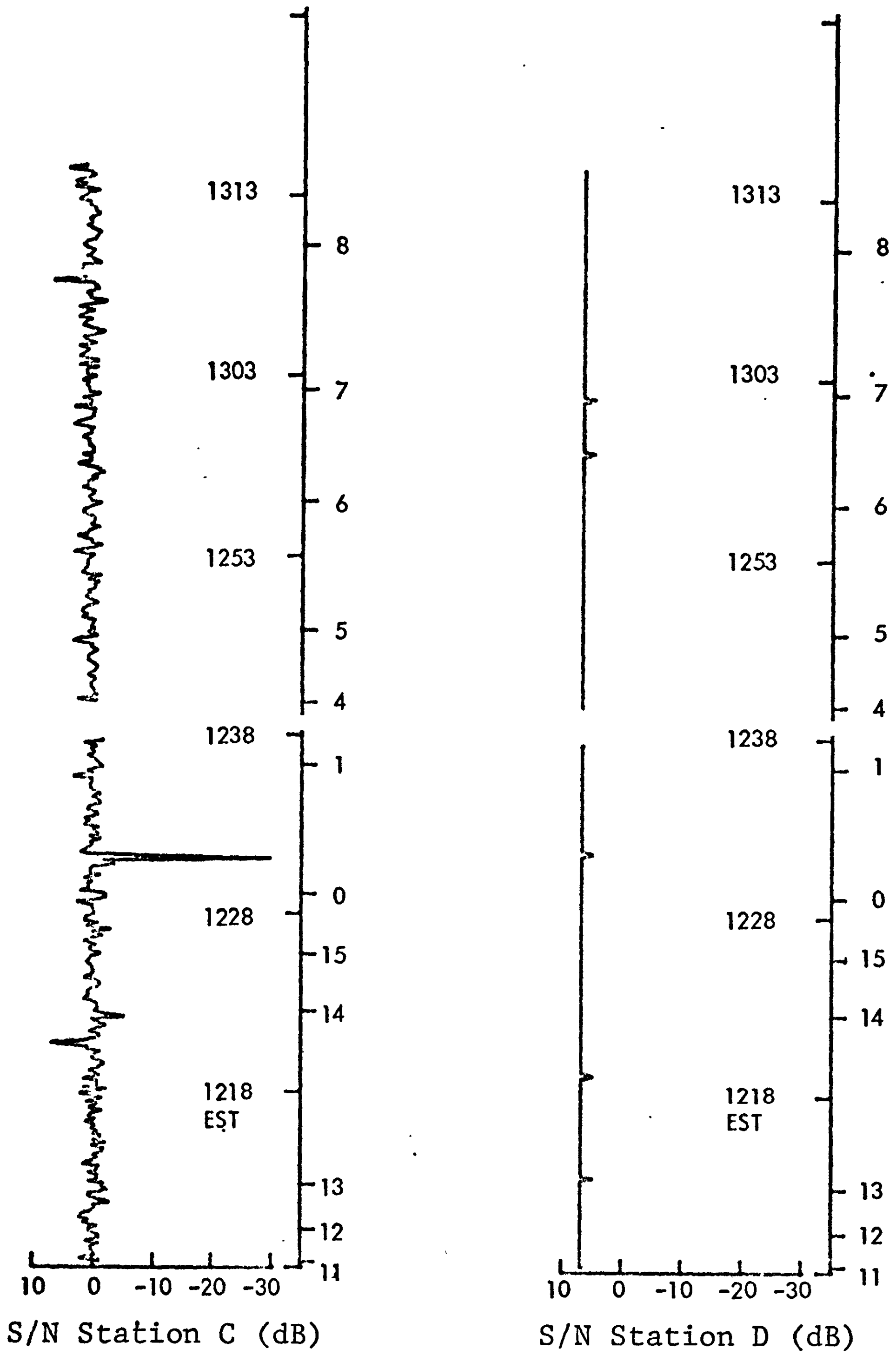


Figure A.3-6 Flight 1-6 (Part 2) S/N Stations C and D

TEST DESCRIPTION

Flight No. 1-7

TEST OBJECTIVES:	Point to point accuracy check through Snow Hill VOR area. Third in a series of flights between Wallops, Snow Hill VOR and Salisbury.
DATE:	21 February 1975
TIME:	1412 - 1432 EST
ORIGIN:	Salisbury
DESTINATION:	Wallops
ROUTE:	Via Snow Hill VOR and powerlines
ALTITUDE:	2000 ft.
WEATHER:	VFR, 15 kts, SW
SUMMARY:	First two thirds of recorded data lost due to improper jack input. Data was begun near Snow Hill VOR 14 minutes after take-off from Salisbury.

TEST DESCRIPTION

Flight No. 1-8

TEST OBJECTIVES:	Initial check of LOP sensitivity with radar coverage along constant A-B and B-D LOPs. This flight to be repeated after sunset (Flight 1-9) and both will investigate interference in the Snow Hill VOR and Wallops areas, coast effects along different LOPs, maneuver effects. Radar coverage will be provided by the Wallops airport FPS-16 tracking radar
DATE:	21 Feburary 1975
TIME:	1624 - 1750 EST
ORIGIN:	Wallops
DESTINATION:	Wallops
ROUTE:	Race track
ALTITUDE:	3000 ft.
WEATHER:	VFR, calm
SUMMARY:	Moderate amount of difficulty in needle following caused by rapid CDI oscillations due to local interference (radar).

Flight No. 1-8 (Con't)

SUMMARY: Oscillations lasted two to five minutes each with breaks in between from ten to thirty seconds. Radar calibration was made at reference point WE 1000 (1000 ft east of the west end of runway 10-28 at Wallops) before and after flight.

TEST DESCRIPTION

Flight No. 1-9

TEST OBJECTIVES:	Provide same information as Flight 1-8 but conducted at night with C-band transponder on.
DATE:	21 February 1975
TIME:	1810 - 1935
ORIGIN:	Wallops
DESTINATION:	Wallops
ROUTE:	Race track
ALTITUDE:	3000 ft.
WEATHER:	VFR, calm
SUMMARY:	Same as Flight 1-8 except more severe oscillations in CDI. Final return over reset point (WE 1000) at 1000 ft was as exact as can be determined visually (within 100 ft).

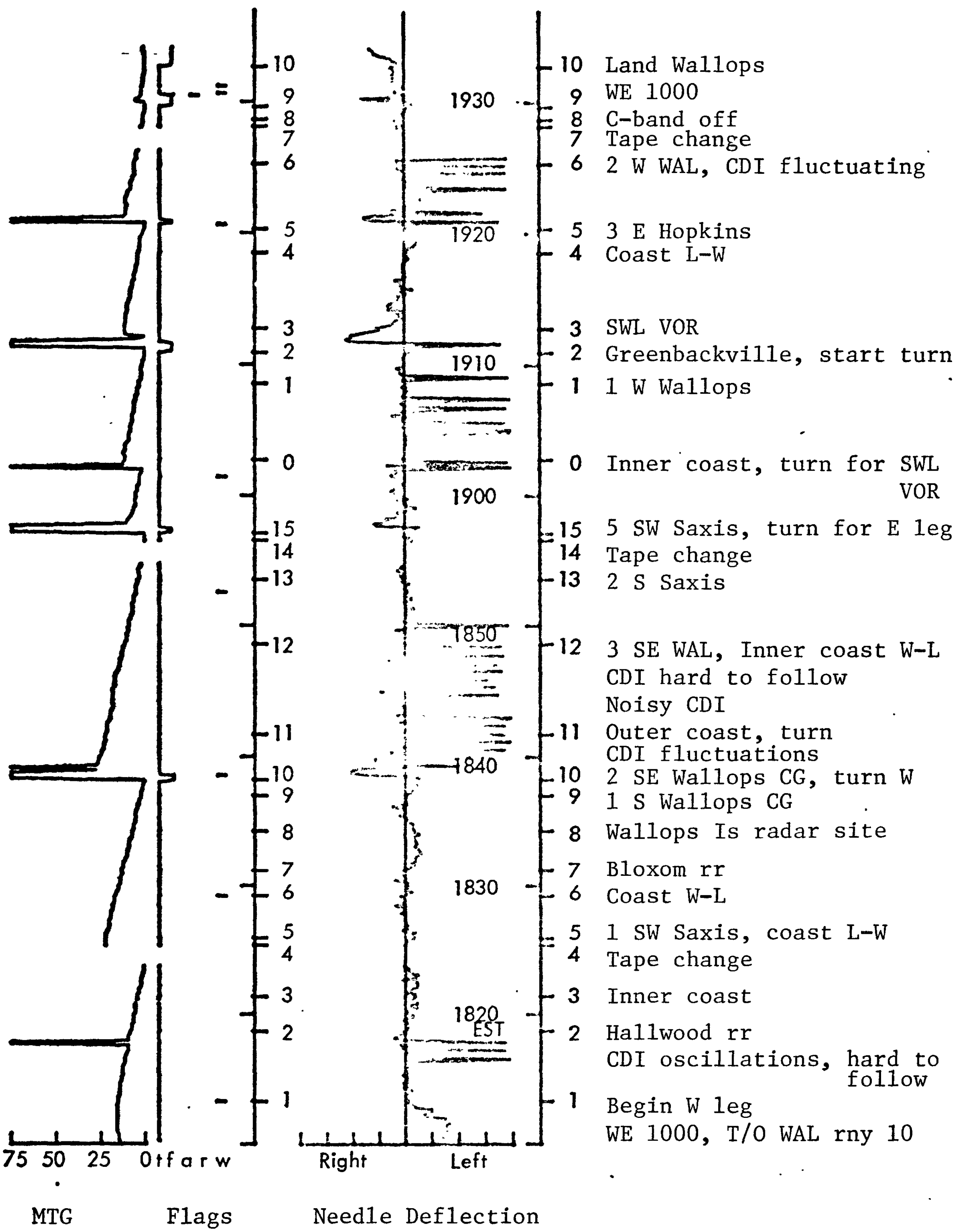


Figure A.4-1 Flight 1-9 Miles to Go and Needle Deflection

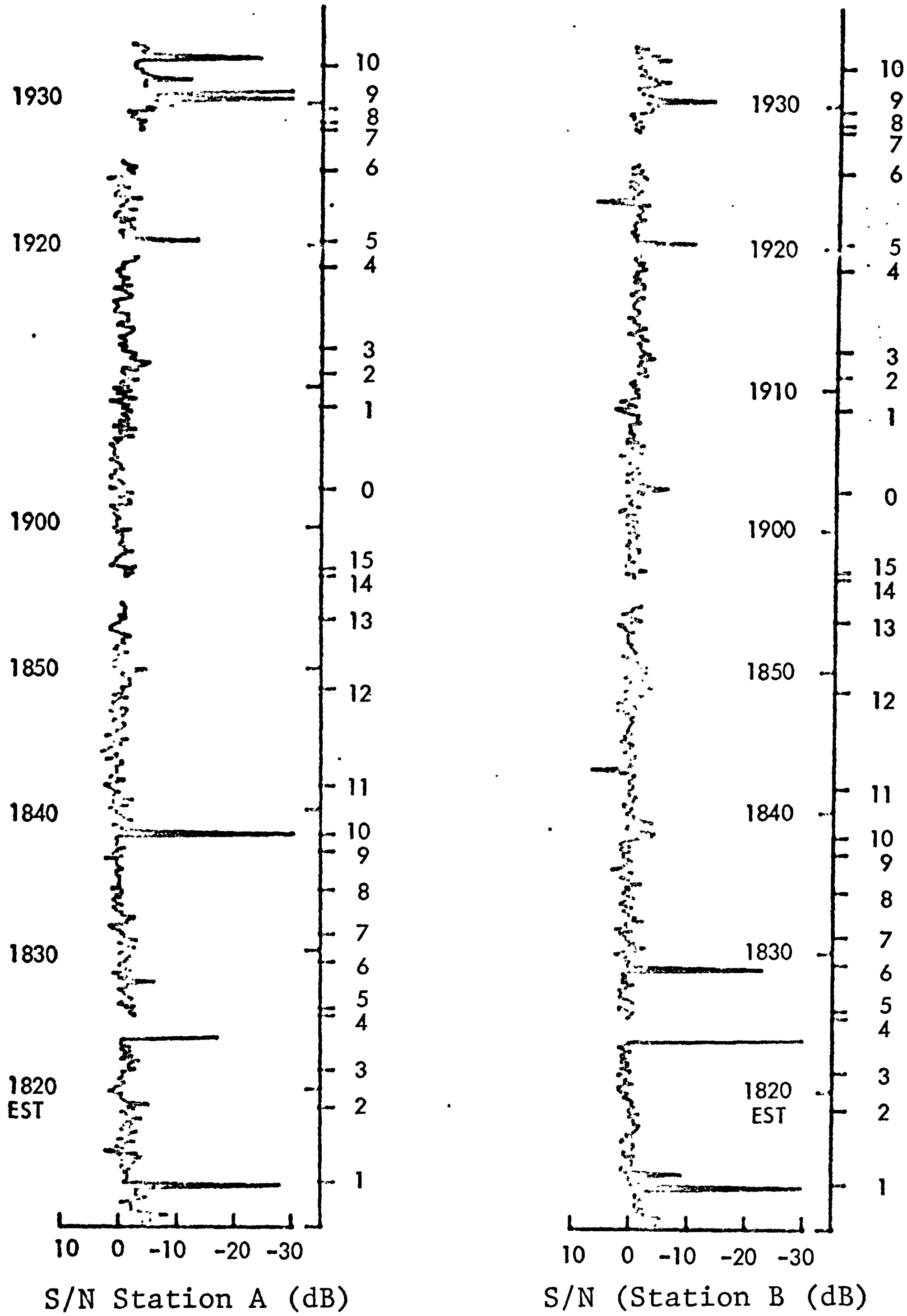


Figure A.4-2 Flight 1-9 S/N Stations A and B

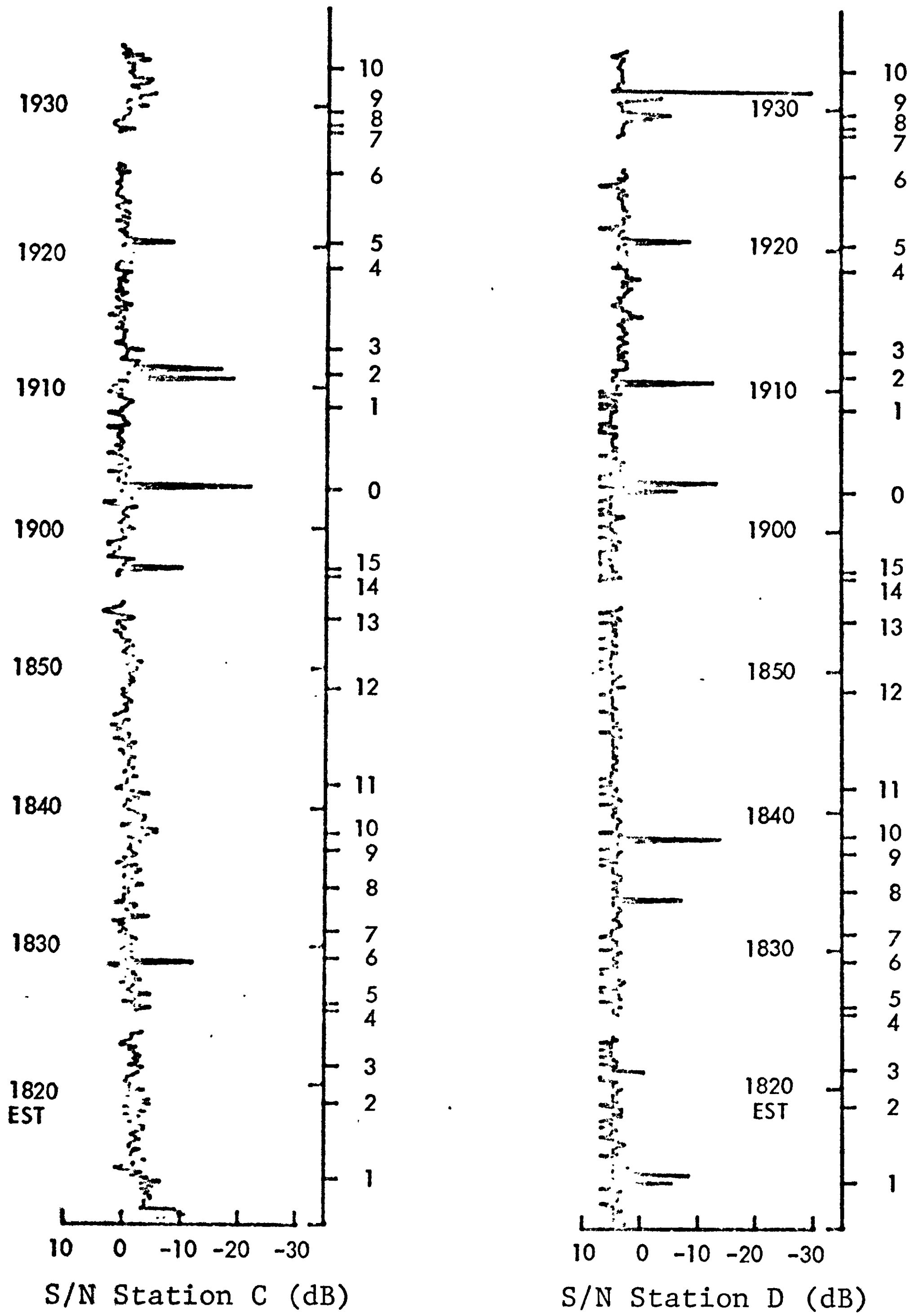


Figure A.4-3 Flight 1-9 S/N Stations C and D

TEST DESCRIPTION

Flight No. 1-10

TEST OBJECTIVES:	Provide additional S/N ratio data and accuracy information in Snow Hill VOR area by flying VOR radials and comparing with Omega results, including use of the course number function.
DATE:	22 February 1975
TIME:	1140 - 1250 EST
ORIGIN:	Wallops
DESTINATION:	Salisbury
ROUTE:	Snow Hill VOR, constant 120° radial
ALTITUDE:	6000, 5000, 4000, 3000, 2000 ft.
WEATHER:	VFR, 10 kts, SW
SUMMARY:	Flights along the 120° Snow Hill VOR radial were made at various altitudes to investigate coastline and interference effects at various altitudes. Considerable coast effect was evident in Omega indicator and considerable scalloping in VOR at lower altitudes.

TEST DESCRIPTION

Flight No. 1-20

TEST OBJECTIVES:	Provide initial S/N data along powerlines and in vicinity of Snow Hill VOR for the second series of Wallops flights.
DATE:	7 March 1975
TIME:	1355 - 1415 EDT
ORIGIN:	Salisbury
DESTINATION:	Wallops
ROUTE:	Via Snow Hill VOR
ALTITUDE:	2000 ft.
WEATHER:	VFR, 10 kts, S
SUMMARY:	Determined CIU difficulty enroute and recorded last two thirds of flight. Used A-C and B-D LOP pairs.

TEST DESCRIPTION

Flight No. 1-21

TEST OBJECTIVES:	Obtain S/N data in precipitation (rain), test results of precipitation on accuracy in the Wallops area. Use different LOP pairs for comparison.
DATE:	7 March 1975
TIME:	1613 - 1722 EDT
ORIGIN:	Wallops
DESTINATION:	Salisbury
ROUTE:	New Church, Kellam (Via railroad)
ALTITUDE:	1000 ft.
WEATHER	Alternating moderate and heavy rain
SUMMARY:	Flight in heavy rain showers produced no observable degradation of S/N ratio or difficulties in navigation. Voice tape for second half of flight was lost. North bound leg along railroad employed A-C and B-D LOP waypoints to Snow Hill VOR and Salisbury. Flight route was Wallops

Flight No. 1-21 (Con't)

SUMMARY: direct New Church railroad bend (Wpt 1), direct Kellam railroad bend (Wpt 2) reset with AC/BD LOPs, direct New Church (Wpt 3), direct Snow Hill VOR (Wpt 4), direct Salisbury (Wpt 5).

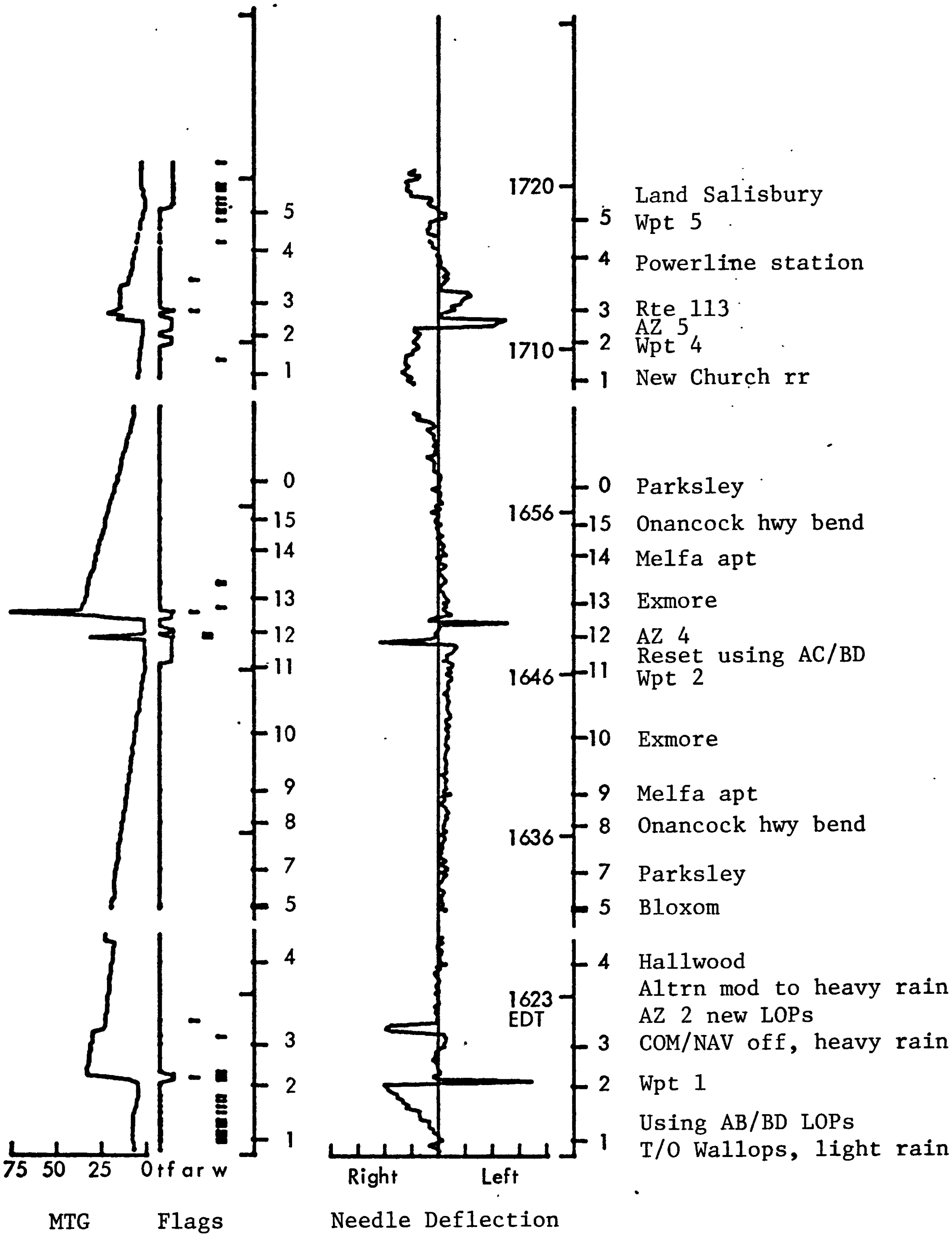


Figure A.5-1 Flight 1-21 Miles to Go and Needle Deflection

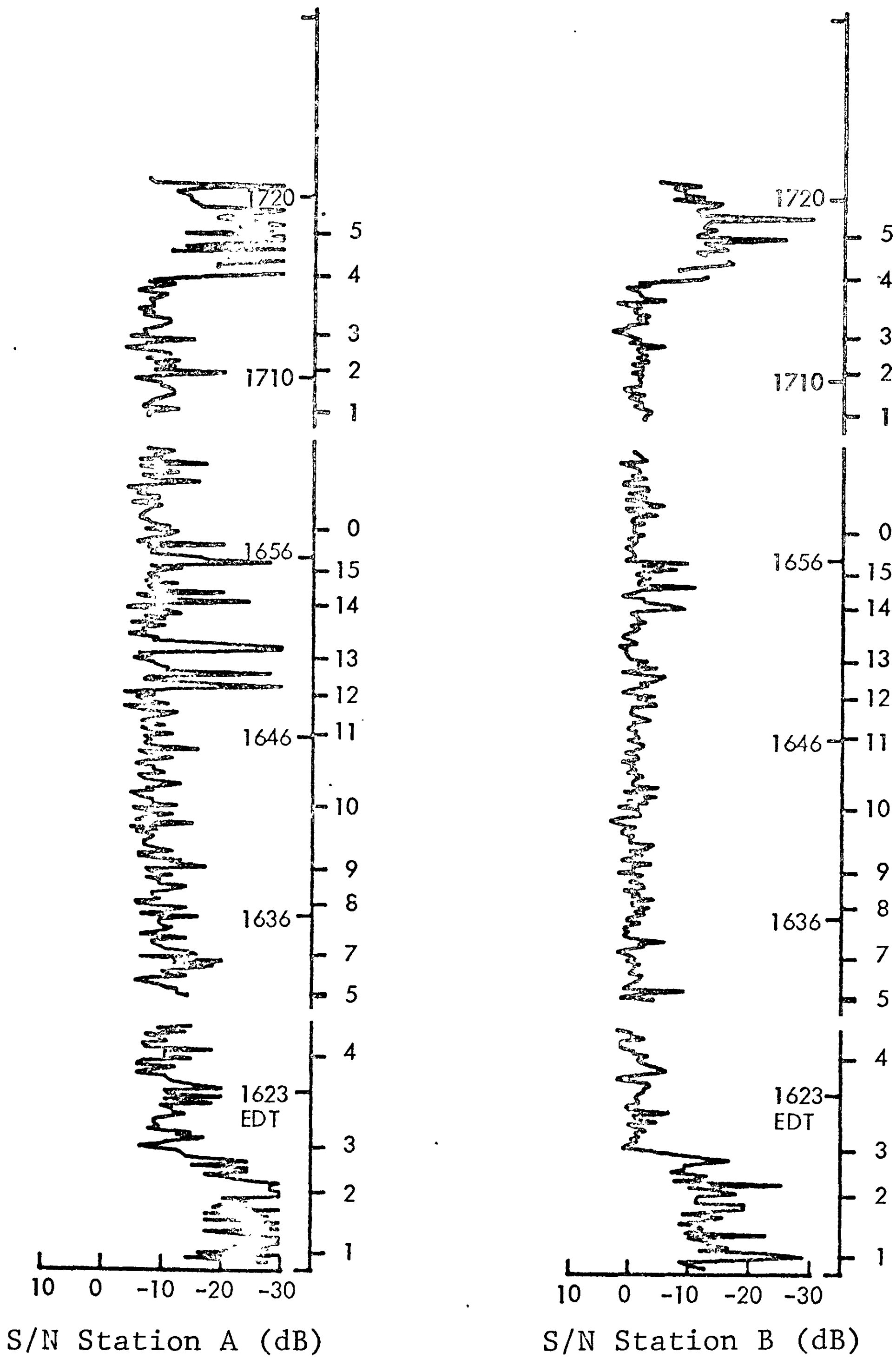


Figure A,5-2 Flight 1-21 S/N Stations A and B

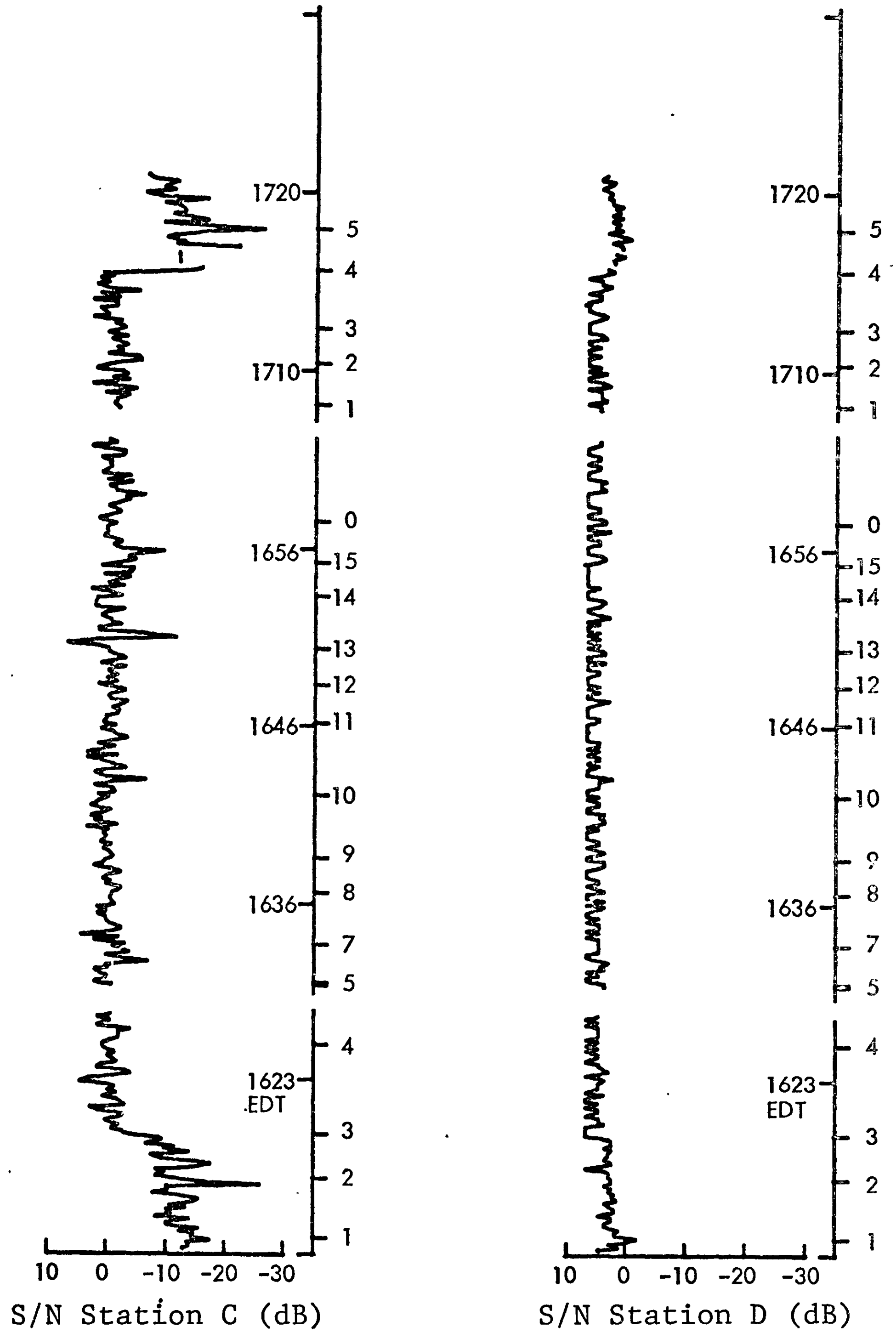


Figure A.5-3 Flight 1-21 S/N Stations C and D

TEST DESCRIPTION

Flight No. 1-22

TEST OBJECTIVES:	Obtain position accuracy checks as a function of LOP pair selection, test coast effects on various LOP pairs, flying along constant LOPs.
DATE:	8 March 1975
TIME:	1000 - 1256 EDT
ORIGIN:	Salisbury
DESTINATION	Salisbury
ROUTE:	Constant LOPs from Snow Hill VOR
ALTITUDE:	2000 ft.
WEATHER:	VFR, 6000 ft broken ceiling moderate turbulence
SUMMARY:	Flew along constant AD LOP (± 1 AB lane) (legs 1 and 2), constant AC LOP (legs 3 and 4), constant AB LOP (± 1 AD lane) (legs 5 and 6), constant BD LOP (legs 7 and 8), constant BC LOP (legs 9 and 10). Climbed to 7200 ft to determine cloud top. Moderate turbulence along route of flight.

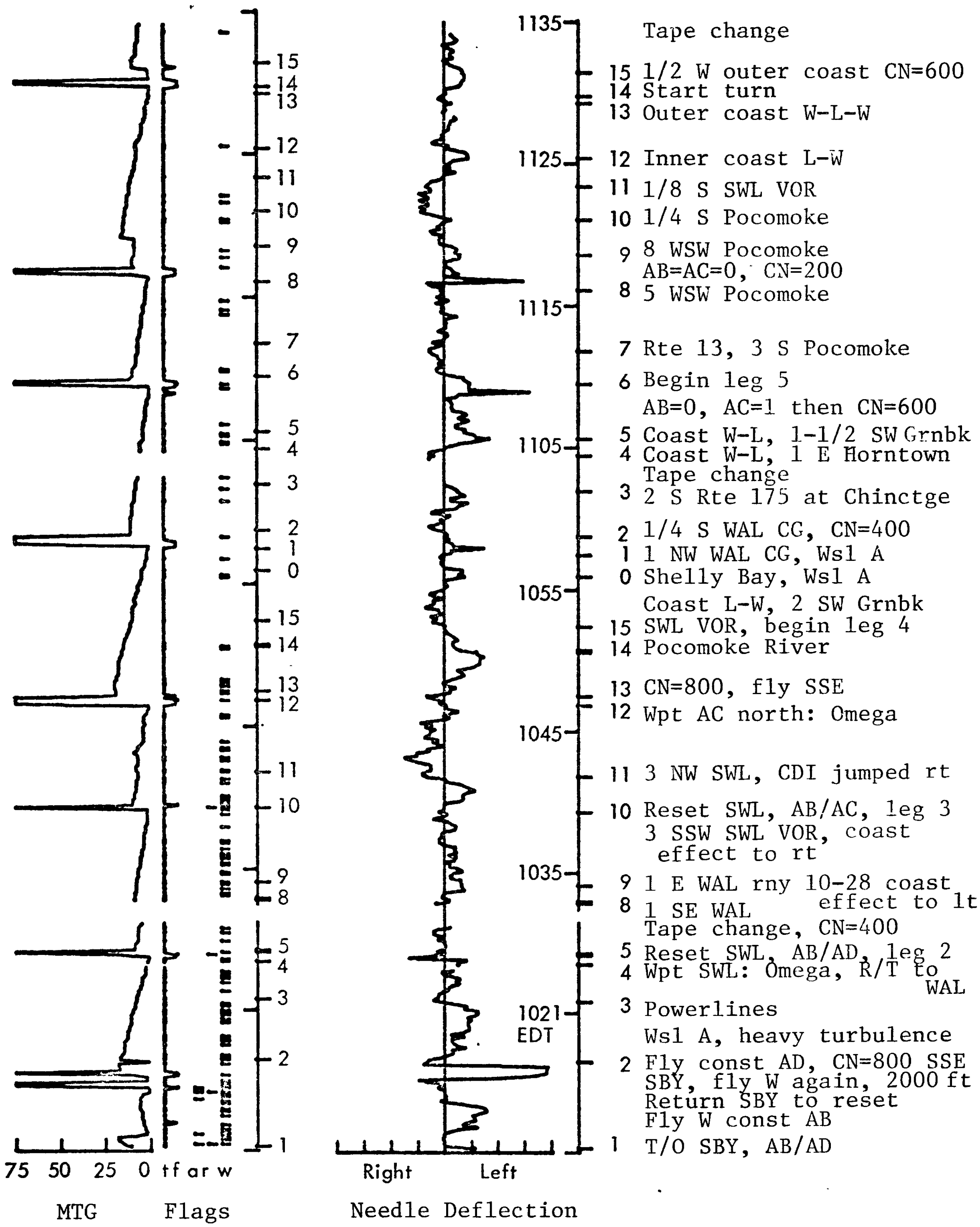


Figure A.6-1 Flight 1-22 (Part 1) Miles to Go and Needle Deflection

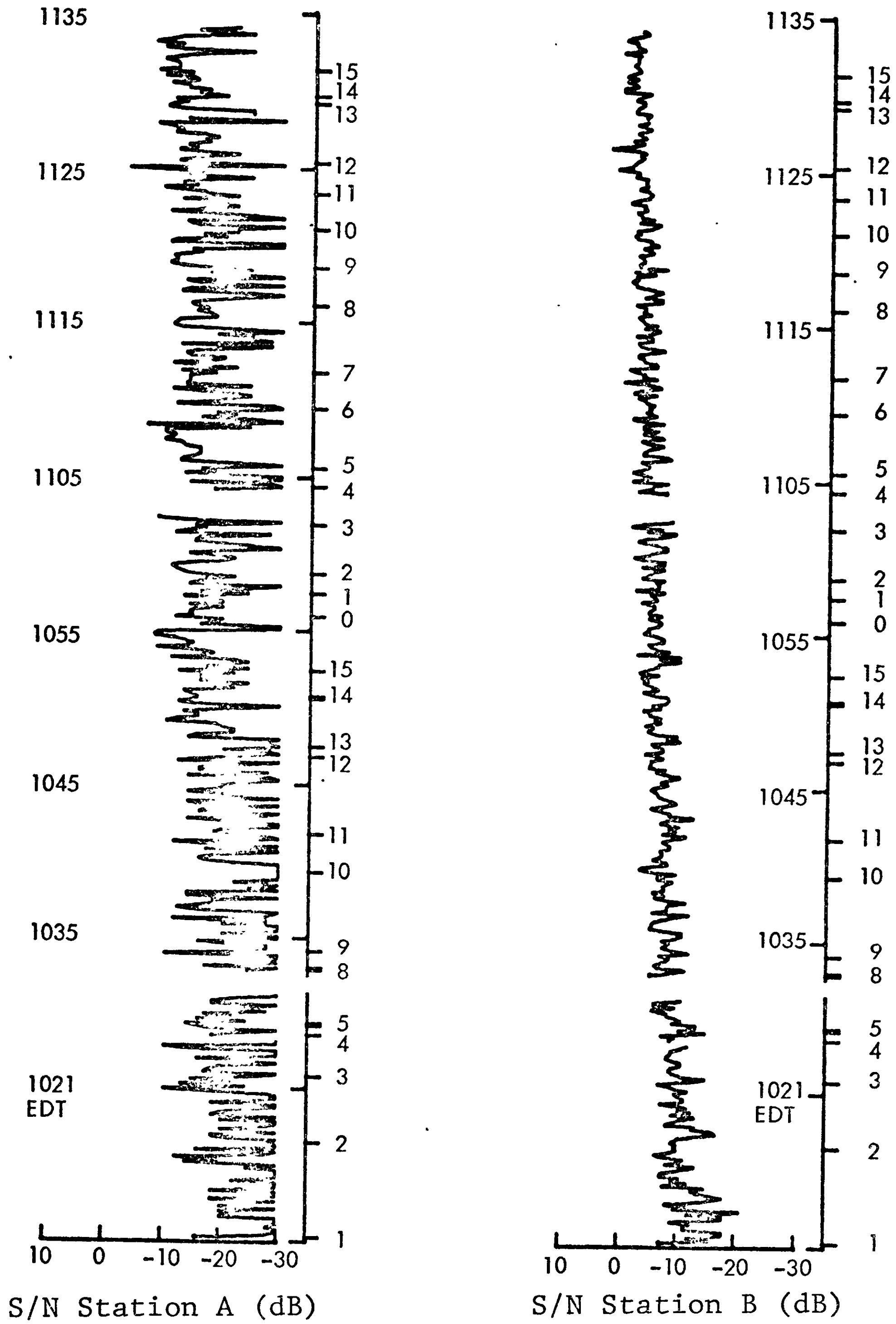


Figure A.6-2 Flight 1-22 (Part 1) S/N Stations A and B

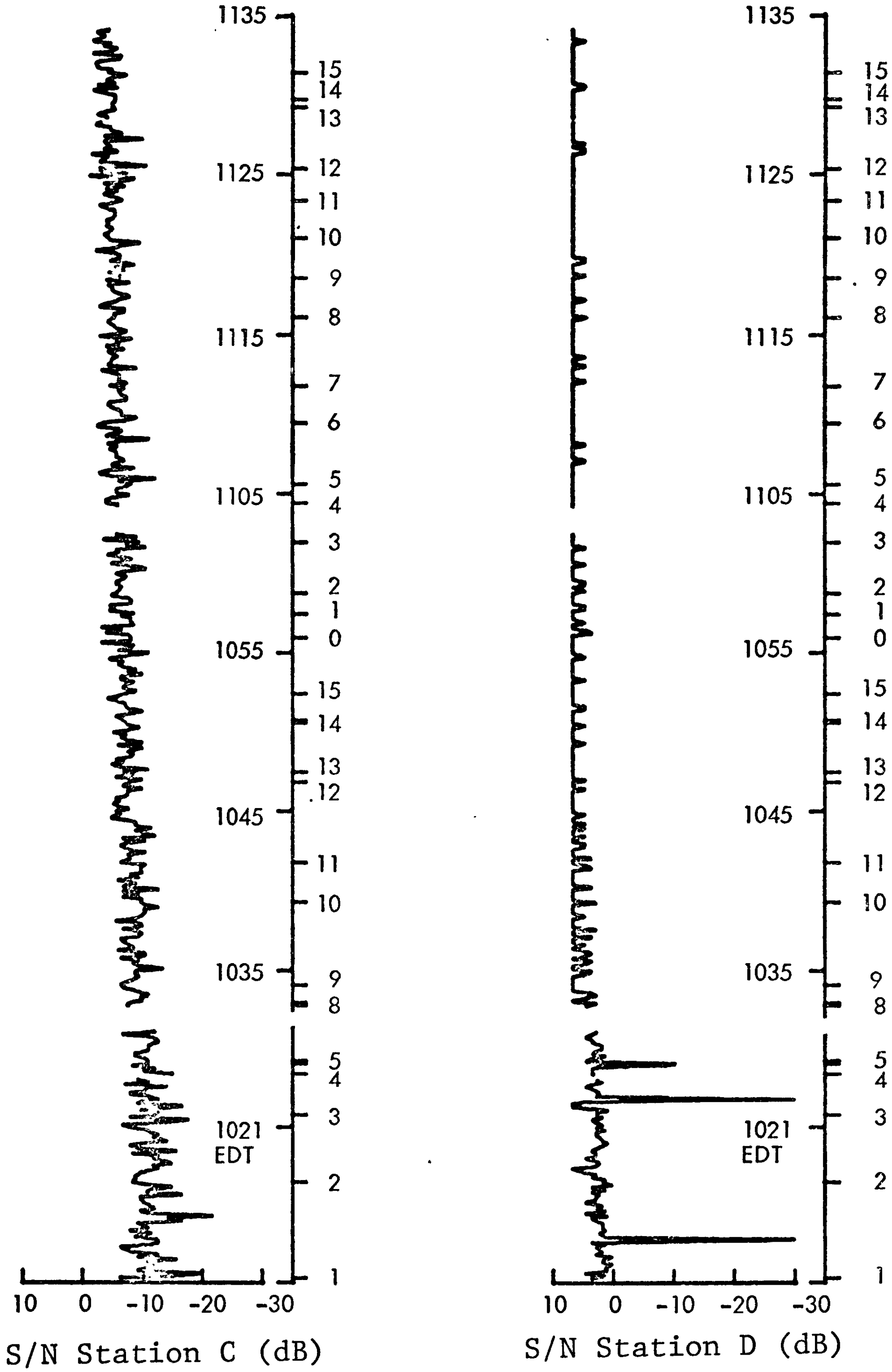


Figure A.6-3 Flight 1-22 (Part 1) S/N Stations C and D

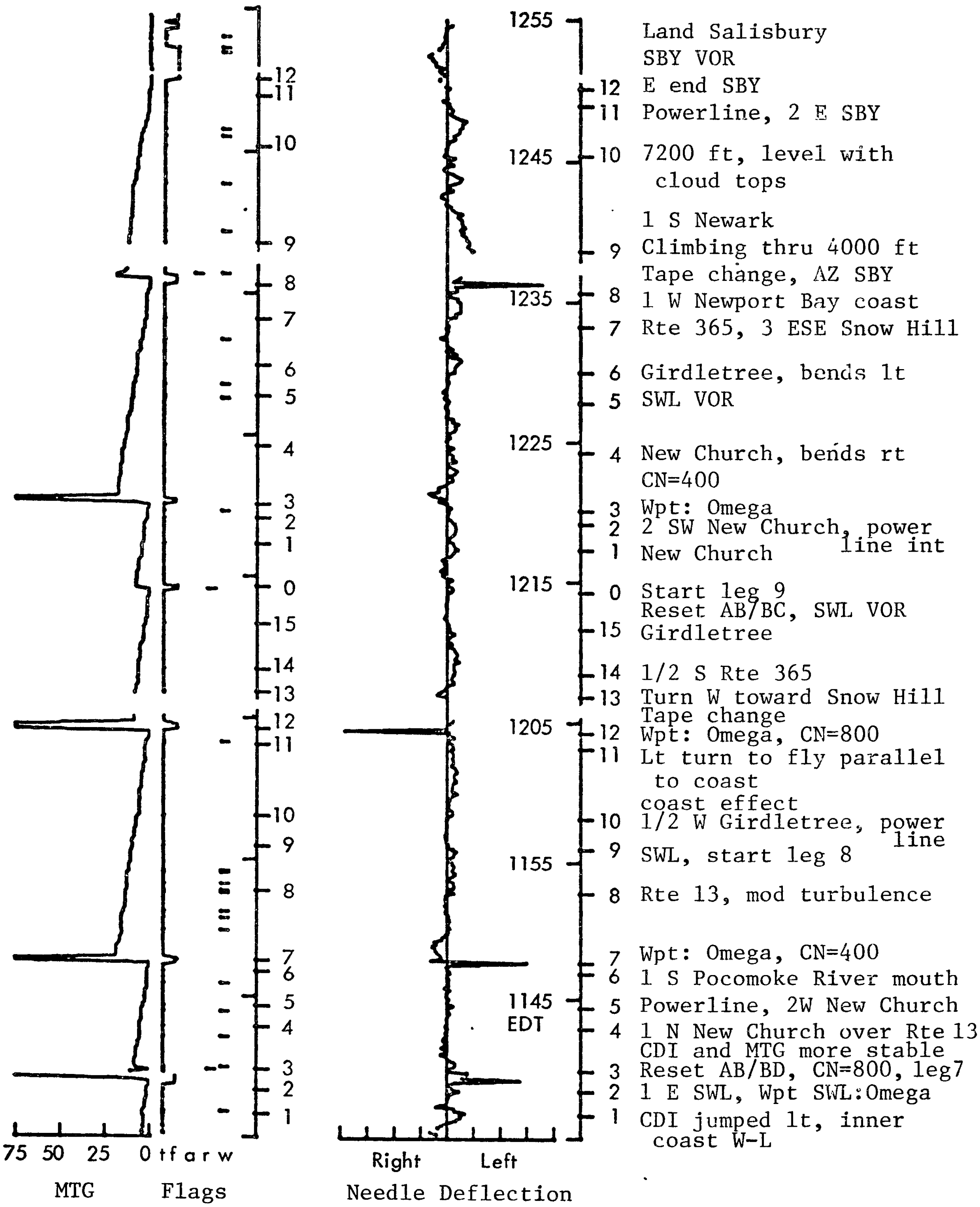


Figure A.6-4 Flight 1-22 (Part 2) Miles to Go and Needle Deflection

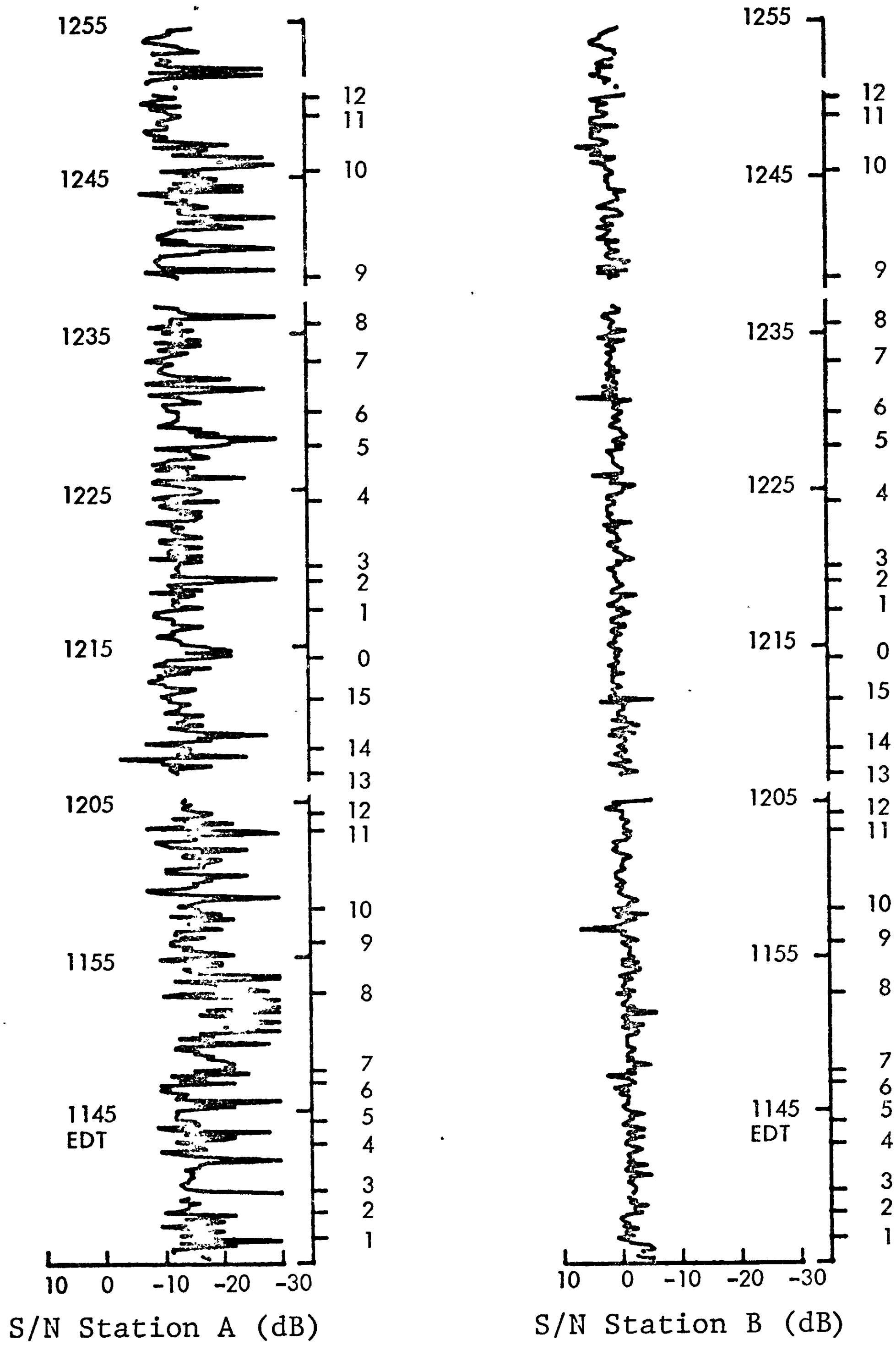


Figure A.6-5 Flight 1-22 (Part 2) S/N Stations A and B

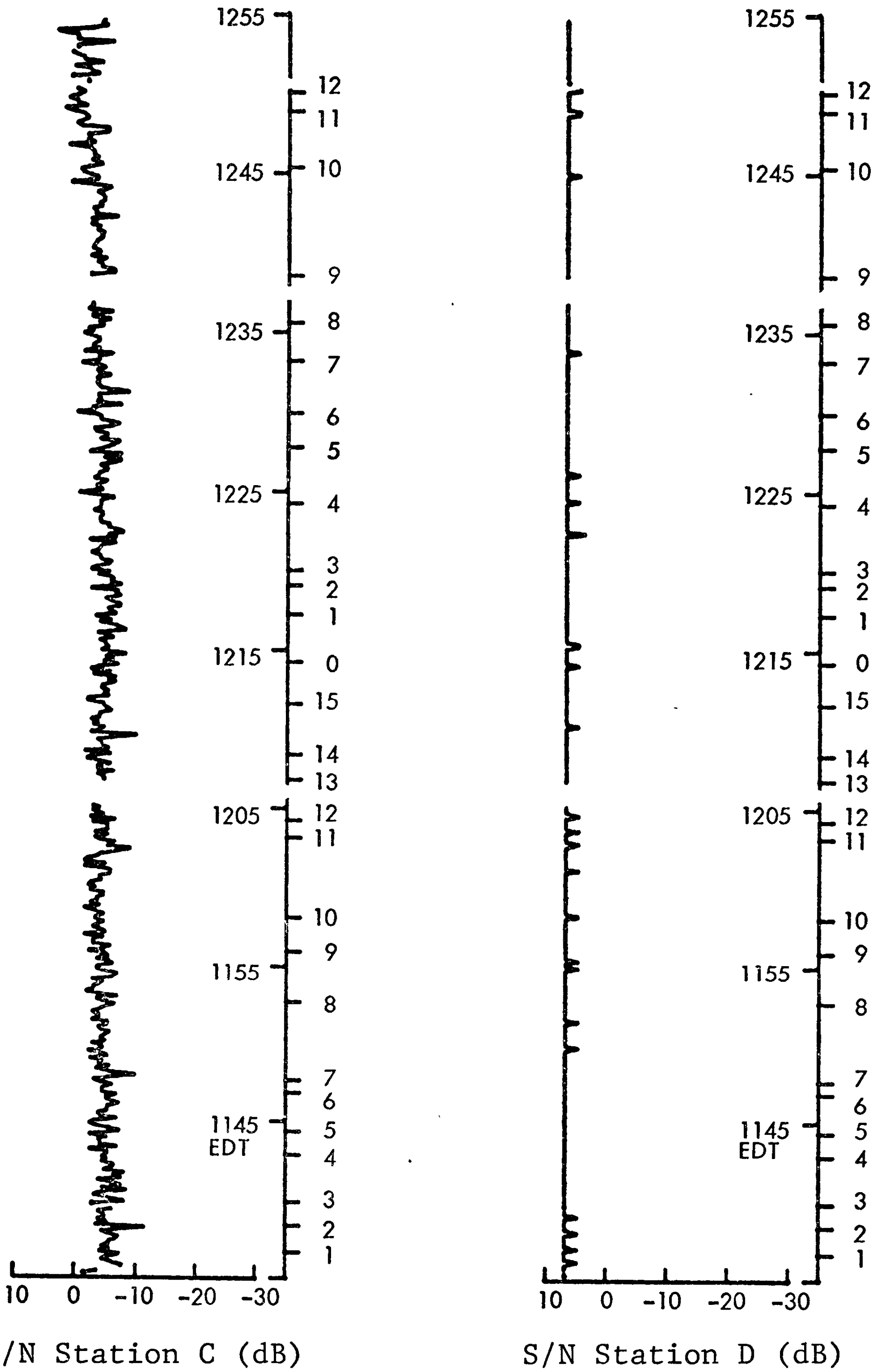


Figure A.6-6 Flight 1-22 (Part 2) S/N Stations C and D

TEST DESCRIPTION

Flight No. 1-23

TEST OBJECTIVES:	Compare Omega course numbers along Snow Hill VOR radials to determine magnitude and direction of coast effects. Check waypoint accuracy. Flight route: Leg 1, 120° out, 330° in; leg 2, 270° out, 060° in; leg 3, 060° out, 270° in; leg 4, 330° out, 120° in; leg 5, 210° out, 360° in; leg 6, 030° out, 180° inbound to the Snow Hill VOR.
DATE:	8 March 1975
TIME:	1556 - 1747 EDT
ORIGIN:	Salisbury
DESTINATION:	Salisbury
ROUTE:	VOR Cloverleaf (30° radials)
ALTITUDE:	3300 ft.
WEATHER:	VFR, 6000 ft broken, 20 kts, NNW
SUMMARY:	Cloverleaf was flown to minimize upwind flying. Detected coast effect scallops

Flight No. 1-23 (Con't)

SUMMARY: half mile in magnitude. No local interference near Snow Hill VOR. Returned within one mile of waypoint each time.

TEST DESCRIPTION

Flight No. 1-24

TEST OBJECTIVES:	Obtain S/N data on non cardinal directions from Snow Hill VOR, test coast effect, determine C-D LOP direction and size. Flight route: leg 1, 135° outbound, 345° in; leg 2, 285° outbound, 075° in; leg 3, 075° out, 285° in; leg 4, 345° out, 135° in; leg 5, 225° out, 015° in; leg 6, 045° out, 195° inbound to the Snow Hill VOR.
DATE:	9 March 1975
TIME:	0956 - 1245 EDT
ORIGIN:	Salisbury
DESTINATION:	Salisbury
ROUTE:	VOR cloverleaf (30° radials)
ALTITUDE:	3500 ft.
WEATHER:	VFR, 15 kts, NW
SUMMARY:	Cloverleaf repeat of Flight 1-23 (offset by 15°). Flew constant C-D LOP east bound over coast, on west bound leg encountered deviation indication to left

Flight 1-24 (Con't)

SUMMARY: which was uncorrectable by maneuvering the aircraft. Reset over Snow Hill VOR using A-B and B-D LOPs to begin ILS approach to Salisbury.

Appendix B

NORTHEAST REGIONAL FLIGHT TESTS

TEST DESCRIPTION

Flight No. 2-1

TEST OBJECTIVES: Initial check of Omega reciever operation, accuracy compared to visual and VOR references.

DATE: 22 November 1974

TIME: 1430 - 1605 EST

ORIGIN: Bedford

DESTINATION: Bedford

ROUTE: Bedford - Lawrence VOR - Bedford

ALTITUDE: 2400 ft.

WEATHER: VFR, 10 kts E, gusting to 20 kts

SUMMARY: Initial flight indicated the necessity for hard mounting the reciever, indicator and antenna coupler to provide the required chassis ground to receive usable signals. No recorded data since flight preceded installation of CIU.

TEST DESCRIPTION

Flight No. 2-2

TEST OBJECTIVES:	Provide initial information concerning the operation of the test equipment along the Northeast Corridor. Route of flight is: Bedford direct Framingham, (Wpt 1), direct Woodstock, Conn. (Wpt 2), direct Central, Conn. (Wpt 3, 7 SW Middletown Conn.), direct Hudson River at Ossining (Wpt 4), along Hudson past East River (Wpt 5), Empire State Building (Wpt 6), Statue of Liberty (Wpt 7), direct Jones Beach (Wpt 8A), direct Jamaica Inlet (Wpt 9A), direct Farmingdale airport (Wpt 10A).
DATE:	23 November 1974
TIME:	0950 - 1145 EST
ORIGIN:	Bedford
DESTINATION:	Farmingdale
ROUTE:	Zulu-2 with divert to Farmingdale
ALTITUDE:	2000 ft, 500 ft through New York TCA
WEATHER:	VFR, 15 kts, SW

Flight No. 2-2 (Con't)

SUMMARY: Some waypoints along the Hudson River were incorrectly computed, but otherwise half mile accuracies were consistently achieved. Only recorded data was strip chart recording of CDI presentation.

TEST DESCRIPTION

Flight No. 2-3

TEST OBJECTIVES:	Initial flight employing interface hardware. Check point to point accuracy, determine S/N levels and interference during Station A transition period.
DATE:	3 December 1974
TIME:	1231 - 1442 EST
ORIGIN:	Farmingdale
DESTINATION:	Bedford
ROUTE:	Farmingdale-Mattituck, Mattituck-Bedford
ALTITUDE:	2000 ft
WEATHER:	VFR in haze, 10 kts W
SUMMARY:	Weak signals precluded successful navigation. Station A phase lock was lost several times on both legs of flight. Flight continued through local sunset, although data tape was stopped.

TEST DESCRIPTION

Flight No. 2-Z1-1

TEST OBJECTIVES:	Provide additional low altitude data in the Northeast Corridor and check CIU operation after modification to mate the CIU with the Wang. Measure mangitude of diurnal effect. Proposed Zulu-1 route was: Farmingdale direct tower 376 (Wpt 8), direct Stacks on Long Island north shore (Wpt 9), direct Griswold (Wpt 10), direct South Foster (Wpt 11), direct Millis (Wpt 12), direct Bedford (Wpt 13).
DATE:	20 December 1974
TIME:	1530 - 1700 EST
ORIGIN:	Farmingdale
DESTINATION:	Bedford
ROUTE:	Zulu-1 from Farmingdale
ALTITUDE:	5500 ft.
WEATHER:	VFR, 18 kts NW

Flight No. 2-Z1-1 (Con't)

SUMMARY: Waypoints set in with +BD LOP changes were inaccurate due to failed sign chip on LOP 2. Accuracy was within one mile with -BD LOP waypoints. Some coast effect was noted near Griswold Airport. Actual flight route was: Farmingdale to a position southwest of Bridgeport (Wpt 9), direct Griswold (Wpt 10), then as planned.

TEST DESCRIPTION

Flight No. 2-Z1-2

TEST OBJECTIVES:	Shakedown flight after repairs to reciever, indicator and interface unit. Collect additional low altitude data. First flight with receiver and indicator hard mounted and antenna cable repaired.
DATE:	24 January 1975
TIME:	1556 - 1720 EST
ORIGIN:	Farmingdale
DESTINATION:	Bedford
ROUTE:	Zulu-1 from Farmingdale
ALTITUDE:	3500 ft.
WEATHER:	VFR in haze, 20 kts WSW
SUMMARY:	Receiver functioned satisfactorily after radios turned off. Encountered difficulty with +BD LOP waypoints due to previously undetected failed chip. Flown at middle altitude to test diurnal and coast effects higher than proposed.VTOL routes.

TEST DESCRIPTION

Flight No. 2-4

TEST OBJECTIVES:	Short range night accuracy check and S/N observations to determine necessity for alternate mounting of receiver as well as general navigational capability ckeck.
DATE:	27 January 1975
TIME:	1733 - 1825 EST
ORIGIN:	Bedford
DESTINATION:	Bedford
ROUTE:	Bedford, Fitchburg, Worcester, Marlboro, Bedford
ALTITUDE:	3000 ft.
WEATHER:	night VFR, 20 kts, WSW
SUMMARY:	LOP 2 sign chip failure detected over Fitchburg. Accurate waypoints on return to Bedford, using opposite sign input on LOP 2.

TEST DESCRIPTION

Flight No. 2-5

TEST OBJECTIVES:	Accuracy check of waypoints with alternate LOP sign input. Leave receiver at Farmingdale for repair.
DATE:	30 January 1975
TIME:	1533 - 1703 EST
ORIGIN:	Bedford
DESTINATION:	Farmingdale
ROUTE:	Bedford, Marlboro, Windham, Flying B, Farmingdale
ALTITUDE:	2500 ft.
WEATHER:	VFR, 15 kts, W
SUMMARY:	Omega receiver functioned normally on flight to Farmingdale and supplied acceptalbe navigation information on the flight. Omega waypoints were within one half mile of visual waypoints. Second half of flight data lost. Noticed coast effect on both sides of Long Island Sound.

TEST DESCRIPTION

Flight No. 2-6

TEST OBJECTIVES:	Single waypoint long distance flight to fully employ Omega RNAV capability. Determine extent of coast effect at higher altitudes. Check interference at altitude and with radios off.
DATE:	31 January 1975
TIME:	1834 - 2004 EST
ORIGIN:	Farmingdale
DESTINATION:	Bedford
ROUTE:	Farmingdale - Bedford direct
ALTITUDE:	5500 ft.
WEATHER:	Night VFR, calm
SUMMARY:	After radios were turned off, receiver indications became very stable. Little observable coast effect at altitude. Indicated waypoint was one mile short of actual, possibly due to flying during transition period for Station D.

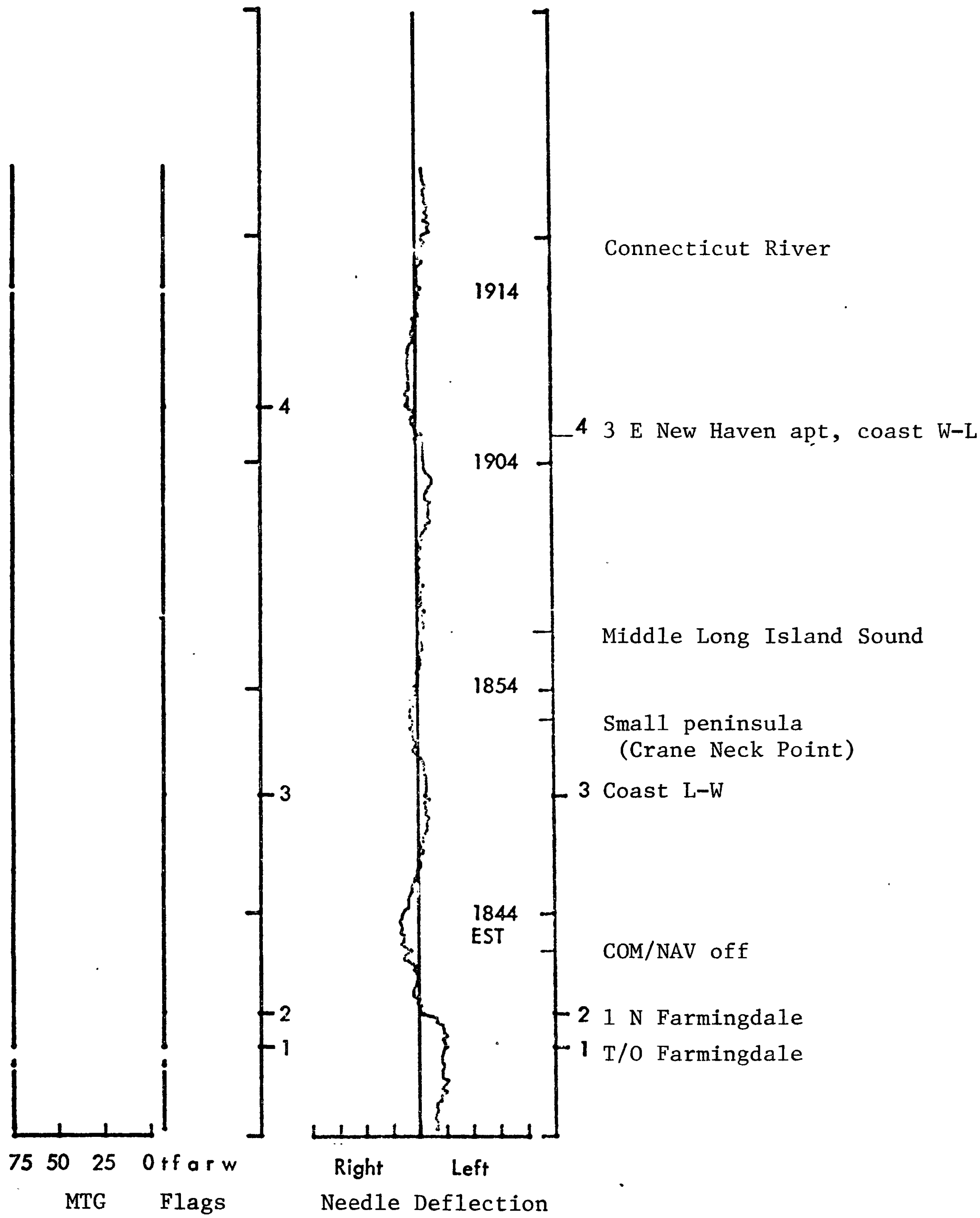


Figure B.1-1 Flight 2-6 (Part 1) Miles to Go and Needle Deflection

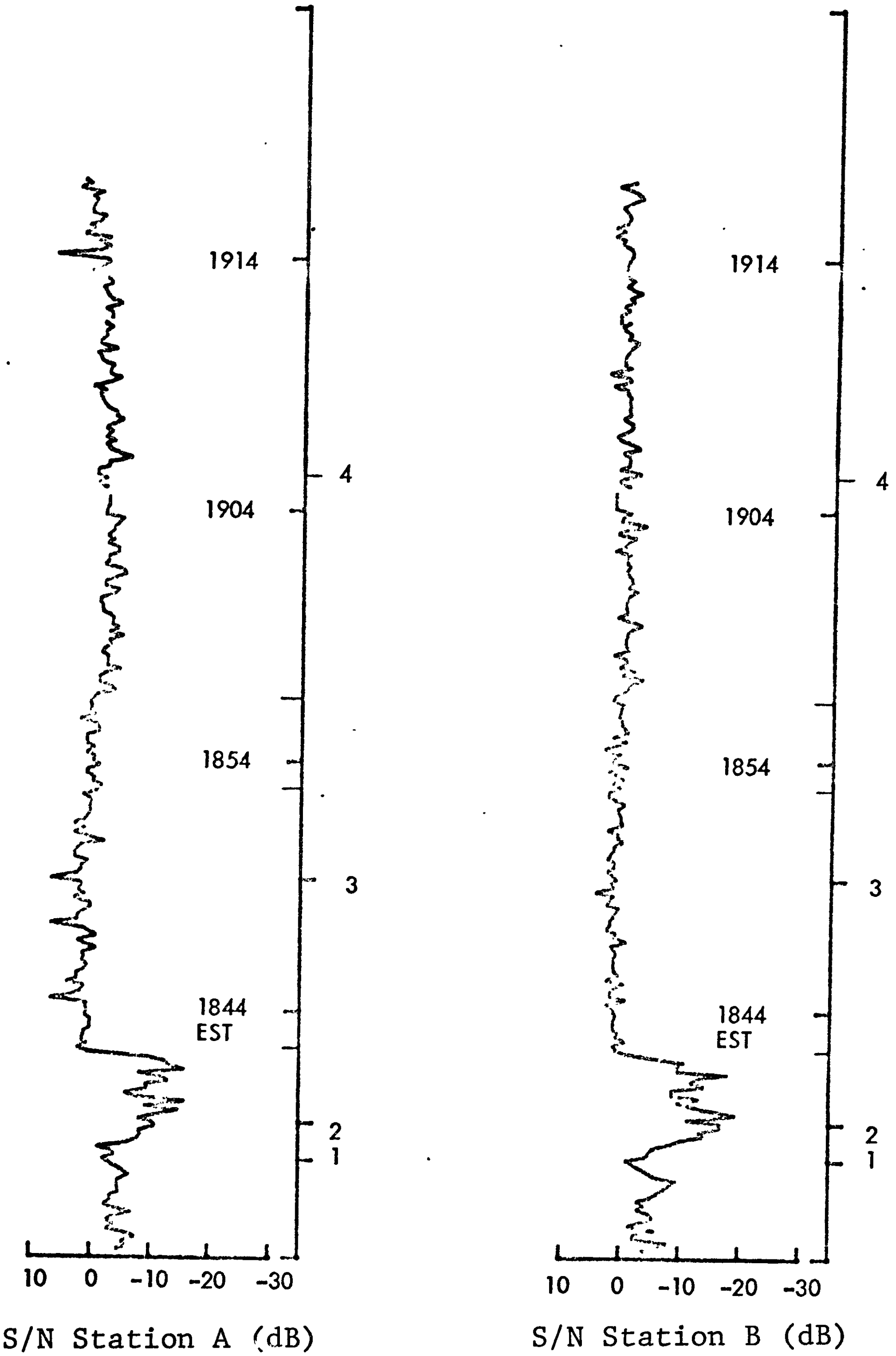


Figure B.1-2 Flight 2-6 (Part 1) S/N Stations A and B

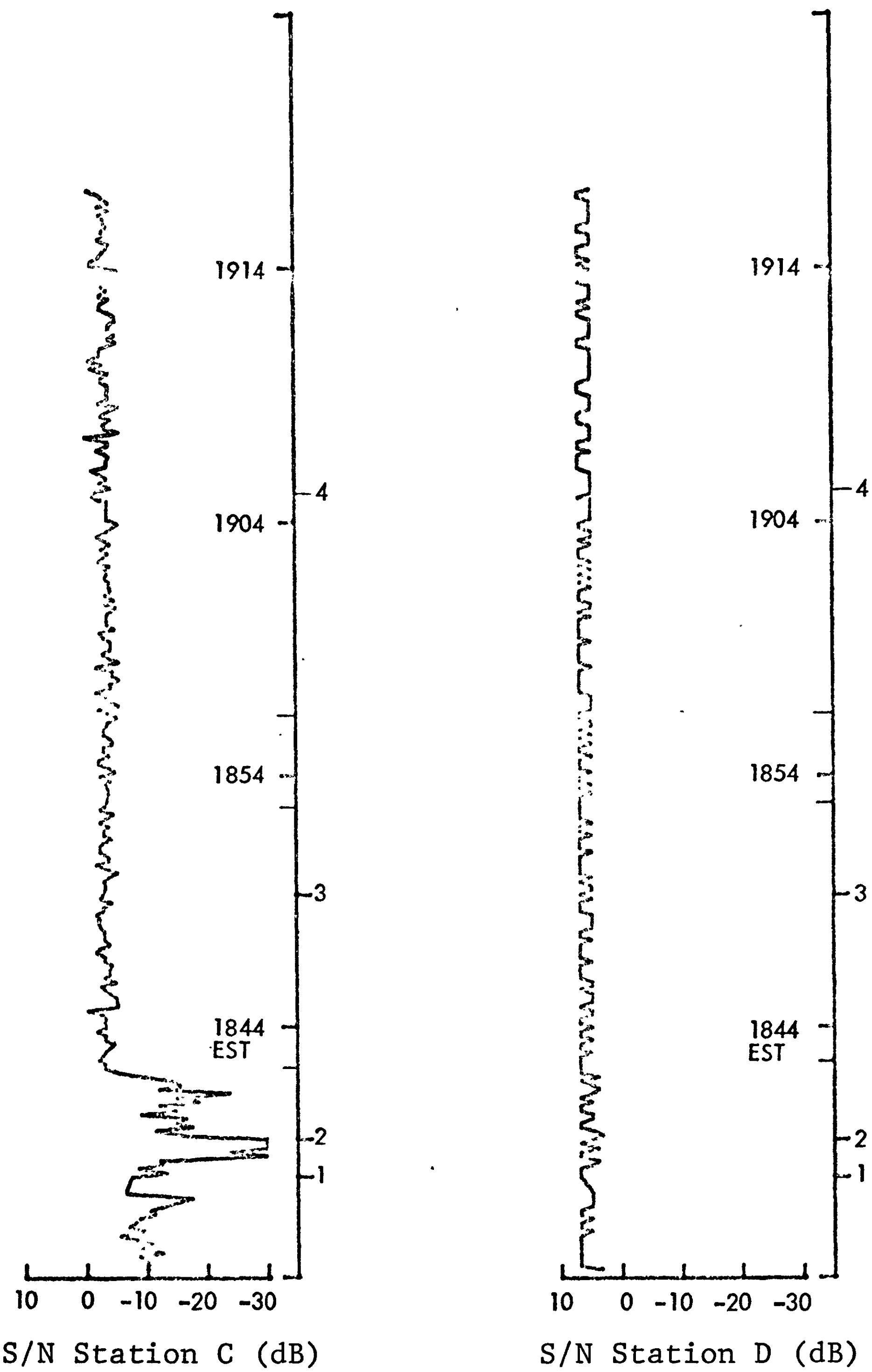


Figure B.1-3 Flight 2-6 (Part 1) S/N Stations C and D

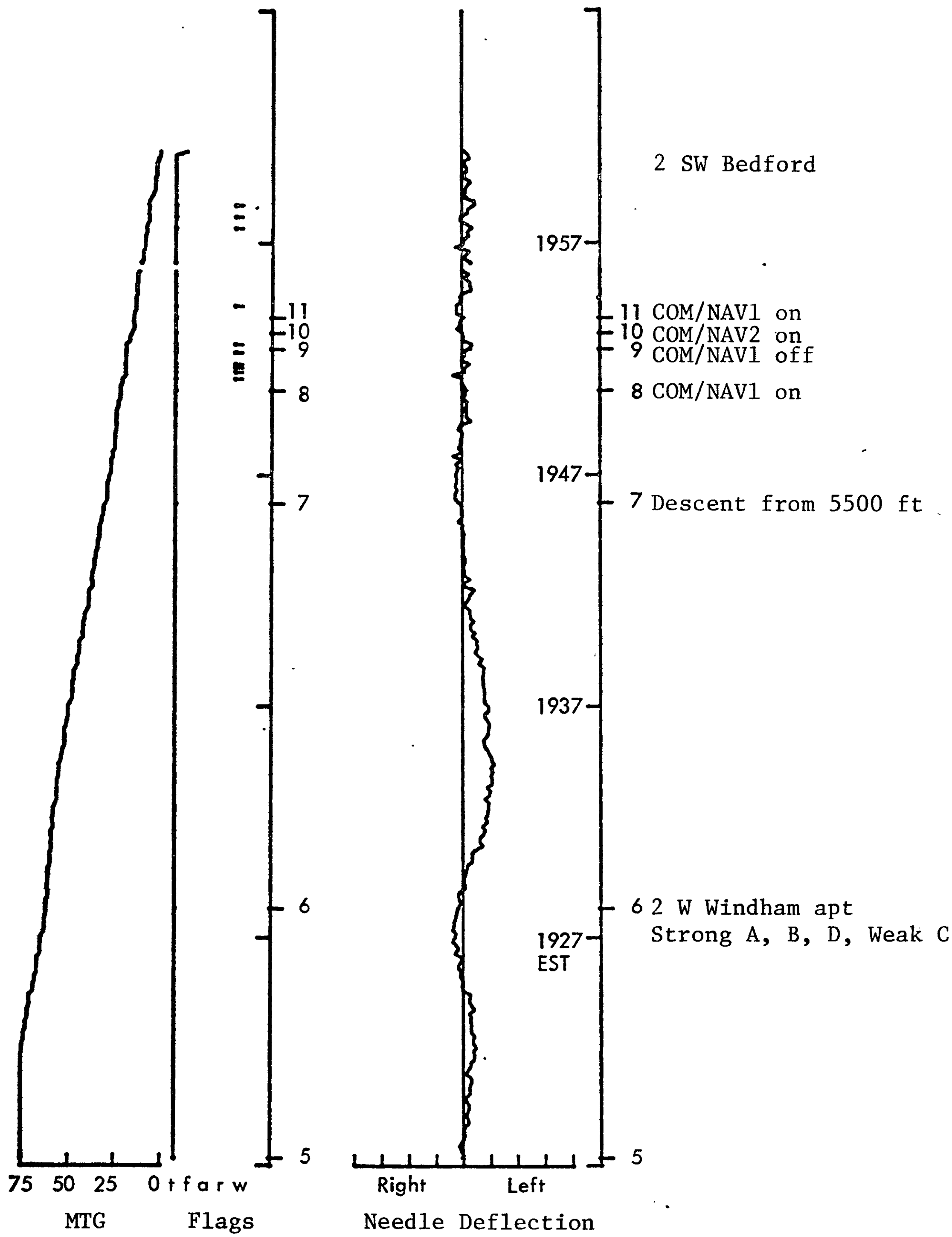


Figure B.1-4 Flight 2-6 (Part 2) Miles to Go and Needle Deflection

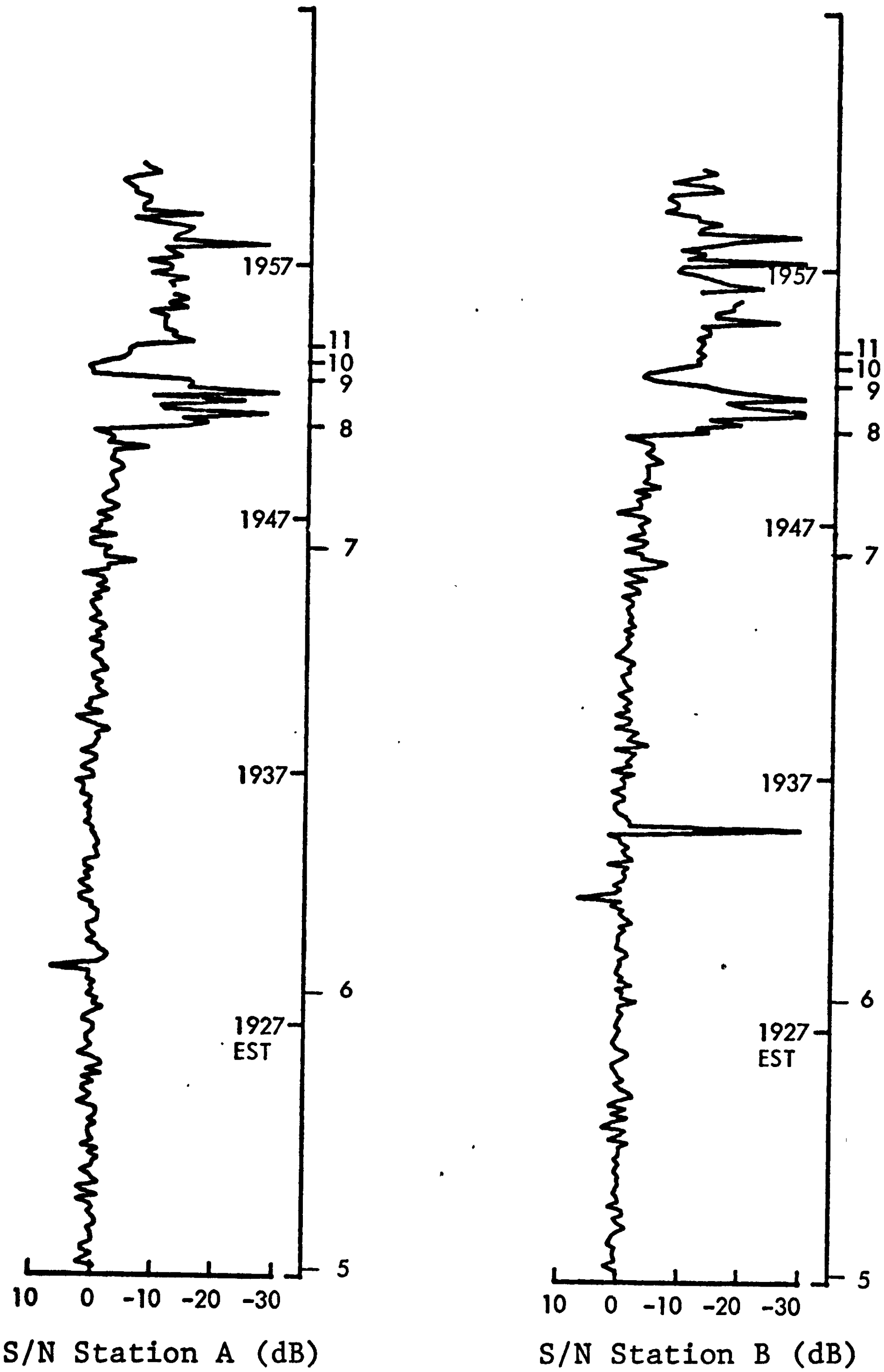


Figure B.1-5 Flight 2-6 (Part 2) S/N Station A and B

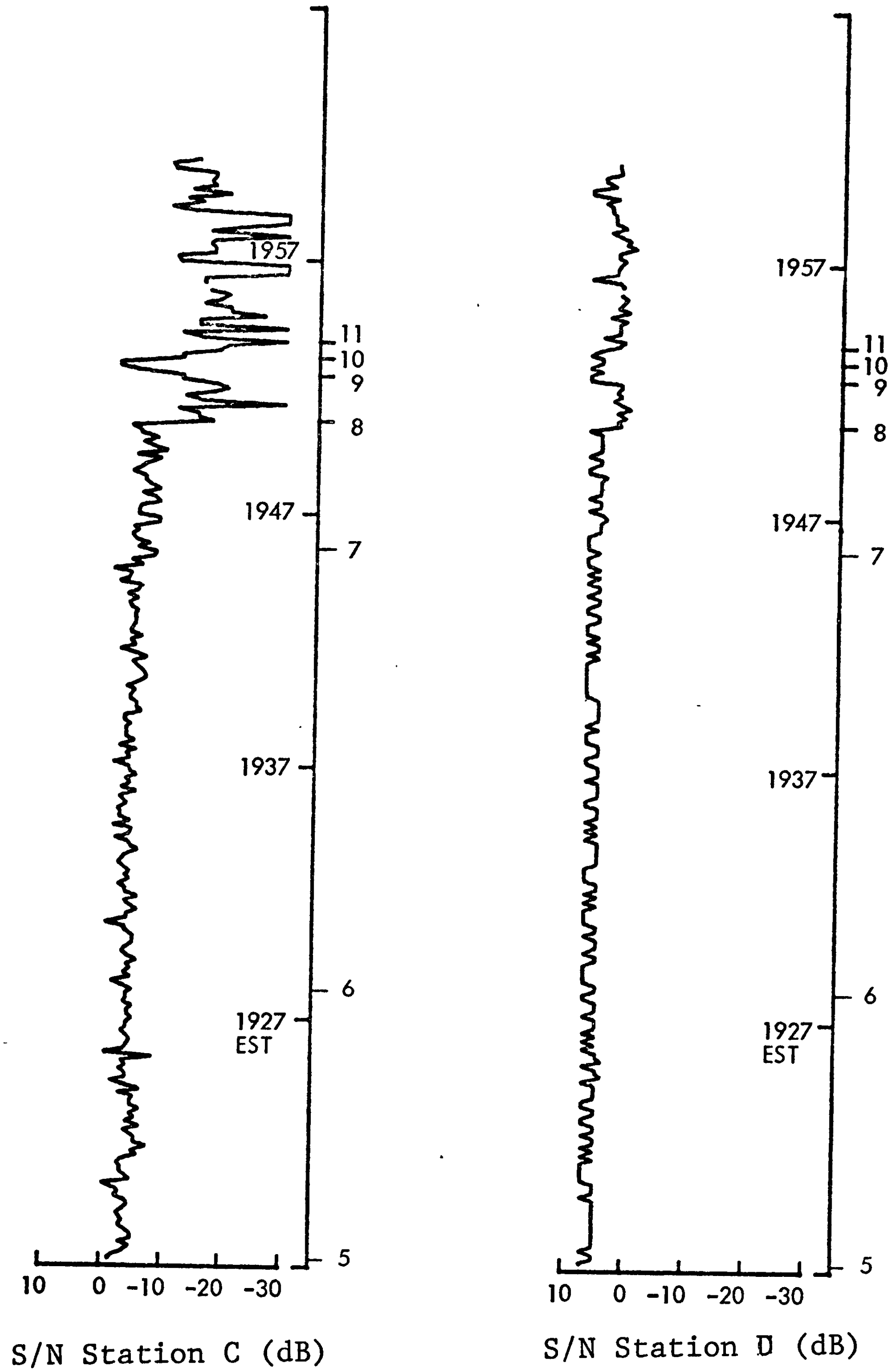


Figure B.1-6 Flight 2-6 (Part 2) S/N Stations C and D

TEST DESCRIPTION

Flight No. 2-7

TEST OBJECTIVES:	Obtain S/N data at low altitude near: television transmitters, urban areas, over powerlines, and during maneuvers. Determine ability to maintain holding pattern and fly approach, in the shadow of Mt. Wachusett. Fly at low altitude (200 ft) perpendicular and parallel to high voltage transmission lines.
DATE:	7 February 1975
TIME:	1617 - 1811 EST
ORIGIN	Bedford
DESTINATION:	Bedford
ROUTE:	Bedford, towers, Framingham, Gardner, Haystack, powerline, Bedford
ALTITUDE:	1000 ft, 200 ft over powerlines
WESTHER:	Night SVFR in scattered snow showers, 5 kts, NW
SUMMARY:	Flew to avoid snow showers, completed two and a half orbits around Norwood

Flight No. 2-7 (Con't)

SUMMARY: television towers at 2000 ft, 1500 ft, and 1000 ft MSL, with no effect on indicators or increase in weak signal lights. This was also true of flight over Framingham, within 200 ft of power-lines and during maneuvers (stalls, spirals and steep backed turns over Haystack). An RNAV approach was made to Gardner Airport with waypoint indication 1/4 mile south of the actual airport. Holding patterns were difficult to fly due to moderate noise in the Station A signal. Recorded data was lost in software transfer.

TEST DESCRIPTION

Flight No. 2-8

TEST OBJECTIVES:	Fly low altitude Zulu routes from Bedford to College Park and return employing all four Zulu routes.
DATE:	10 February 1975
TIME:	1009 - 1215 EST
ORIGIN:	Bedford
DESTINATION:	Flushing
ROUTE:	Zulu-2 to Statue, divert Flushing
ALTITUDE:	2000 ft, 1100 through New York TCA
WEATHER:	VFR, 20 kts, W, slight haze
SUMMARY:	Flight proceeded as planned until passing the Statue of Liberty when Station D (North Dakota) ceased transmitting. A return to Flushing Airport was made by pilotage. Second half of data lost during software transfer.

TEST DESCRIPTION

Flight No. 2-9

TEST OBJECTIVES:	Test alternate LOP pairs AB and BC. Fly alternate Zulu route to Bedofrd from Flushing after Station D stopped transmitting.
DATE:	10 February 1975
TIME:	1300 - 1450 EST
ORIGIN:	Flushing
DESTINATION:	Bedford
ROUTE:	Flushing, Bridgeport, Windham, Bedford
ALTITUDE:	2000 ft.
WEATHER:	VFR, 20 kts, W
SUMMARY:	Experienced difficulty obtaining synchronization at Flushing. Reset using AB and BD LOPs as Station D had returned momentarily. Lost track over tower 376 waypoint when Station D stopped transmitting again. Reset over Bridgeport using AB and BC LOPs, and returned to Bedford successfully. Recorded data was lost during transfer through software.

TEST DESCRIPTION

Flight No. 2-10

TEST OBJECTIVES: Fly low altitude Zulu routes from Bedford to College Park, Maryland using Station pairs A-B and B-C. The Zulu-W route begins at the Statue of Liberty (Wpt 7), direct Verrazano Bridge (Wpt 8), direct Jersey rail yard (Wpt 9), direct Dublin (Wpt 10), direct powerline and river (Wpt 11), direct Dayton (Wpt 12), direct College Park (Wpt 13).

DATE: 14 February 1975

TIME: 1034 - 1413 EST

ORIGIN: Bedford

DESTINATION: College Park, Maryland

ROUTE: Z2 and ZW

ALTITUDE: 2000 ft., 1100 ft through New York TCA

WEATHER: VFR, 10 kts, SW gusting to 25 kts

SUMMARY: Skipped waypoint 7 due to traffic in the area. As the flight proceeded, the waypoint indications were increasingly early

Flight No. 2-10 (Con't)

SUMMARY: due to possible calculation error or weak Station A S/N. Approaching the Susquehanna River it was determined that the A-B LOP had shifted by 2 lanes and compensation was made. The final waypoint indication was 2 miles late with the altered LOP inputs.

TEST DESCRIPTION

Flight No. 2-11

TEST OBJECTIVES:	Provide S/N data during precipitation. Investigation of terrain effect of southern Catskills and Berkshires. Provide initial information on use of system during IFR conditions.
DATE:	17 February 1975
TIME:	1621 - 1931 EST
ORIGIN:	Dulles Airport, Washington, D. C.
DESTINATION:	Bedford
ROUTE:	Dulles, Martinsburg VOR, Lancaster, Lake Henry VOR, Pawling VOR, Bedford
ALTITUDE:	7000 ft.
WEATHER:	IFR in varying light to heavy rain, light icing conditions
SUMMARY:	Takeoff at Dulles Airport in light rain with one mile visibility. Waypoints were chosen along the expected IFR clearance route wherever VORs coincided with

Flight No. 2-11 (Con't)

SUMMARY: airports due to lack of precomputed IFR waypoints. Weak Station A S/N caused track loss. Receiver was reset over Honesdale Airport and again 6 miles south of Monticello Airport. This same offset bias was shown when landing at Bedford. Light and heavy rain encountered enroute had no observable effect on S/N. Flight was conducted at high enough altitude as not to show terrain effects. Reset location inaccuracies precluded measuring any small diurnal effect present.

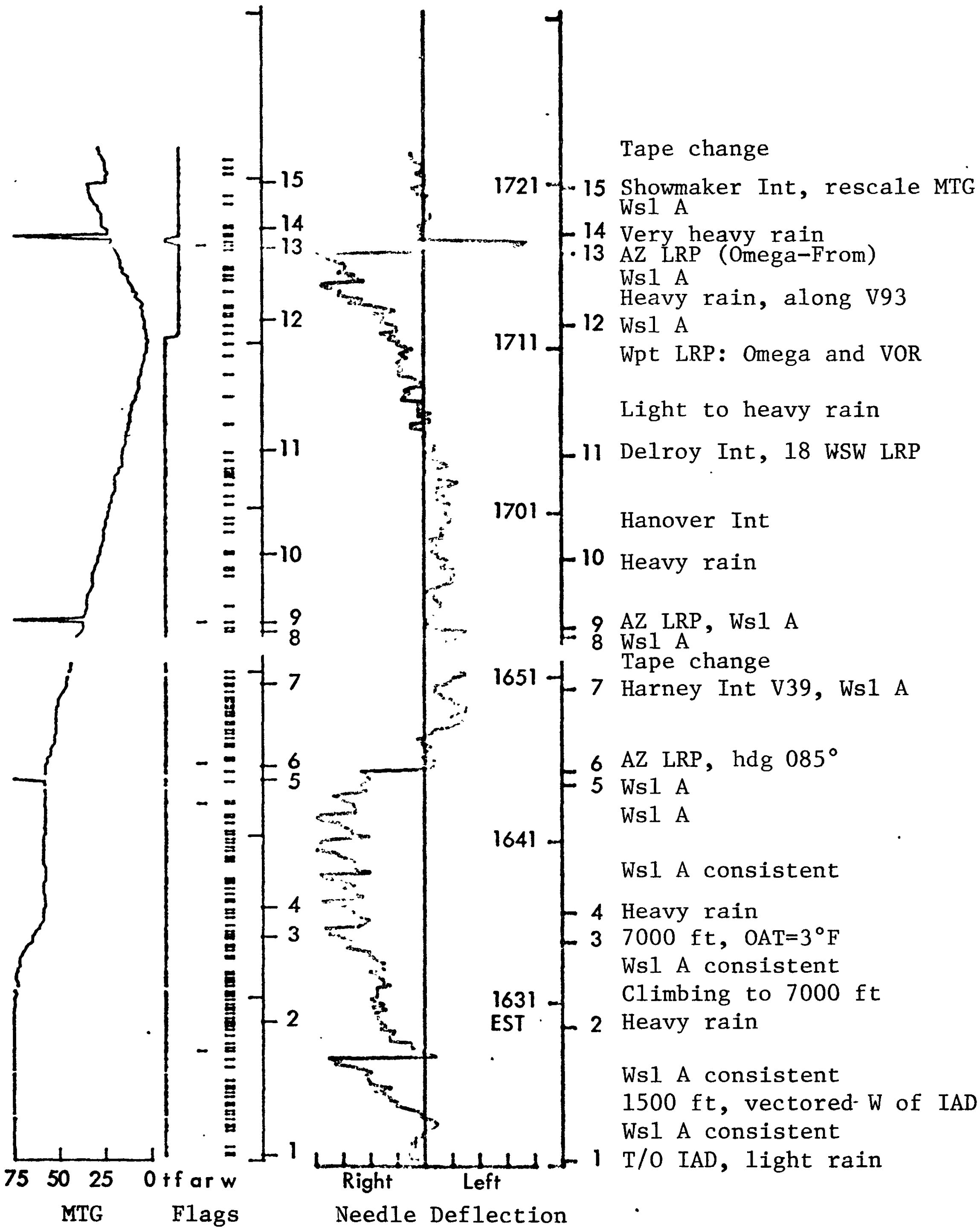


Figure B.2-1 Fight 2-11 (Part 1) Miles to Go and Needle Deflection

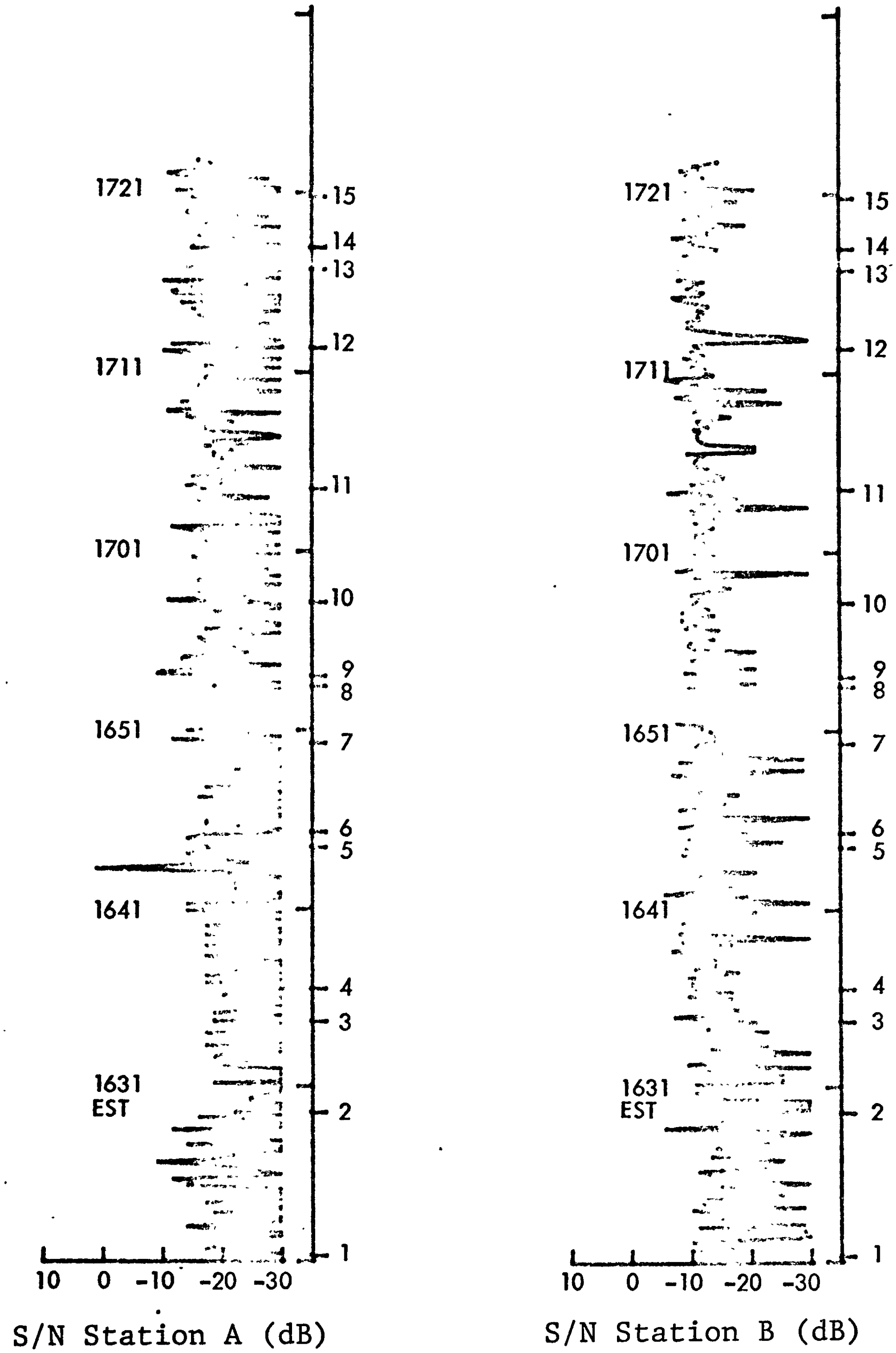


Figure B.2-2 Flight 2-11 (Part 1) S/N Stations A and B

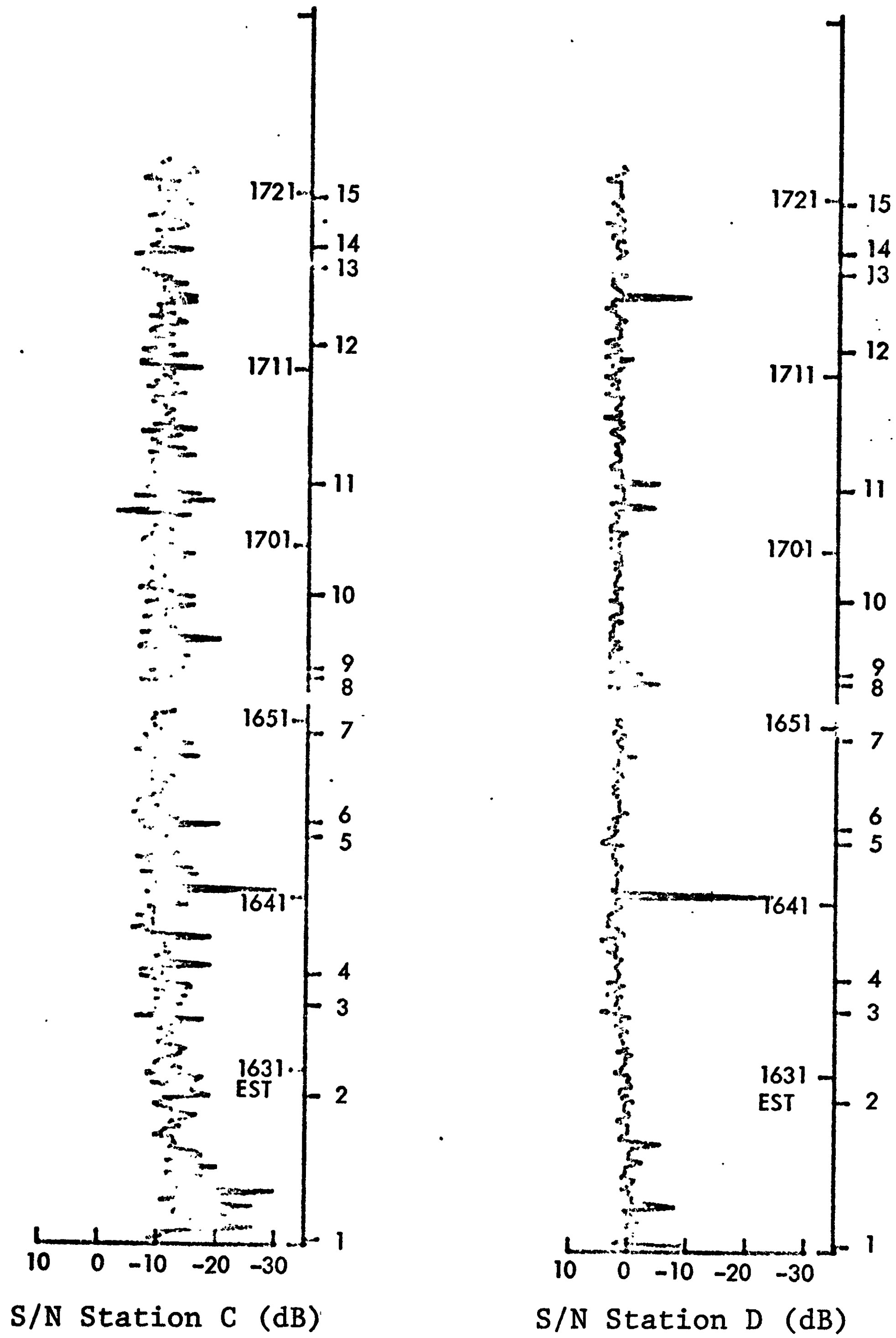


Figure B.2-3 Flight 2-11 (Part 1) S/N Stations C and D

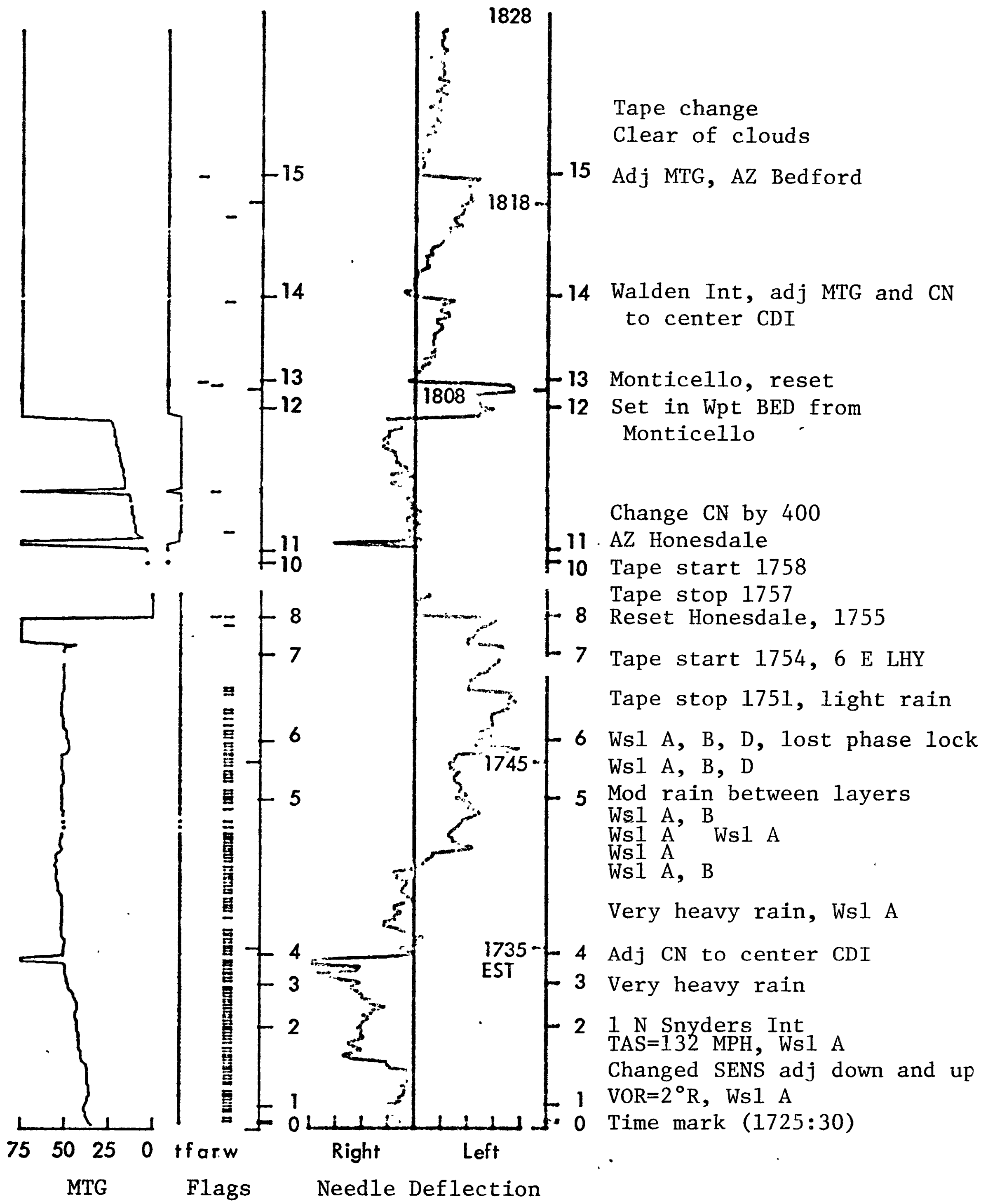


Figure B.2-4 Flight 2-11 (Part 2) Miles to Go and Needle Deflection

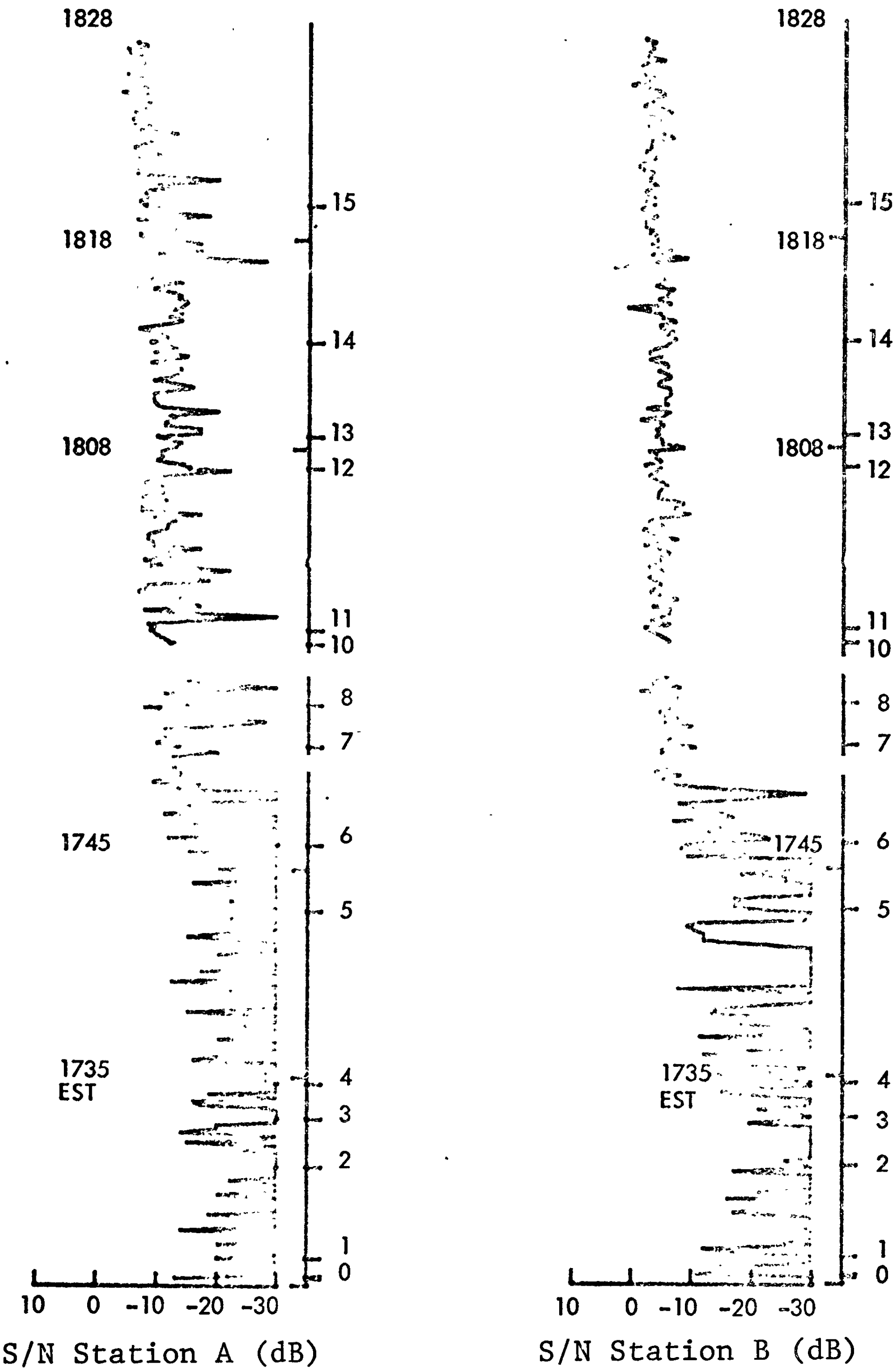


Figure B.2-5 Flight 2-11 (Part 2) S/N Stations A and B

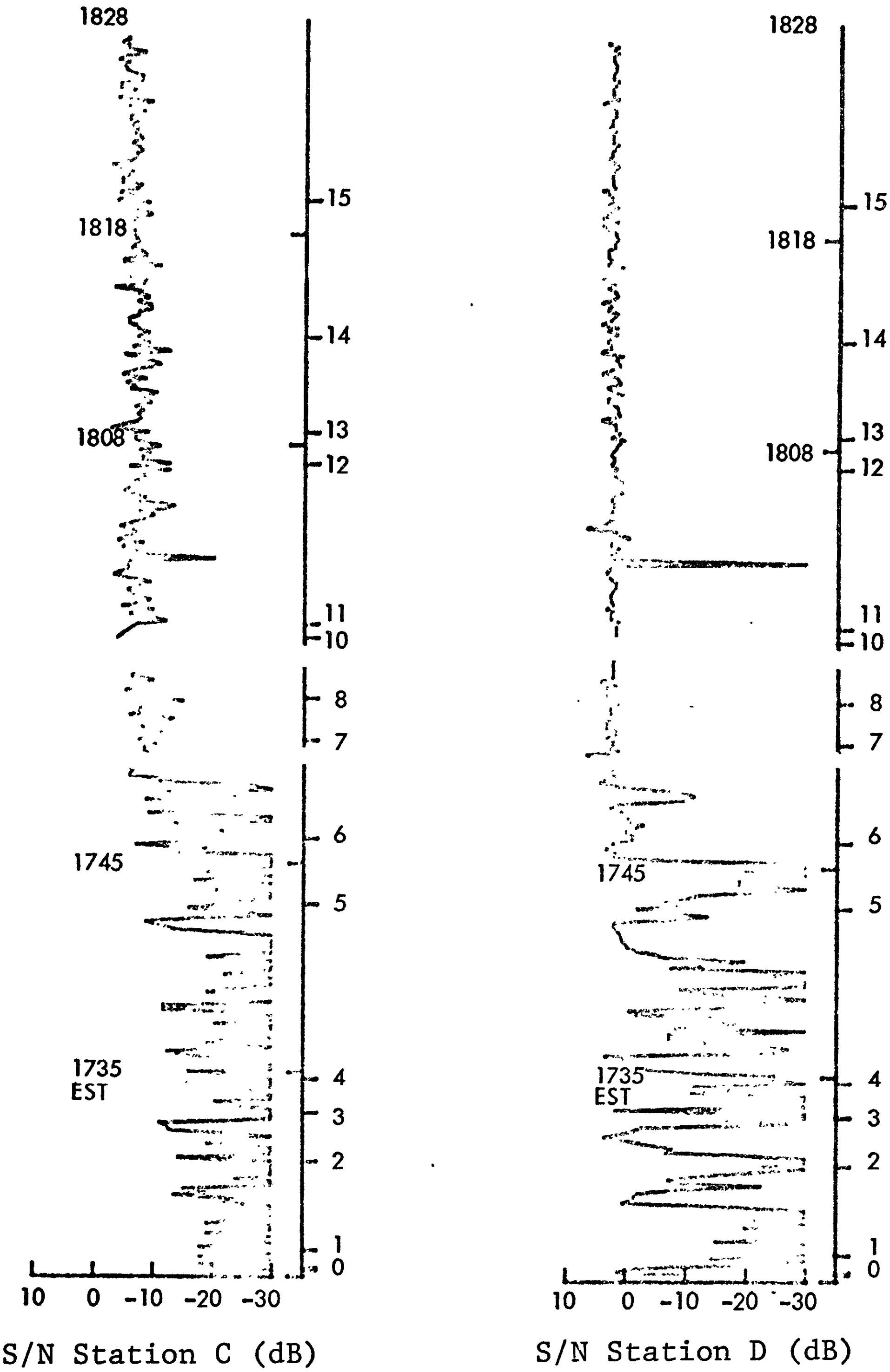


Figure B.2-6 Flight 2-11 (Part 2) S/N Stations C and D

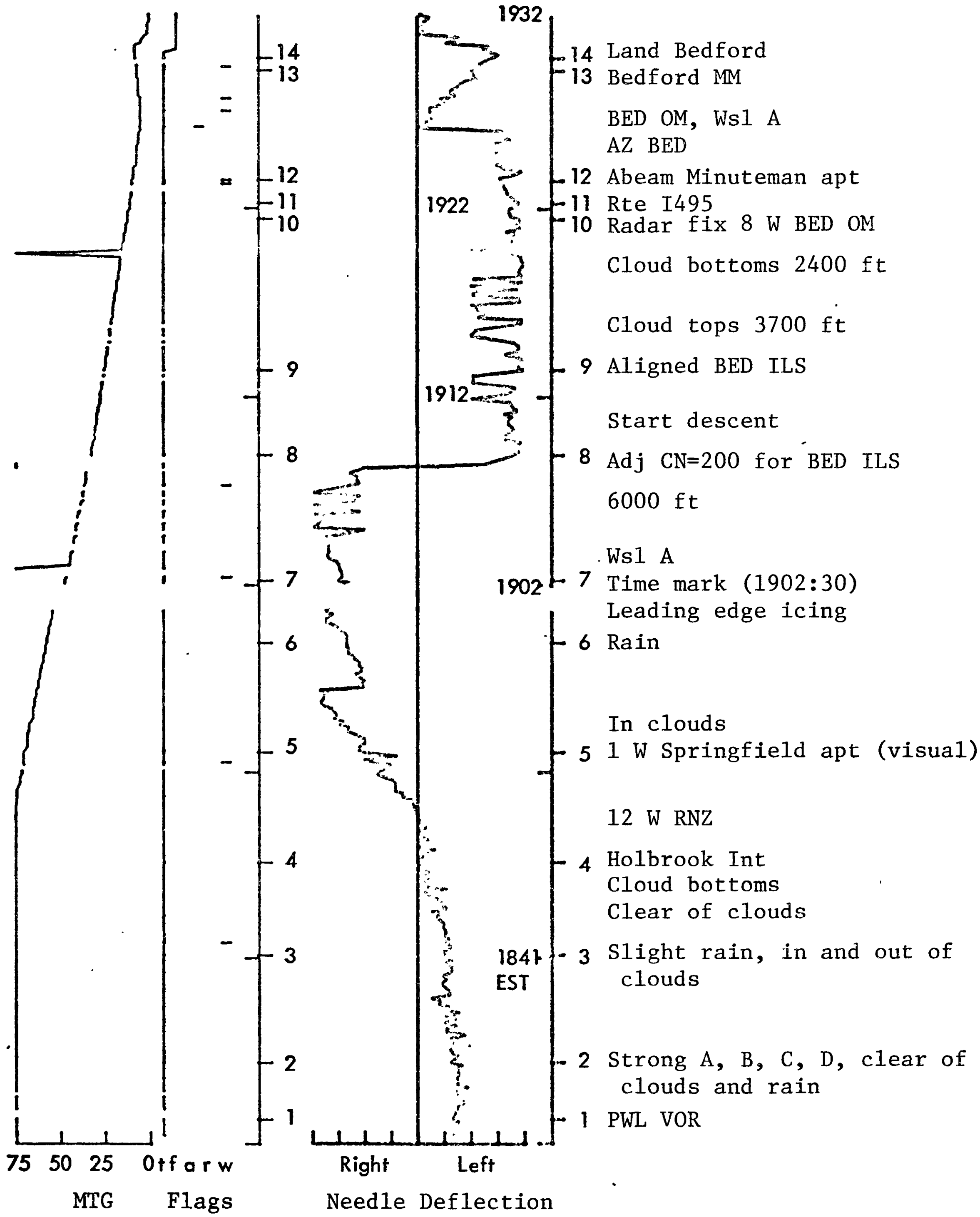


Figure B.2-7 Flight 2-11 (Part 3) Miles to Go and Needle Deflection

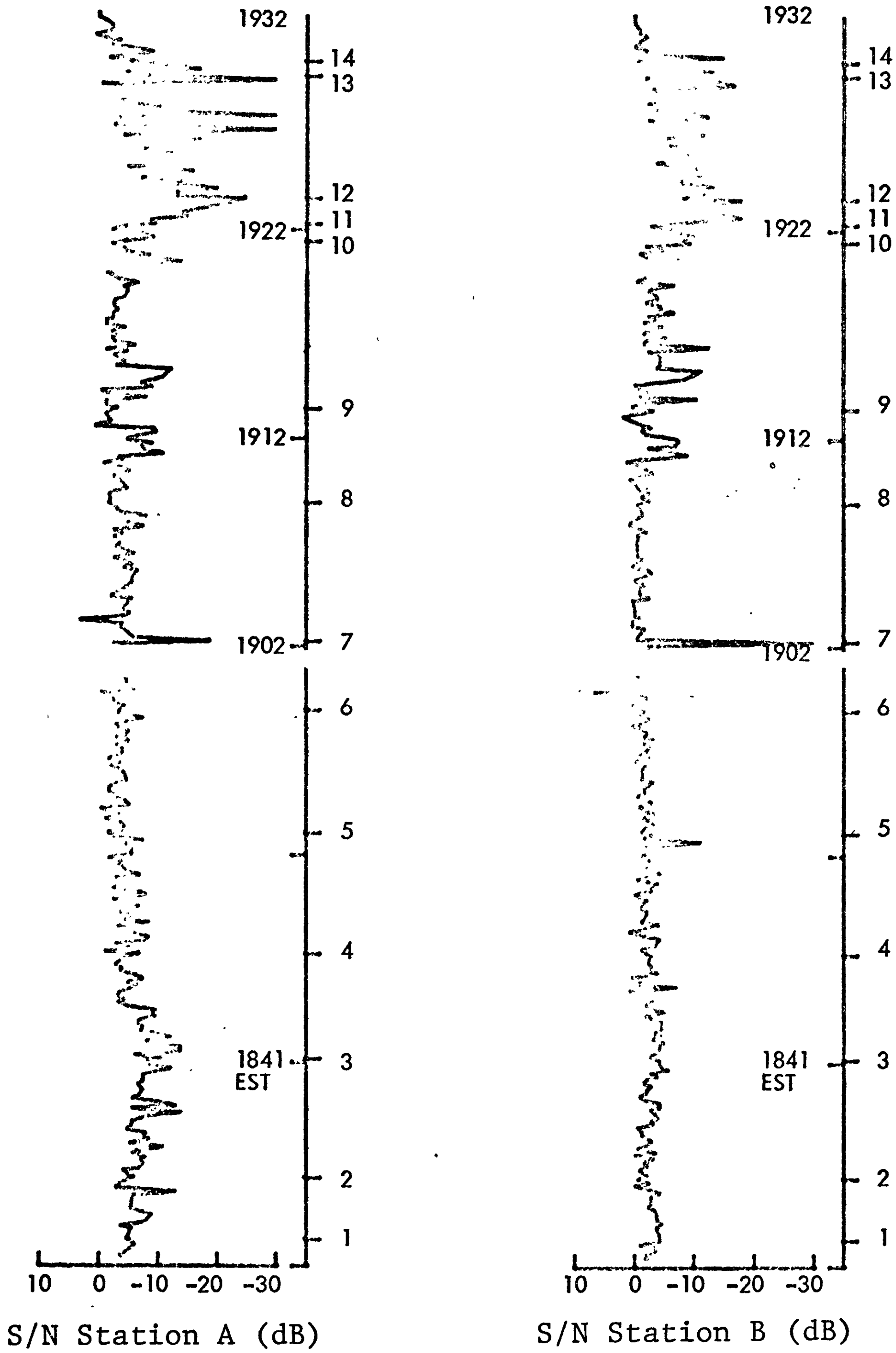


Figure B.2-8 Flight 2-11 (Part 3) S/N Stations A and B

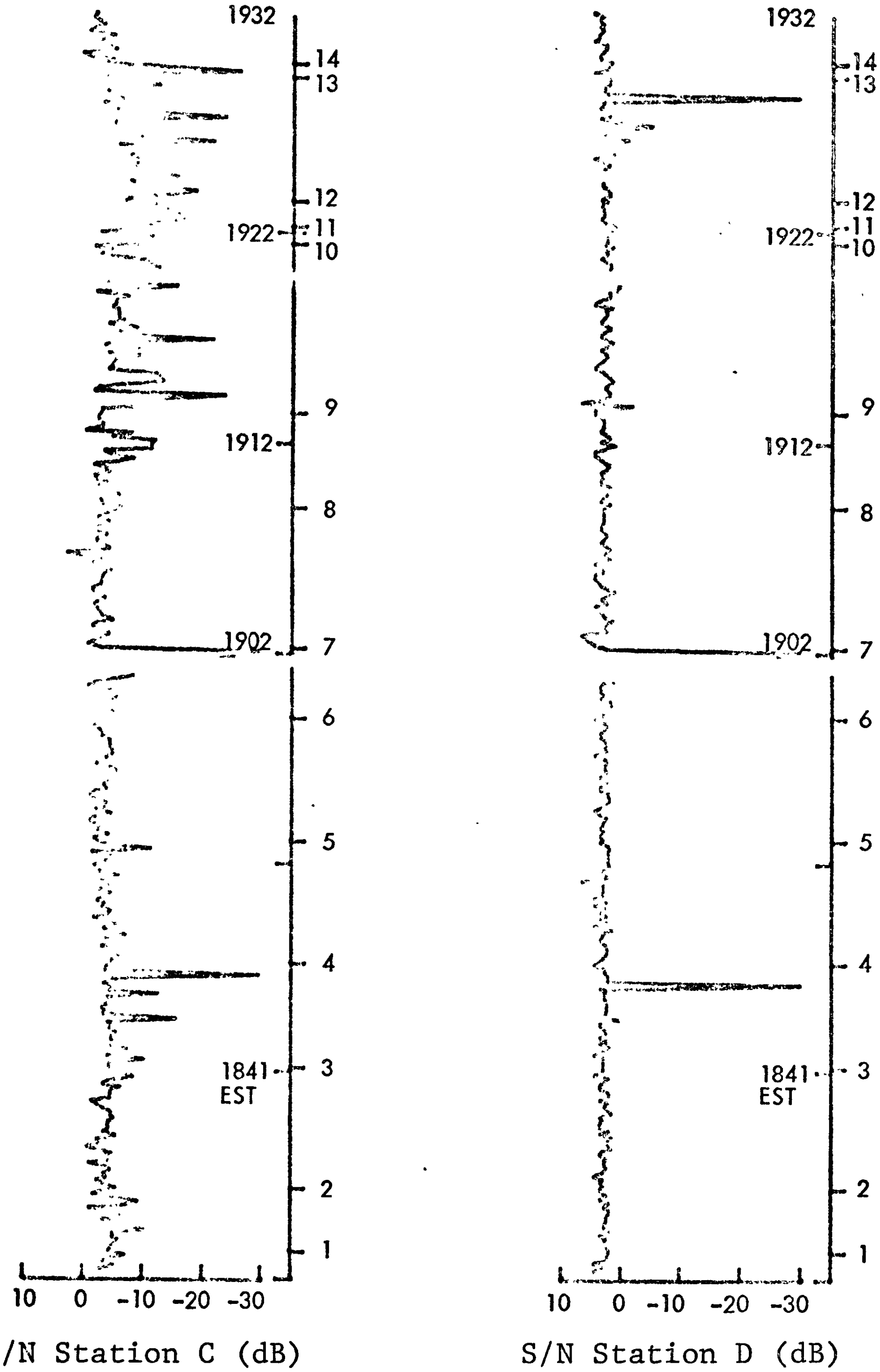


Figure B.2-9 Flight 2-11 (Part 3) S/N Stations C and D

TEST DESCRIPTION

Flight No. 2-12

TEST OBJECTIVES: Obtain additional S/N data along Zulu routes before diverting to Salisbury. The Zulu-S route begins at the Statue (Wpt 7), direct Verrazano Bridge (Wpt 8), Preston Airport (Wpt 9), Bordentown (Wpt 10), Camden (Wpt 11), Salem (Wpt 12), then direct to Vienna Maryland (Wpt 13), Salisbury (Wpt 14).

DATE: 19 February 1975

TIME: 1210 - 1530 EST

ORIGIN: Bedford

DESTINATION: Salisbury

ROUTE: Zulu-2, Zulu-S, divert Salisbury

ALTITUDE: 2000 ft., 1100 ft through New York TCA

WEATHER: VFR, 15 kts, SW

SUMMARY: Flight proceeded as planned, with radios off for the majority of the flight. Skipped waypoints 5 and 6 as they are very close and almost colinear with 4.5 and 7.

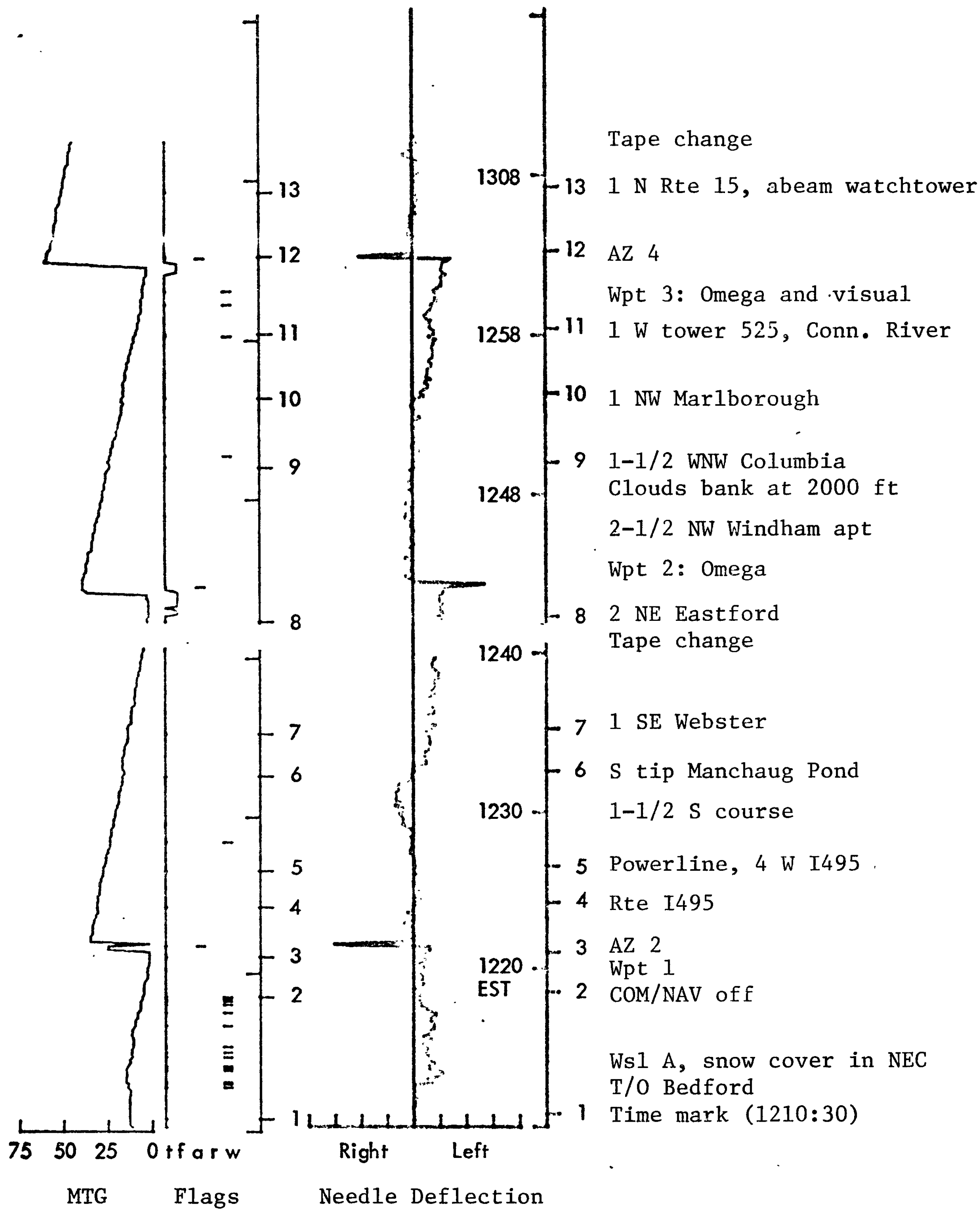


Figure B.3-1 Flight 2-12 (Part 1) Miles to Go and Needle Deflection

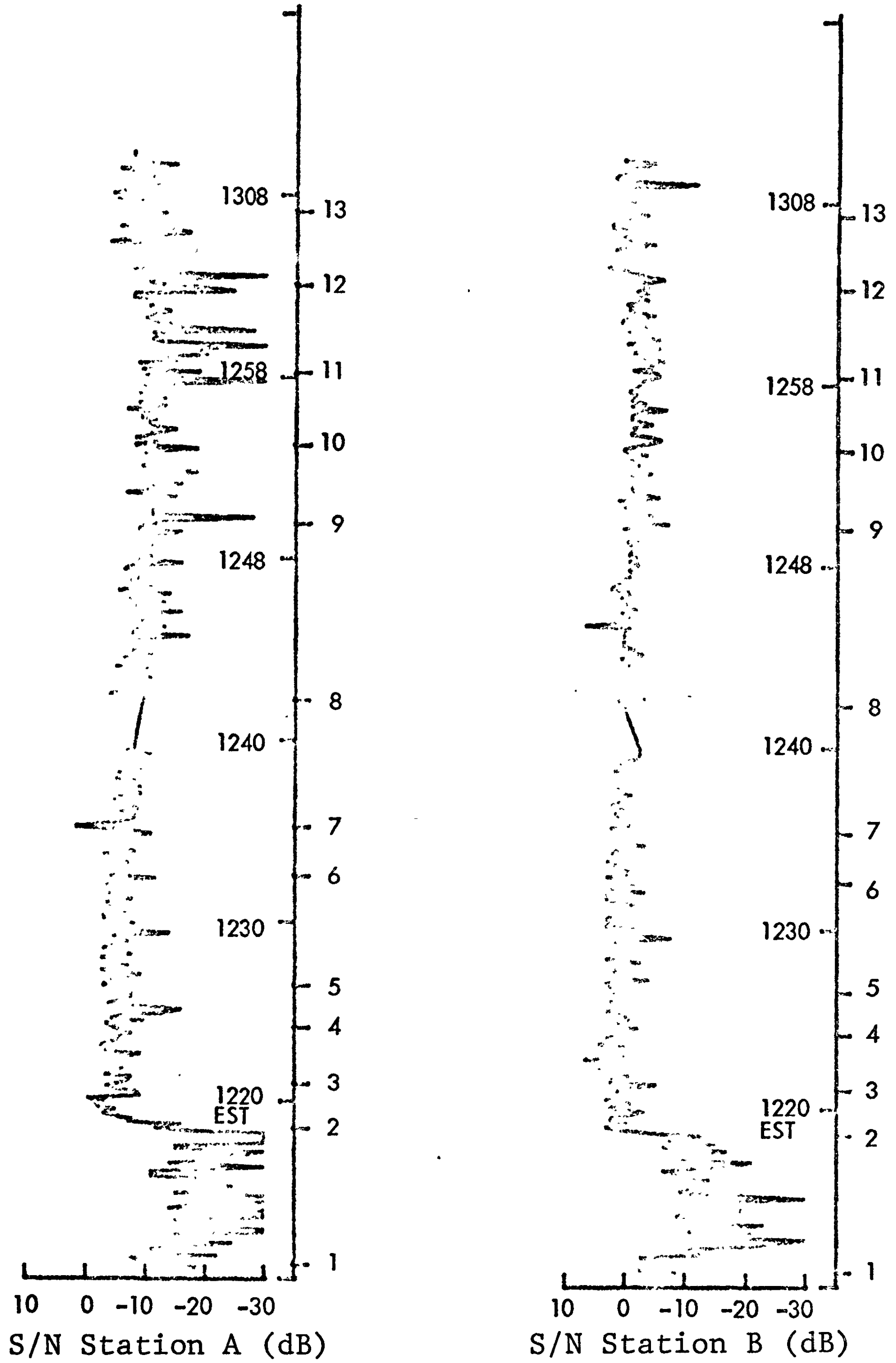


Figure B.3-2 Flight 2-12 (Part 1) S/N Stations A and B

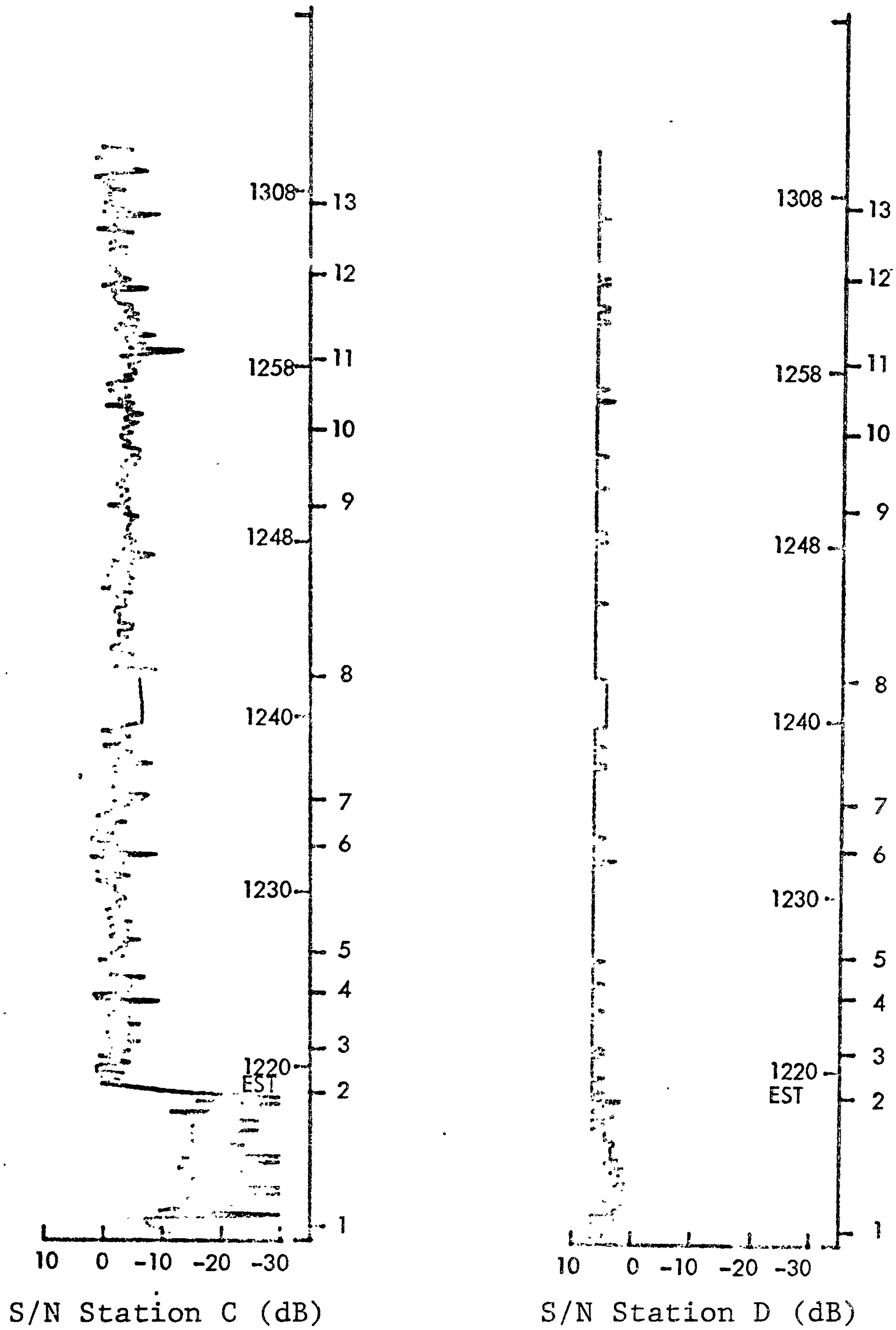


Figure B.3-3 Flight 2-12 (Part 1) S/N Stations C and D

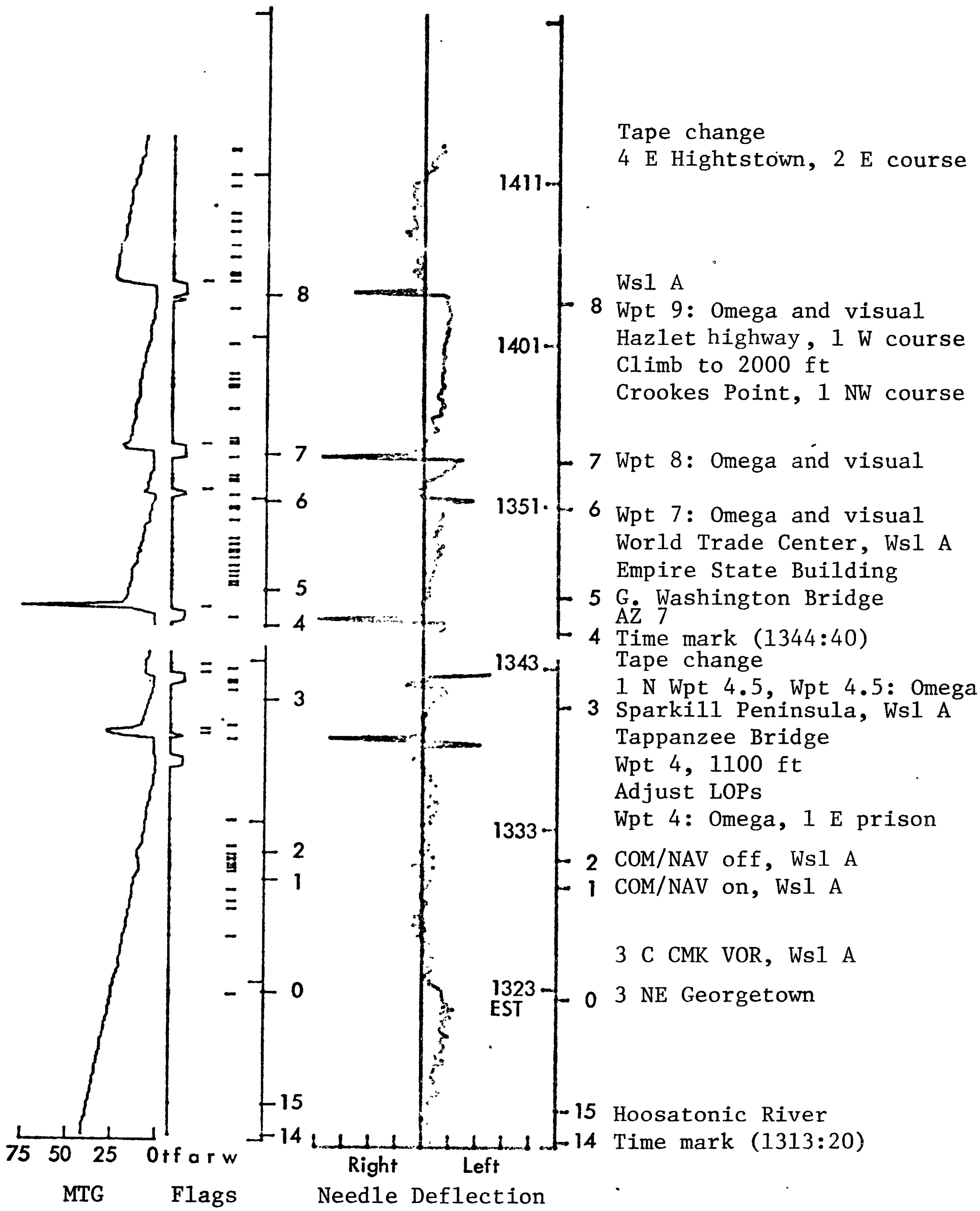


Figure B.3-4 Flight 2-12 (Part 2) Miles to Go and Needle Deflection

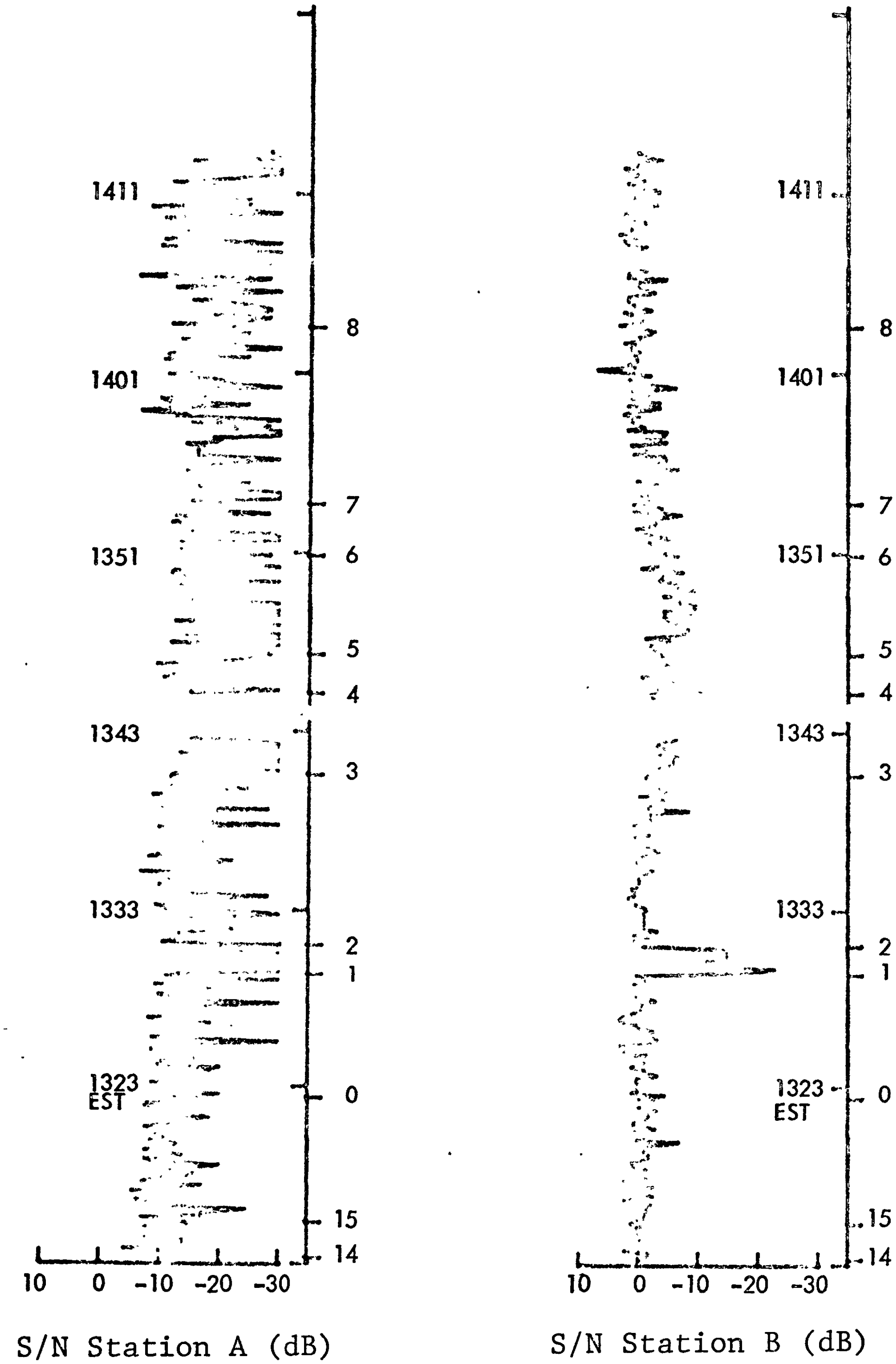


Figure B.3-5 Flight 2-12 (Part 2) S/N Stations A and B

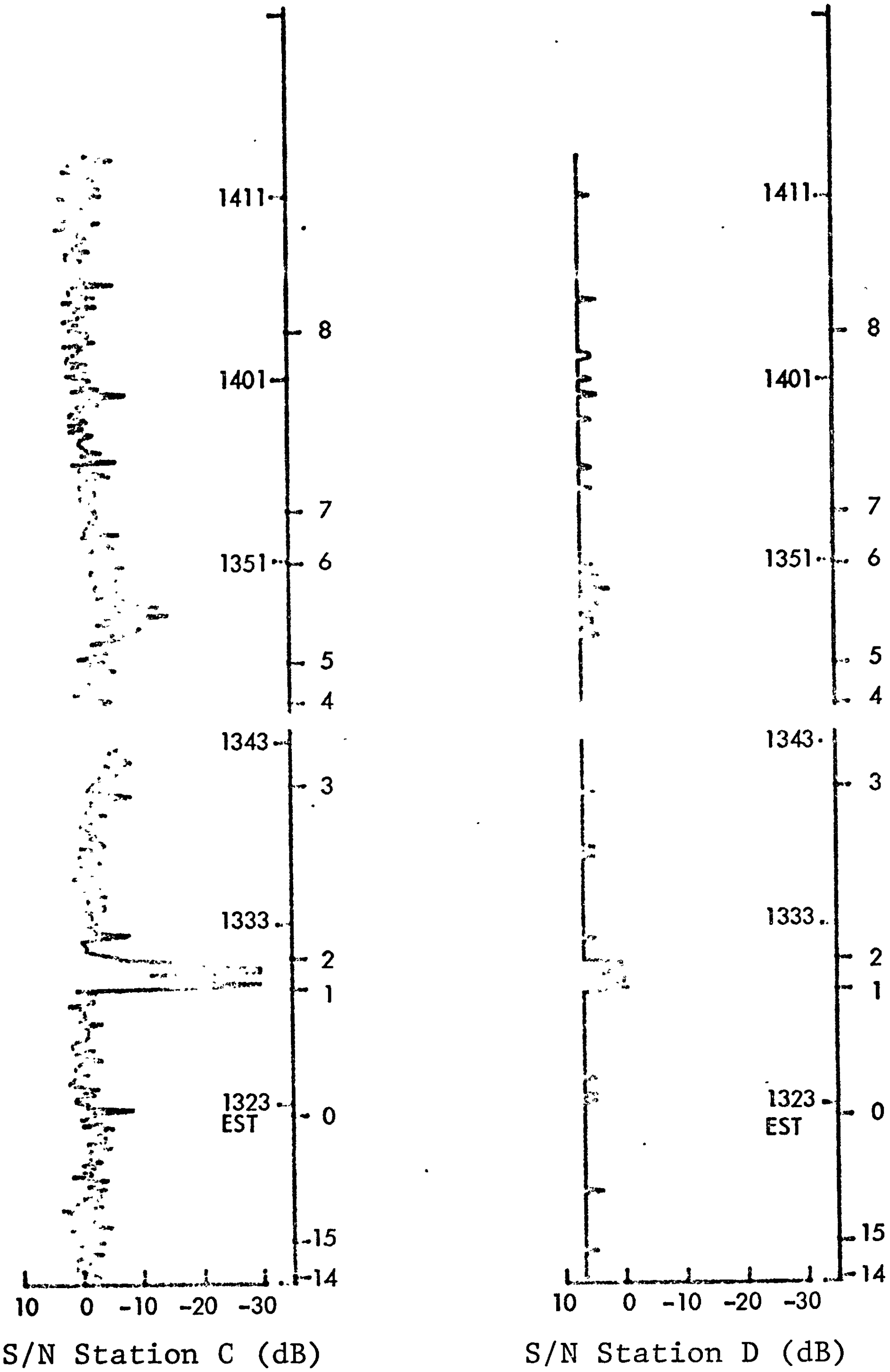


Figure B.3-6 Flight 2-12 (Part 2) S/N Stations C and D

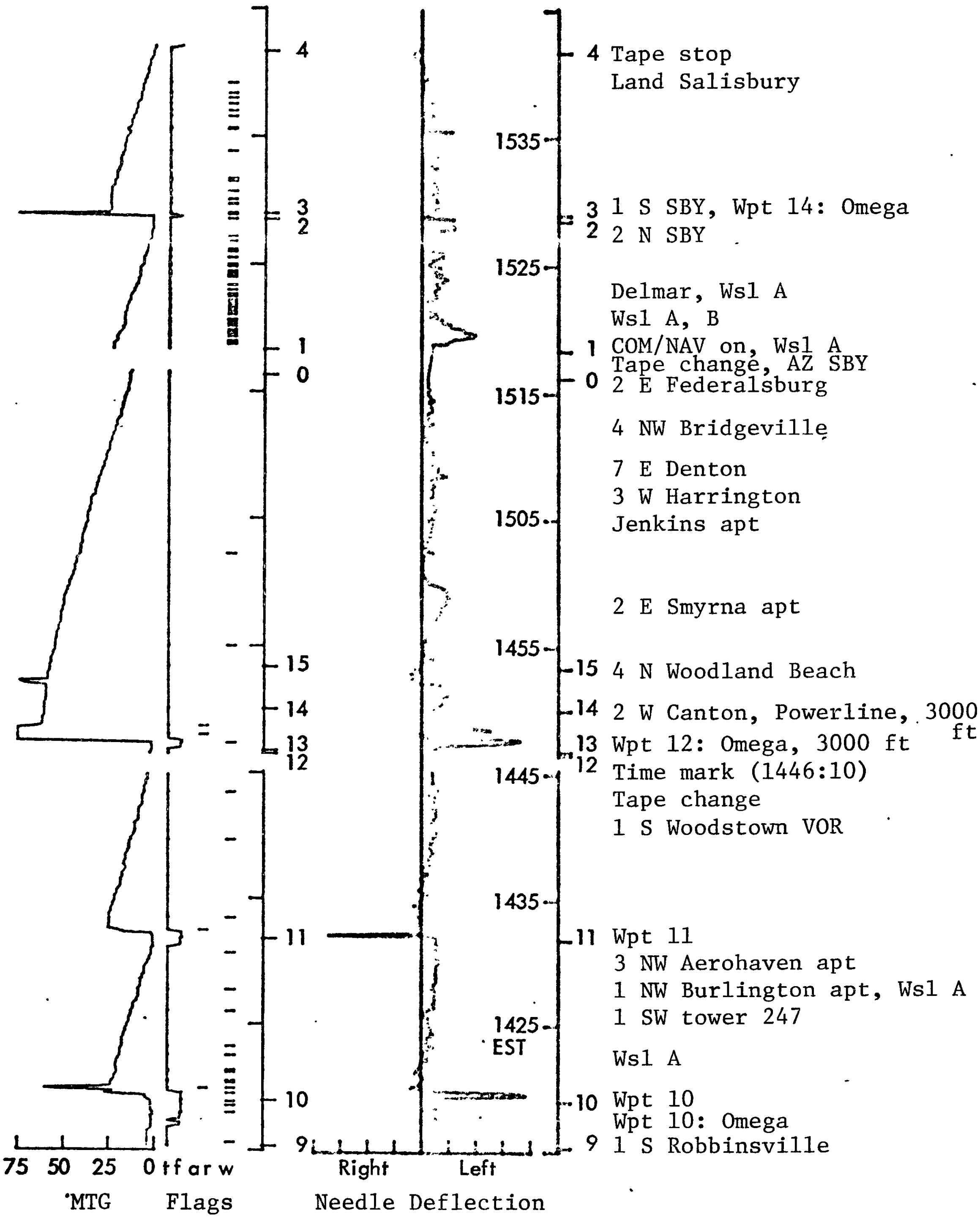


Figure B.3-7 Flight 2-12 (Part 3) Miles to Go and Needle Deflection

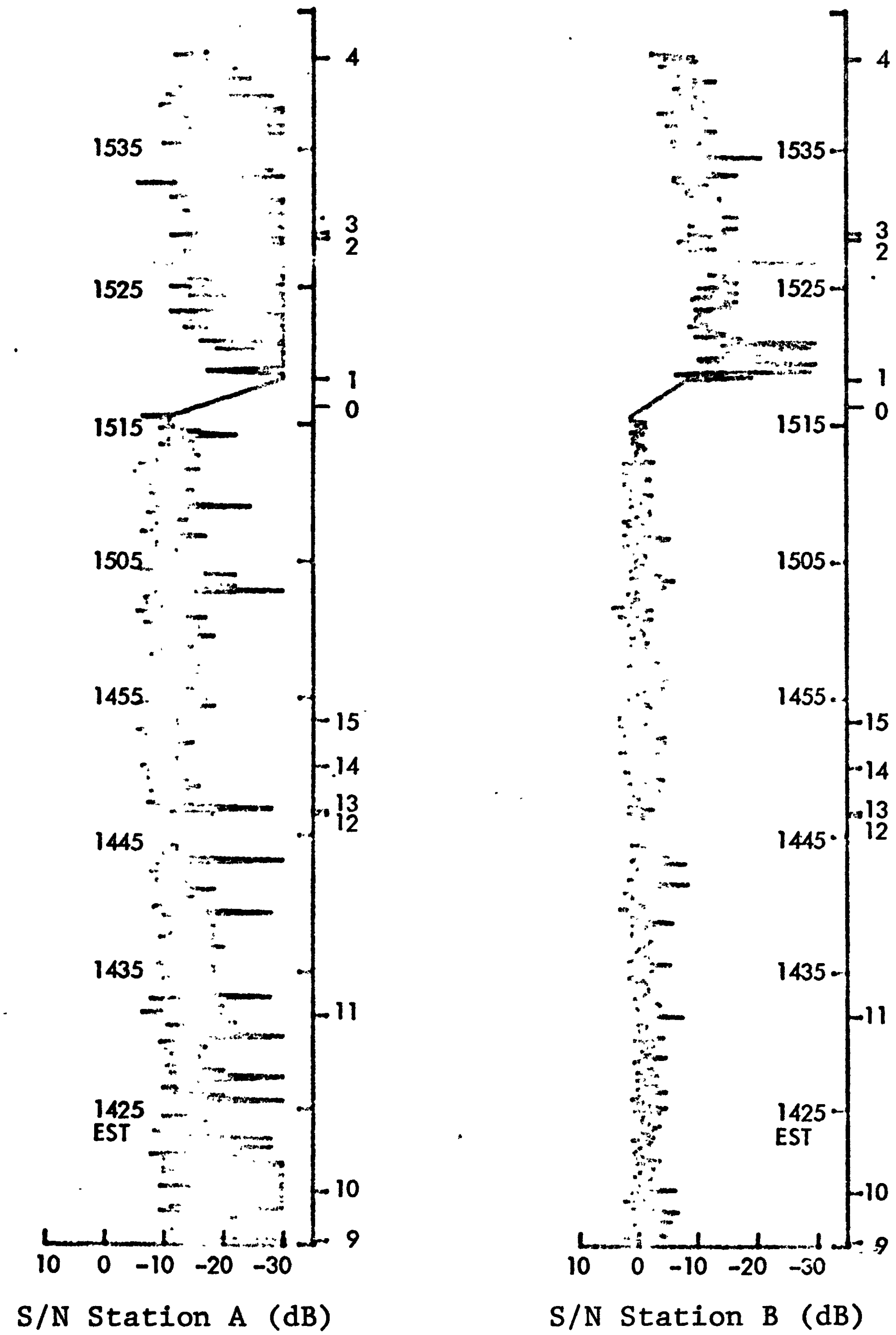


Figure B.3-8 Flight 2-12 (Part 3) S/N Stations A and B

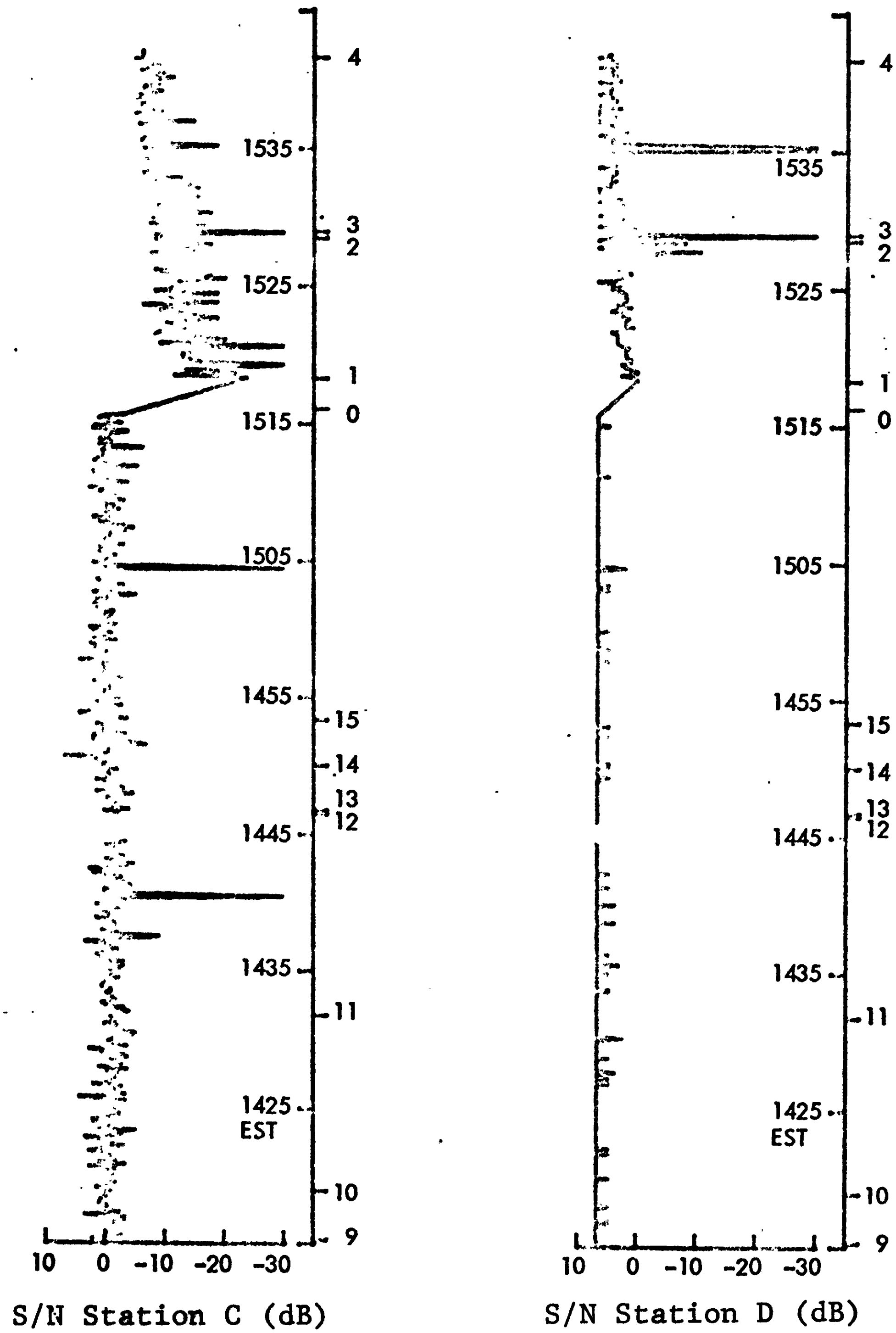


Figure B.3-9 Flight 2-12 (Part 3) S/N Stations C and D

TEST DESCRIPTION

Flight No. 2-13

TEST OBJECTIVES:	Provide S/N data and waypoint accuracy check enroute from Salisbury to Bedford via airports and along the Z-1 route. Flight route was Salisbury direct Wildwood (Wpt 1), direct NAFEC (Wpt 2), direct Lakehurst (Wpt 3), direct Preston (Wpt 4), direct Jones Beach (Wpt 5), Jamaica Inlet (Wpt 6), tower 376 (Wpt 8), then via Zulu-1 to Bedford.
DATE:	22 February 1975
TIME:	1225 - 1608 EST
ORIGIN:	Salisbury
DESTINATION:	Bedford
ROUTE:	Zulu-1
ALTITUDE:	5500 ft, 500 ft through New York TCA
WEATHER:	VFR, 15 kts, SW
SUMMARY:	Voice tape discovered inoperative over Long Island. Miles to go stopped

Fight No. 2-13 (Con't)

SUMMARY: decreasing over Delaware and again over Connecticut (analysis showed strong S/N ratios). Later in the flight the MTG began to increment properly again.

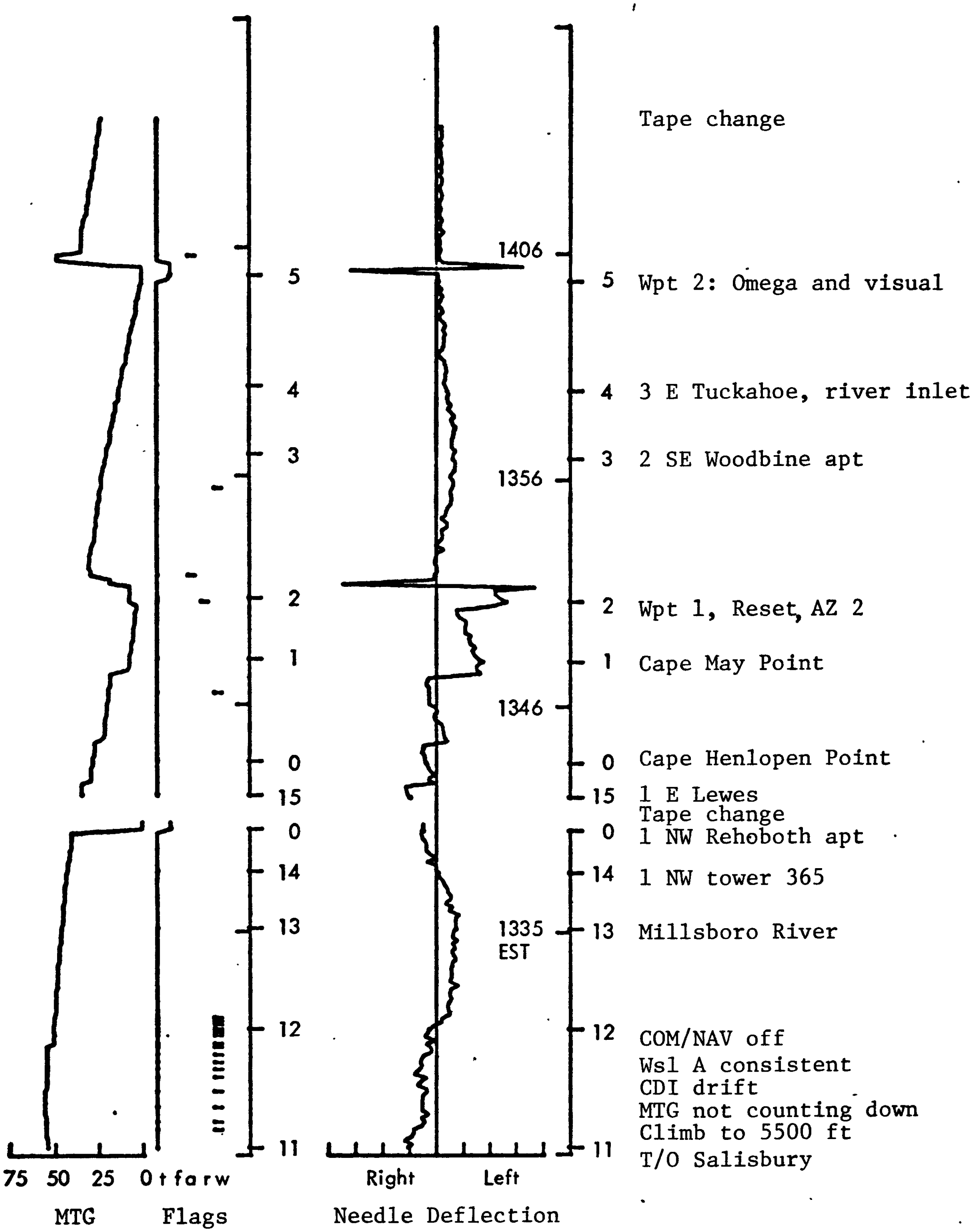


Figure B.4-1 Flight 2-13 (Part 1) Miles to Go and Needle Deflection

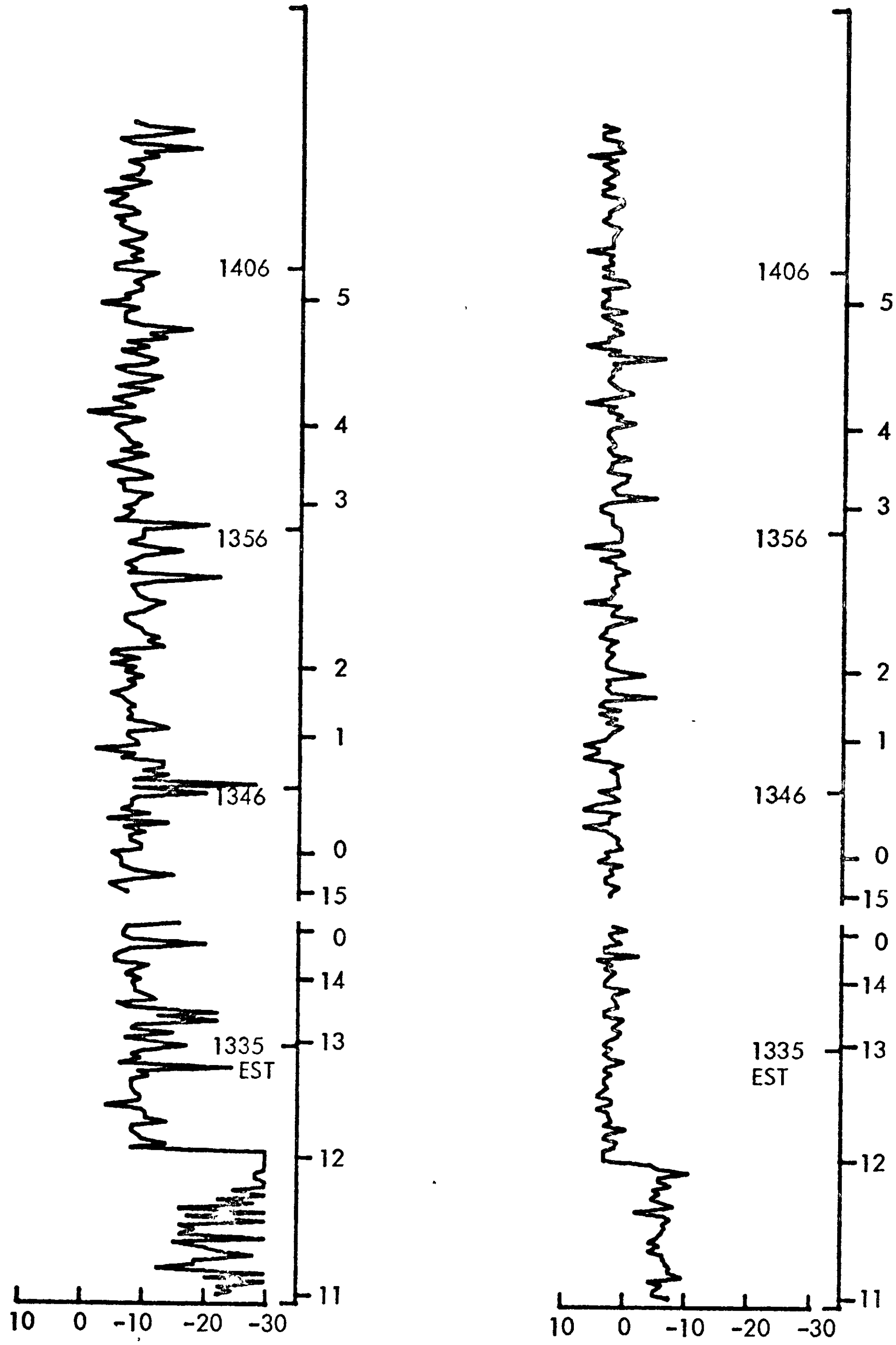


Figure B.4-2 Flight 2-13 (Part 1) S/N Stations A and B

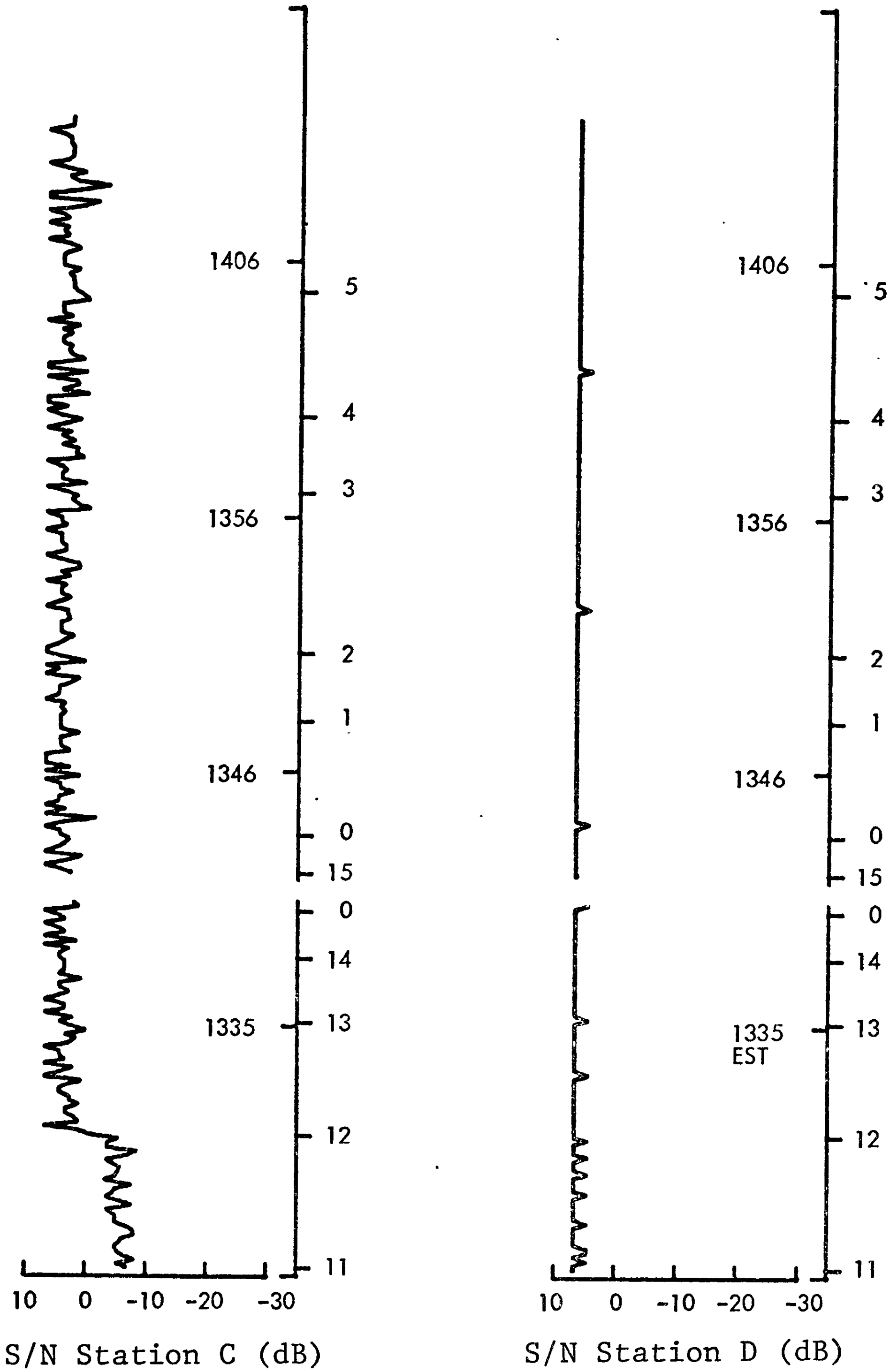


Figure B.4-3 Flight 2-13 (Part 1) S/N Stations C and D

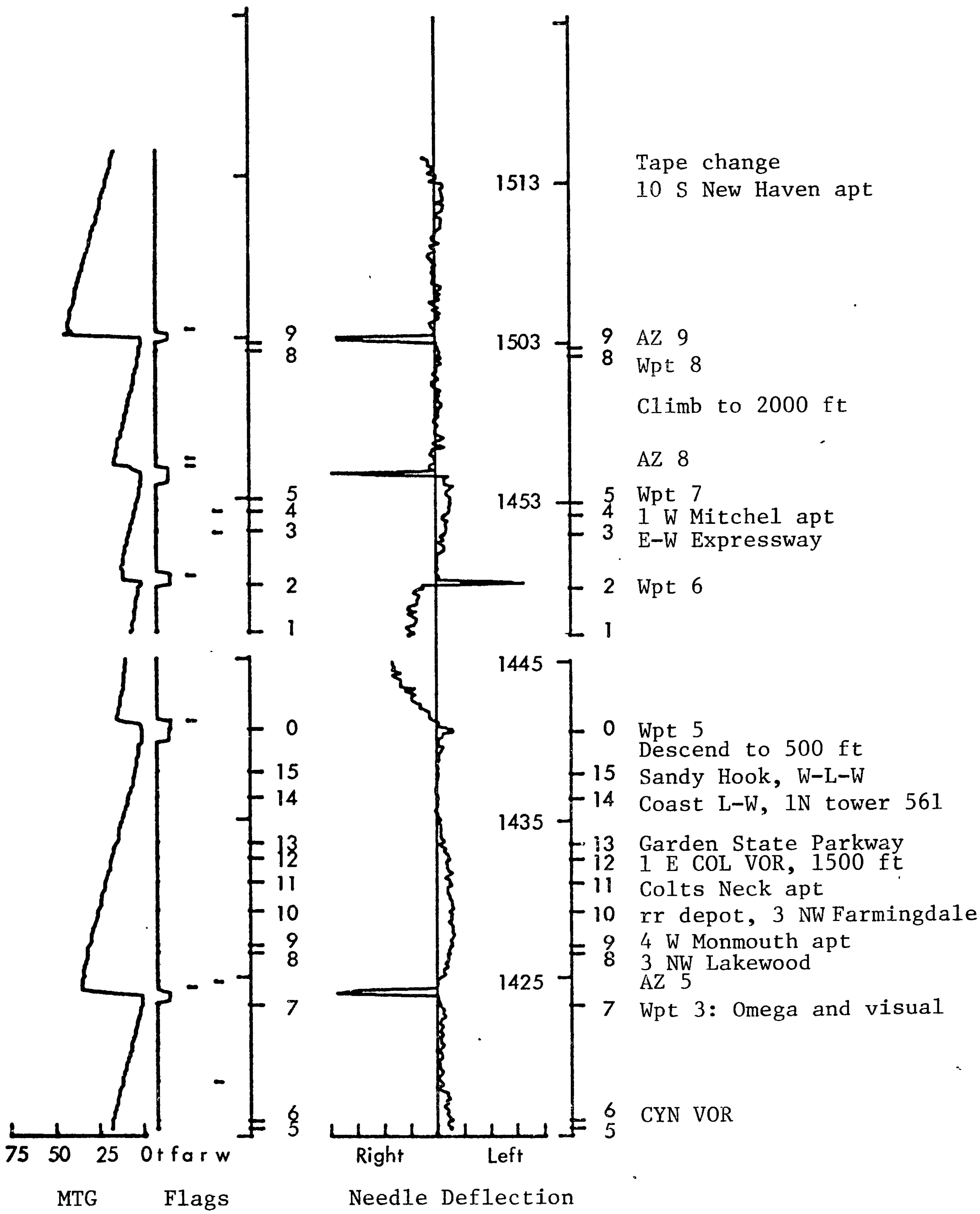


Figure B.4-4 Flight 2-13 (Part 2) Miles to Go and Needle Deflection

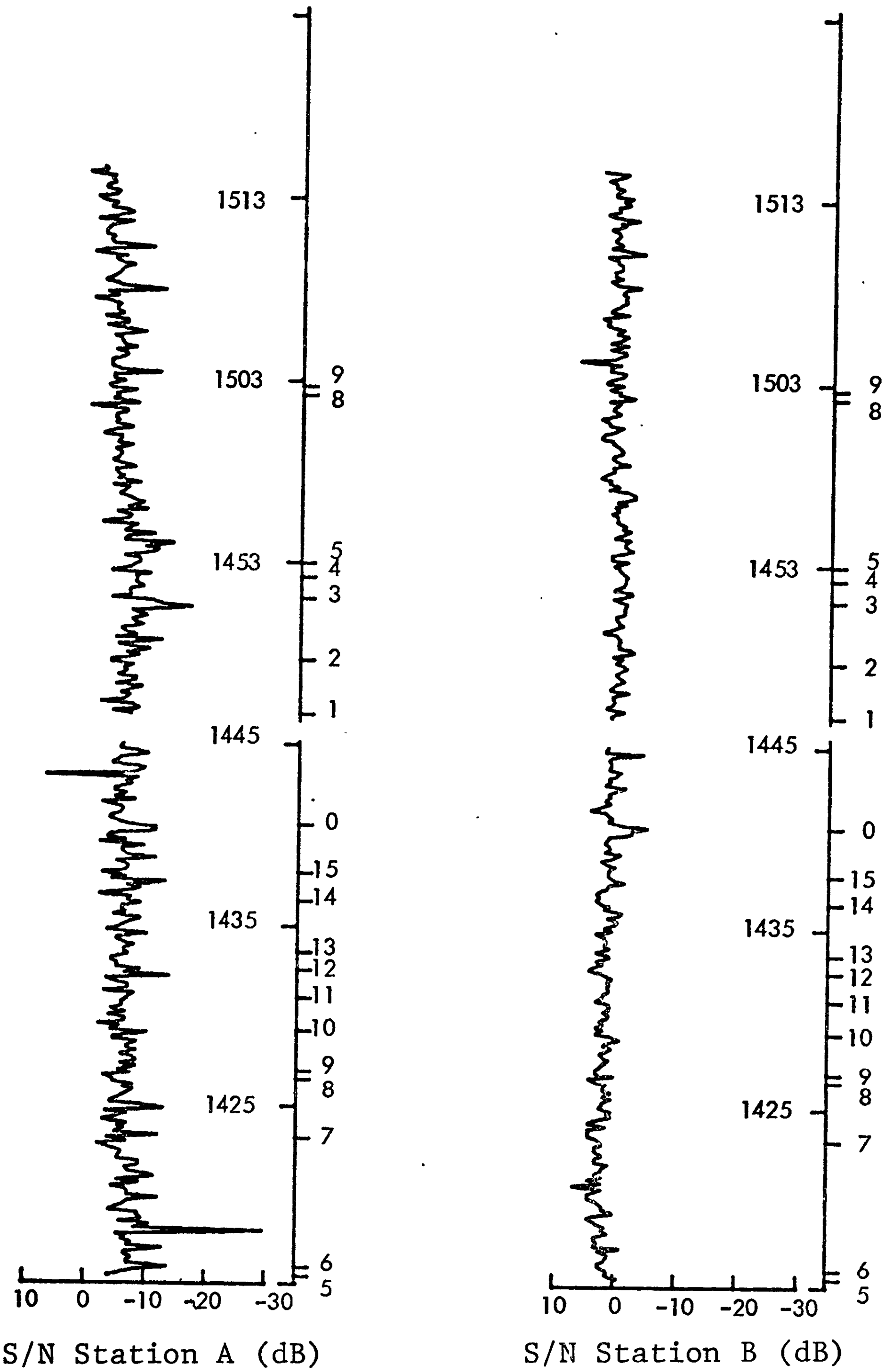


Figure B.4-5   Flight 2-13 (Part 2) S/N Stations A and B

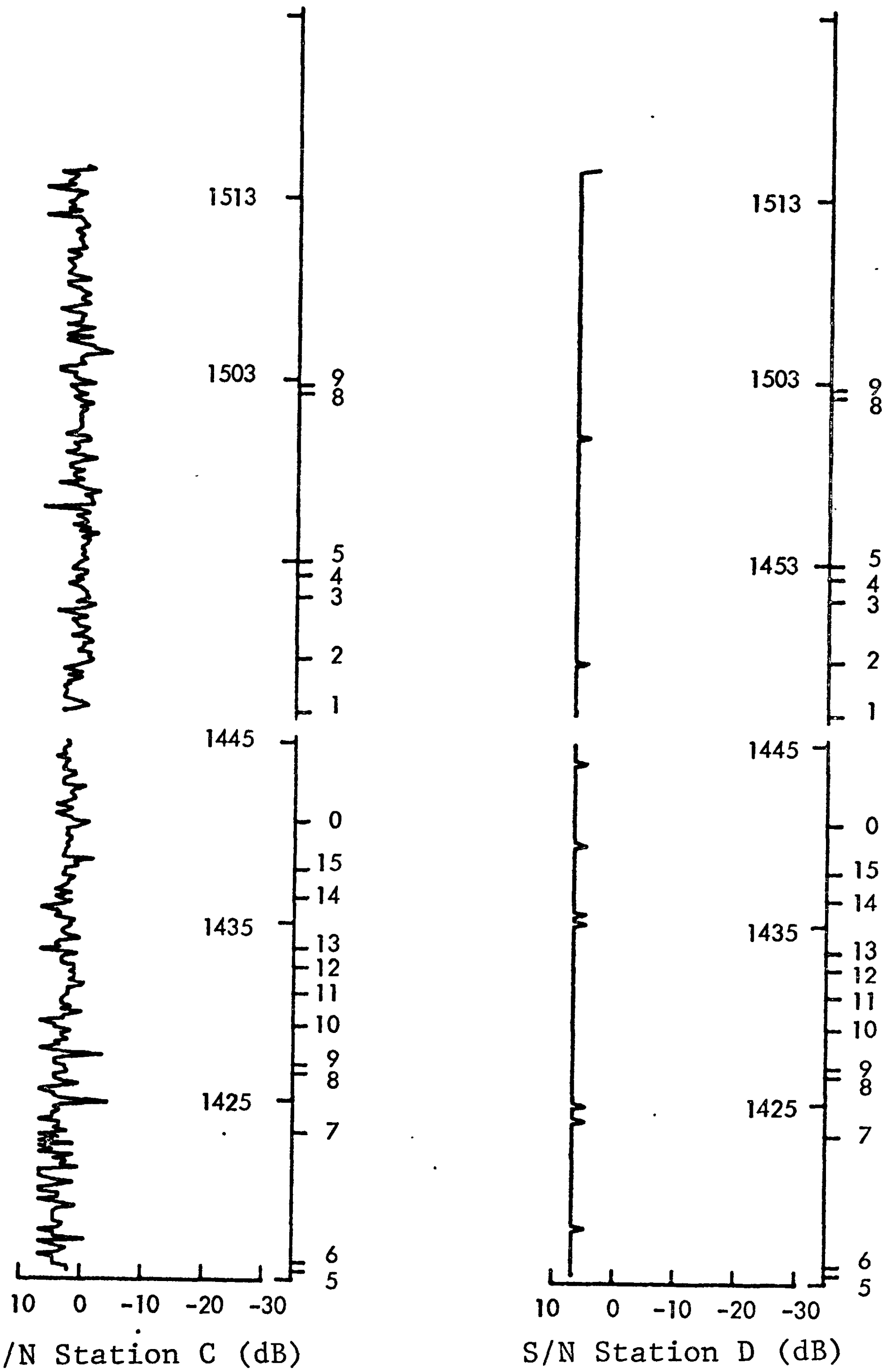


Figure B.4-6 Flight 2-13 (Part 2) S/N Stations C and D

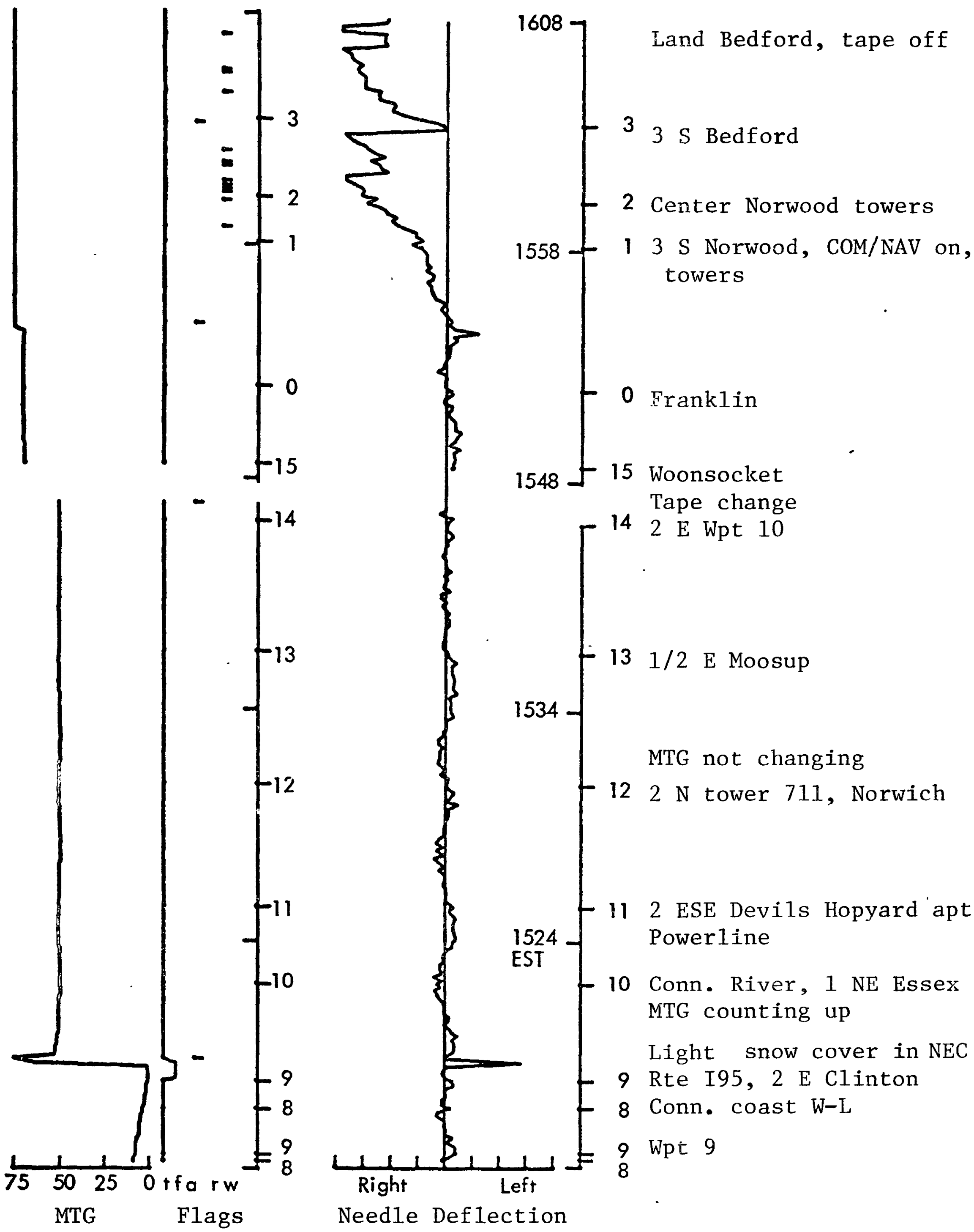


Figure B.4-7 Flight 2-13 (Part 3) Miles to Go and Needle Deflection

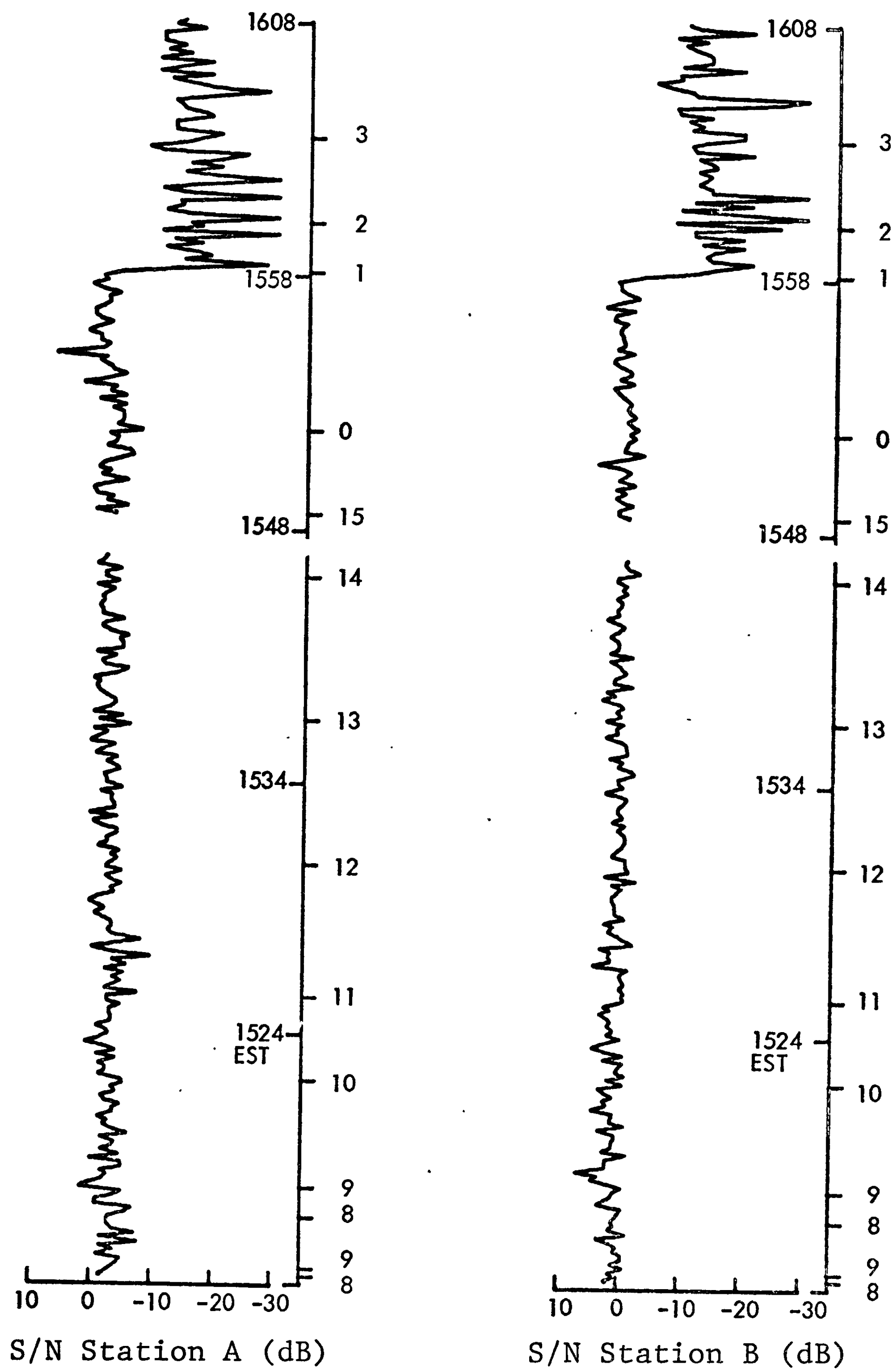


Figure B.4-8 Flight 2-13 (Part 3) S/N Stations A and B

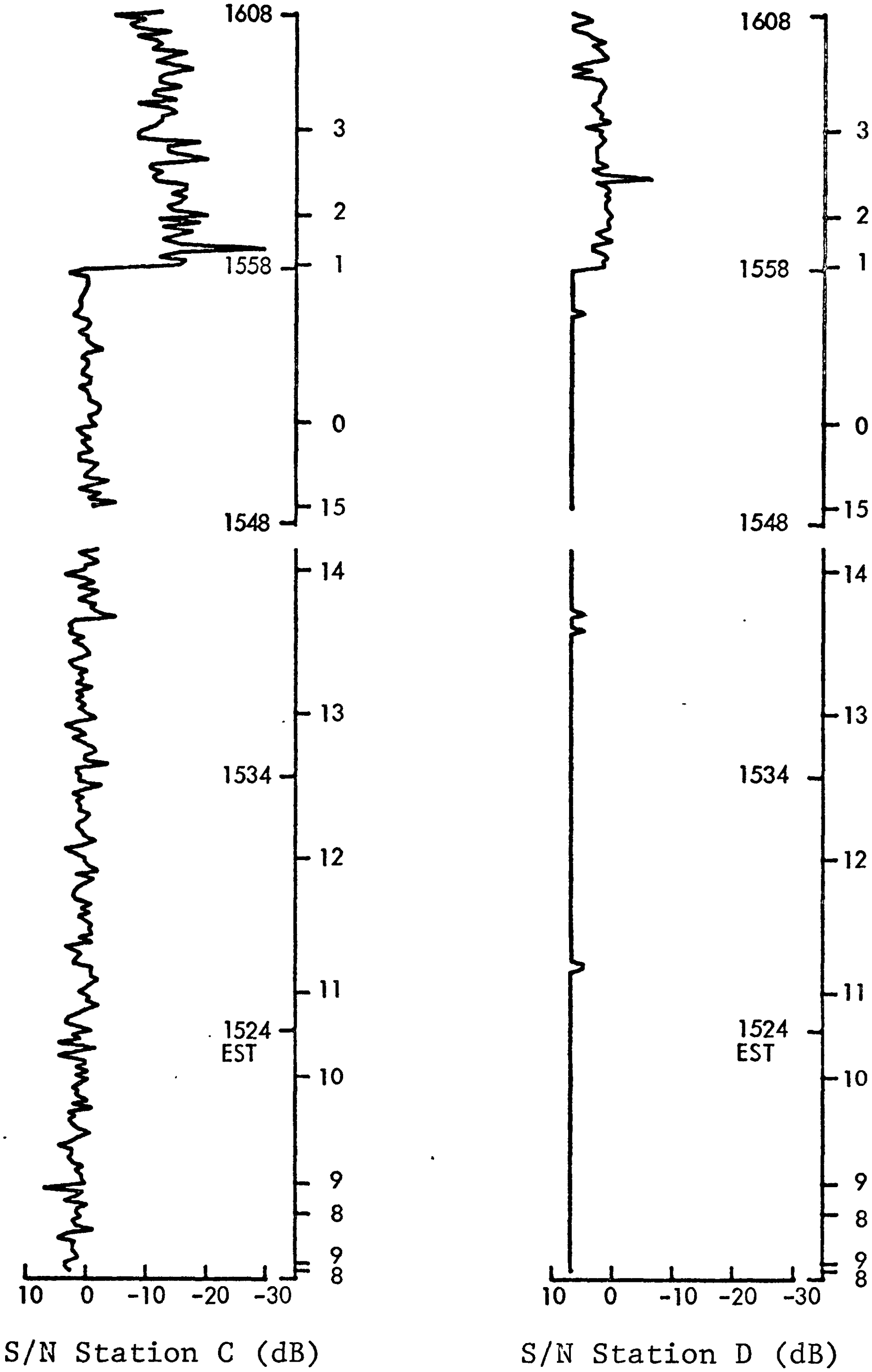


Figure B.4-9 Flight 2-13 (Part 3) S/N Stations C and D

TEST DESCRIPTION

Flight No. 2-21

TEST OBJECTIVES:	Obtain data for Flight 2-7 for which data was lost. Test CIU output with most significant byte chip replaced for LOP 1 readout.
DATE:	27 February 1975
TIME:	1917 - 2021 EDT
ORIGIN:	Bedford
DESTINATION:	Bedford
ROUTE:	Bedford, television tower, Framingham, Gardner, Haystack, Lowell, Bedford
ALTITUDE:	2000 ft.
WEATHER:	Night VFR
SUMMARY:	Flight proceeded as planned. Operation of radios directly affected S/N ratios, transmissions affected data output. Replaced chip worked well on map plot.

TEST DESCRIPTION

Flight No. 2-31

TEST OBJECTIVES:	Check CIU operation with additional chip replacement.
DATE:	5 March 1975
TIME:	
ORIGIN:	Haverhill
DESTINATION:	Bedford
ROUTE:	Along AB LOP to BD LOP through Bedford
ALTITUDE:	1200 ft.
WEATHER:	VFR, 15 kts SW

SUMMARY: Some difficulty was encountered with input of proper initial waypoint along constant AB LOP. Reasonable navigation followed, with final waypoint indication near the airport reference point at Bedford. Recorded data was garbled.

TEST DESCRIPTION

Flight No. 2-41

TEST OBJECTIVES:	Provide Zulu route data and preliminary S/N in the Wallops area for the second set of Wallops flights.
DATE:	7 March 1975
TIME:	0926 - 1302 EDT
ORIGIN:	Bedford
DESTINATION:	Salisbury
ROUTE:	Zulu-2, divert Salisbury
ALTITUDE:	2000 ft, 500 ft through New York TCA, 3000 ft
WEATHER:	VFR, 3500 ft broken cover, 15 kts, S
SUMMARY:	Good navigation along route, final waypoint indication one mile south, southwest actual waypoint. Recorded data ceased over Lakehurst due to failed connector at recorder. Station H (Japan) signals clearly visible.

TEST DESCRIPTION

Flight No. 2-44

TEST OBJECTIVES:	Provide final S/N data in Wallops area. Check Zulu route at high altitude (5500 ft to 7500 ft). Fly from Salisbury direct Jones Beach (Wpt 1), tower 376 (Wpt 8), north Long Island stacks (Wpt 9), Griswold (Wpt 10), South Foster (Wpt 11), Millis (Wpt 12), Bedford (Wpt 13).
DATE:	9 March 1975
TIME:	1330 - 1646 EDT
ORIGIN:	Salisbury
DESTINATION:	Bedford
ROUTE:	Direct beach Wpt, Zulu-1 to Bedford
ALTITUDE:	5500 ft, 7500 ft over New York TCA
WEATHER:	VFR, 15 kts, NNE
SUMMARY:	Lost track due to weak S/N for Station A over southern New Jersey. Tried using BC and BD LOP pair unsuccessfully. Resumed using AB and BD over stacks wpt, flying constant BD LOP Bridgeport to Bedford.

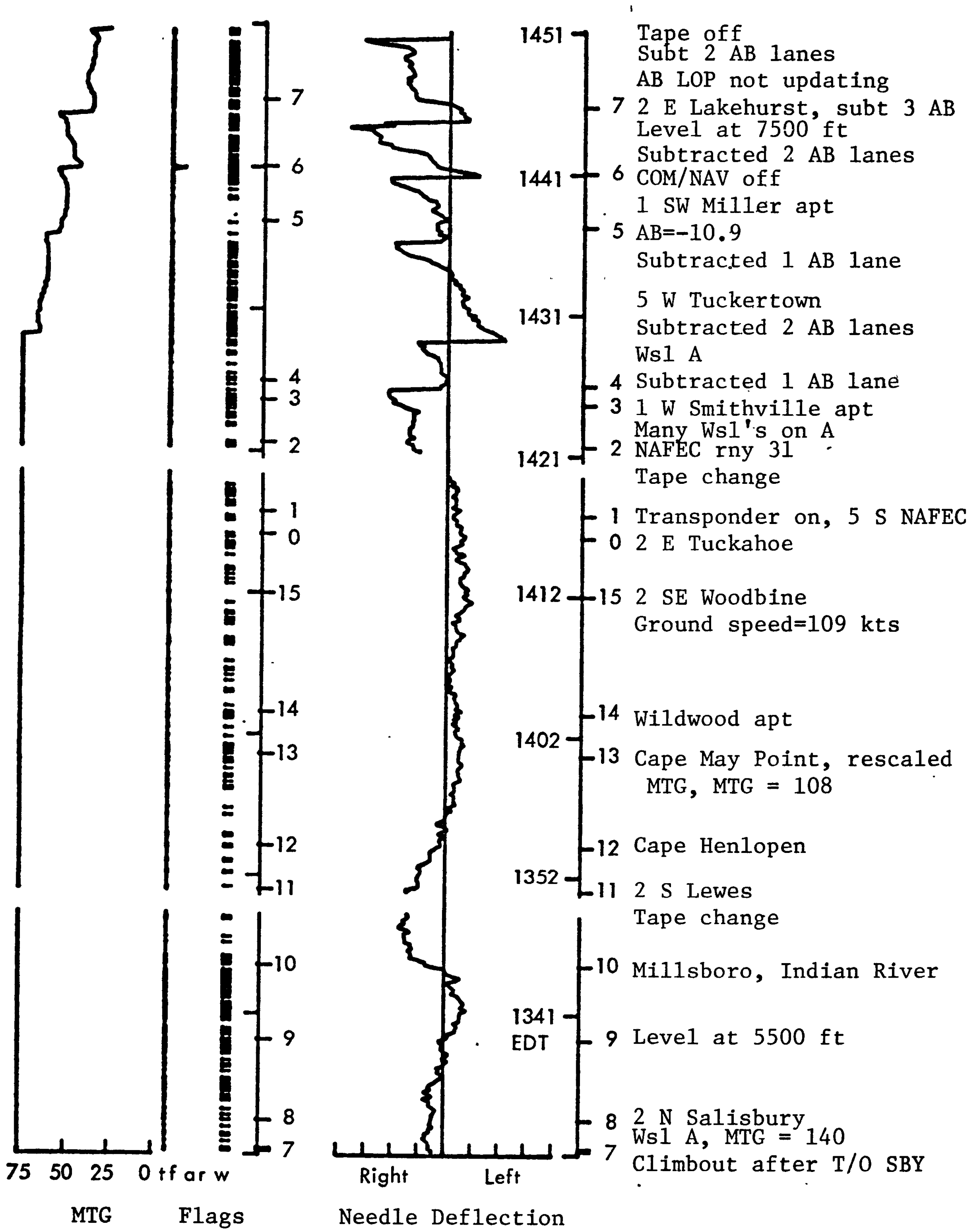


Figure B.5-1 Flight 2-44 (Part 1) Miles to Go and Needle Deflection

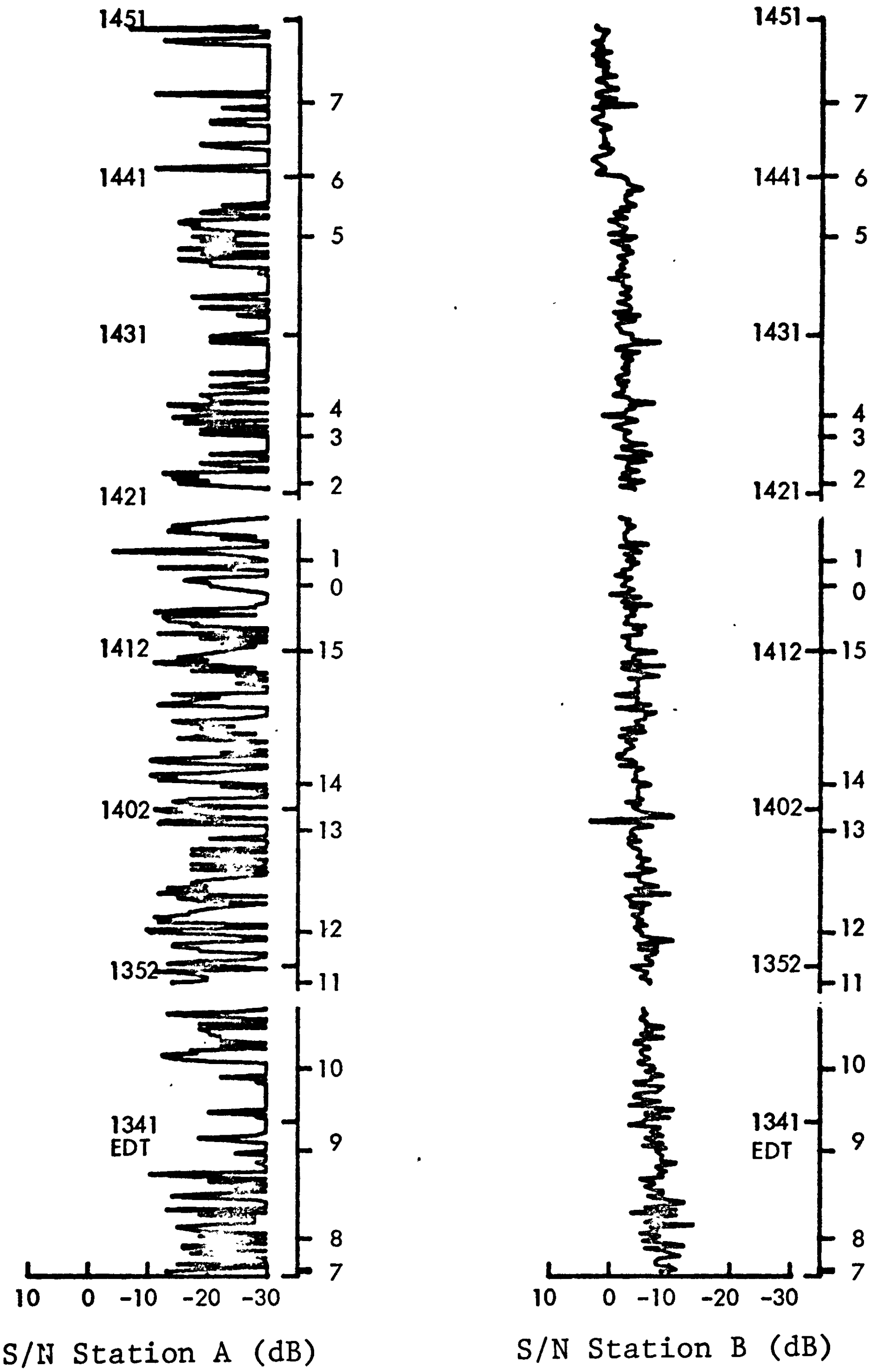


Figure B.5-2 Flight 2-44 (Part 1) S/N Stations A and B

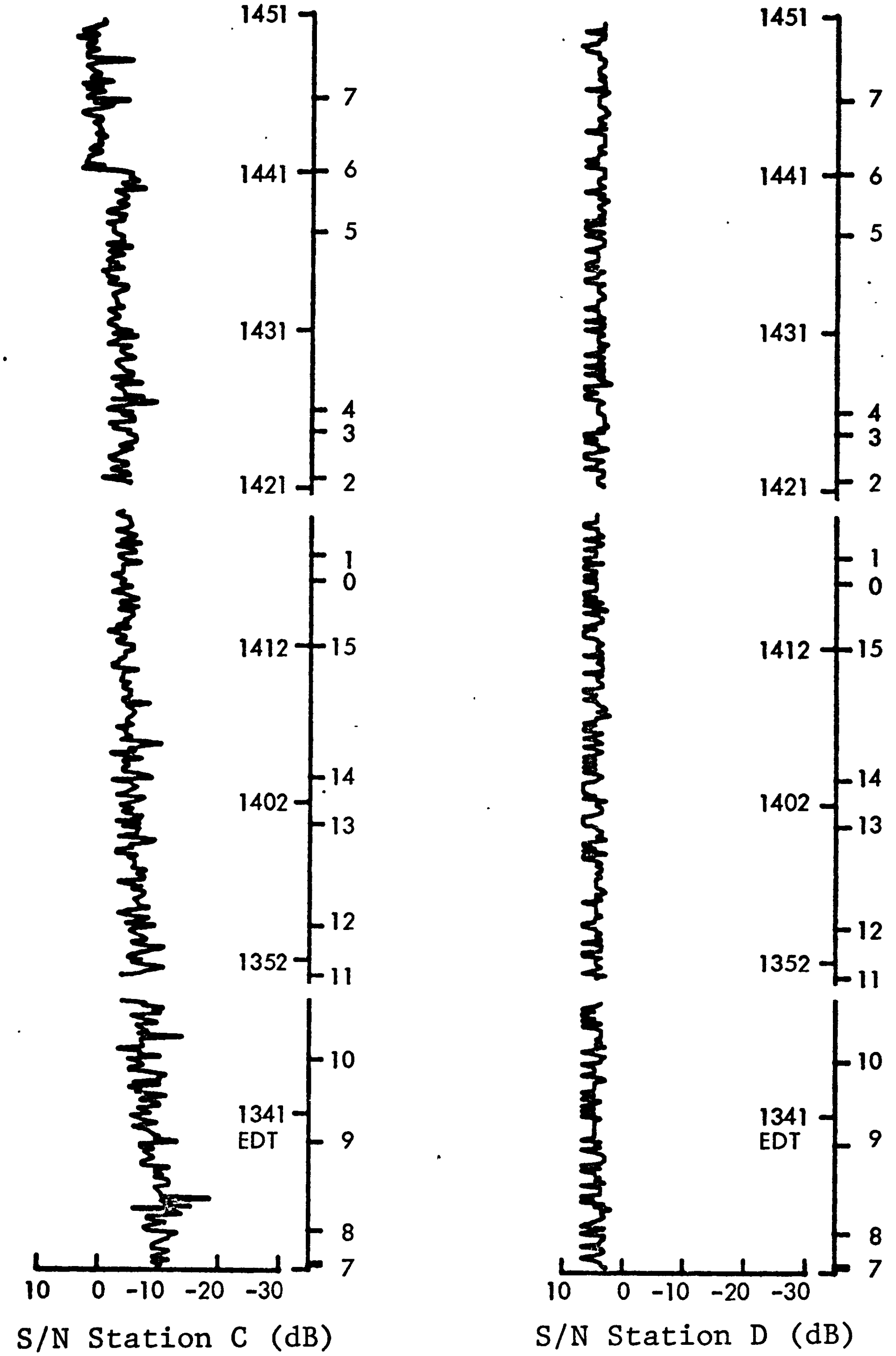


Figure B.5-3 Flight 2-44 (Part 1) S/N Stations C and D

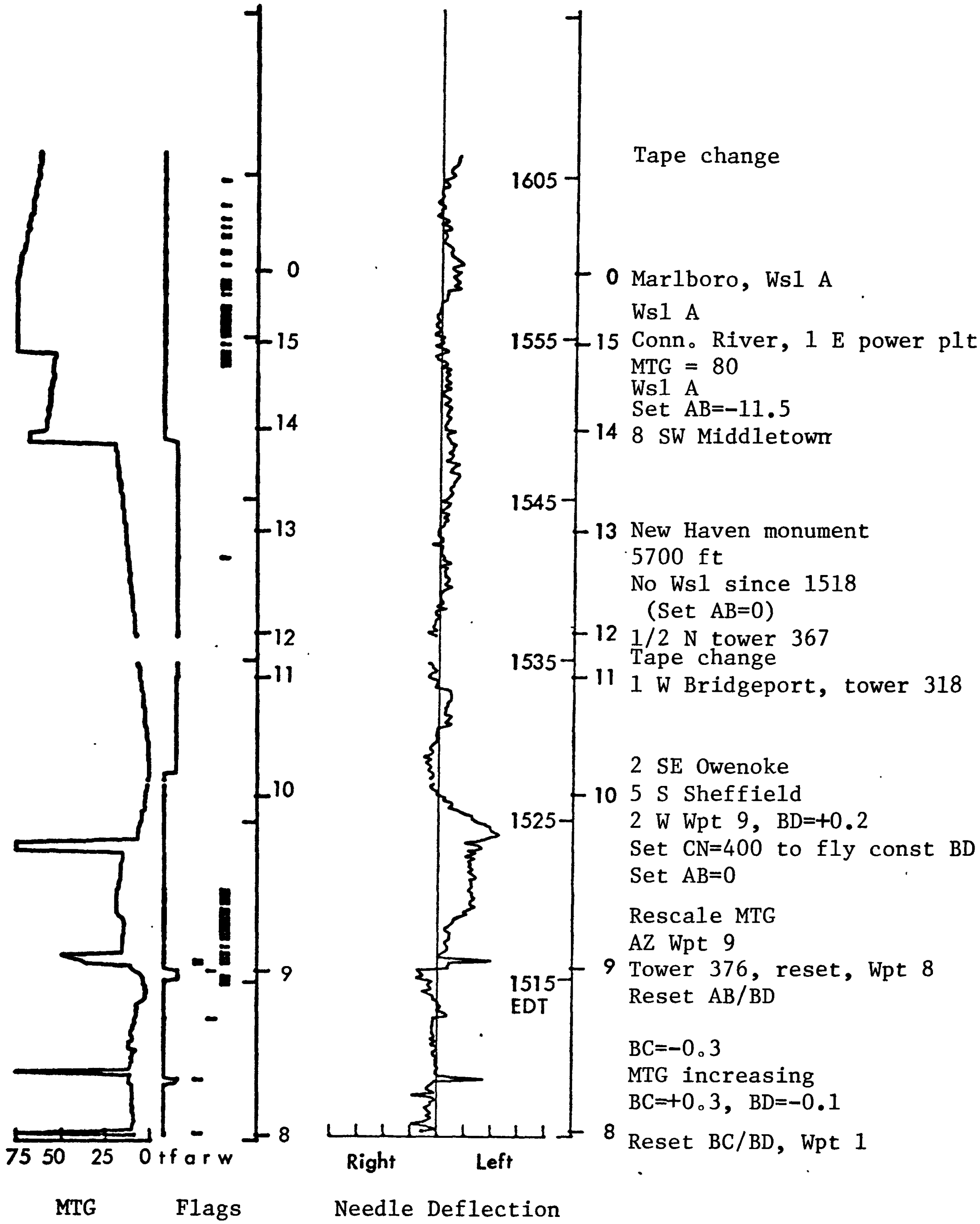


Figure B.5-4 Flight 2-44 (Part 2) Miles to Go and Needle Deflection

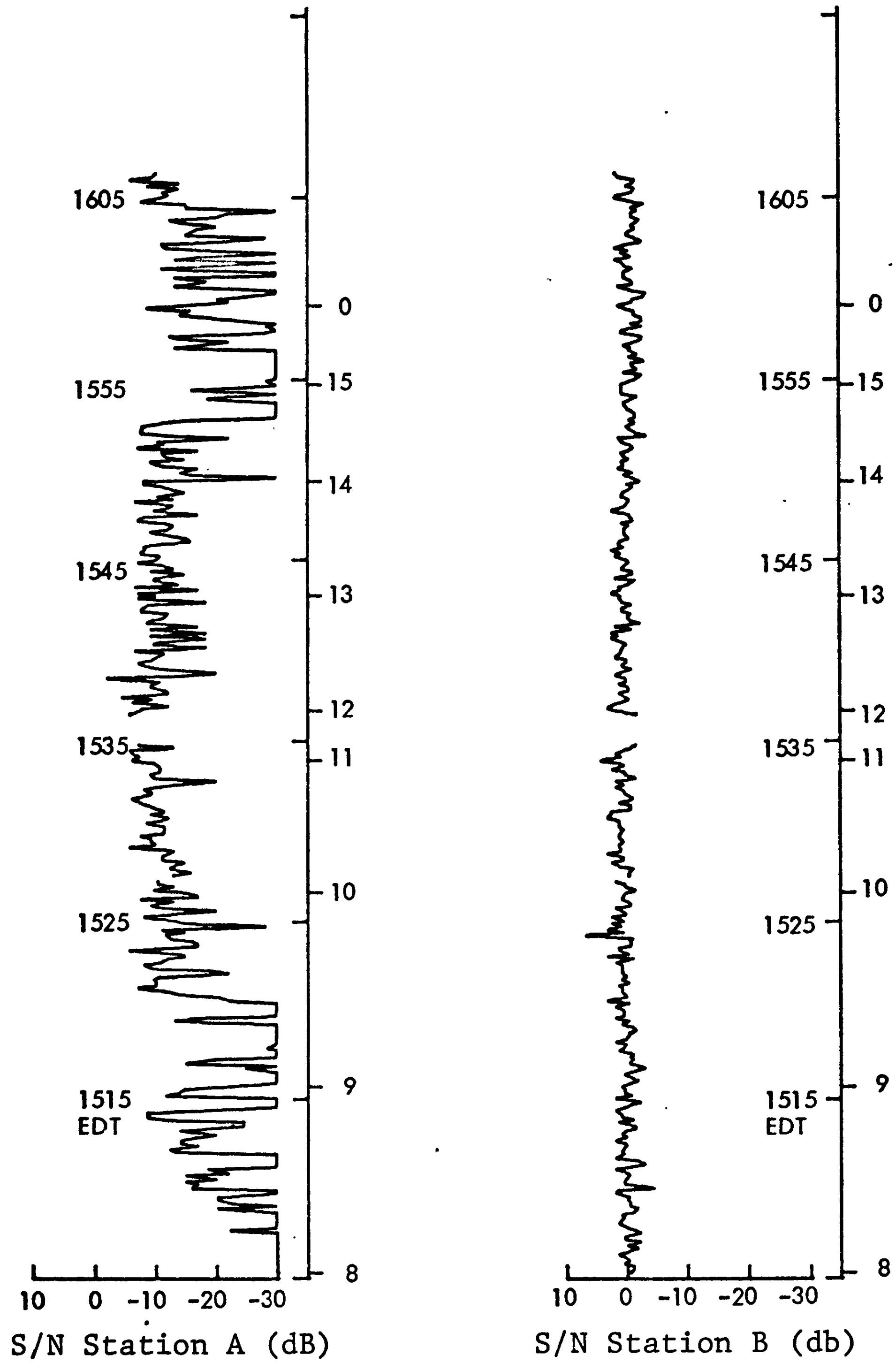


Figure B.5-5 Flight 2-44 (Part 2) S/N Stations A and B

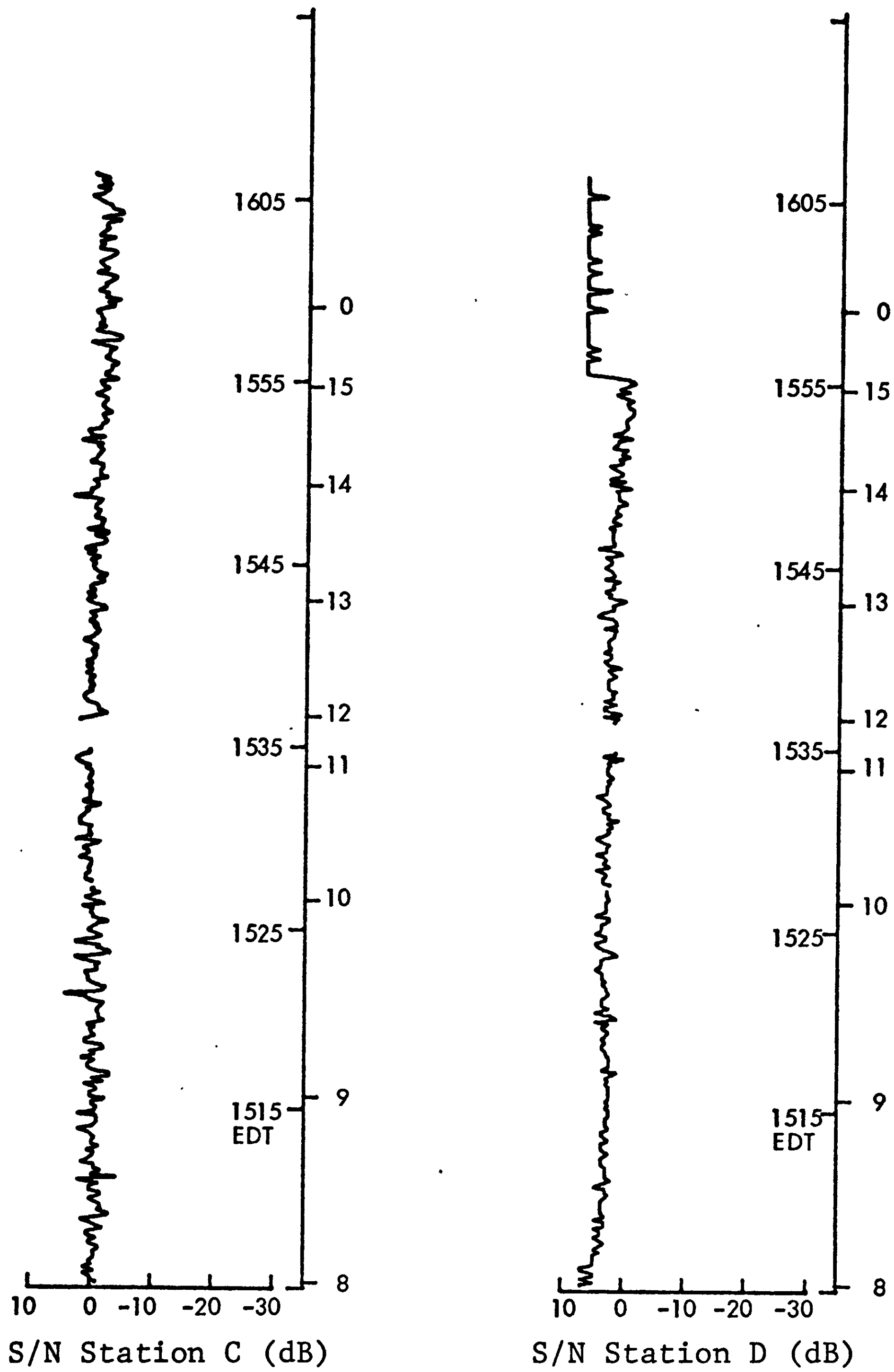


Figure B.5-6 Flight 2-44 (Part 2) S/N Stations C and D

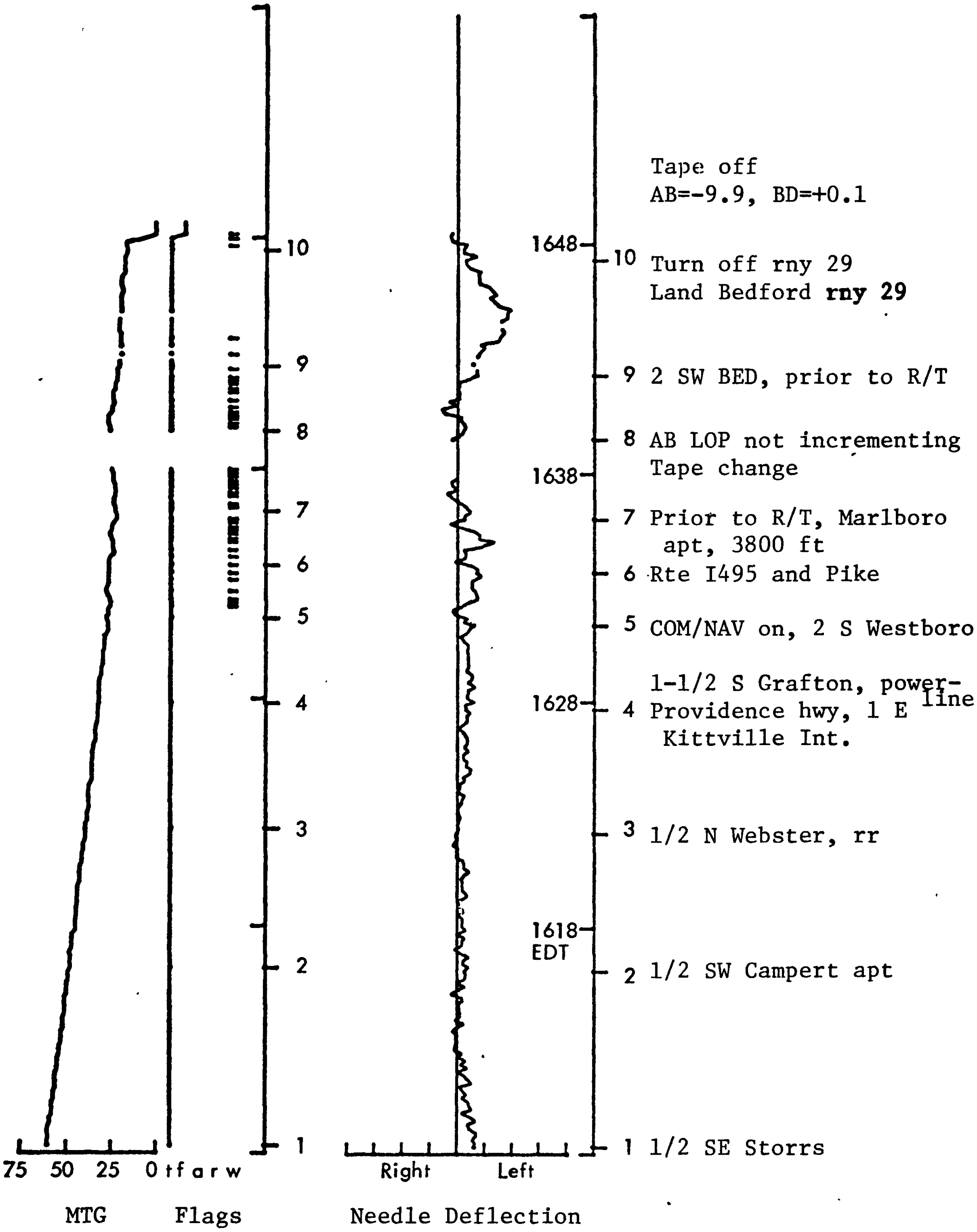


Figure B.5-7 Flight 2-44 (Part 3) Miles to Go and Needle Deflection

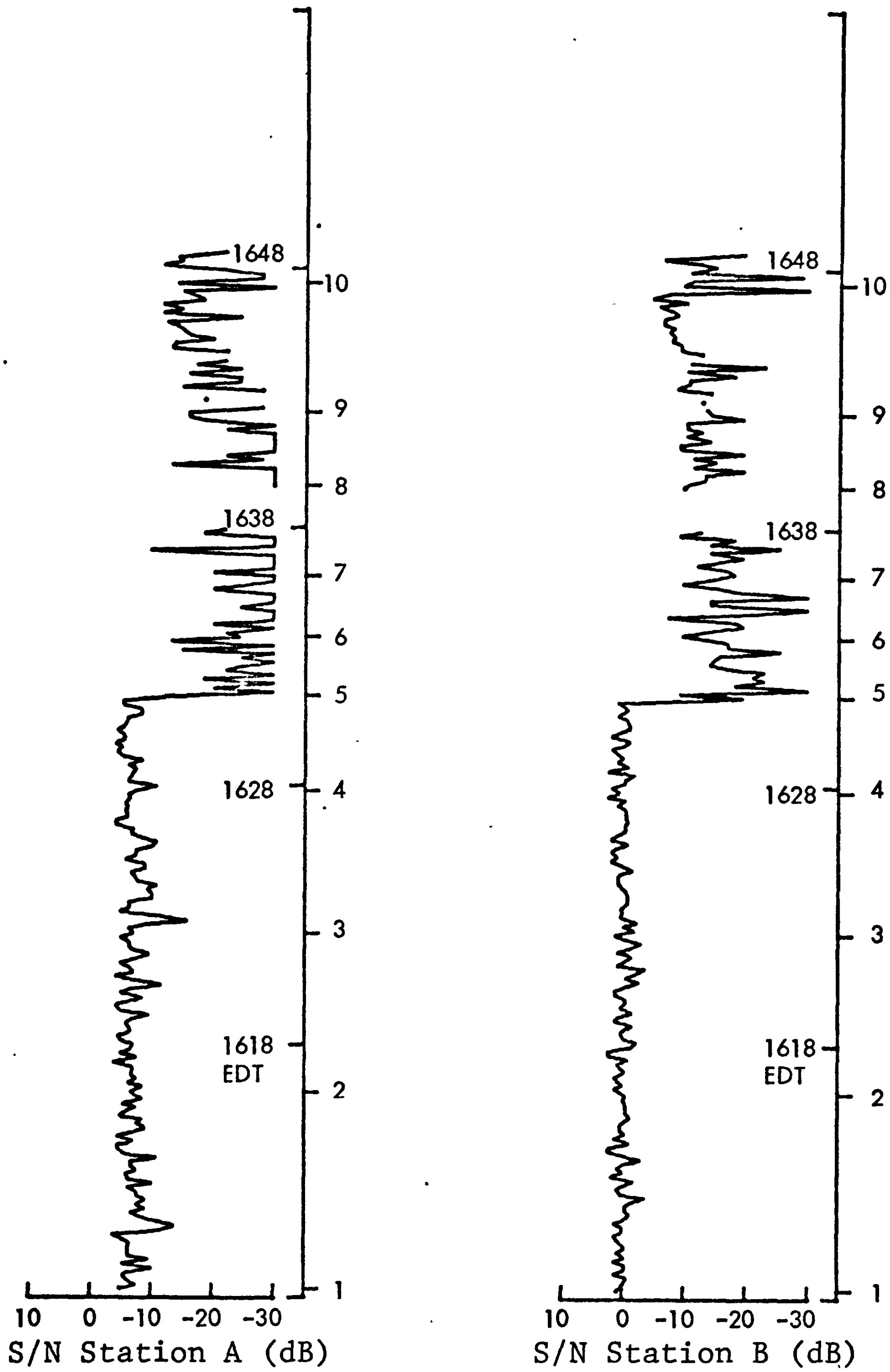


Figure B.5-8 Flight 2-44 (Part 3) S/N Stations A and B

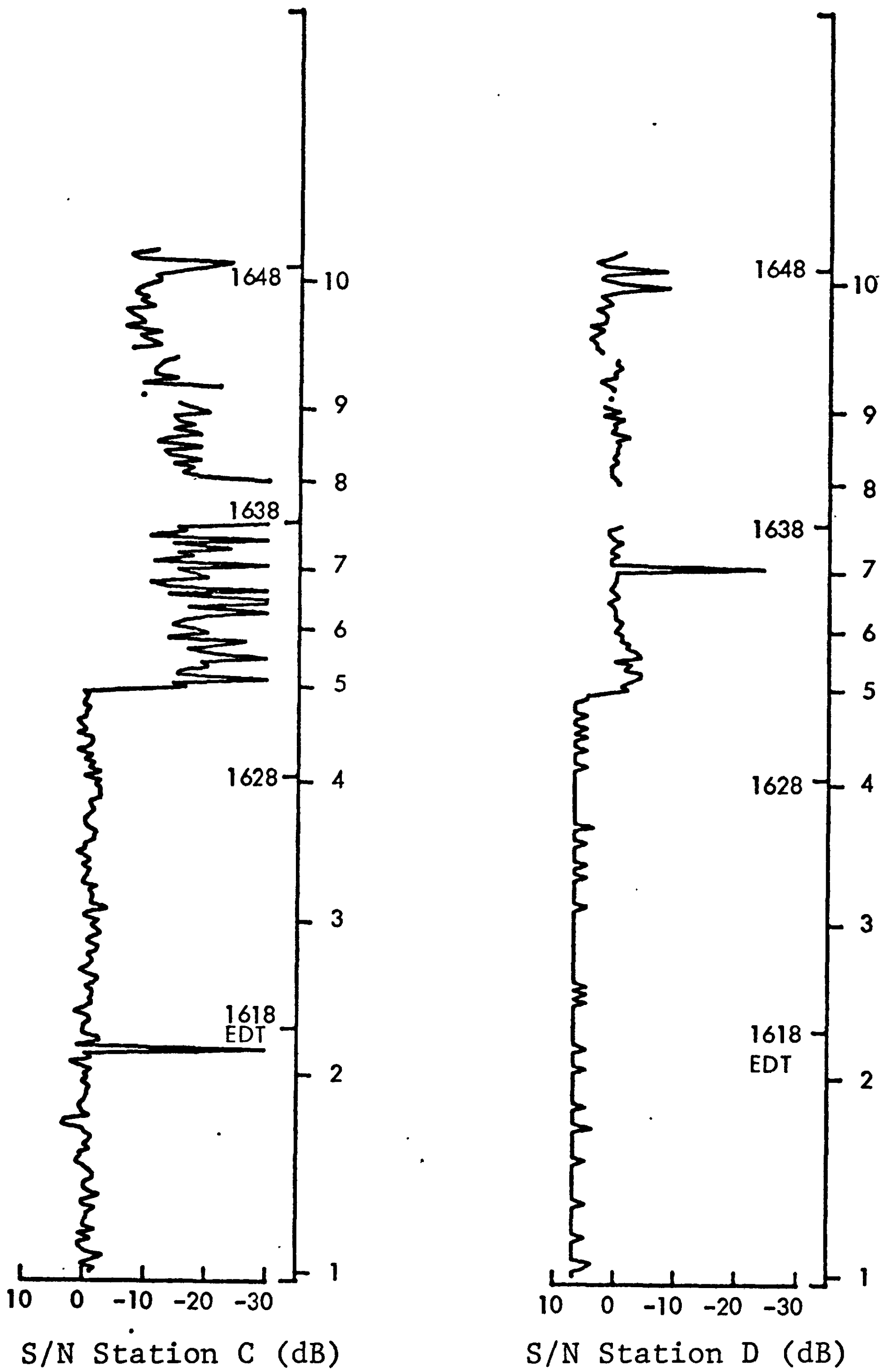


Figure B.5-9 Flight 2-44 (Part 3) S/N Station C and D

TEST DESCRIPTION

Flight No. 2-51

TEST OBJECTIVES:	Obtain definitive S/N and accuracy information while flying below the peaks of surrounding mountainous terrain near Mt. Washington. Obtain additional samples of S/N near power lines and plants. Overfly coastlines to detect any influence. Take S/N measurements during maneuvers including a series of power on and power off stalls.
DATE:	20 April 1975
TIME:	1335 - 1710 EDT
ORIGIN:	Bedford
DESTINATION:	Bedford
ROUTE:	Franconia, Whitefield, Bartlett, Libby, Bartlett, Saco, Shipping Light, Bedford
ALTITUDE:	2500 ft for first mountain circuit, 7000 ft for second
WEATHER:	VFR, clear 50 nm visibility becoming hazy

Flight No. 2-51 (Con't)

SUMMARY: Flight proceeded well with waypoints within 1/2 nm even in Franconia Notch. After clearing the notch the A-B LOP jumped one lane southwest or stopped incrementing. Navigation proceeded normally after subtracting 1 lane from A-B. No significant difference in weak signals at different altitudes. No weak signals after leaving mountains, during flight over powerlines. No coast effects. Obvious weakening of S/N when radios were turned on.

Appendix C

INTERIM WARNING SYSTEM PLAN FOR LOW COST OMEGA RECEIVER USERS

Users will require some form of local broadcast warning such as an ATIS message or weather service announcement as to the current and expected status of the Omega system. This message should include: enumeration of any stations at reduced power or that plan power reductions in the next 24 hours, any stations off the air or that plan periods of discontinuity of transmissions, any local signal disturbances due to sudden ionospheric disturbances or polar cap absorptions that are in progress or can be forecast from solar observations. A method of giving the pilot information as to system usability would be to assign a linear 0-10 scale of signal strength and clarity for each station of nominal local use (e.g., four or five stations). Alternatively the ATIS could give an Omega alert status (e.g., green, yellow, red) which would warn the pilot of conditions for proper navigation were marginal or bad, such that the pilot might then contact the weather service for a more complete description of system performance.

The advent of differential Omega, which might be an automated uplink to the receiver similar to DABS in format, will allow uplink signals to light colored alert lights to warn the pilot, or flash station letter lights to indicate a particularly weak or non-transmitting station. The more sophisticated receivers might decode messages for alpha numeric display to indicate directly to the pilot what the nature of the malfunction was.

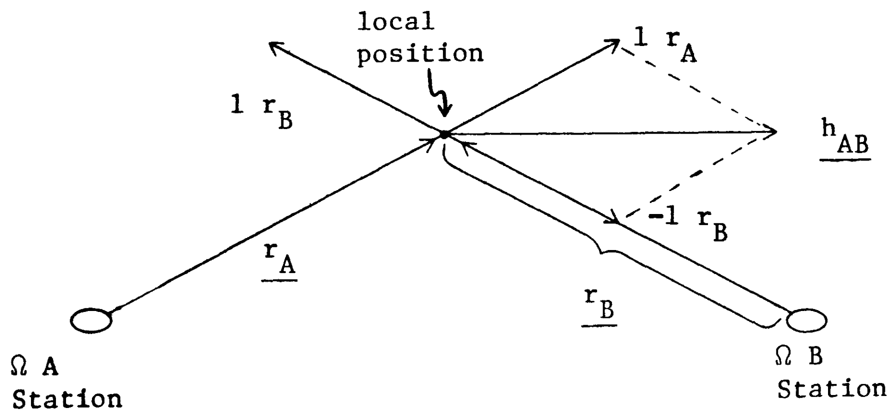
DERIVATION OF h-VECTORS

The h-vectors in hyperbolic navigation are gradients of lines of position with respect to changes in lattitude and longitude. They are derived as follows: first the azimuths to the transmitters from reception point are calculated by

$$\tan A_x = \frac{-\cos L_x \sin \Delta\lambda}{\sin L_x \cos L_o - \cos L_x \sin L_o \cos \Delta\lambda} \qquad \text{(Ref. 3)}$$

where x is the transmitter, o the local position, L is lattitude, λ is longitude, A is azimuth angle

The property of the h-vector is that it is always normal to the local LOP and in the direction of increasing LOP number:



$$\phi = |\underline{r}_A| - |\underline{r}_B| \qquad \underline{h}^T \equiv \frac{\partial\phi}{\partial\underline{r}} = \underline{1r_A} - \underline{1r_B}$$

The magnitude of the h-vector is then:

$$|\underline{h}_{AB}| = (2) \left| \sin \frac{(A_A - A_B)}{2} \right| \quad \text{cycles/local cycle}$$

and its direction:

$$d_{AB} = \tfrac{1}{2}(A_A + A_B) + \pi/2$$

to put the magnitude in the desired dimensions:

$$\text{one 10.2 kHz cycle} = \frac{c}{f} = \frac{161{,}948.7}{10{,}200} = 15.88 \text{ nm}$$

and

$$|\hat{\underline{h}}_{AB}| = \frac{|\underline{h}_{AB}|}{15.88} \frac{\text{cycle}}{\text{nm}}$$

It is then desired to generate the transformation matrix:

$$\begin{Bmatrix} \Delta AB \\ \Delta BD \end{Bmatrix} = \begin{bmatrix} h_1 & h_2 \\ h_3 & h_4 \end{bmatrix} \begin{Bmatrix} \Delta N \\ \Delta E \end{Bmatrix}$$

where ΔAB = position change from point to point in A-B lanes

ΔN = change in nm north = Δlat

ΔE = change in nm east = $-\Delta$ lon cos lat

$h_1 = |\hat{\underline{h}}_{AB}| \cos d_{AB}$ $\quad h_3 = |\hat{\underline{h}}_{BD}| \cos d_{BD}$

$h_2 = |\hat{\underline{h}}_{AB}| \sin d_{AB}$ $\quad h_4 = |\hat{\underline{h}}_{BD}| \sin d_{BD}$

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