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STATIC EVALUATION OF A NAVSTAR GPS (MAGNAVOX Z-SET) RECEIVER MAY-SEPTEMBER 1979

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16. Abstract

This report documents the results of the static testing of a NAVSTAR Global Positioning System (GPS) single channel sequential receiver (Magnavox Z-Set). These tests were performed at the Coast Guard District 11 office in Long Beach, CA from May to September 1979. The objective of these tests was to obtain baseline performance data on the NAVSTAR GPS system in a static environment for later comparison with the results of dynamic testing on board a ship.

Results showed that the Z-Set operated reliably and that the accuracy with which the set calculated its three dimensional position equalled or exceeded the accuracy with which it is specified to operate.

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PREFACE

The NAVSTAR Global Positioning System (GPS) is a satellite navigation system under development and deployment by the Department of Defense. It has potential as a multi-modal, multi-user navigation system able to provide extremely accurate position and velocity information over the entire globe.

The United States Coast Guard and the United States Maritime Administration are interested in NAVSTAR GPS as an addition to, or replacement for existing navigation systems. However, only a full evaluation of the NAVSTAR GPS performance characteristics will determine which navigational requirements can be met by this system. Thus, the Transportation Systems Center of the United States Department of Transportation performed tests on the Z-Set, a proposed low-cost single-channel sequential receiver/processor, under static conditions in Long Beach, California, during the Summer of 1979 for the purpose of obtaining preliminary performance data which would comprise the first phase of testing and evaluation, eventually leading to a decision on the use of NAVSTAR GPS for the marine community. The results, conclusions and recommendations of this program are contained herein.

The Transportation Systems Center wishes to acknowledge the help and assistance of those who made this report possible. Thanks are due to Captain Culbertson of the Coast Guard Eleventh District, who extended his hospitality and provided the cooperation of the entire district, and to Walt Dean of Verdes Engineering, who operated the Z-Set and recorded the data. Thanks are also extended to Captain Don Feldman of Coast Guard Headquarters, Washington, D.C. who provided the overall coordination with DOD and MARAD.

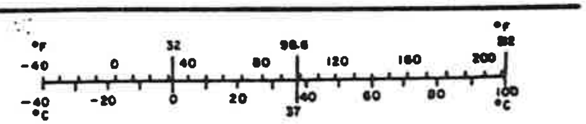
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

This report documents the results of static testing of a NAVSTAR Global Positioning System (GPS) single channel sequential receiver (MAGNAVOX Z-Set). These tests were performed at the Coast Guard District 11 Office in Long Beach, California, from May to September, 1979. The objective of these tests was to obtain baseline performance data on the NAVSTAR GPS system in a static environment for later comparison with the results of dynamic testing on board a ship. These tests were Phase I of a three phase program which involves the U.S. Coast Guard (USCG), the U.S. Maritime Administration (MARAD), Department of Defense (DOD), Department of Transportation/Transportation Systems Center (DOT/TSC), Texas A&M University (TAMU) and several contractors.

The NAVSTAR GPS is a system concept presently under development by DOD. This satellite-based system will provide to worldwide users continuous, real-time, all-weather, high-accuracy position information. Position information is acquired in a passive mode with receive-only equipment. This system is described more fully in Section 2.

NAVSTAR GPS has potential as a multi-modal and multi-user civil navigation system because of its ability to provide worldwide coverage with high accuracy to a wide range of users. Its relatively untested status, the challenges of achieving economical user equipment, and the transition procedures which will be necessary for phaseover to a new system from existing systems all point toward the 1990's as the earliest possible time for its widespread civil use. Given the satisfactory attainment of the technical and operational goals of NAVSTAR GPS, it is viewed as a potential replacement or supplement to the other systems such as LORAN-C, OMEGA, and TRANSIT. The Department of Transportation is addressing the technical issues which are pertinent to civil use (marine, air, and land) so that a technically and operationally sound decision can be made concerning the ultimate role of NAVSTAR GPS for civil users. Current plans call for the DOT to make this decision by the end of Calendar Year 1983. The results of Coast Guard tests and studies will be an important input to the DOT decision. An overall picture of the major activities of the DOT NAVSTAR GPS research and development program is shown in Figure 1.1, which indicates the division and interfaces of the marine, air and land activities.

The objectives of the Coast Guard marine program are to acquire a sufficient data base to determine where the NAVSTAR GPS system can satisfy the navigation performance requirements, and also to investigate the economic and operational aspects which will affect the eventual recommendation concerning marine use of NAVSTAR GPS.

The Department of Commerce Maritime Administration (MARAD) is also interested in evaluating the NAVSTAR GPS as a navigation aid for improving the operating efficiency and the economic competitive posture of U.S. commercial ships. The NAVSTAR GPS system offers the potential for worldwide navigation accuracy superior to any current navigation system. With this improved navigation capability ships can select shorter routes and avoid severe weather areas, thus reducing operating time and costs. MARAD is participating with the U.S. Coast Guard in this joint program of evaluating the NAVSTAR GPS system in comparative tests with other navigation systems (e.g. OMEGA, LORAN-C and TRANSIT) in actual shipboard at-sea operations to determine accuracy, reliability

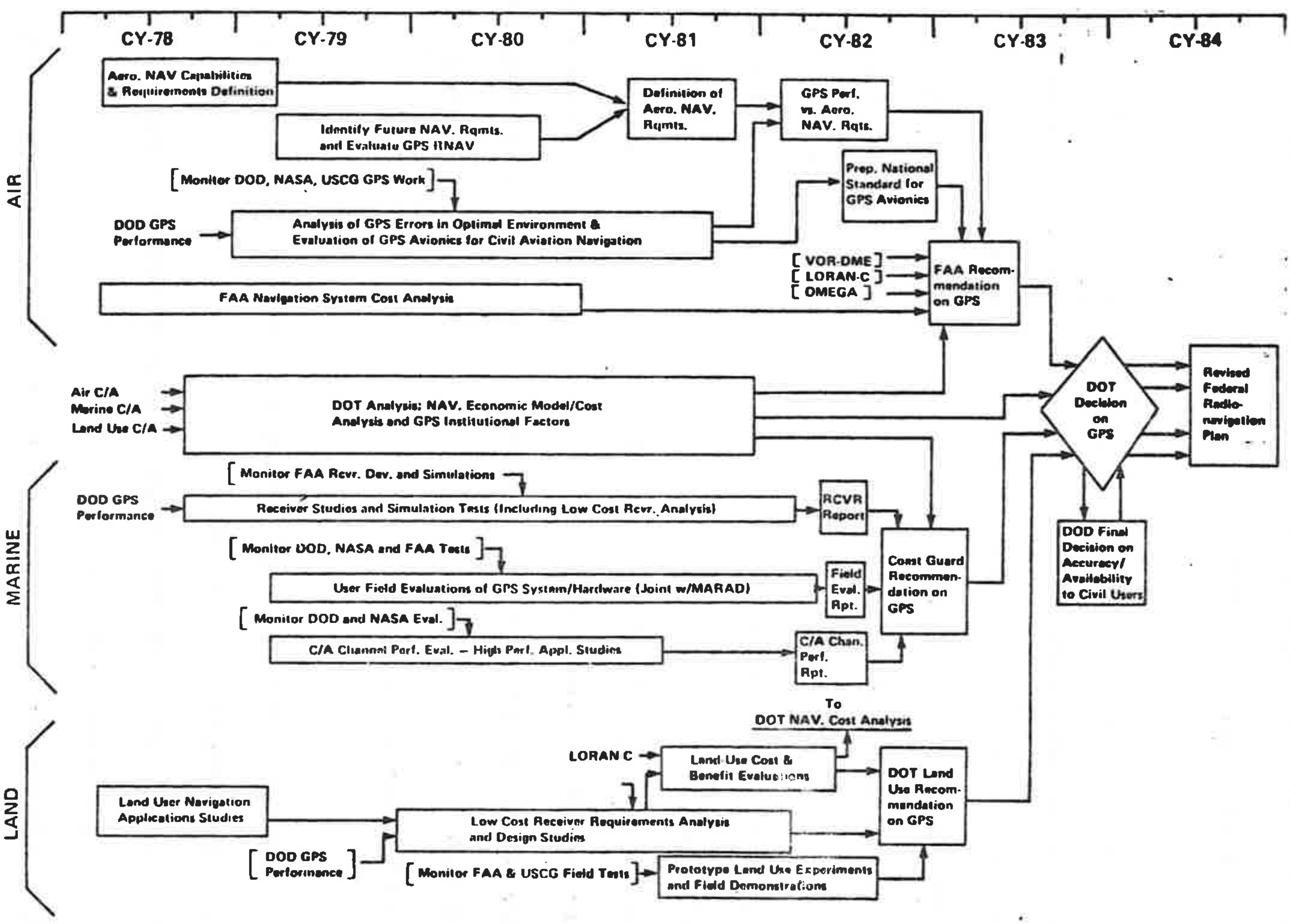


FIGURE 1.1. DOT R&D ACTIVITIES FOR GPS

and operator workload features. If these tests produce favorable results for the marine navigation needs, future developments may be pursued, including tests on commercial vessels by their operators in routine ocean operations and development of low-cost receiver equipment.

The most important criterion of system performance is the position accuracy achievable under operational conditions. This accuracy is dependent on a number of factors, including vehicle dynamics, propagation interference (multipath, ionosphere and radio frequency interference/electromagnetic compatibility (RFI/EMC)), and receiver-processor design. Accuracy data acquired by the DOD indicates that the clear/acquisition (C/A) signal, under controlled test conditions, has surpassed its design specifications. Under operational conditions the system may not achieve this accuracy. The chief concern of the Coast Guard and the marine user at this time is to establish the system accuracy under realistic operational conditions and to determine the navigation requirements (coastal, harbor or high areas) the system must meet. Other performance parameters of interest to the user are time-to-first-fix (TTFF), acquisition time, re-acquisition performance, and update rate.

The major R&D activities related to marine uses of NAVSTAR GPS are:

1. Low-cost receiver technology studies,
2. User field tests for comparative assessment of NAVSTAR GPS versus alternative navaids,
3. Assessment of the clear/acquisition (C/A) signal performance potential.

Issues important to the use of NAVSTAR GPS for marine navigation include:

1. Accuracy - can it serve only as a ¼ nautical mile (1 drms) navigation system suitable for the coastal waterways, or can it also serve in the 8-20 meter (2 drms) error category potentially required for harbor approaches and harbor navigation?

2. What are the technical and economic issues that dominate a NAVSTAR GPS receiver designed for civil marine use? What is a realistic estimate of receiver cost, and what technological factors might significantly alter this estimate? What receiver performance and cost tradeoffs are feasible to develop NAVSTAR GPS equipment acceptable to 1) commercial ships over 1600 gross tons (GT), 2) all ships and tugs-with-barges over 300 GT, and 3) all other present users of radionavigation systems?

3. Comparison of NAVSTAR GPS with the current marine aids to navigation is required. This comparison should be made with regard to navigation accuracy and repeatability, operational features and human factors. It should be made in numerous different geographic locations with vessels of different sizes under all types of operating conditions. This work should incorporate the special features required of the electronics system when operating in a variety of environments, e.g. ocean and harbor.

USER FIELD TESTS

These tests comprised part of a cooperative program involving the Coast Guard and MARAD in which MARAD supplied the DOD NAVSTAR GPS Z-Set receiver system, and the Coast Guard provided the data collection system and acquired the data for use by both agencies. The receiver for these tests operates only with the C/A code. The objectives of these tests are 1) to learn the performance characteristics of the NAVSTAR GPS system operating in typical marine environments, and 2) to compare the accuracy of NAVSTAR GPS with other aids to navigation such as LORAN-C, OMEGA and TRANSIT in a series of relative accuracy tests.

Phase I involved the static test of the receiver, as reported herein; and, Phase II will consist of a shipboard evaluation of the NAVSTAR GPS system (along with LORAN-C, OMEGA, and TRANSIT) on the TAMU research vessel "GYRE" as it performs its normal oceanographic research cruises in the Gulf of Mexico and along the eastern shore of the U.S. during the Spring of 1980. Following this at-sea evaluation, Phase III will allow testing of the NAVSTAR GPS system (along with existing marine radionavigation systems) in an operational environment of commercial vessels in various navigational areas.

A final report on the NAVSTAR GPS receiver field evaluation will be issued at the conclusion of Phase III of the program and will provide an input to the Coast Guard recommendation on NAVSTAR GPS.

2. DESCRIPTION OF THE GLOBAL POSITIONING SYSTEM

2.1 OVERVIEW

The NAVSTAR Global Positioning System is a satellite navigation system under development by the U.S. Department of Defense. When fully operational it will consist of 24 satellites spaced equally around the earth in twelve-hour orbits at an altitude of approximately 20,000 Km. There will be three orbit planes, each containing eight satellites and each inclined by 63^{o} with respect to the equatorial plane. Each orbit plane will be offset from the other by 120^{o} in longitude. At any given time anywhere in the world a user will be able to view six to eleven satellites. A user with a NAVSTAR GPS receiver will compute in real time, unambiguously, vehicle position and velocity (Refs. 1,2,3,5).

The NAVSTAR GPS system can be divided into three segments: 1) The ground segment consists of four monitor stations, an upload station and a master control station. The monitor stations are located at Hawaii, Alaska, Guam, and Vandenberg Air Force Base, California. The monitor stations are unmanned data collection centers under the control of the master control center. The master control center and upload center are both at Vandenberg Air Force Base. 2) The space segment consists of the 24-satellite constellation, which transmits highly stable, precisely timed radio frequency (rf) signals which are processed by the user to compute navigation fixes. 3) The user segment consists of the user's antenna, preamplifier, receiver and position display. The receiver receives the rf transmissions, demodulates the data transmitted, stores the data, and processes it under the control of a central processor. Each of these segments will be discussed later.

The NAVSTAR GPS transmits digital information to the user that enables him to accurately calculate his position and velocity. The message was carefully designed after much analysis and many studies which weighed all factors to determine the most precise and efficient algorithms and data format. User algorithms were tested by simulation which demonstrated space vehicle accuracy to 1.5 meters with precise parameters. Ultimate accuracy of the system depends on the type of user equipment.

NAVSTAR GPS was designed to meet the following performance objectives: 1) high accuracy, 20 meters (2 drms) position location, 2) real time navigation, 3) worldwide operation, 4) tolerance to intentional or non-intentional jamming. The codes, data format, and signal structure were established to meet these objectives (Refs. 2, 14).

The evolution of the NAVSTAR GPS program is shown in Figure 2.1. The concept validation phase has been completed. This phase includes the launching of 6 satellites, the establishment of the control segment, the development of prototype user equipment employing both P and C/A signals and equipment employing only the C/A signal, and the combined testing of the three segments to demonstrate basic system operation.

If all indicated program milestones are met, the NAVSTAR GPS will be available in 1987 to provide world-wide three dimensional navigation signals.

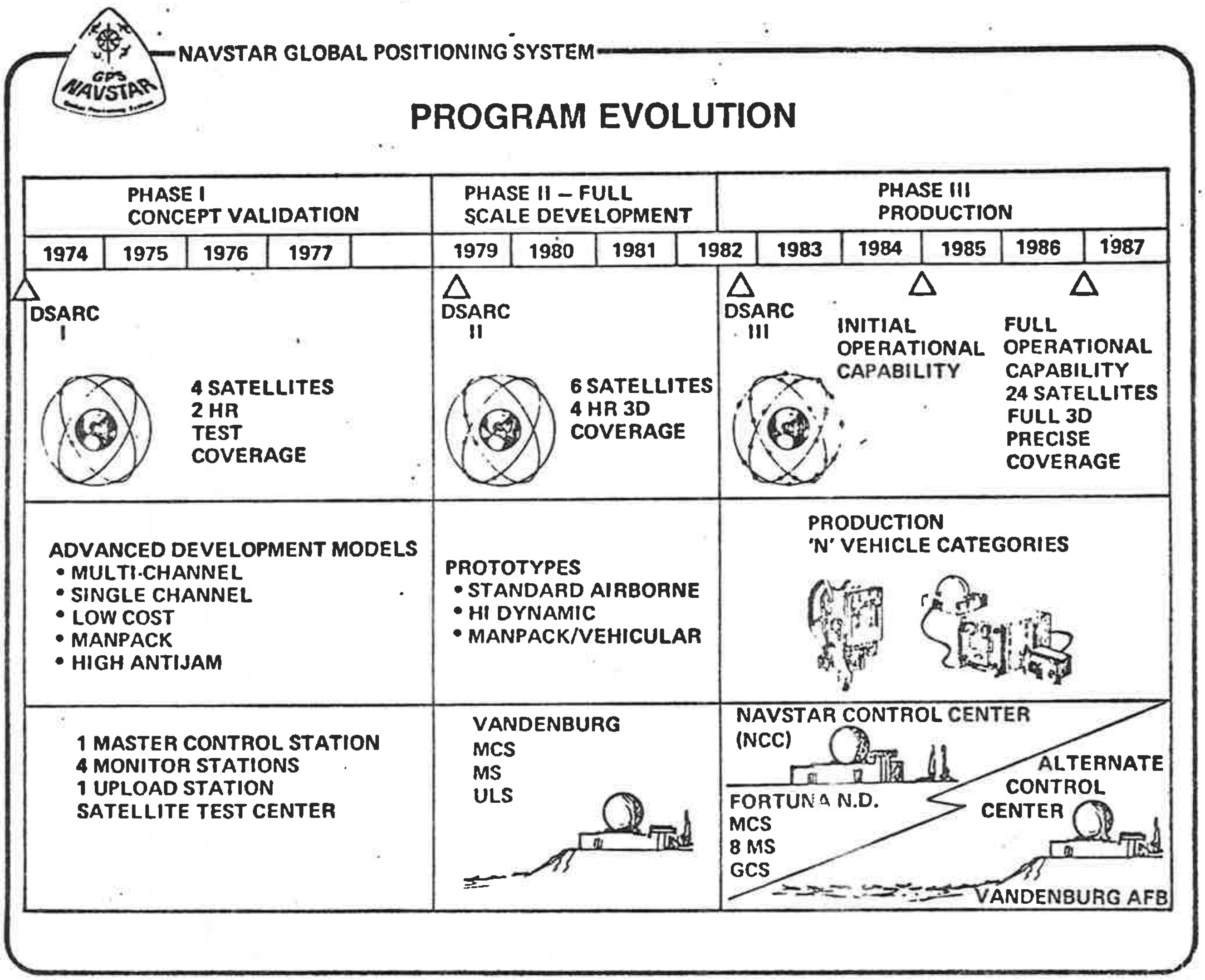


FIGURE 2.1. GPS PROGRAM SCHEDULE

The availability of navigational signals of adequate accuracy at all times, including times of stress, is essential to reliance on a given system for safety of navigation. A preliminary evaluation of the proposed NAVSTAR GPS signals indicates that many civil requirements probably could be met with the clear/acquisition signal. Conversely, guaranteed availability of optimum performance may diminish national security objectives, so that a tradeoff or compromise is necessary. Hence, a proposed national policy is being developed on the criteria which will govern availability and accuracy. This policy proposes that NAVSTAR GPS clear/acquisition (C/A) signal be made continuously available on an international basis for civil and commercial use at the highest level of accuracy consistent with national security interests. It is presently projected that an accuracy of 200 meter CEP (500 meter 2 drms) will be available during the first year of full NAVSTAR GPS operation with accuracy available to civil users increasing as time passes. This policy is a key element in determining the navigational services that can be based on use of NAVSTAR GPS signals (Ref. 14).

2.1.1 Range Measurements

The satellite-transmitted signal contains precise information on the time of transmission and also data with satellite position information, ionospheric correction and other ephemeris data. The user receiver calculates the satellite position and measures the transit time from satellite to receiver, corrupted by user clock bias, for each satellite of the constellation. Knowing the precise position of each of four NAVSTAR GPS satellites and measuring the transit time of the electromagnetic transmissions from each to the user results in a set of four equations in four unknowns, the user position in 3 spatial coordinates and time. Note that if it were possible to synchronize the user clock to the NAVSTAR GPS clock time precisely, only three satellites would be necessary. But since that is not the case, four are necessary. Thus, each range measurement made is actually a pseudo-range until the set of equations is solved and the time difference between the user and space clocks is determined. Thus:

$$\hat{R}_i = R_i + C\Delta t_{A_i} + C(\Delta t_u - \Delta t_{s_i})$$

R_i = pseudo-range

C = speed of light

Δt_u = user's clock offset from NAVSTAR GPS time

Δt_{s_i} = space vehicle clock offset (small)

Δt_{A_i} = propagation delays

This says that the measured pseudo-range is equal to the actual range to the satellite corrupted by propagation delays due to the atmosphere and any other interference, plus the difference between the space vehicle clock offset and user clock offset. Once four equations in four unknowns have been established, they are solved to obtain X, Y, Z (position) and t (time).

2.1.2 NAVSTAR GPS Coordinates

The coordinate system for NAVSTAR GPS is the earth-centered earth-fixed (ECEF) coordinate system. All calculations internal to the system are performed in this coordinate system. It is a three axis orthogonal system whose (0,0,0) coordinate is the center of the earth. The X axis is in the equatorial plane so that the XZ plane is coincident with the Greenwich Meridian plane. The Z axis is coincident with the earth spin axis, i.e., toward the North Pole, and the Y axis is orthogonal to the other two to form a right hand orthogonal system. The reference ellipsoid used to approximate the geoidal properties of the earth is the WGS-72 datum. The fundamental parameters of latitude, longitude, and altitude are with respect to this model. Once a position fix has been determined in ECEF coordinates, a coordinate transformation is made to display the position in east-north-up (ENU) coordinates, i.e. latitude, longitude and altitude (Ref. 12).

2.2 SPACE SEGMENT

Each satellite transmits NAVSTAR GPS signals on two frequencies 1575.42 MHz and 1227.6 MHz. The 1575.42 MHz carrier is designated L1 and the 1227.6 MHz carrier is designated L2. The frequencies are in the L-Band region of the UHF frequency band. The bandwidth allocation is more easily obtainable here and ionospheric delays are more favorable than in other parts of the spectrum. The in-phase component of L1 is binary phase-shift-keyed modulated by a 10.23 MHz precision (P) binary code, and the quadrature component is modulated by a 1.023 MHz clear/acquisition (C/A) binary code. Each component is further modulated by the 50 bps binary data stream to result finally in a quadrature modulated carrier whose in-phase component is modulated by $P \oplus D$ and whose quadrature component is modulated by $C/A \oplus D$. ($\oplus$ = modulo two summation). The L2 signal will be bi-phase modulated by either the P or C/A code, but when fully operational, the P code will probably be used.

2.2.1 P Code

The P code is a pseudo-random-noise (PRN) sequence with a chipping rate of 10.23 Mbps. The code is generated by the modulo 2 sum of two PN codes $X1(t)$ and $X2(t + n_i T)$ where T is the period of one P code chip. The P code has a period of 267 days. Each satellite delays the code by a minimum of seven days to establish for itself a unique seven day portion of the code. At the end of the week the code generators are reset to their initial states. X1(t) itself is the modulo 2 sum of two PRN codes as is X2(t). X1(t) has a period of 1.5 seconds or 15,345,000 chips, whereas X2(t) has a period 37 chips longer. It is this difference in period length of 37 chips which allows the composite P code to have a period of 267 days so as to allow each satellite a unique portion of that code. The Z count (Section 2.2.3) is the number of 1.5 second X1(t) epochs transpired since the beginning of the week and is the system nominal time tag (Refs. 2, 8, 10).

2.2.2 C/A Code

The C/A code, a Gold code, is much shorter than the P code. It is 1023 bits long, which at a 1.023 Mbps rate, results in a code period of 1 millisecond. It is synchronized with the $X_1(t)$ epoch, as is the 50 bps information stream. Gold codes are formed by the product of the outputs of two linear feedback shift registers both of the same period. The advantage of the code is that the cross correlation between any two Gold codes of the same family is - 1/P, where P is the period, i.e. code length in chips. The autocorrelation function is 1/P everywhere except at synchronization, where the function rises to +1. This is of great importance in the satellite signal acquisition (Refs. 2, 7, 8).

2.2.3 Data

The 50 bps data is divided into frames, each frame consisting of 1500 bits. Each frame consists of five 300 bit subframes which are divided into ten 30 bit words. The first word of each frame is a telemetry (TLM) word which indicates the status of the data uploading operation while it is is progress. The next word of each subframe is the handover word (HOW). It contains the

17 bit Z count, which is the space vehicle time at the leading edge of the next subframe, a one bit synchronization flag, a three bit subframe identification, two non-information bits and six bits of parity. The HOW is also used to aid in the acquisition of the P code. The synchronization flag alerts the user that the data frame may not be aligned with the X1 code epoch, an unlikely occurrence. The rest of the first subframe contains data block I (Section 2.2.3.1). Data block II (Section 2.2.3.2) is transmitted in the last eight words of subframes 2 and 3. Subframe 4 contains a message block and subframe 5 contains data block III (Section 2.2.3.3). Each data block will be discussed in detail in the following sections. (See Figure 2.2.)

2.2.3.1 Data Block I

Data block I contains frequency standard corrections, an associated Age of Data (AODC) word and ionospheric propagation delay model coefficients. The ionospheric delay model is for single frequency users only. Those users with receivers capable of dual frequency reception will be able to make ionospheric corrections, since it is known that ionospheric delay is proportional to $1/f^2$. Figure 2.3 lists the parameters sent for data block I and what each represents (Ref. 3).

2.2.3.2 Data Block II

Data block II contains the space vehicle ephemeris. It is generated by the control segment and represents the transmitting space vehicle's ephemeris and associated age of data (AODE) words. The parameters are those necessary to solve Kepler's equation:

$$E(t) = M(t) + e \sin E(t)$$

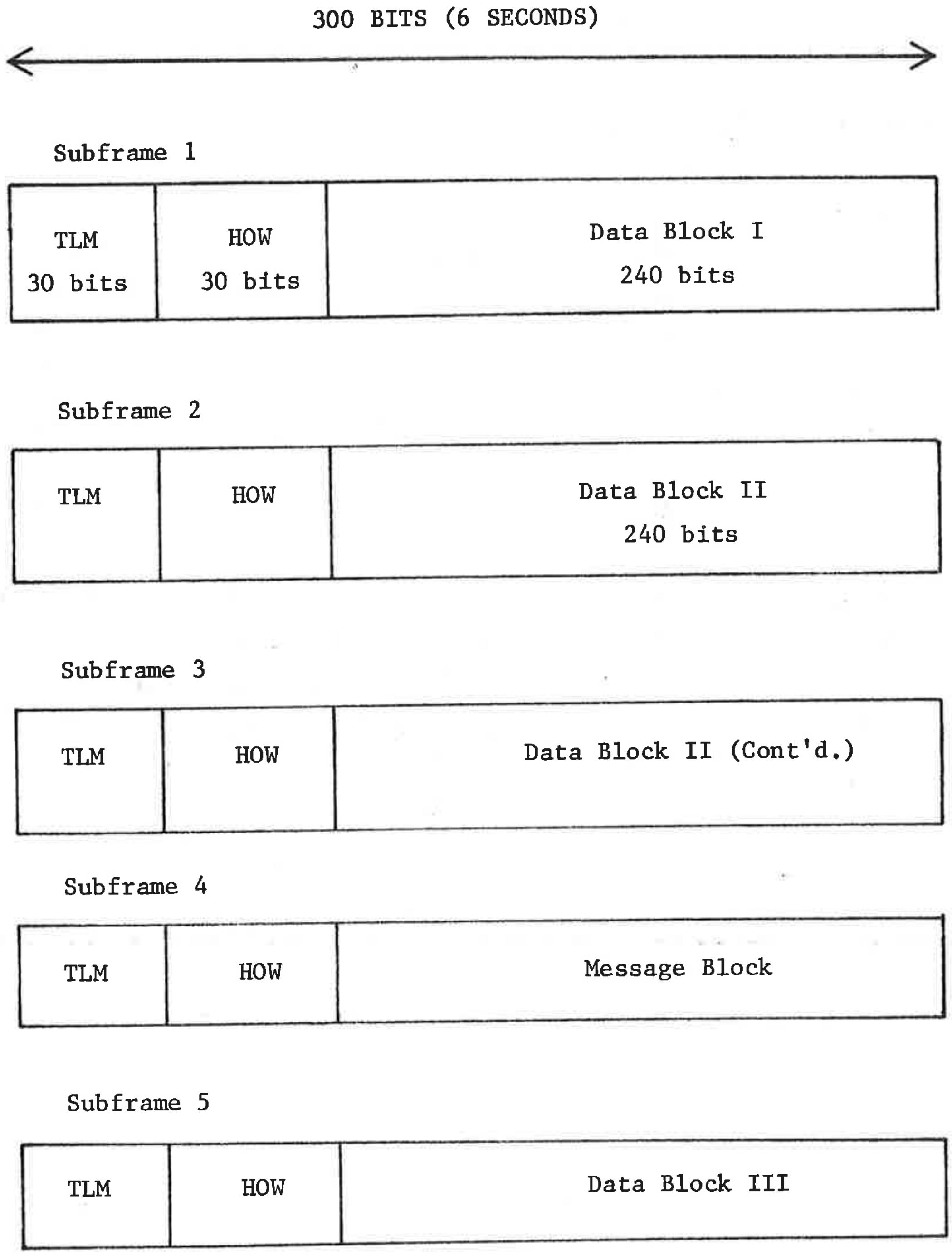


FIGURE 2.2. NAVIGATION MESSAGE FRAME (30 sec.) (1500 bits)

Parameter	No. of Bits	Description
Spare	24	
Spare	24	
α_0	8	Ionospheric Model Amplitude Coefficients
α_1	8	" " " "
α_2	8	" " " "
α_3	8	" " " "
β_0	8	Ionospheric Model Period Coefficients
β_1	8	" " " "
β_2	8	" " " "
β_3	8	" " " "
T_{GD}	8	L1 User Only - Group Delay Correction
AODC	8	Age of Data (Clock)
t_{oc}	16	Data Block I Reference Time
a_2	8	Satellite Clock Correction Coefficients
a_1	16	" " " "
a_0	22	" " " "

FIGURE 2.3. DATA BLOCK I

and subsequent solutions for the true anomaly:

$$\sin \nu(t) = \frac{\sqrt{(1-e^2)}\ \sin E(t)}{1-e \cos E(t)}$$

and:

$$\cos \nu(t) = \frac{\cos E(t)-e}{1-e \cos E(t)}$$

The purpose of the ephemeris is to provide extremely accurate space vehicle information which will lead the user to calculate his position and velocity very accurately. Figure 2.4 lists the parameters sent for data block II and what each represents (Ref. 3).

2.2.3.3 Data Block III

Data block III contains the NAVSTAR GPS almanac. The almanac contains 25 sets of data, one for each satellite plus a dummy set. Thus, unlike data blocks I and II, which repeat every frame, the almanac requires 25 transmissions of subframe 5 before it is completely transmitted. Thus, it repeats every 12.5 minutes. A satellite almanac consists of satellite ID, health, orbit parameters and clock corrections. It is obvious that the almanac for a given satellite is a much abridged version of the satellite ephemeris. Also, the almanac will be updated weekly as opposed to the hourly updating of the ephemeris of data block II. The purpose of the almanac is to aid in satellite selection and acquisition and to provide the user with knowledge of a faulty operating satellite. Figure 2.5 lists the parameters sent in data block III and what each represents (Ref. 3).

Parameter	No. of Bits	Description
AODE	8	Age of Data (ephemeris)
Mo	32	Keplerian Parameters
Δ_n	16	" "
e	32	" "
$\sqrt{A}$	32	" "
Ω_o	32	" "
i_o	32	" "
w	32	" "
$\dot{\Omega}$	24	" "
C_{uc}	16	Amplitude Correction Coefficients
C_{us}	16	" " "
C_{rc}	16	" " "
C_{rs}	16	" " "
C_{ic}	16	" " "
C_{is}	16	" " "
t_{oe}	16	Ephemeris Reference Time
AODE	8	Age of Ephemeris Data

FIGURE 2.4. DATA BLOCK II

Parameter	No. of Bits	Description
ID	8	Satellite ID Number
e	16	Eccentricity
t_{oa}	8	Almanac Reference Time
δ_i	16	Inclination Correction from Nominal
Health	8	Space Vehicle Health
$\dot{\Omega}$	16	Keplerian Parameters
$\sqrt{A}$	24	" "
Ω_o	24	" "
ω	24	" "
M_o	24	" "
a_o	8	Clock Correction Parameters
a_1	8	" " "
Spare	6	

FIGURE 2.5. DATA BLOCK III

2.3 GROUND SEGMENT

As stated earlier the ground segment (called control segment) of NAVSTAR GPS consists of four unmanned monitor stations (MS), a master control station (MCS) and an upload station (ULS). The master control station and upload station are at Vandenberg Air Force Base, California. The purpose of the ground segment is to continuously monitor the health of the entire NAVSTAR GPS system, to upload new ephemeris and almanac data to the space vehicles when required, and to alert users of any and all problematical or informational aspects of GPS (Ref. 4).

2.3.1 Monitor Station

Each monitor station contains a 4-channel receiver, environmental data sensors, an atomic frequency standard, and computer processing equipment. The receiver measures the pseudo-range and delta pseudo-range of the NAVSTAR GPS signal and receives the navigation data. The environmental sensors collect meteorological data which will form a basis for tropospheric corrections. Ranging measurements are sent every 6 seconds from each MS to the MCS.

2.3.2 Master Control Station Upload Facility

The master control station receives the ranging measurements from each of the monitor stations. Corrections are made to account for the known biases: ionospheric, tropospheric, special relativistic effects, satellite and monitor station antenna phasing offsets, earth rotation and time corrections. Then the MCS applies these to a smoother which edits all measurements, throws out those that are beyond a fixed number of standard deviations away from the norm, and applies curve fitting techniques to establish smoothed range and delta range measurements. The smoothed measurements then are sent to a Kalman estimator that establishes all space vehicle parameters, which for Phase I with six satellites and four MS results in 85 estimated values. On a daily basis ephemeris is sent from the MCS to the Naval Surface Weapons Center (NSWC) at Dahlgren, Virginia via telephone link so that they can establish reference ephemeris. The computed reference ephemeris is sent weekly from NSWC to Vandenberg for uploading.

During Phase I testing the satellites are uploaded at least once per day. Generally there will be two navigation message uploads, a 6 hour update and a 26 hour update. The 6 hour update will be used to initialize or refresh user navigation data. The 26 hour uploading supports once-a-day uploading and final uploading before the satellite disappears from the upload station visibility. In addition the MCS sends special messages and diagnostics to the satellite if required (Ref. 4).

2.4 USER SEGMENT

The user segment consists of that set of electronic equipment which receives the NAVSTAR GPS signals, processes them to determine desired quantities, i.e. position, velocity, and time, and displays them in an appropriate manner. Generally the user equipment consists of the NAVSTAR GPS antenna or antennas depending on configuration, the preamplifier to set the system noise figure, the receiver, the computer processing equipment and the display. In this section will be discussed the NAVSTAR GPS range equations, signal structure, signal reception and processing, user equipment, the Z-Set (hardware and software), and sources of error.

2.4.1 Signal Structure

The NAVSTAR GPS spread spectrum (Ref. 2) signal on L1 from the i^{th} satellite is of the form:

$$S_{L1_i} = A_{P_i} P_i(t)D_i(t) \cos(w_i t + \phi) + Ac_i C_i(t)D_i(t) \sin(w_i t + \phi)$$

where:

Ap_i = amplitude factor for P code

Ac_i = amplitude factor for C/A code

$P_i(t)$ = 10.23 Mbps PRN P code

$C_i(t)$ = 1.023 Mbps Gold code (C/A)

$D_i(t)$ = 50 bps data

The L2 signal format is similar but will likely have on the P code term. The receiver will receive outputs from 6 to 11 satellites. Each signal will have been doppler-shifted due to the relative movement between the spacecraft and the user. The user's equipment will see a combined signal of the form (for L1):

$$S = \sum_{i=1}^{n} S_{L1_i} = \sum_{i=1}^{n} A_{P_i} P_i(t)D_i(t) \cos((w_i + w_d)t + \phi_i) + \sum_{i=1}^{n} A_{c_i} C_i(t)D_i(t) \sin((w_i + w_d)t + \phi_i)$$

where $6 < n < 11$ and w_{d_i} = doppler frequency offset

For the NAVSTAR GPS Phase I segment the C/A code is 3 to 6 db stronger than the P code. The user equipment will have to receive this composite signal, select the most advantageous four satellites, sequentially or simultaneously acquire and track each one while rejecting all others, remove the transmitted data, and process the data to calculate the desired position information.

During Phase I the following signal levels will be present at the output of a 0 dBIC antenna with right hand circular polarization for a satellite at an elevation angle greater than 5^{o}:

Signal Component	Power Received
L1 P	-163 dBW
L1 C/A	-160 dBW
L2 P	-166 dBW
L2 C/A	-166 dBW

The system noise temperature is related to the antenna temperature by:

$$T_{eq} = \frac{T_a}{L} + \frac{L-1}{L} T_o + (NF-1)T_o$$

where L = the signal loss due to the antenna-to-preamplifier cable

NF = system noise figure

T_{eq} = system noise temperature

T_a = antenna temperature

This results in a carrier to noise density ratio of 38.6 dBHz considering a 2dB carrier loss due to cable, filter and correlation. However the performance would certainly degrade in the presence of intentional or unintentional high unintentional high-level jamming, severe multipath at low elevation angles, or increases in N_o due to ionospheric disturbances. It should be mentioned that because of the spread spectrum nature of the system, interference must be 60 dB above the receiver noise density to cause a 3 dB change in C/N_o. Thus, the system is reasonably immune to jamming (Ref. 2).

2.4.2 User Equipment

There have been a number of NAVSTAR GPS receivers built to date, differing in cost and complexity. The X, Y and Z-sets were built by Magnavox. The X-Set receiver simultaneously tracks four satellites, uses L1 and L2, accommodates high dynamics users, has a maximum time to first fix of 180 seconds, and yields a navigational accuracy of 20 meters (2 drms) horizontally and 25 meters (2 drms) vertically. The Y-Set receiver sequentially tracks four satellites, uses L1 and L2, accommodates medium dynamics users, has a maximum time to first fix of 300 seconds, and yields a navigational accuracy similar to the X-Set. The Z-Set receiver sequentially tracks four satellites, uses only the C/A signal of L1, accommodates lower dynamics users, has a maximum time to first fix of 300 seconds, and results in a navigational accuracy of 200 meters (2 drms) (Ref. 14). Since the Z-Set is the simplest, it is also the least expensive. It is expected that Z-Sets can be produced for $10K - $15K in large quantities (Ref. 8). More will be stated about the Z-Set later. It should be stated briefly that Texas Instruments has also developed NAVSTAR GPS receivers, designated High Dynamic User Equipment (HDUE), Missile Borne Receiver Set (MBRS), and the Manpack/Vehicular User Equipment (MVUE). The HDUE is a 5-channel, high performance set designed for high dynamics users. The MBRS is a 4-channel, high performance set designed for the Minuteman missile test program. The MVUE is a single channel set designed for manned vehicles such as trucks, tanks, and jeeps (Ref. 6). Collins Radio has also designed some receivers.

2.4.3 Z-Set

The Z-Set, utilizing the C/A L1 signal, was developed as a prototype for low cost user equipment. It consists of an antenna, whose gain and directivity are dictated by user application (but in most cases the antenna pattern provides 3 dB upper hemispherical coverage), a preamplifier mounted physically close to the antenna to set the noise figure of the system, and the Z-Set itself. The preamplifier has 30 dB of gain at 1575.42 MHz with a noise figure of 4 dB. The receiver/processor unit consists of a receiver with a multiple down conversion RF/IF unit, baseband loops and detectors, frequency synthesizer, C/A code generator, user clock, 5.115 MHz reference oscillator and receiver I/O connected to the processor bus (Ref. 9). The reference oscillator is a good quality oven-controlled unit which has minimum sensitivity to vibration since phase noise and short-term drift will adversely affect performance. From this oscillator are generated the various local frequencies required for down conversion and the basic timing pulses required by the user time clock (UTC) which forms the basis for the time reference against which signal arrival times are made. The processor used is the LSI-11 16 bit microcomputing module. The processor controls the Z-Set operation and performs a variety of tasks which will be discussed in detail later. Basically, the best combination of four healthy satellites must be selected, signals must be acquired, tracked, and codes synchronized, pseudo-ranges must be computed, the navigation algorithm invoked and an unambiguous position solution determined and displayed (Ref. 11).

2.4.3.1 Z-Set Computer

The Z-Set computer program, called Z User Set Computer Program (ZUSCP), is used to provide the control and processing logic required by the system to receive and process NAVSTAR GPS signals and to display position, velocity, and time under the dynamics of the host vehicle. The ZUSCP has ten functions. They are: 1) system monitor, 2) control/display processing, 3) receiver processing, 4) satellite data gathering, 5) navigation, 6) satellite selection, 7) built-in test, 8) instrumentation, 9) executive, 10) satellite position computation (Ref. 12). The ZUSCP provides for the following modes: 1) initialization, 2) almanac collect, 3) time-to-first-fix (TTFF), 4) sequential track, 5) receiver test mode. The sequential track mode is the desired state of the ZUSCP. All other states exist to achieve this one. In the sequential track state, the time dwells, scheduled times for required system events, are fixed and scheduled. At other times and during other modes of operation, the dwells may be variable depending on the time required to perform a particular function (Ref. 12).

Once all ephemeris has been collected, the set is ready for computation of navigation parameters. The navigation function takes the pseudo-range and delta pseudo-range information, invokes the navigation algorithms, which are controlled by an 8-state Kalman filter, and produces the ECEF coordinates of the current position and velocity (Ref. 13). These values in ECEF coordinates are converted to ENU coordinates for display. The display presents latitude and longitude to the nearest arc second, and altitude to the nearest foot.

2.4.3.2 Z-Set Accuracy

The ultimate position and velocity error is due to a number of sources which can be lumped into two types: User Equivalent Ranging Error (UERE), which is a combination of all system range measurement errors, and Geometrical Dilution of Precision (GDOP), which is a measure of the additional error due to the relative position of the measurement system and the space vehicles. Position accuracy is a product of the UERE and GDOP.

2.4.3.2.1 UERE

The major components of UERE are satellite ephemeris error, atmospheric effects, i.e. tropospheric and ionospheric delays, satellite timing error, receiver noise and resolution errors, and multipath. The following table lists the error sources and predicted 1σ range errors due to them (Ref. 9):

Error Source	Range Error (ft.)	Range Rate Error
Satellite Ephemeris	12	-
Satellite Clock	8 - 50	-
Z-Set Receiver	45	.2
Multipath	4 - 50	-
Atmospheric:		
Ionospheric	13 - 40	-
Tropospheric	7 - 15	-
	50 - 95	.2

These values are the rms 1σ values.

2.4.3.2.2 Geometrical Effects

User positional accuracy is a function of the inherent accuracy of the system and the dilution of that basic accuracy due to unfavorable system geometry and time. This unfavorable geometry is quantized by a factor called geometrical dilution of precision (GDOP). Perfect geometry implies a GDOP of 1 and can in theory range in value from 1 to infinity. However, for NAVSTAR GPS, the GDOP is expected to have a value less than 4.5 (95% probability) for a minimum elevation angle of 5^{o}. Detailed explanation of GDOP occurs in Section 3.2 (Ref. 10).

3. OPERATIONAL FACTORS

3.1 SATELLITE COVERAGE

During the period of receiver evaluation at Long Beach (May-August, 1979), only four satellites were in orbit: NAVSTAR #1-2-3-4, in orbit slots #1-5-6-3, respectively. A computer program was obtained from the Space and Missile Systems Organization (SAMSO), the DOD agency responsible for deployment and operation of NAVSTAR GPS, which provided satellite positions as a function of time during the 24 hours following midnight, January 1, 1979. Using this algorithm, and the fact that satellite positions advance by a fixed amount (4 minutes, 3.4 seconds) daily, a program was developed to calculate "look angles" to the satellite from an observer on earth for the nominal 24 hour period, which could then be extrapolated forward for any day of the year. The algorithm for computing satellite "look angles" appears in Appendix A.

A plot of satellite elevation angle versus time is shown in Figure 3.1. Note that there is 4-satellite coverage for approximately 105 minutes, followed by 3-satellite coverage for another 2½ hours. Figure 3.2 shows the satellite position (azimuth and elevation) plotted in polar coordinates. The relative positions of the satellites with time will be discussed further in relation to geometric dilution of precision.

The time at which the 4-satellite cluster was simultaneously visible advanced by 2 hours per month; a table indicating the start time on dates throughout the test period appears in Figure 3.3.

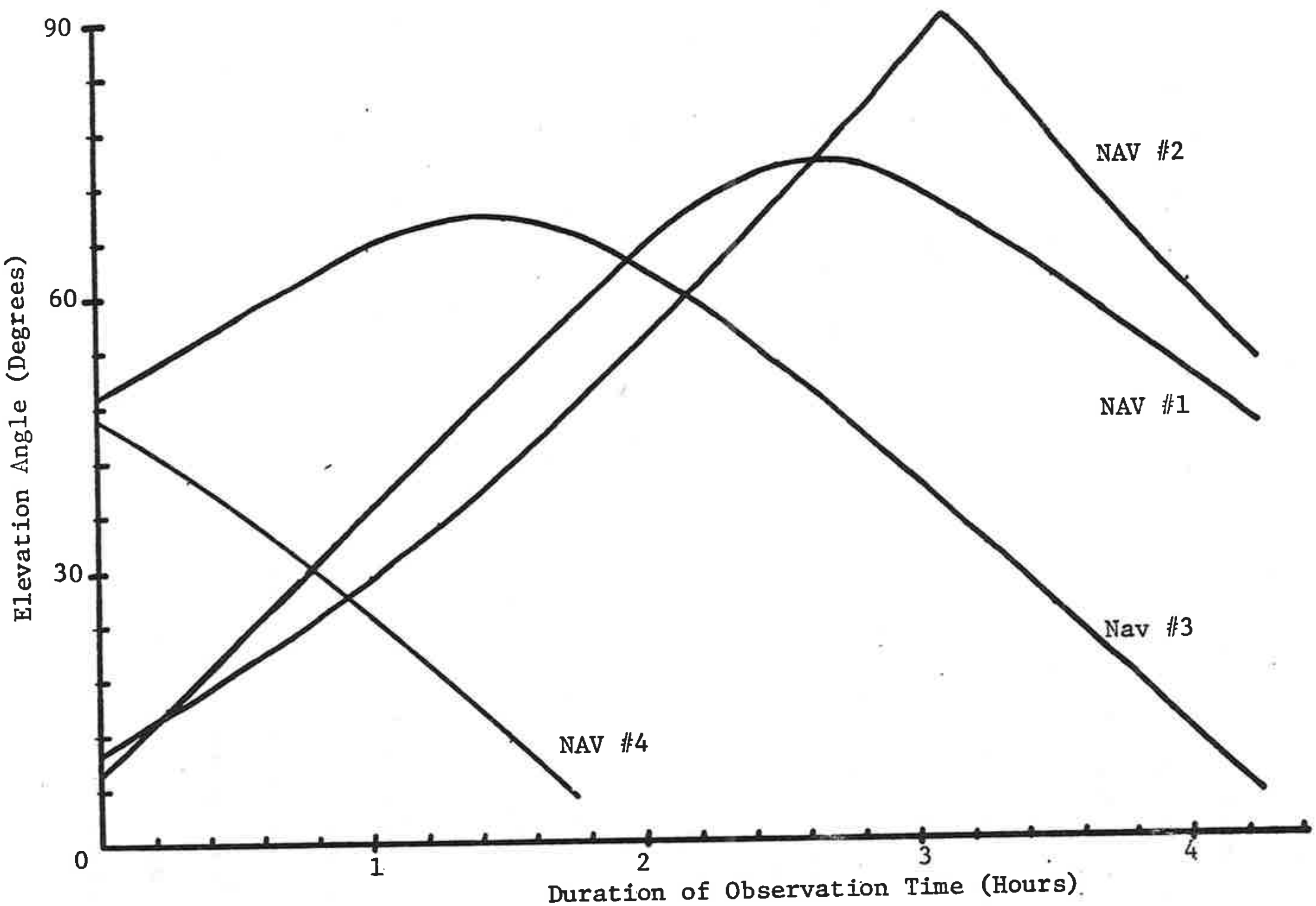


FIGURE 3.1. AZIMUTH ANGLE VS. TIME

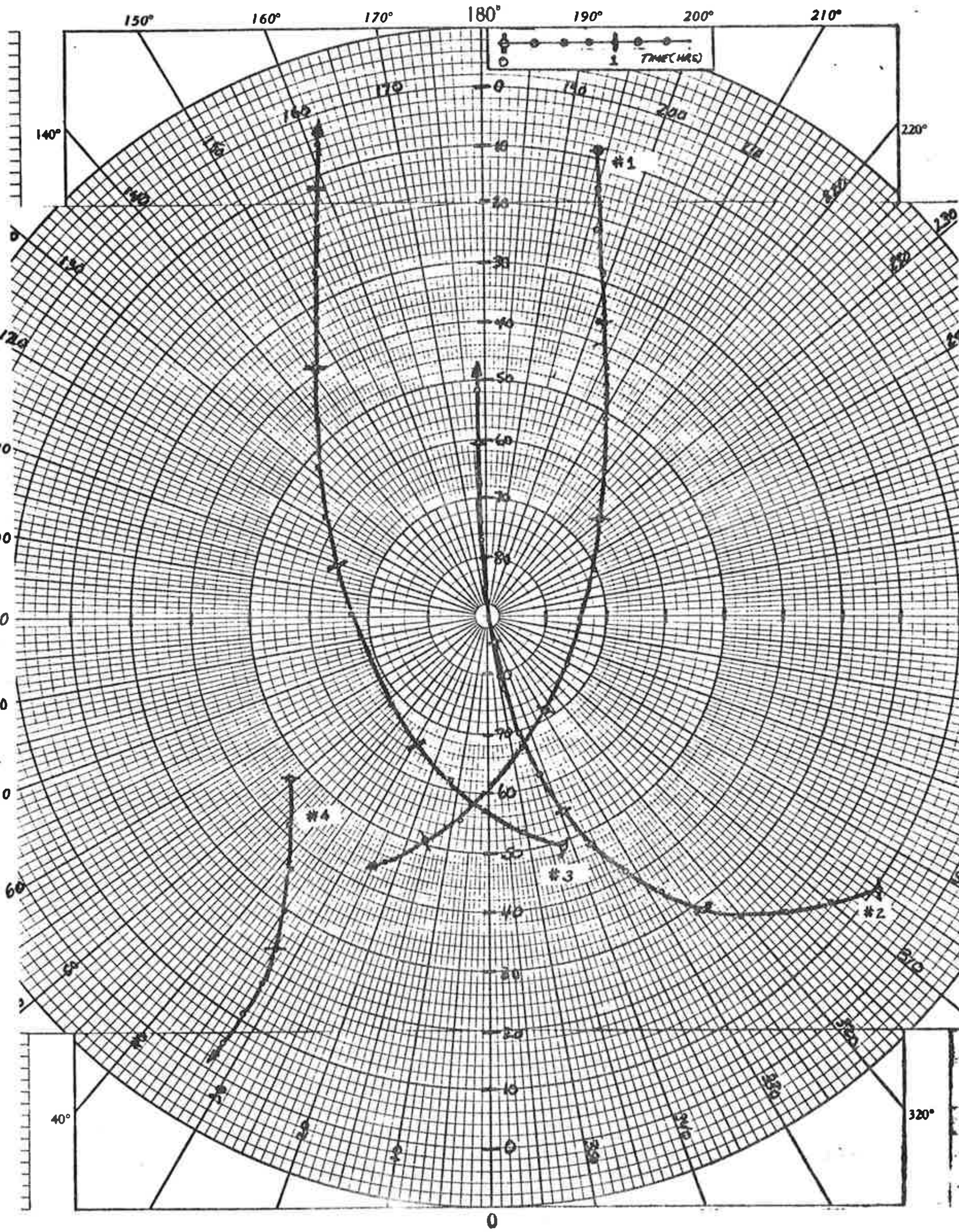


FIGURE 3.2. POLAR PLOT OF SATELLITE TRACKS VS. TIME

Date	GMT	Local
May 13	0635	11:35 PM
" 20	0606	11:06
" 27	0538	10:38
Jun 3	0509	10:09
" 10	0441	9:41
" 17	0413	9:13
" 24	0344	8:44
Jul 1	0316	8:16
" 8	0247	7:47
" 15	0219	7:19
" 22	0151	6:51
" 29	0122	6:22
Aug 5	0054	5:54
" 12	0025	5:25
" 19	2357	4:57
" 26	2329	4:29
Sep 2	2300	4:00

FIGURE 3.3. SATELLITE VISIBILITY TIMES FOR LONG BEACH, CALIFORNIA (Time at which observation period begins)

3.2 GEOMETRIC DILUTION OF PRECISION

The magnitude of the user position errors in the NAVSTAR GPS system is determined by the magnitude of the ranging errors (from the satellites) combined with the geometry of the 4-satellite configuration. The effects of the relative geometry of the satellite locations with respect to the user position is termed the "geometric dilution of precision" (GDOP). The concept of GDOP was originally developed for hyperbolic ranging systems over the surface of the earth, but the definition has been extended to include satellite ranging systems such as NAVSTAR GPS. The parameters of GDOP for the satellite-based system include dilution of precision in three dimensions (PDOP), in two horizontal dimensions (HDOP), in the vertical dimension (VDOP), and in time (TDOP), in terms of a "ranging equivalent" to the user clock bias. The following relationships exist:

$$\text{GDOP} = \sqrt{(\text{PDOP})^2 + (\text{TDOP})^2}$$

and

$$\text{PDOP} = \sqrt{(\text{HDOP})^2 + (\text{VDOP})^2}$$

The rms position error is related to the rms range error by:

$$\sigma_P = \text{PDOP} \times \sigma_r$$

$$\sigma_H = \text{HDOP} \times \sigma_r$$

$$\sigma_V = \text{VDOP} \times \sigma_r$$

where σ_P, σ_H, σ_V are, respectively, the rms position error, the rms horizontal component of position error, and the rms vertical component of position error.

For NAVSTAR GPS, typical values will be as follows during full 24-satellite operation:

PDOP 2.6

HDOP 1.4

VDOP 2.2

TDOP 1.2

Thus, the selection of satellites which gives the smallest value of GDOP is very important and, in fact, this is the criterion for satellite selection, constant monitoring, and regular constellation update.

As mentioned previously, only 4 satellites were in orbit during the test period. During the period of simultaneous 4-satellite visibility, the value of HDOP varied between 1.6 and 2.6 and VDOP varied between 2.5 and 4.0. Once the fourth satellite set over the horizon, the HDOP factor rose from 2.4 to 3.3 over the next 30 minutes (VDOP rose from 2.4 to 3.0), and because of the very poor geometry between the remaining three satellites, the HDOP and VDOP gradually became very large and returned to a value of 3.5 over the final 2¼ hours of the coverage period. The values of HDOP and VDOP versus time are shown in Figures 3.4 (A,B). The algorithm for computing GDOP factors, which was developed from an article by H.B. Lee, MIT Lincoln Lab, appears in Appendix B.

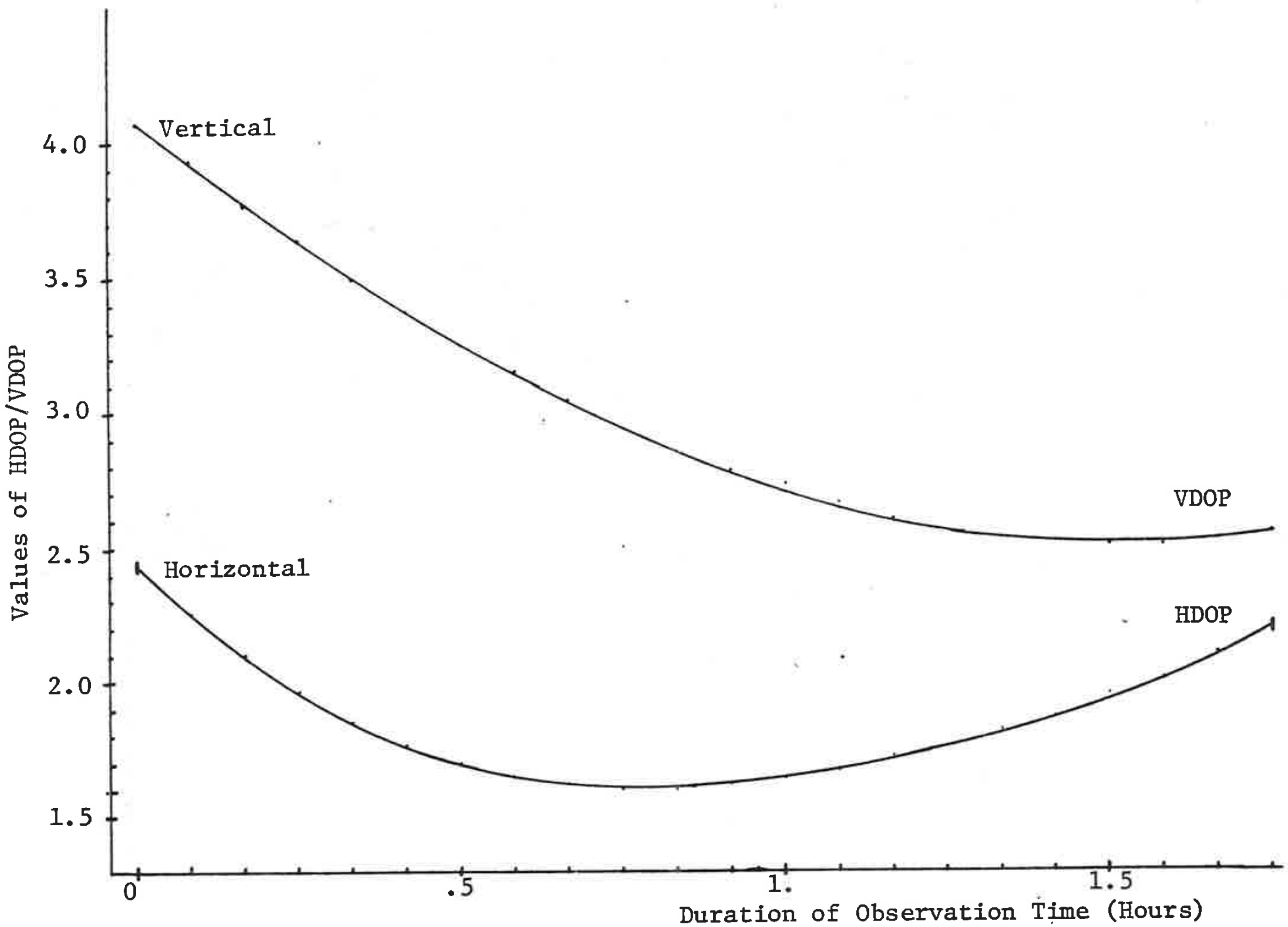


FIGURE 3.4A. HDOP/VDOP DURING FOUR SATELLITE COVERAGE

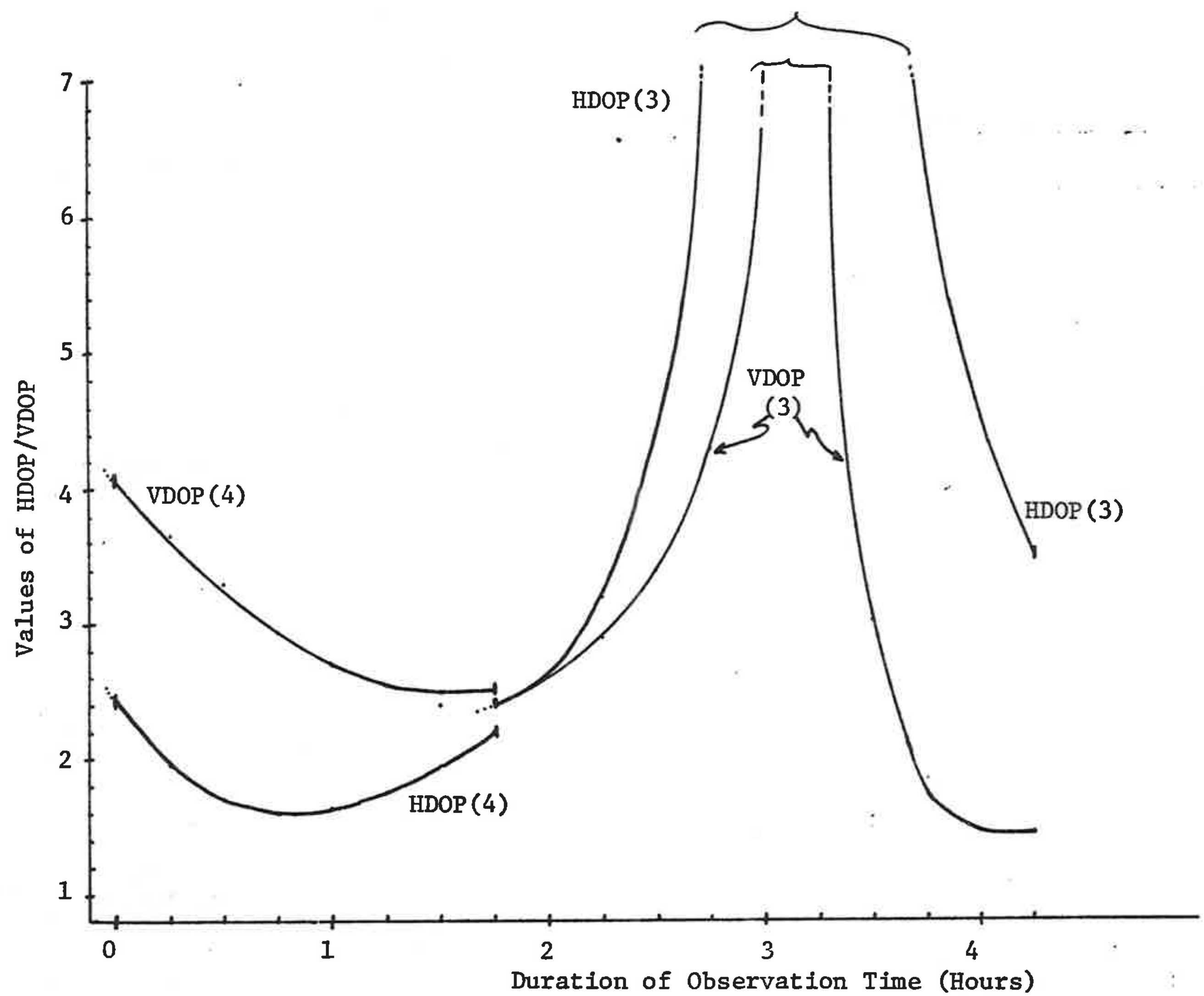


FIGURE 3.4B. HDOP/VDOP DURING ENTIRE PERIOD

3.3 UPLOAD DATA

The Ground Control segment of the NAVSTAR GPS system consists of the four monitor stations (Vandenberg, Guam, Hawaii, and Alaska), and the Master Control Segment and Upload Facility at Vandenberg Air Force Base. Personnel at Vandenberg track each satellite using a Magnavox X-set receiver and process 15 minutes of data through a Kalman filter cycle (K-point) to compute the upload corrections. Upload values are transmitted to the satellite at a predetermined time (usually 30 minutes after coming into view and only once per pass) and stored in the satellite 5 minutes prior to first use. SAMSO has established a standard called "User Equivalent Range Error" (UERE). If UERE exceeds 4 meters during periods of testing, an additional "contingency" upload is performed.

The effects of the upload on system performance are readily observable. The uploaded ephemeris data is made available to all users within a few minutes of receipt in the satellite, and each model receiver mechanizes the implementation of uploaded ephemeris values differently. The Z-Set is designed to seek out new ephemeris data under only 3 conditions: during receiver initialization, as a result of manual "Almanac Collect" command, or at one hour intervals following the last ephemeris collection. This infrequent collection cycle is necessitated by the time-share nature of the single data channel, and elimination of navigation updates during ephemeris collection. The impact of this design limitation is discussed in the data analysis section.

The required coordination with SAMSO to obtain upload data was easily accomplished. Personnel at SAMSO provided copies of daily "Control Segment Operations Activity," showing system status, activity, upload times and problems, and a graph of UERE values prior to and after upload. (See sample on Figure 3.5.) These activity sheets were available only 5 days per week, although the uploads occurred 7 days per week. Hence, there is no written upload documentation on weekend evenings. During the last week of June, a recorded telephone message was initiated which gave a report of "activity, status, and planned events" for the previous night's upload.

3.4 IONOSPHERIC DELAY ERRORS

Electromagnetic radiation travels slower through the ionosphere than in free space due to electron interaction; and its velocity decrement is proportional to the electron density along the signal path. Observed ionospheric delays vary widely due to the dependence on time of day, season, geographic location, and solar activity. Ionospheric delay can potentially cause errors of several hundred feet in the navigation solution if not corrected.

It was not possible to accurately quantize the amount of range error due to ionospheric delay during this phase of testing.

26 JUN 1979

9

NAVSTAR

CONTROL SEGMENT OPERATIONS

26 Jun 79 DATE

CURRENT ACTIVITY:

- NAVSTAR 1-4 TRACKING, UPLOADING.
- RECEIVER POWER PROTECT SYSTEM AT AMS IS OPERATIONAL.

STATUS:

CS EQUIPMENT	UP/ DOWN	NAVSTAR	UP/ DOWN	UPLOAD INFO/26 JUN COMMENT
Master Control Sta	U	1	U	U(26) AT 0415, 0530Z
Upload Station	↓	2	↓	U(26) AT 0400Z
Van MS	↓	*3	↓	0400Z
Alaska MS	↓	4	↓	0400Z
Hawaii MS	↓	5		
Guam MS	↓	6		
STC Term	↓	7		
NSWC Term	↓	8		

PROBLEMS:

* NAV 3 BIT HIT IN PARITY TABLE; CURED BY INIT UPLOAD AT 0215Z, 26 JUN 79.

26 JUN 1979

8

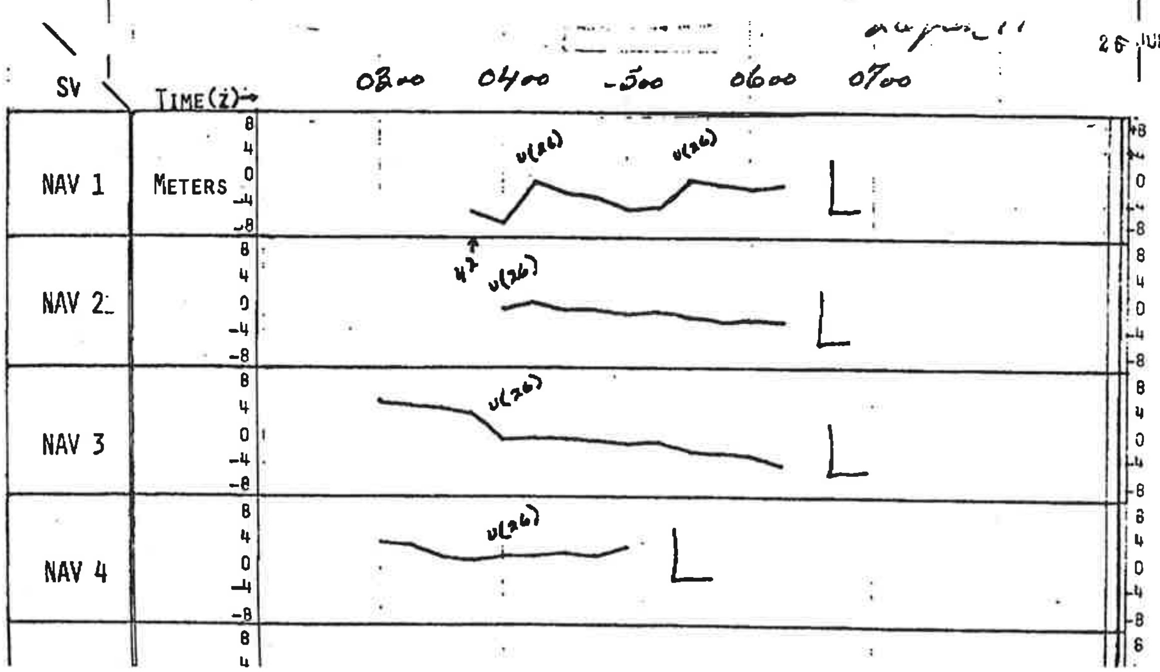


FIGURE 3.5. UPLOAD PERFORMANCE REPORT SAMPLE

4. EXPERIMENTAL CONFIGURATION

The Magnavox Z-Set receiver was installed in the Rescue Coordination Center (RCC) of the USCG District 11 Office. Magnavox packaged the receiver box, control and display unit (CDU), and power supplies in a sea-pallet, for current and future environmental requirements. A picture of the Z-Set as it was configured for the Long Beach tests is shown in Figure 4.1.

The antenna was mounted on the northeast corner of the roof. (See Figure 4.2.) The single frequency (1575 MHz) omnidirectional antenna built by Chu Associates receives circularly polarized signals and has 3 dB gain, with 50 ohm impedance. A graph showing the antenna coverage pattern is shown in Figure 4.3. The antenna preamplifier was mounted within a few inches of the antenna. The cable between the preamp and the receiver was approximately 300 feet long. This cable was RG213, which exhibits about 10 dB loss per 100 feet. However, as noted in Section 6, lengthening or shortening the cable distance seemed to have no observable effect upon performance.

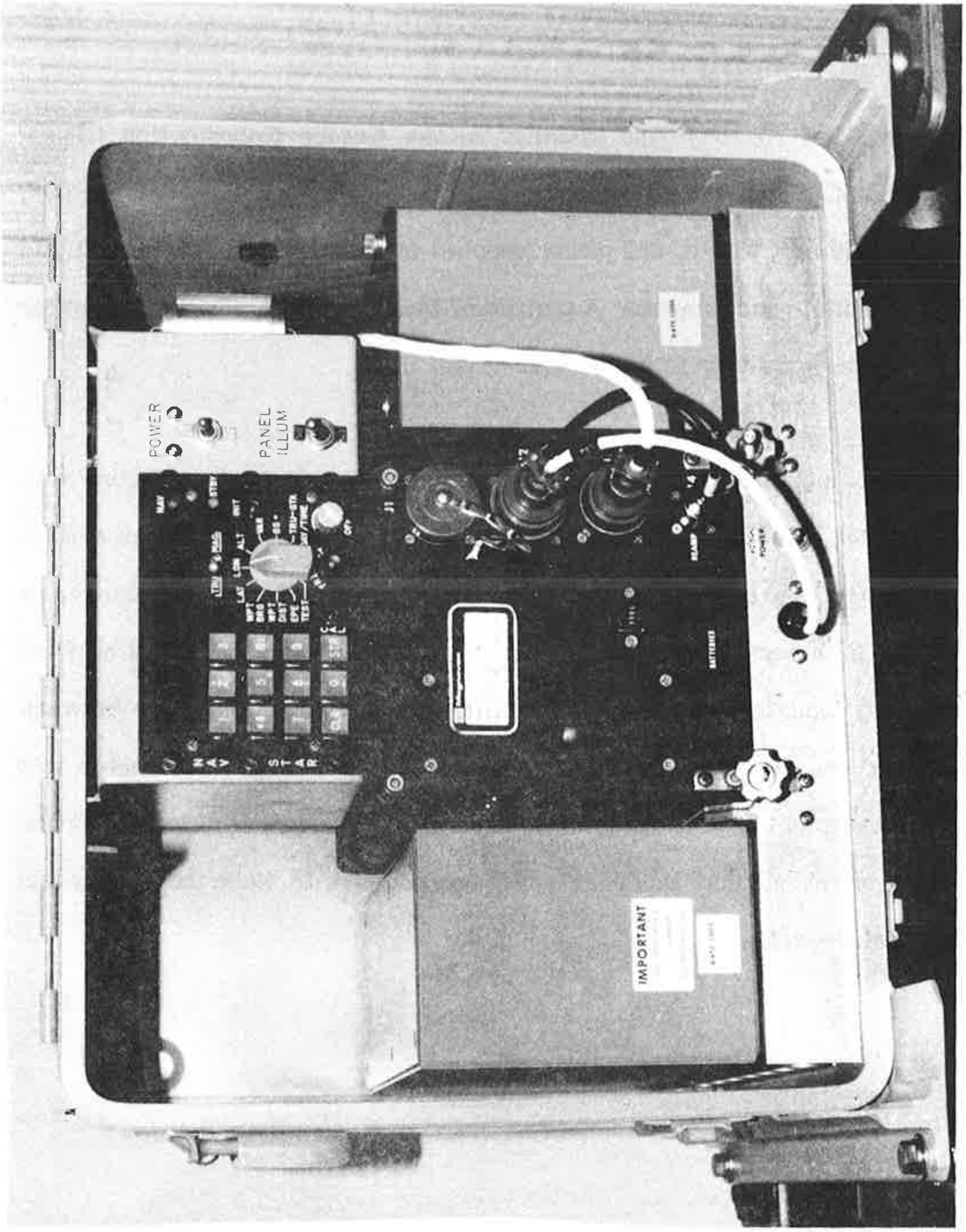


FIGURE 4.1. Z-SET

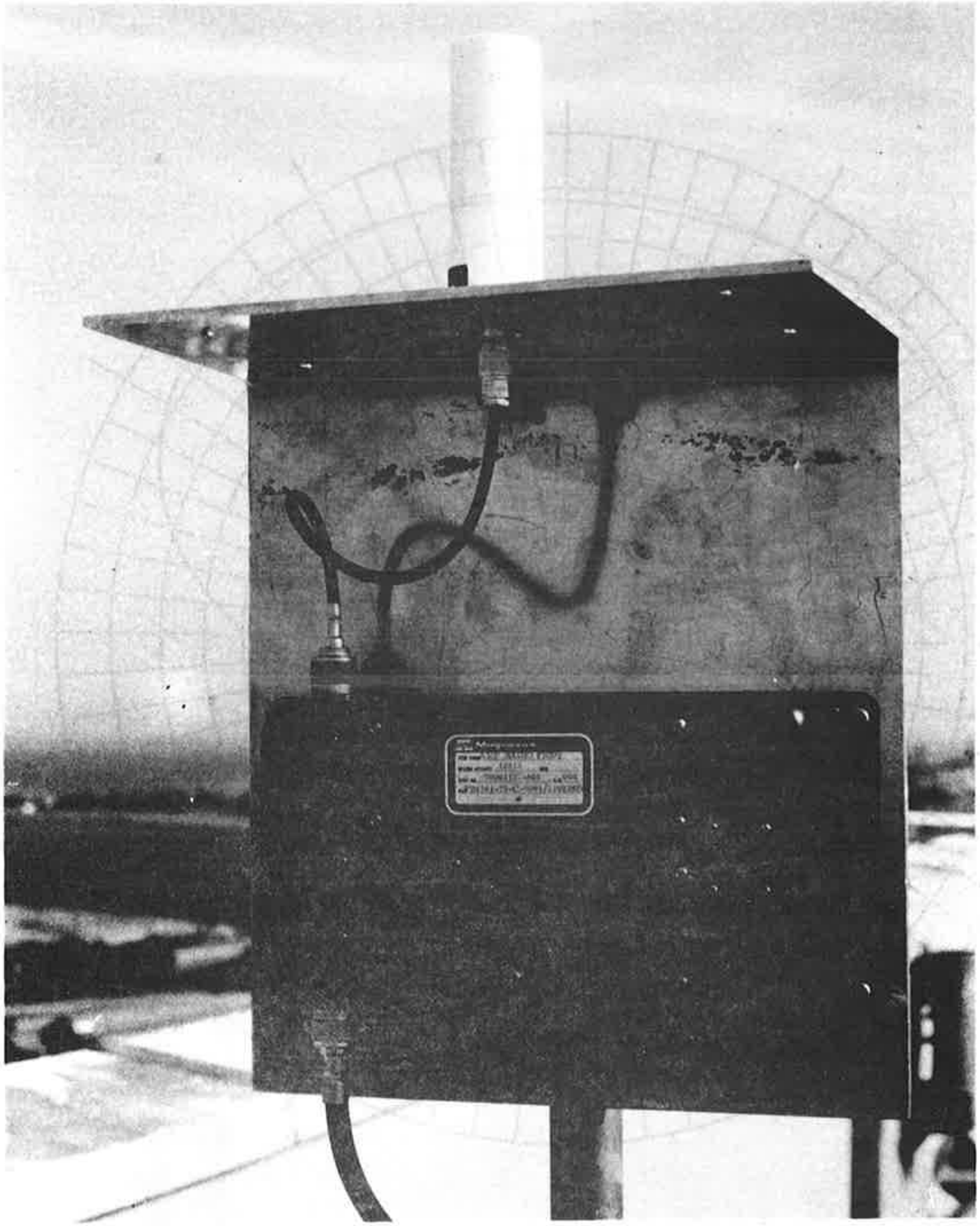


FIGURE 4.2. ANTENNA INSTALLATION

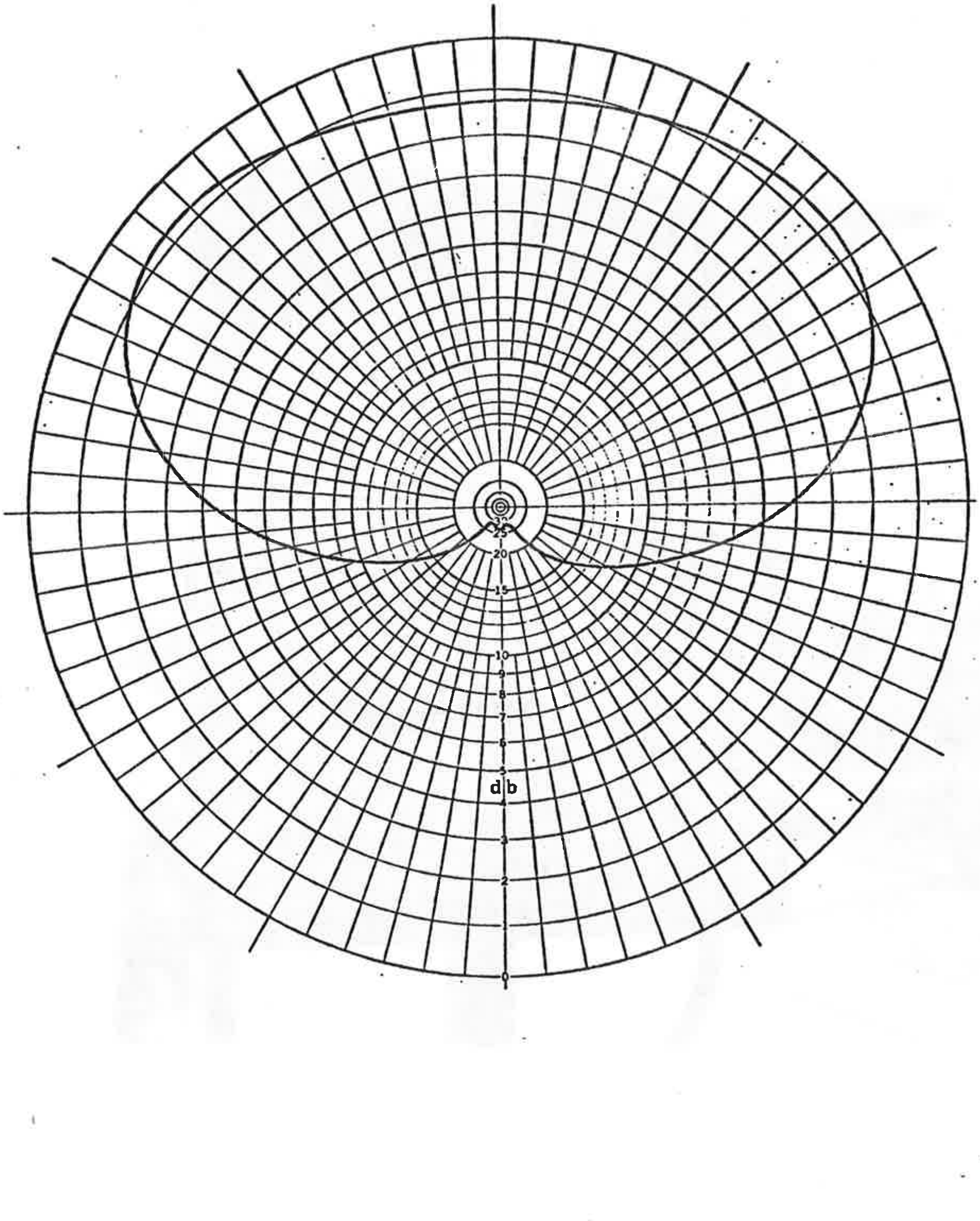


FIGURE 4.3. ANTENNA COVERAGE PATTERN

5. DATA COLLECTION OVERVIEW

5.1 COORDINATE SYSTEM AND SATELLITE SURVEY REFERENCE

The coordinate system for NAVSTAR GPS is the ECEF system with the displayed outputs presented in the ENU system all based on the WGS-72 datum. Thus, values of longitude, latitude and altitude presented in this report are the values of the parameters as measured in this system. (See Section 2.2.1). It should be noted that the WGS-72 datum establishes a reference ellipsoid to approximate the geoid (the earth) and that there is a difference between the two. At Long Beach the altitude difference is approximately 33.51 meters.

Determination of the accuracy with which the Z-Set can calculate its position requires comparison of the Z-Set's estimated position to that of a known reference. Thus, to establish this reference, a Magnavox MX-1502 satellite surveyor was used from May 14 to May 16. The MX-1502 uses the Navy Navigation Satellite System (NNSS), TRANSIT, to calculate latitude, longitude and altitude, also in WGS-72 coordinates. Thus, data collected from the Z-Set can be directly compared with the reference data established by TRANSIT and statistics computed.

During the period when the TRANSIT receiver was used, seven 3-dimensional fixes were obtained with the surveyor located 2 meters from the NAVSTAR GPS Z-Set antenna, which was mounted on top of the Coast Guard building in Long Beach, California. The following values were obtained:

	Mean	Std Dev (meters)
Latitude	33^{o} 46' 1.7.6"	6.1
Longitude	118^{o} 12' 5.867"	11.8
Altitude	33.4 meters	6.7

5.2 Z-SET DATA FORMAT

The Z-Set was developed by Magnavox as a cockpit replacement unit for the DOD tactical air navigation system (TACAN); the display parameters were optimized for aircraft operation. There were more outputs available for display than were needed during this test project; hence, some were not recorded. Data collection was limited to the six quantities shown in Figure 5.1: latitude; longitude; altitude; day/time; estimated position error (EPE), which is the trace of the filter covariance matrix; and status, which showed how many satellites were being tracked and from how many ephemeris data had been collected. The navigation outputs were updated every 1.2 seconds.

Data	Resolution	Example
Latitude	1 sec	330^{o} 46' 01" N
Longitude	1 sec	118^{o} 12' 06" W
Altitude	1 foot	111 feet
Day/Time	1 sec	5 0731 25"
EPE	.01 NM	.01 NM
Status		44

FIGURE 5.1. Z-SET DATA COLLECTION PARAMETERS

5.3 DATA COLLECTION

All data collection was performed manually by recording Z-Set output values on data sheets. The Z-Set has a feature called "FREEZE/ENTER" by which, with a push of a button, the contents of all display registers are stored simultaneously. Since only one data quantity can be displayed at a time, this function allows recording of several data values that are valid at the same time. The operator observed the time display and used the "FRZ-ENT" button to "freeze" all data at desired intervals (e.g., every 5 minutes). After the desired data was selected for display using the rotary dial and recorded, the "FRZ-ENT" switch was depressed a second time to resume normal operation.

Data was also recorded on some selected test days every 1.2 seconds by monitoring the display when the function switch was placed at one position. This was done for altitude only. Thirty to sixty samples were sequentially recorded, which allowed one to observe changes in the altitude computation after each filter cycle, and afforded sample-to-sample analysis.

Limitations in the data collection process during this first phase were few but significant: 1) the latitude/longitude values were displayed to a precision of 1 arc-second (approx. 30 meters), not allowing observation of changing data to a greater resolution. 2) The single display did not allow both simultaneous observations of three position elements (latitude/longitude/altitude) plus time and sequential values of these data - a choice between one or the other was always made. Changes to the display format/hardware in future phases of this program have been suggested to eliminate these problems.

5.4 AUXILIARY DATA

In addition to the Z-Set outputs recorded manually, copies of the daily status reports from the SAMSO upload facility were obtained Monday through Friday. (No written upload reports were available on weekends.) These indicated the time and quality of uploads and system performance during the 4 hours of satellite visibility.

6. TEST RESULTS

The Z-Set was installed at the USCG District 11 office early in May 1979 and removed early in September. The following is a summary of data collection activity:

- There were 112 days of potential data collection, from May 13 to September 1, 1979.
- Of these, data collection was scheduled for 64 days. No data collection was scheduled for the remaining 48 days.
- Of the 64 days scheduled for data collection, the NAVSTAR GPS four satellite constellation was not available for use on 33 days, primarily because of a failure in the frequency standard on board one satellite.
- Of the remaining 31 days, there were 11 days for which data was unusable for a variety of reasons: no upload data, moved location, procedures error, etc.
- The remaining 20 days, on which there is verification of the upload performance for 4 satellites, constitute the valid data upon which this report is based. A summary of daily activity over the entire period is shown in Figure 6.1.

6.1 CATEGORIZATION

The events which categorize one (daily) satellite observation period are: 1) 4 satellites become covisible with acceptable HDOP (≤ 2.5) for 105 minutes; 2) an upload is performed during the early segment of visibility; 3) the fourth satellite disappears below the horizon to create a period of acceptable HDOP

	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
May	13	14 U/	15	16 (#1)	17 U/	18 U/	19 U/
	20	21 U/	22 U/	23	24	25	26
	27	28	29	30	31	1	2 X
June	3 X	4 X	5 X	6 X	7 X	8 X	9 X
	10 X	11 X	12 (#2)	13 X	14	15 X	16 U/
	17	18 (#3)	19 (#4)	20 (#5)	21 (#6)	22 (#7)	23
	24	25 U/	26 (#8)	27 (#9)	28 (#10)	29 U/	30 (#11)
July	1	2	3 (#12)	4 (#13)	5 (#14)	6	7 X
	8 X	9 X	10 X	11 X	12 X	13 X	14 X
	15 X	16 X	17	18 X	19 X	20 X	21
	22	23 X	24 (#15)	25 (#16)	26 (#17)	27 X	28
	29	30 (#18)	31 (#19)	1 X	2 X	3 X	4
August	5	6	7	8 X	9	10	11
	12	13	14 X	15	16	17	18
	19	20	21	22	23	24	25
	26	27	28	29 (#20)	30	1 U/	2 U/

No Data Collected	Data Unusable	No 4-Sat. Coverage	Nth Day of Data Collection
d	d U/	d X	d (#N)

FIGURE 6.1. DAILY ACTIVITY SUMMARY

($\leq$3) for another 30 minutes; 4) the GDOP deteriorates rapidly to a very high number and returns to 3.5 after 2 hours.

The data is categorized in the following manner for analysis:

Category 1: 4 satellites, prior to upload

Category 2: 4 satellites, after uploaded ephemeris collected by Z-Set

Category 3: 3 satellites, HDOP$\leq$3

Category 4: 3 satellites, HDOP$\geq$3

Only the second category, when there are 4 satellites in view and the ephemeris upload has been successfully performed (and collected by the Z-Set) will be reported on in detail. This data is the most meaningful since it is a sample of the NAVSTAR GPS operation which is truly representative of final implementation, that is, four satellites in use with current ephemeris and acceptable GDOP values. The other data is of interest for informational purposes but is of lesser value in terms of the assessment of NAVSTAR GPS for marine use. The other three categories will be described separately as nonoptimum conditions.

6.2 FOUR-SATELLITE DATA, AFTER UPLOADED EPHEMERIS COLLECTED

The data values recorded for the 20 days of collected data, as well as plots of the daily individual activity, are shown in Appendix C. A series of three graphs showing plots of all 4-satellite Category 2 data values over the 20 days appears in Figure 6.2 (A-B-C). A tabular summary of this data appears

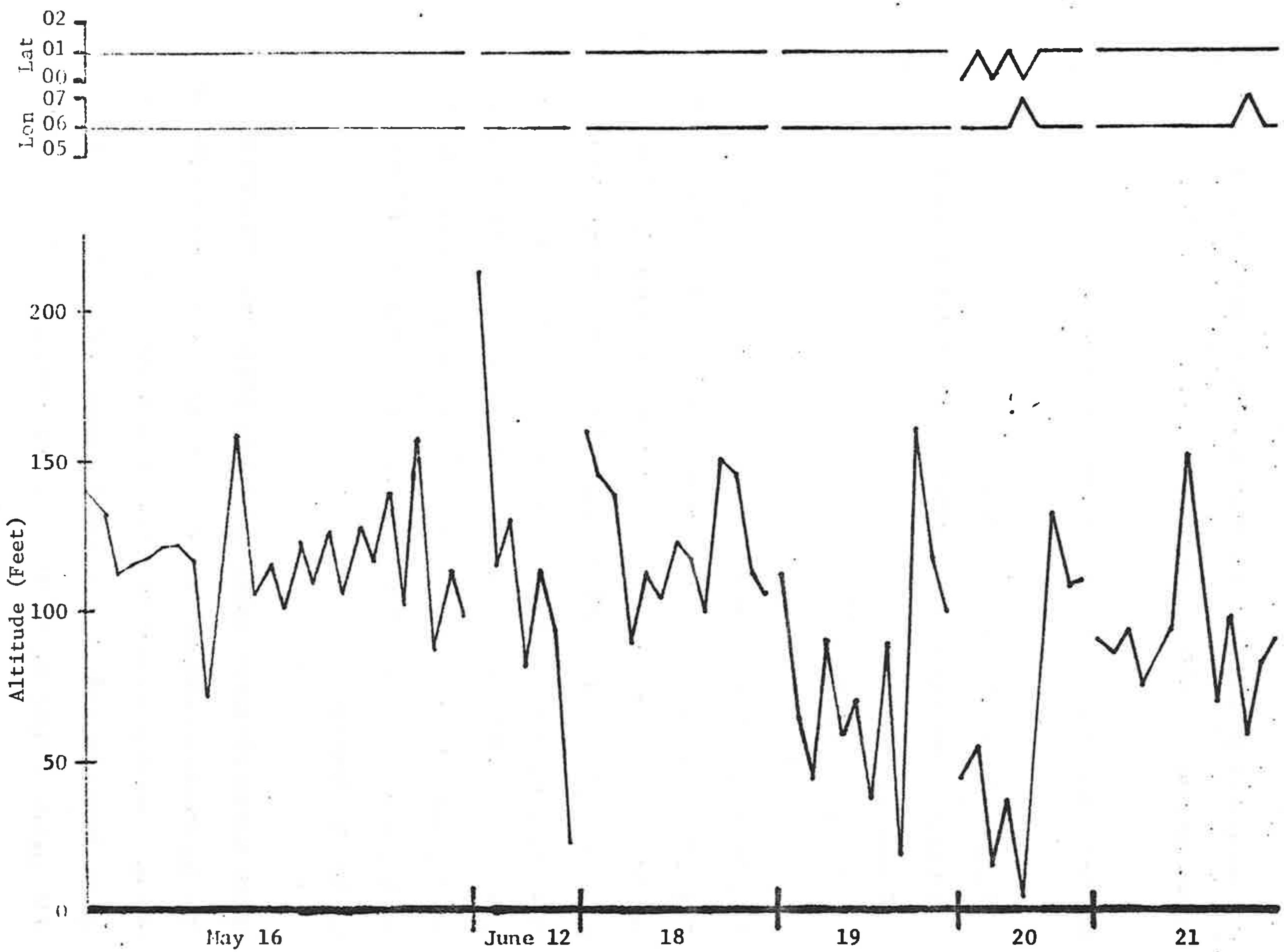


FIGURE 6.2A. FOUR SATELLITE DATA

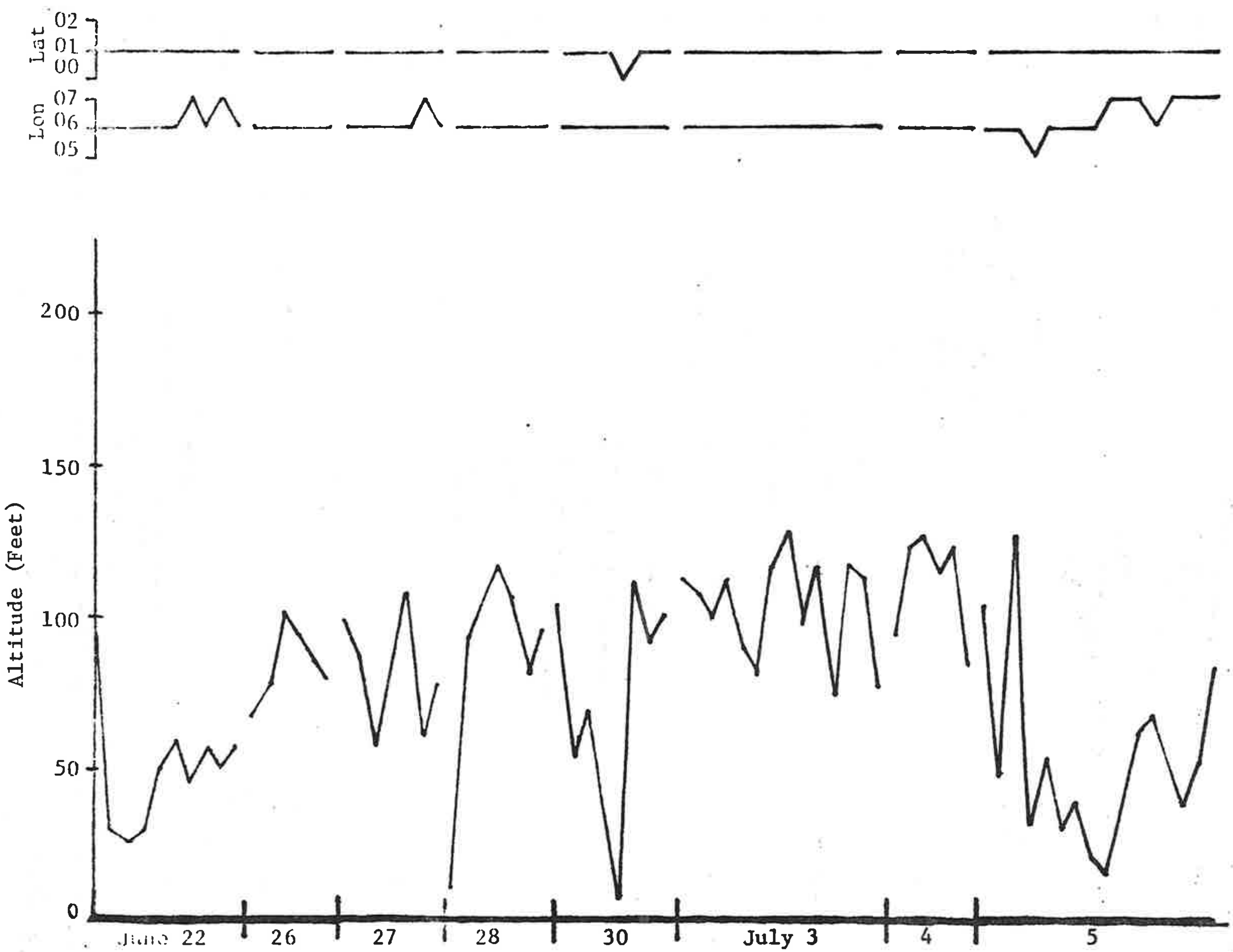


FIGURE 6.2B. FOUR SATELLITE DATA (Continued)

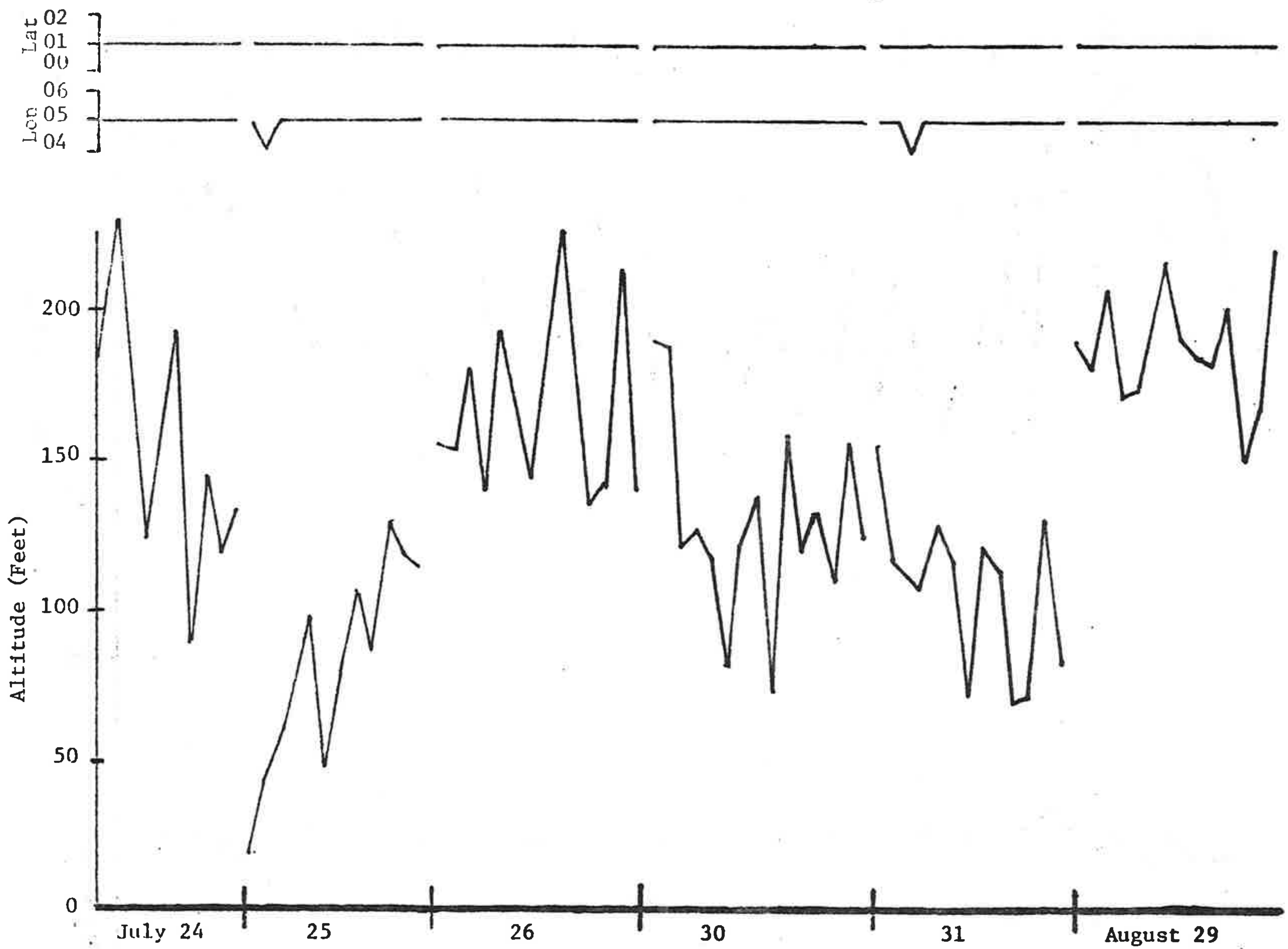


FIGURE 6.2C. FOUR SATELLITE DATA (Concluded)

in Figure 6.3. This summary shows the date, the number and duration of observations, and the daily means and standard deviations of the collected data.

Over the 20 days when valid data was collected, there are 233 data points which cover 16½ hours. In the latitude channel, 229 observations were made with a value of 33° 46' 01" and only 4 observations varied from this value by 1 arc second. In longitude, 220 observations were made with a value of 118° 12' 07". Note that on 12 days out of the 20, there were no latitude/longitude fluctuations at all, and on 5 or more days, only 1 change in latitude/longitude was observed. The mean altitude reading was 106.4 feet with a standard deviation (1σ) of 46.4 feet. A plot of the daily averages of altitude and 1σ standard deviation is shown in Figure 6.4. The reference latitude (Section 5.1) is 33° 46' 01.7". The Z-Set calculated its latitude to be 33° 46' 01" 98% of the time. This is an error of .7" which equates to 70 feet (since 1" of latitude is approximately 100 feet). The other 2% of the time (4 readings) the Z-Set latitude was calculated to be 33° 46' 00" which implies an error of 170 feet. The reference longitude (Section 5.1) is 118° 12' 06", 94% of the time. At this latitude, 1 arc second is equal to approximately 83 feet. Thus .1 arc second of longitude equates to approximately 8 feet. 1% of the time (3 readings) the Z-Set calculated value of longitude was 118° 12' 05" for an error of 75 feet, and 5% of the time (10 readings) 118° 12' 7" was the value generated, in error by 91.3 feet. From Figure 3.4a, the HDOP is seen to vary from 1.6 to 2.5. Thus, (Section 2.4.3.2.1), a rms 1σ positional error of 80 to 237 feet can be expected. All errors in the computation of latitude and longitude fall well within this range.

Date	Lat 00	Lat 01	Lat 02	Lon 05	Lon 06	Lon 07	Altitude Avge	Altitude 1-σ	n	Δ T Hr:mn
5/16	–	26	–	–	26	–	117.3	19.4	26	1:10
6/12	–	7	–	–	7	–	110.0	57.6	7	:30
6/18	–	13	–	–	13	–	122.5	22.7	13	:57
6/19	–	12	–	–	12	–	79.4	40.3	12	:55
6/20	3	6	–	–	8	1	62.4	45.2	9	:40
6/21	–	13	–	–	12	1	91.5	22.7	13	1:00
6/22	–	10	–	–	8	2	50.8	22.4	10	:45
6/26	–	6	–	–	6	–	83.3	12.8	6	:25
6/27	–	7	–	–	6	1	80.7	18.8	7	:30
6/28	–	7	–	–	7	–	86.7	35.2	7	:27
6/30	1	7	–	–	8	–	71.6	37.2	8	:28
7/3	–	14	–	–	14	–	102.7	17.5	14	1:05
7/4	–	6	–	–	6	–	111.2	18.5	6	:25
7/5	–	16	–	1	10	5	53.9	30.9	16	1:15
7/24	–	10	–	–	10	–	155.5	42.5	10	:45
7/25	–	12	–	1	11	–	81.4	34.5	12	:57
7/26	–	15	–	–	15	–	164.4	29.6	15	1:10
7/30	–	15	–	–	15	–	129.8	33.0	15	1:10
7/31	–	13	–	1	12	–	106.5	27.1	13	1:00
8/29	–	14	–	–	14	–	185.6	18.8	14	1:05
Summary	4	229	0	3	220	10	106.4	46.4	233	16:39

FIGURE 6.3. SUMMARY OF FOUR SATELLITE DATA, AFTER UPLOAD

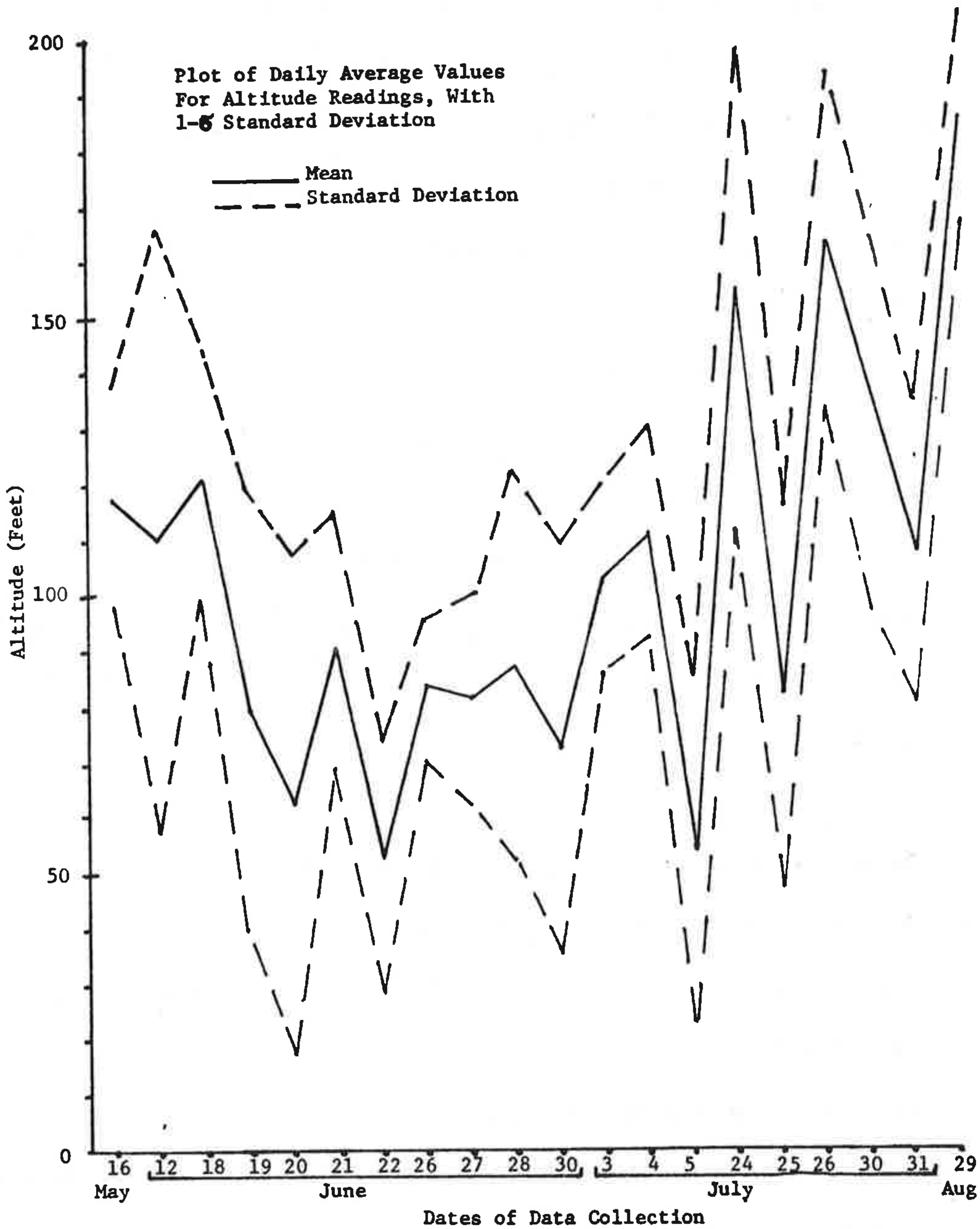


FIGURE 6.4. PLOT OF DAILY AVERAGE VALUES OF ALTITUDE

The reference altitude (Section 5.1) was 33.4 meters (111 feet). The mean altitude for all the measurements was 106.4 feet, 4.6 feet from the reference value with a standard deviation of 46.4 feet. Referring to Figure 6.2, it can be seen that the highest altitude recorded was 240 feet, yielding an error of 129 feet, and that the lowest reading was 6 feet, yielding an altitude error of 105 feet. With a VDOP of 2.5 to 4.0 (Figure 3.4a) a rms 1 σ error of 125 feet to 380 feet can be expected. The errors in altitude of the highest and lowest readings are still within the bounds of expected system performance as are, of course, all the more accurate values. The standard deviation of the errors is important because it establishes a quantization of the repeatability of the process. The average standard deviation is 29.3 feet, which means that on the average the altitude measurement is repeatable to 29.3 feet (1σ) on a daily basis.

In summary, the accuracy with which this Z-Set, operating in a static ($V_x = 0$, $V_y = 0$, $V_z = 0$) condition, located in Long Beach, California, from May to August 1979, on the top of the Coast Guard 11 Headquarters building, calculated its latitude, longitude and altitude, equalled or exceeded the accuracy with which this equipment is specified to operate. The latitude error was 70 feet 98% of the time. The longitude error was 8 feet 94% of the time. The mean altitude error (over 20 days) was 4.6 feet with a standard deviation of 46.4 feet, and the average standard deviation of the altitude errors over the whole test period was 29.4 feet.

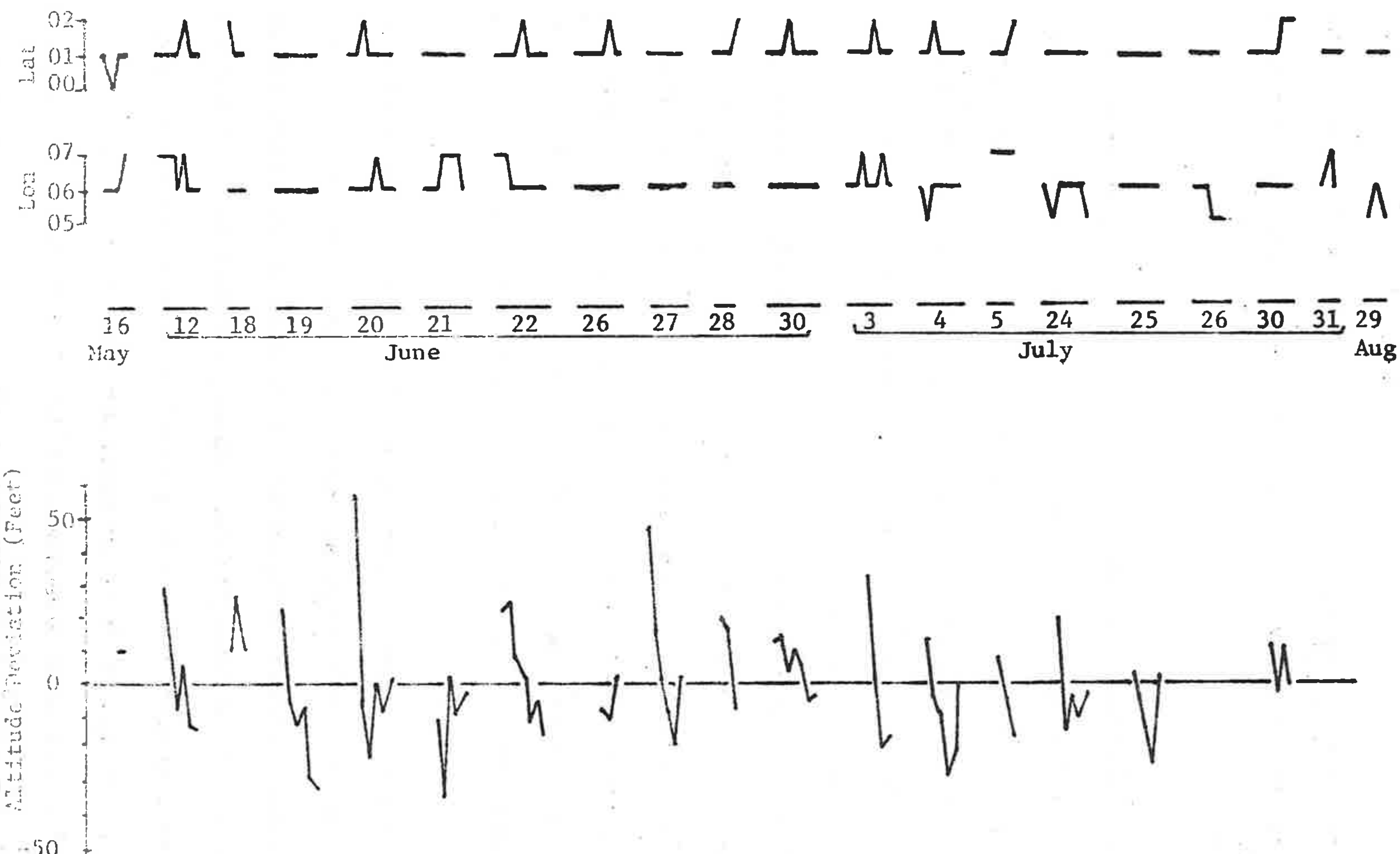
6.3 THREE-SATELLITE DATA, AFTER UPLOAD

As was explained in Section 6.1, after more than 105 minutes when four satellites are covisible, the fourth satellite sets over the horizon to create 3-

satellite coverage with acceptable HDOP (≤3) for another 30 minutes. The data for this period of coverage, during the same 20 days when 4-satellite data is available, is documented here.

It should be noted that the Kalman filter of the Z-Set processes the keyboard altitude input differently for a position determination based on only three satellite signals as opposed to the full complement of four. In the four satellite mode, 4 independent pseudo-range measurements are processed to yield the three components of position and velocity as well as time and time bias. If there are four satellites in use, the CDU entered altitude is processed only one, but if there are fewer than four in use, an "altitude hold" will be initiated in which the keyboard altitude entry is weighted as an independent measurement for each filter cycle. Hence the observed reading is a fairly stable quantity close to the input value. Notes in the data will reflect when keyboard entries of altitude have been made, in order to stabilize the vertical channel after the transition to 3 satellites.

The data observed appears in Appendix C. A plot of the Z-Set calculated values of latitude and longitude as well as the altitude deviations from the entered value are shown in Figure 6.5. A summary of the distribution of observed radings for 3-satellite data appears in Figure 6.6. Of the 118 latitude readings taken over the 20 days, 33^{o} 46' 01" occurred 105 times, i.e., 89% of the readings, 33^{o} 46' 00" occurred once, and 33^{o} 46' 02" occurred 12 times. Of the 118 longitude readings, 118^{o} 12' 06" was recorded 95 times (i.e. 81% of the time) 118^{o} 12' 05" occurred 7 times, and 118^{o} 12' 07" occurred 16



Deviations from keyboard entry of altitude, reset after 3-satellite transition, are shown, rather than observed values.

FIGURE 6.5. THREE SATELLITE DATA, AFTER UPLOAD

Date	Lat 00	Lat 01	Lat 02	Lon 05	Lon 06	Lon 07
5/16	1	3	–	–	3	1
6/12	–	6	1	–	3	4
6/18	–	2	1	–	3	–
6/19	–	7	–	–	7	–
6/20	–	6	1	–	6	1
6/21	–	7	–	–	6	1
6/22	–	7	1	–	6	2
6/26	–	6	1	–	7	–
6/27	–	6	–	–	6	–
6/28	–	3	1	–	4	–
6/30	–	7	1	–	8	–
7/3	–	6	1	–	5	2
7/4	–	6	1	1	6	–
7/5	–	3	1	–	–	4
7/24	–	7	–	2	5	–
7/25	–	7	–	–	7	–
7/26	–	5	–	2	3	–
7/30	–	5	2	–	7	–
7/31	–	3	–	–	2	1
8/29	–	3	–	2	1	–
Summary	1	105	12	7	95	16

Altitude: 81 points
Average deviation is -.31 feet
Standard Deviation (1σ) is 16.7 feet

FIGURE 6.6. DISTRIBUTION OF LAT/LON READINGS FOR THREE SATELLITE DATA, AFTER UPLOAD

times. There were 81 recorded altitude measurements. The mean deviation from the entered value for the test period was -.3 feet with a standard deviation (1σ) of 16.7 feet.

Comparison of latitude data with the reference data of Section 5.1 shows the most commonly occuring value of 33° 46' 01" was in error by 70 feet. The readings of 33° 46' 02" were in error by 30 feet and the one recorded reading of 33° 46' 00" was in error by 170 feet. As was true for the four satellite data all these values fall within the specified error range for this equipment.

Comparison of longitude data with the reference data of Section 5.1 shows that the most commonly occurring value of 118° 12' 06" was in error by 8 feet. The readings of 118° 12' 07" were in error by 91.3 feet and the 118° 12' 05" readings were in error by 74.4 feet.

Since, for a position determination using three satellites versus four, the keyboard entered value of altitude is used each filter cycle with the same variance, the spread of the Z-Set calculated values of altitude is less than that calculated using four satellites. For four satellites, the standard deviation of the mean altitude was 29.3 feet whereas for three satellites the standard deviation about the mean altitude was 16.7 feet, approximately half.

6.4 DATA ERROR TO UPLOAD

When four satellites were in view, SAMSO required at least 15 minutes to track each satellite and to process ranging data through a Kalman filter to produce ephemeris corrections. Thus, the early segment of each satellite coverage time period contains navigation data based upon ephemeris which is

24 hours old. Although this represents a degradation not planned for the operational system, it is of interest to note how accurate the current system is "at its worst." A compilation of the actual data appears in Appendix C. A summary of the latitude, longitude, and altitude readings appears in Figure 6.7.

The spread of longitude and latitude readings covers 5 arc seconds. The maximum latitude error is 270 feet 6% of the time; 170 feet 47% of the time; 130 feet 2% of the time; 70 feet 40% of the time; and 30 feet 5% of the time. The maximum longitude error is 174 feet, 4% of the time; 157 feet 19% of the time; 91.3 feet 6% of the time; 74.7 feet 40% of the time; and 8 feet 31% of the time. The mean altitude was 125 feet with a standard deviation of 155.7 feet.

6.5 DATA OVER THE ENTIRE COVERAGE PERIOD

To complete the profile of data over the entire coverage period each day, the 3-satellite data for the last segment of coverage, when HDOP values rise dramatically and then return, must be discussed. To do this within the proper context, the data from a 2½ hour period is presented in its entirety, as shown in Figure 6.8.

Note that prior to 0800, when there are 4 satellites in view, latitude and longitude are constant, and the altitude value is low. Once the fourth satellite disappears from view, the latitude and longitude start to fluctuate, and the altitude (once reset to "240") is fairly stable. During the period of very poor HDOP (as denoted by high values of EPE), all navigation data degrades, and then gradually returns to stable values.

Date	Lat 59	Lat 00	Lat 01	Lat 02	Lat 03	Lon 04	Lon 05	Lon 06	Lon 07	Lon 08
5/16	-	-	-	-	-	-	-	-	-	-
6/12	5	11	-	-	-	-	7	8	1	-
6/18	-	-	1	-	-	-	1	-	-	-
6/19	-	-	6	-	-	-	3	3	-	-
6/20	-	6	6	-	-	-	2	10	-	-
6/21	-	-	5	-	-	-	1	4	-	-
6/22	-	11	-	-	-	7	3	1	-	-
6/26	-	11	1	-	-	7	4	1	-	-
6/27	-	6	5	-	-	9	2	-	-	-
6/28	-	9	5	-	-	2	12	-	-	-
6/30	-	5	7	-	-	-	11	1	-	-
7/3	-	-	2	-	-	-	-	2	-	-
7/4	-	8	4	-	-	2	8	-	2	-
7/5	3	-	2	-	-	-	-	4	-	1
7/24	-	-	-	7	3	-	-	1	4	5
7/25	-	-	4	-	-	-	-	4	-	-
7/26	-	-	1	-	-	-	-	1	-	-
7/30	-	-	-	-	-	-	-	-	-	-
7/31	-	-	6	-	-	-	2	4	-	-
8/29	-	-	1	-	-	-	-	-	1	-
Summary	8	67	56	7	3	27	56	44	8	6

Altitude: 141 points
Average reading is 125. feet
Standard Deviation (1σ) is 155.7 feet

FIGURE 6.7. DISTRIBUTION OF LAT/LON READING FOR FOUR SATELLITE DATA, PRIOR TO UPLOAD

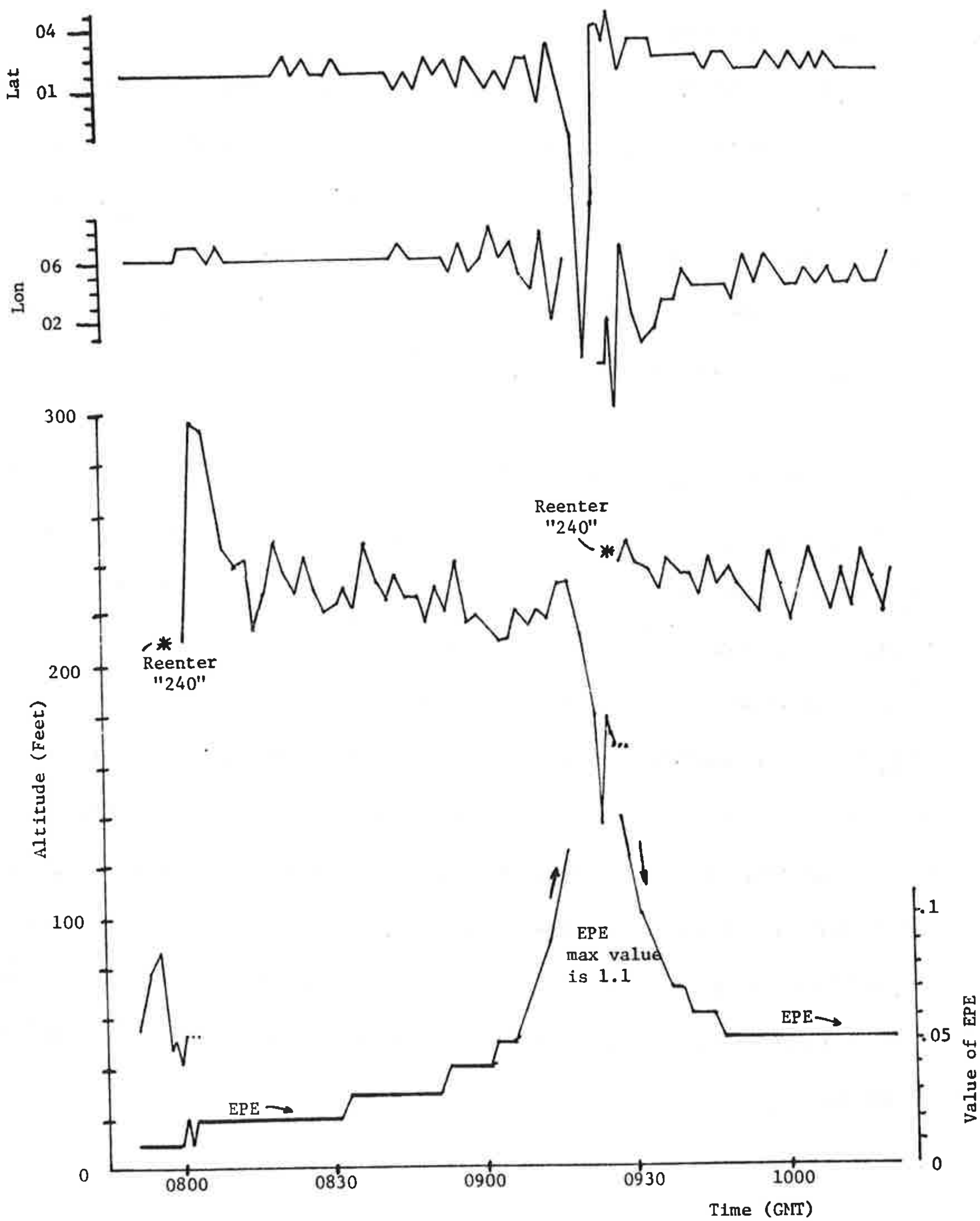
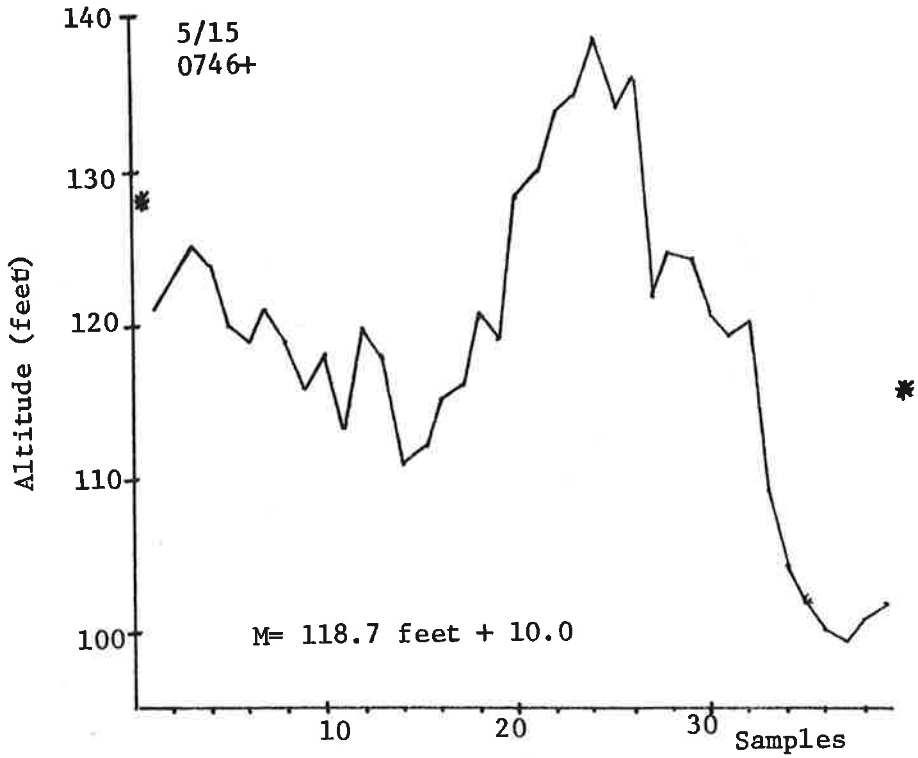


FIGURE 6.8. DATA FROM ONE ENTIRE COVERAGE PERIOD

6.6 CONSECUTIVELY SAMPLED DATA

In addition to the data collected simultaneously at discrete intervals (usually 5 minutes), there were brief periods when sequential data samples were collected over a small interval (30 to 60 seconds). Since the altitude channel showed fluctuations with every (1.2 second) filter cycle, whereas the latitude/longitude were unchanging over such time samples, the altitude readout was selected for observation.

Graphs of the sequentially sampled altitude data are shown in Figure 6.9 (A-E). On each graph is the date and time of sample, indications of altitude readout at regular sample intervals, the plot of sequential data, and the average data value, with 1 standard deviation. Nine separate intervals from 3 different days, are shown to enforce the feeling that the data shown is typical of the activity in the altitude channel throughout the entire period of testing. In the final graph (Figure 6.9 F), sequentially sampled values of speed are shown. Since the magnitude (speed) and direction (heading) of the velocity could not be sampled sequentially and simultaneously, they were observed separately. Shown are the values of speed over short sample periods; the heading values were uniformly distributed around the 360^{o} of the compass.



* indicates samples taken at regular intervals

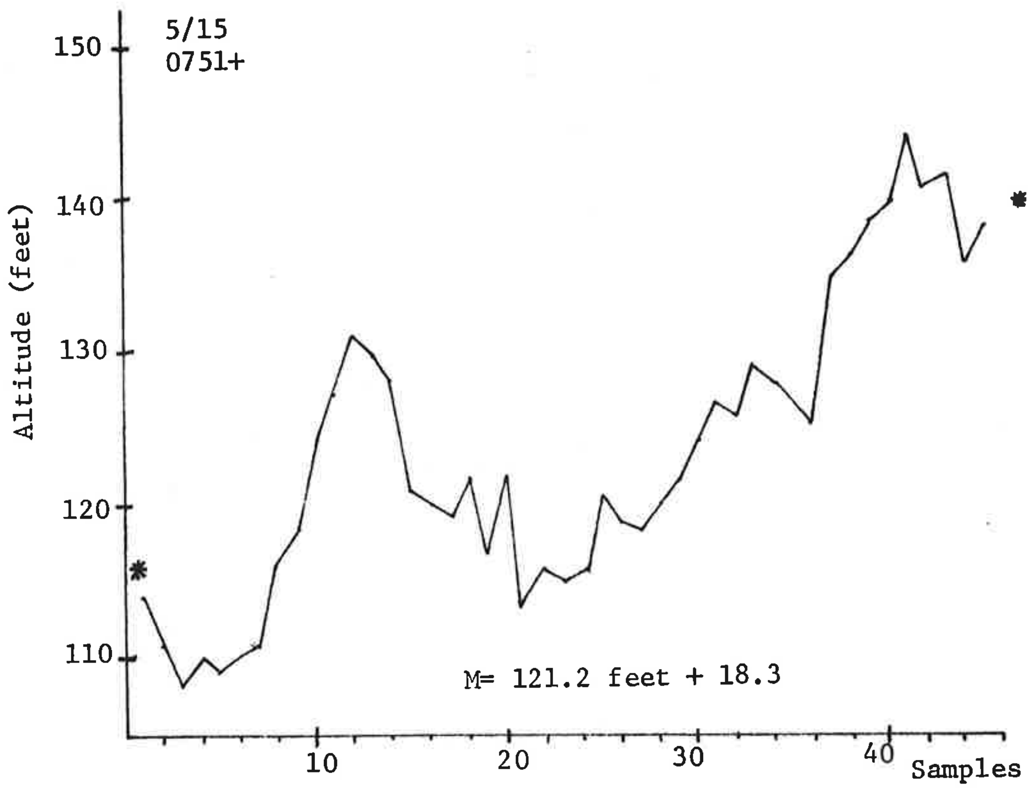
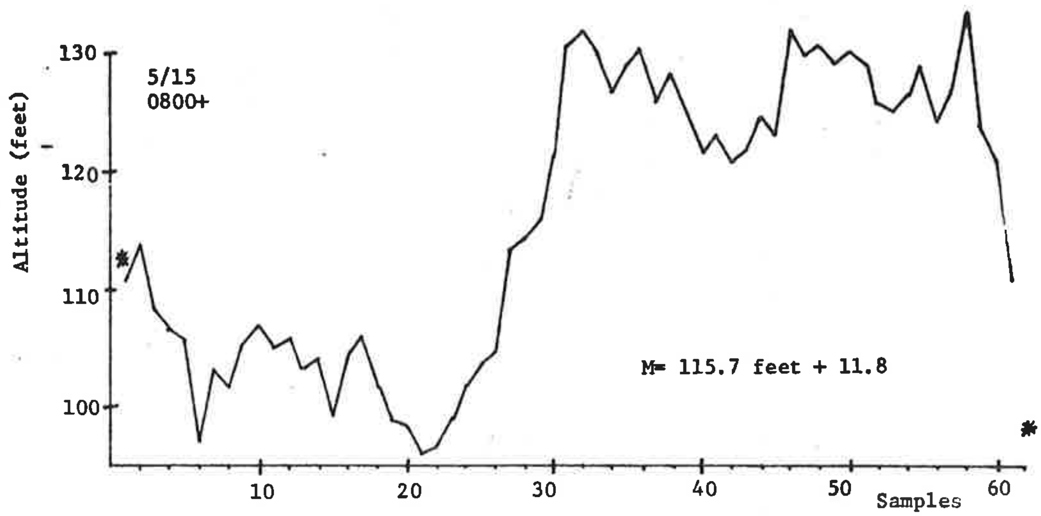


FIGURE 6.9A. CONSECUTIVE SAMPLES OF ALTITUDE DATA



* indicates samples taken at regular intervals

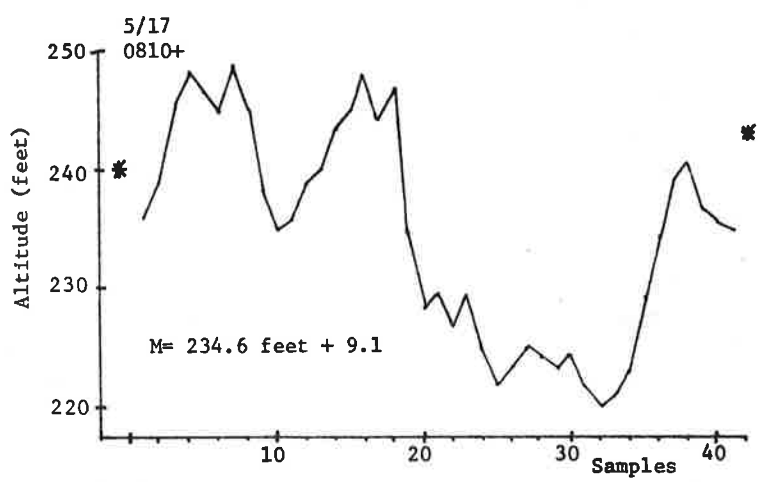
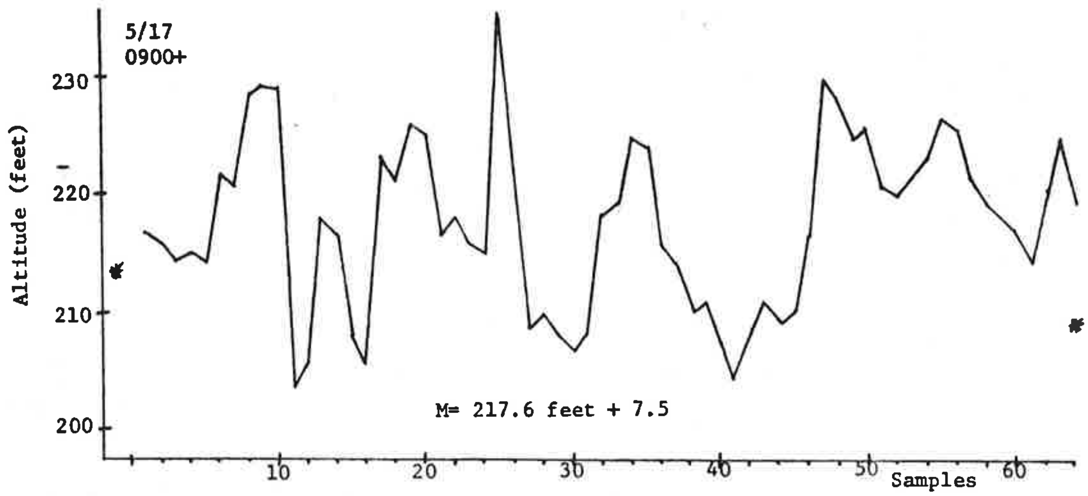


FIGURE 6.9B. CONSECUTIVE SAMPLES OF ALTITUDE DATA (Continued)



* indicates samples taken at regular intervals

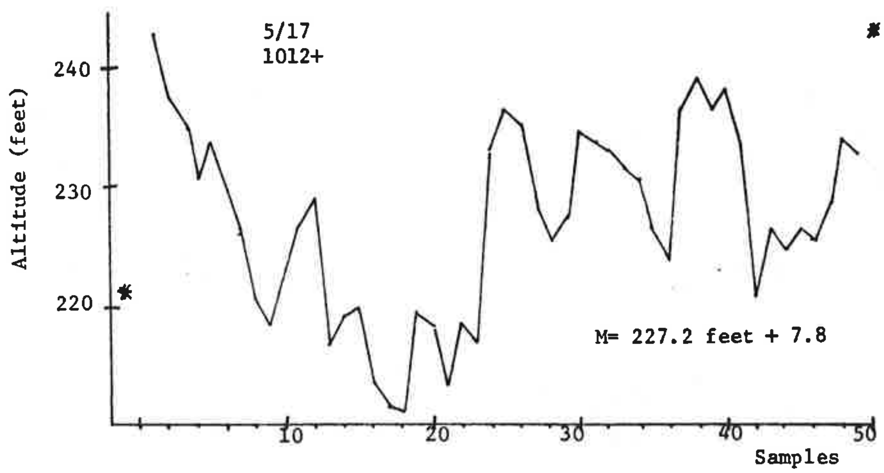
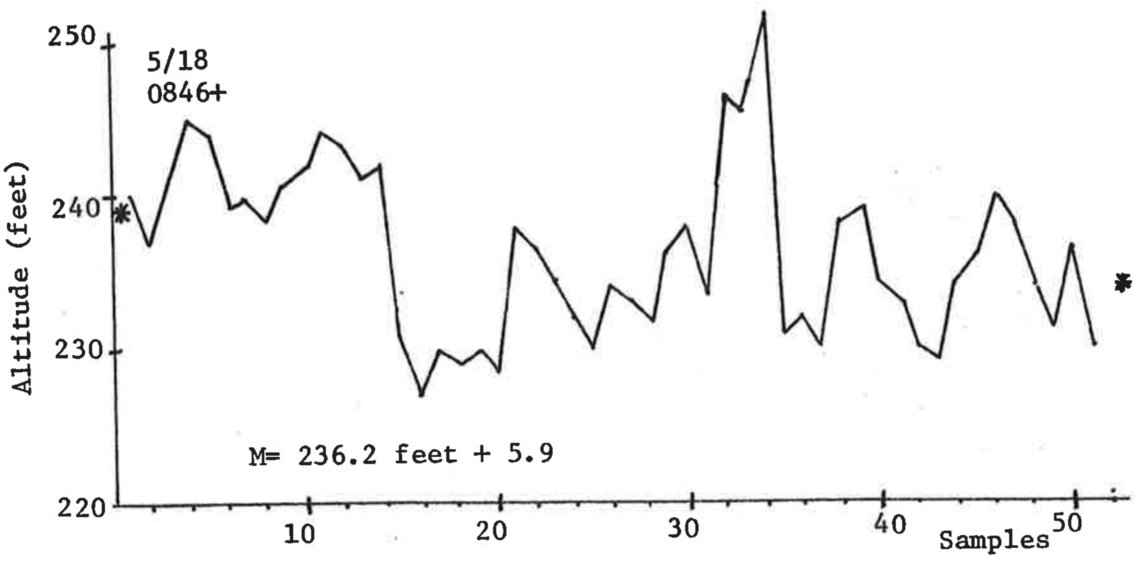


FIGURE 6.9C. CONSECUTIVE SAMPLES OF ALTITUDE DATA (Continued)



* indicates samples taken at regular intervals

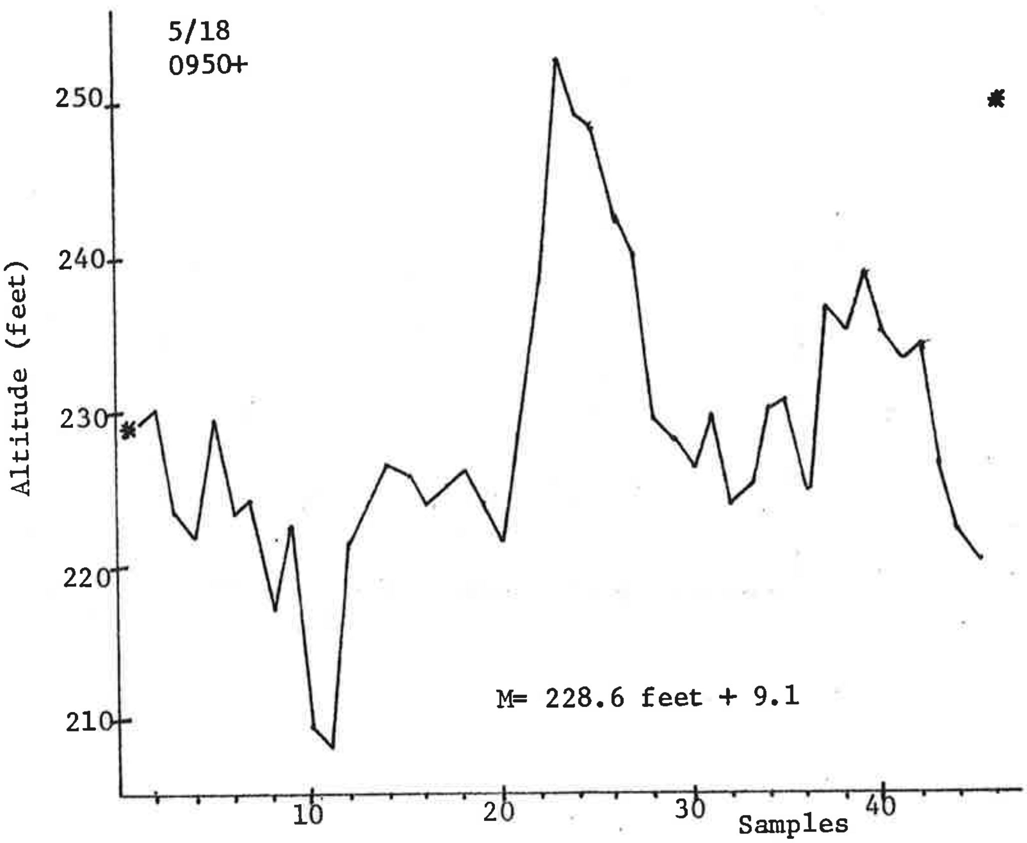
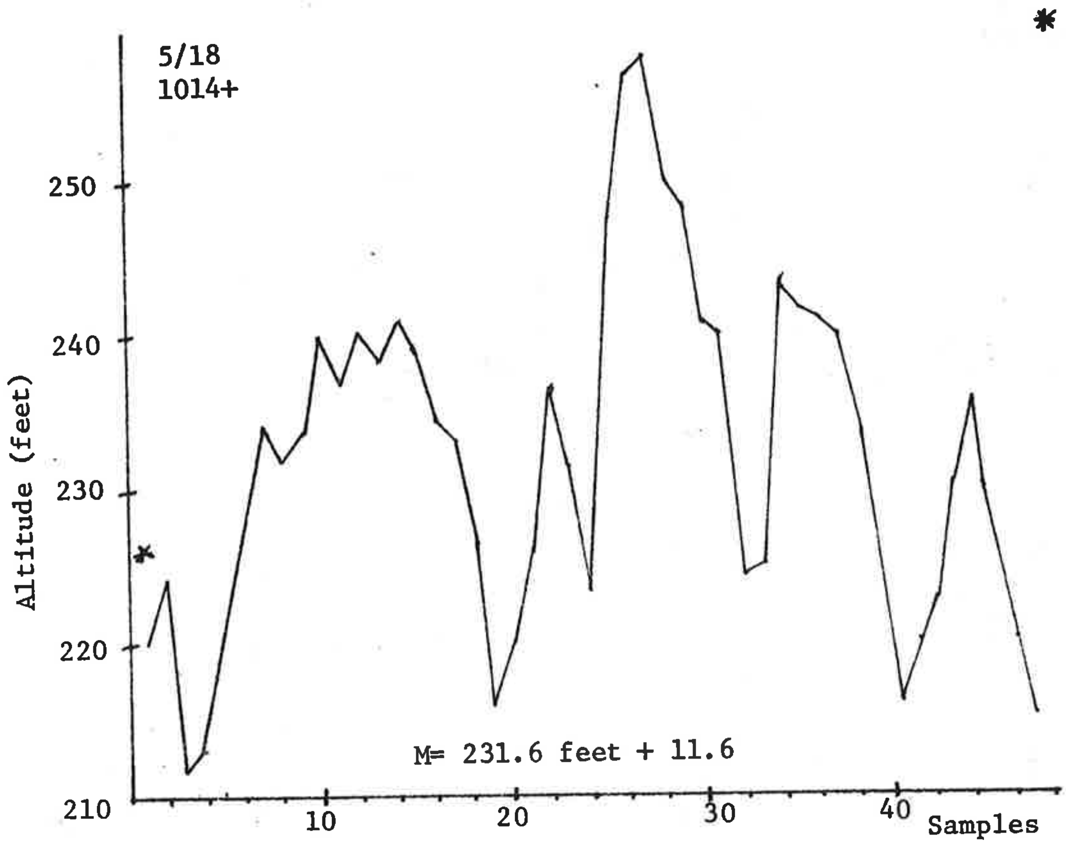
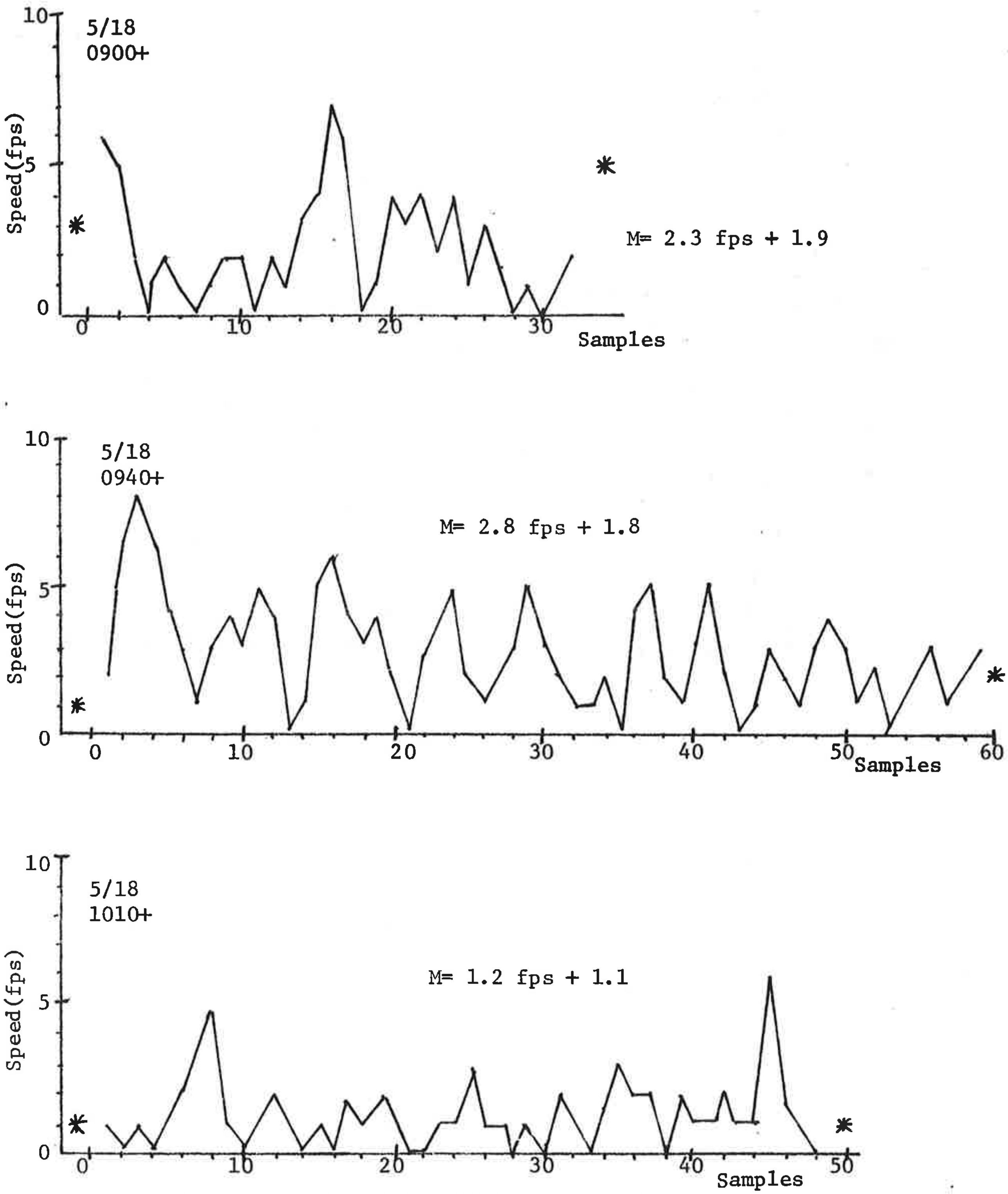


FIGURE 6.9D. CONSECUTIVE SAMPLES OF ALTITUDE DATA (Continued)



*Indicates samples taken at regular intervals.

FIGURE 6.9E. CONSECUTIVE SAMPLES OF ALTITUDE DATA (Concluded)



* indicates samples taken at regular intervals

FIGURE 6.9F. SPEED VS. CONSECUTIVE SAMPLES

7. CONCLUSIONS AND RECOMMENDATIONS

The following items were learned from these tests:

1) The Z-Set is a reliable instrument; it never failed to operate satisfactorily during the entire test period.

2) Because the GPS Program is in the developmental stage at present, there was only a limited period of 4-satellite coverage each day during which data could be collected. These test periods were adequate for this evaluation program. As more satellites are launched, coverage times will increase.

3) Failure of the frequency standard on board one (or more) satellites disrupted the continuity of the data collection.

4) The Z-Set worked extremely well as it was designed; however, limitations in the display resolution and in access to internal computations reduce its effectiveness as a research tool.

5) Manual recording of data puts severe constraints on the collection of sequential, simultaneous data.

6) In summary, the accuracy with which this Z-Set, operating in a static ($V_x = 0$, $V_y = 0$, $V_z = 0$) condition, located in Long Beach, California, from May to August 1979, on the top of the Coast Guard 11 Headquarters building, calculated its latitude, longitude, and altitude, equalled or exceeded the accuracy with which this equipment is specified to operate. The latitude error was 70 feet 98% of the time; the longitude error was 8 feet 94% of the time; the mean altitude error (over 20 days) was 4.6 feet with a standard deviation of 46.4 feet and the average standard deviation of the altitude errors over the whole test period was 29.4 feet.

The following are recommended:

1) Further static testing of the Z-Set, with access to internal computations and with greater precision of the output parameters, will yield more exact values of latitude/longitude error.

2) The man/machine interface in the maritime environment will require more evaluation than could be achieved during these tests, and must be explored further.

3) There are components of system error (e.g. ionospheric disturbance and receiver clock instability) which could not be determined during this first phase of test, but which must be considered in future phases of testing.

8. REFERENCES

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13. Burke, J.J., "Understanding Kalman Filtering and Its Application in Real Time Tracking Systems," MITRE Corporation, National Technical Information Service, U.S. Department of Commerce, AD-751485, July 1972.

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APPENDIX A

ALGORITHM TO COMPUTE SATELLITE "LOOK ANGLES"

Note: This algorithm, originally developed by the Aerospace Corporation, was obtained from SAMSO in January 1979 and adapted for use at TSC.

Inputs: Latitude & Longitude of observer on earth.
Time Controls

Output: Elevation and azimuth angle from observer to each of six satellites.
Latitude & Longitude of ground track traced by each satellite.

Only the first six satellites scheduled for launch are included in this report. The remaining 18 satellites may be added at a future date if orbit parameters are entered. There is a numbering convention which must be understood. Orbit slot numbers were preassigned prior to launch, and satellites were launched into desired slot positions to optimize geometry. Thus, NAVSTAR #1-2-3-4 are in slot #1-5-6-3, respectively. NAVSTAR #5-6 (yet to be launched) will be in slot #4-2, respectively. NAVSTAR # will be used throughout as a reference number.

System constants are:

$D2R = \pi/180. = .017453293$ (converts degrees to radians)

$RA = 14342.31/3444. = 4.164433798$ (orbit height - earth radius)

There are three parameters for each of the six satellites:

$AO = \frac{1}{4}(t_A) * D2R + {}_A * D2R$ where t_A = time (ascending node)

$AP = -\frac{1}{2}(t_A) * D2R$ $\quad$ ${}_A$ = longitude (ascending node)

$EN = i_0 * D2R$ $\quad$ i_0 = inclination angle

They are computed below:

NAV #	SLOT #	AO	AP	EN
1	1	2.061670179	-2.482730861	63.25
2	5	.009235701	-.995855783	63.18
3	6	-.003272492	-.237801111	63.
4	3	2.089959057	-.828885950	63.
5	4	-.007563093	-1.712749773	63.
6	2	2.089940949	-1.786780822	63.

The algorithm to compute satellite "look angles" is as follows:

(1) Input observer position in latitude (ϕ) and longitude (λ)

(2) Define an E matrix:

$$\hat{E} = \begin{bmatrix} -\sin\lambda & \cos\lambda & 0. \\ -\cos\lambda\ \sin\phi & -\sin\lambda\ \sin\phi & \cos\phi \\ \cos\lambda\ \cos\phi & \sin\lambda\ \cos\phi & \sin\phi \end{bmatrix}$$

(3) Input time (T) in minutes past midnight, on January 1, 1979.

Time of observation runs from 0 to 1440.

(4) For any given satellite (1-6), compute

AN = AO - T/(4 * DZR)

AT = AP + T/(2 * DZR)

(5) Compute:

CAN = cos(AN) SAN = sin(AN)

CAT = cos(AT) SAT = sin(AT)

CEN = cos(EN) SEN = sin(EN)

(6) Compute:

$$X_1 = CAN * CAT - SAN * CEN * SAT$$

$$X_2 = SAN * CAT + CAN * CEN * SAT$$

$$X_3 = SEN * SAT$$

(7) Compute (optionally):

$$SX = \sqrt{X_1^2 + X_2^2}$$

$$AT = \text{Arctan}(X_3/SX)$$

$$AN = \text{Arctan}(X_2/X_1)$$

AT, AN are latitude, longitude of satellite ground track.

(8) Given $\overline{X} = (X_1,X_2,X_3)$ from step 6,

Compute $\overline{Y} = (Y_1,Y_2,Y_3)$ from

$$\overline{Y} = RA * \hat{E} * \overline{X} - (0,0,1)$$

(9) Compute: $$SY = \sqrt{Y_1^2 + Y_2^2}$$

(10) Compute: $$EL = \text{Arctan}(Y_3/SY) \quad (-\pi/2 \text{ to } \pi/2)$$

$$AZ = \text{Arctan}(Y_1/Y_2) \quad (-\pi \text{ to } \pi)$$

EL and AZ are the elevation and azimuth angle from an observer to the satellite.

For a new observer position, return to step 1.

For a new time input, go to step 3.

Shown on the next page is a sample output.

TIME GAUSTAP #		1 N1 FL/AZ	2 NEA FL/AZ	3 FL/AZ	4 FL/AZ	5 N? FL/AZ	6 N? FL/AZ
	1515.	1.9/193.	40.4/169.	5?.?/ 61.	0.0/ 0.	5.6/300.	44.[illegible]
	1520.	4.0/193.	43.6/168.	49.5/ 57.	0.0/ 0.	7.0/302.	45.[illegible]
	1525.	[illegible]/193.	46.3/168.	48.[illegible]/ 54.	0.0/ 0.	8.4/304.	47.2/[illegible]
	1530.	8.[illegible]/194.	49.0/168.	46.9/ 51.	0.0/ 0.	9.8/305.	49.[illegible]
	1535.	10.6/194.	51.7/167.	45.[illegible]/ 48.	0.0/ 0.	11.2/307.	50.1/[illegible]
	1540.	12.9/194.	54.4/166.	43.5/ 4[illegible].	0.0/ 0.	12.7/309.	51.6/[illegible]
	1545.	15.1/195.	57.2/165.	41.9/ 44.	0.0/ 0.	14.2/310.	53.1/[illegible]
8	1550.	17.4/195.	59.9/164.	40.0/ 42.	0.0/ 0.	15.7/312.	54.[illegible]
9	1555.	19.7/196.	62.7/163.	38.0/ 40.	0.0/ 0.	17.3/314.	5[illegible]
10	1600.	22.0/196.	65.4/162.	36.1/ 38.	0.0/ 0.	18.9/315.	57.[illegible]
11	1605.	24.4/197.	68.1/160.	34.2/ 37.	0.0/ 0.	20.5/317.	59.0/ [illegible]
12	1610.	26.7/198.	70.8/157.	32.0/ 36.	0.0/ 0.	22.2/318.	60.4/ [illegible]
13	1615.	29.1/199.	73.4/153.	29.9/ 35.	0.0/ 0.	23.9/320.	61.8/ 1[illegible].
14	1620.	31.6/199.	75.9/149.	27.8/ 34.	0.0/ 0.	25.7/321.	63.1/ 1[illegible].
15	1625.	34.0/200.	78.1/141.	25.7/ 34.	0.0/ 0.	27.5/323.	64.[illegible]
16	1630.	36.4/202.	80.1/130.	23.6/ 33.	0.0/ 0.	29.3/324.	65.4/ 25.
17	1635.	38.9/203.	81.5/114.	21.5/ 33.	0.0/ 0.	31.2/326.	66.4/ [illegible]
18	1640.	41.3/204.	82.1/ 95.	19.4/ 32.	0.0/ 0.	33.1/327.	67.3/ [illegible]
19	1645.	43.8/206.	81.5/ 76.	17.3/ 32.	0.0/ 0.	35.1/328.	67.9/ [illegible]
20	1650.	46.2/207.	80.3/ 60.	15.2/ 32.	0.0/ 0.	37.1/330.	68.4/ [illegible]
21	1655.	48.7/209.	78.4/ 49.	13.2/ 32.	0.0/ 0.	39.2/331.	68.6/ [illegible]
22	1700.	51.1/211.	76.2/ 42.	11.1/ 32.	0.0/ 0.	41.3/332.	68.5/ [illegible]
23	1705.	53.5/213.	73.8/ 37.	9.1/ 33.	0.1/317.	43.4/333.	68.2/ [illegible]
24	1710.	55.9/216.	71.4/ 34.	7.1/ 33.	1.9/319.	45.6/335.	67.7/ [illegible]
25	1715.	58.2/219.	68.9/ 31.	5.1/ 33.	3.6/319.	47.8/336.	66.9/ 91.
26	1720.	60.5/222.	66.3/ 30.	3.1/ 34.	5.4/320.	50.1/337.	65.9/ 97.
27	1725.	62.7/225.	63.8/ 29.	1.2/ 34.	7.3/321.	52.4/338.	64.7/103.
28	1730.	64.9/229.	61.3/ 28.	0.0/ 0.	9.1/322.	54.8/339.	63.2/109.
29	1735.	66.9/234.	58.8/ 27.	0.0/ 0.	11.0/323.	57.2/340.	61.7/113.
30	1740.	68.8/240.	56.3/ 27.	0.0/ 0.	13.0/324.	59.6/341.	60.0/119.
31	1745.	70.6/246.	53.9/ 27.	0.0/ 0.	15.0/324.	62.1/342.	58.2/122.
32	1750.	72.1/253.	51.4/ 27.	0.0/ 0.	17.0/325.	64.6/343.	56.3/126.
33	1755.	73.3/262.	49.0/ 28.	0.0/ 0.	19.0/325.	67.2/344.	54.3/129.
34	1800.	74.2/271.	46.6/ 28.	0.0/ 0.	21.1/326.	69.7/345.	52.2/132.
35	1805.	74.7/282.	44.3/ 28.	0.0/ 0.	23.2/326.	72.4/345.	50.1/135.
36	1810.	74.8/292.	42.0/ 29.	0.0/ 0.	25.3/327.	75.0/346.	48.0/138.
37	1815.	74.4/302.	39.7/ 30.	0.0/ 0.	27.5/327.	77.7/347.	45.8/140.
38	1820.	73.7/312.	37.5/ 31.	0.0/ 0.	29.7/327.	80.4/347.	43.6/142.
39	1825.	72.7/320.	35.4/ 31.	0.0/ 0.	31.9/327.	83.2/347.	41.3/144.
40	1830.	71.5/328.	33.2/ 32.	0.0/ 0.	34.1/327.	85.9/346.	39.1/146.
41	1835.	70.0/335.	31.2/ 33.	0.0/ 0.	36.3/327.	88.7/338.	36.8/148.
42	1840.	68.4/341.	29.1/ 34.	0.0/ 0.	38.6/326.	88.5/184.	34.5/149.
43	1845.	66.7/346.	27.1/ 35.	0.0/ 0.	40.9/326.	85.7/177.	32.2/151.
44	1850.	65.0/351.	25.2/ 36.	0.0/ 0.	43.2/325.	82.8/176.	29.9/152.
45	1855.	63.2/355.	23.3/ 37.	0.0/ 0.	45.4/324.	80.0/176.	27.7/153.
46	1900.	61.3/359.	21.4/ 39.	0.0/ 0.	47.7/323.	77.2/176.	25.5/154.
	1905.	59.5/ 2.	19.5/ 40.	0.0/ 0.	49.9/321.	74.3/176.	23.1/155.
	1910.	57.6/ 5.	17.7/ 41.	0.0/ 0.	52.1/320.	71.5/177.	20.8/156.
	1915.	55.8/ 8.	16.0/ 42.	0.0/ 0.	54.2/318.	68.6/177.	18.6/157.
	1920.	54.0/ 11.	14.3/ 44.	0.0/ 0.	56.3/315.	65.8/177.	16.4/158.
	1925.	52.1/ 14.	12.6/ 45.	0.0/ 0.	58.3/312.	63.0/178.	14.1/159.
	1930.	50.3/ 16.	10.9/ 47.	0.0/ 0.	60.1/308.	60.2/178.	11.9/159.
	1935.	48.6/ 19.	9.3/ 48.	0.0/ 0.	61.8/304.	57.4/179.	9.7/16[illegible]
	1940.	46.8/ 21.	7.8/ 50.	0.0/ 0.	63.2/300.	54.6/179.	7.6/16[illegible]
55	1945.	45.1/ 23.	6.2/ 51.	0.0/ 0.	64.5/294.	51.8/179.	5.4/16[illegible]
56	1950.	43.4/ 26.	4.7/ 53.	0.0/ 0.	65.4/288.	49.1/179.	3.3/16[illegible]
57	1955.	41.7/ 28.	3.3/ 54.	0.0/ 0.	66.0/282.	46.4/180.	1.2/16[illegible]

APPENDIX B

ALGORITHM TO COMPUTE GDOP FROM MOMENT OF INERTIA

Reference is "Accuracy of Range-Range ... Systems", H.B. Lee, IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-11, No. 6, November 1975.

Given an observer on the earth and "look angles" EL and AZ (elevation and azimuth angles) to n satellites, the algorithm to compute GDOP is as follows:

1. Draw a sphere of unit radius centered at the observer.

2. Draw unit vectors from the origin of the unit sphere to each satellite, where each

$$\overline{i} = \left\{\cos(EL)\cos(AZ), \cos(EL)\sin(AZ), \sin(EL)\right\}$$

3. Locate the center of mass (assume unit mass at each satellite).

$$X_{cm} = \left(\sum_{n=1}^{4} i_{xn}\right)/4$$

$$Y_{cm} = \left(\sum_{n=1}^{4} i_{yn}\right)/4$$

$$Z_{cm} = \left(\sum_{n=1}^{4} i_{zn}\right)/4$$

4. Calculate the location of the unit masses (n = 1,2,3,4) with respect to the center mass.

$\bar{X}n = \bar{i}_n - \bar{X}cm$

5. Compute $\hat{L}$ matrix =

$$\begin{bmatrix} \sum_1^4 X_j^2 & \sum_1^4 Y_j X_j & \sum_1^4 Z_j X_j \\ \sum_1^4 X_j Y_j & \sum_1^4 Y_j^2 & \sum_1^4 Z_j Y_j \\ \sum_1^4 X_j Z_j & \sum_1^4 Y_j Z_y & \sum_1^4 Z_j^2 \end{bmatrix}$$

6. Compute $\hat{L}^{-1}$ = $\begin{bmatrix} Gxx & Gyx & Gzx \\ Gxy & Gyy & Gzy \\ Gxz & Gyz & Gzz \end{bmatrix}$

7. Then GDOP = $\sqrt{Gxx + Gyy + Gzz}$

HDOP = $\sqrt{Gxx + Gyy}$

VDOP = $\sqrt{Gzz}$

APPENDIX C

DATA

Data in this section is extracted from data sheets.

Each day of data is presented as:

NUMBER	DATE	REFERENCE ALTITUDE	
Time	Lat	Lon	altitude
(GMT)	(sec)	(sec)	(feet)

SUMMARY: FOUR SATELLITE DATA, AFTER UPLOAD

(#1) 5/16z

06:53	01	06	140
54	"	"	132
57	"	"	111
59	"	"	116
07:00	"	"	118
03	"	"	122
21	"	"	122
23	"	"	117
25	"	"	71
27	"	"	121
29	"	"	158
32	"	"	105
34	"	"	115
36	"	"	101
38	"	"	123
40	"	"	109
42	"	"	127
44	"	"	105
46	"	"	128
50	"	"	116
52	"	"	140
54	"	"	99
56	"	"	158
58	"	"	86
08:00	"	"	112
03	"	"	98

26 POINTS OVER 1:10

(#2) 6/12

05:50	01	06	213
55	"	"	115
06:00	"	"	131
05	"	"	81
10	"	"	114
15	"	"	94
20	"	"	22

7 POINTS OVER :30

(#3) 6/18

04:58	01	06	160
05:00	"	"	144
05	"	"	137
10	"	"	88
15	"	"	112
05:20	01	06	104
25	"	"	122
30	"	"	117
35	"	"	97
40	"	"	151
45	"	"	145
50	"	"	111
55	"	"	105

13 POINTS OVER :57

(#4) 6/19

04:50	01	06	112
55	"	"	65
05:00	"	"	43
05	"	"	93
10	"	"	58
15	"	"	71
20	"	"	37
25	"	"	89
30	"	"	18
35	"	"	160
40	"	"	118
45	"	"	99

12 POINTS OVER :55

(#5) 6/20 REDUCED CABLE

05:05	00	06	45
10	01	"	55
15	00	"	14
20	01	"	37
25	00	07	4
30	01	06	55
35	"	"	135
40	"	"	107
45	"	"	110

9 POINTS OVER :40

(#6) 6/21 REDUCED CABLE

04:30	01	06	90
35	"	"	85
40	"	"	94
45	"	"	74
50	"	"	85
04:55	01	06	96
05:00	"	"	151
05	"	"	114
10	"	"	69
16	"	"	98
20	"	"	59
25	"	"	82
30	"	"	92

13 POINTS OVER 1:00

(#7) 6/22

04:50	01	06	103
55	"	"	29
05:00	"	"	26
05	"	"	29
10	"	"	49
15	"	"	61
20	"	07	45
25	"	06	57
30	"	07	51
35	"	06	58

10 POINTS OVER :45

(#8) 6/26

04:50	01	06	66
55	"	"	76
05:00	"	"	102
05	"	"	93
10	"	"	84
15	"	"	79

6 POINTS OVER :25

(#9)	6/27		
04:50	01	06	98
55	"	"	85
05:00	"	"	57
05	"	"	81
10	"	"	108
15	"	07	59
20	"	06	77

7 POINTS OVER :30

(#10)	6/28		
04:48	01	06	11
50	"	"	93
55	"	"	103
05:00	"	"	117
05	"	"	106
10	"	"	81
15	"	"	96

7 POINTS OVER :27

(#11)	6/30		
04:32	01	06	104
34	"	"	52
36	"	"	70
40	"	"	38
45	"	"	6
50	"	"	111
"	"	"	91
05:00	"	"	101

8 POINTS OVER :28

(#12)	7/3		
03:45	01	06	112
50	"	"	108
55	"	"	97
04:00	"	"	112
05	"	"	89
10	"	"	80
15	"	"	115
20	"	"	129
25	"	"	98
30	"	"	117
35	"	"	73
40	"	"	117
45	"	"	115
50	"	"	76

14 POINTS OVER 1:05

(#13)	7/4		
04:30	01	06	94
35	"	"	123
40	"	"	127
45	"	"	114
50	"	"	126
55	"	"	83

6 POINTS OVER :25

(#14)	7/5		
03:30	01	06	105
35	"	"	48
40	"	"	131
45	"	05	31
50	"	06	53
55	"	"	29
04:00	"	"	39
05	"	"	20
10	"	"	15
15	"	"	37
20	"	07	61
25	"	"	69
30	"	06	53
35	"	07	38
40	"	"	50
45	"	"	83

16 POINTS OVER 1:15

(#15)	7/24		
02:50	01	06	186
55	"	"	230
03:00	"	"	182
05	"	"	123
10	"	"	154
15	"	"	194
20	"	"	88
25	"	"	146
30	"	"	118
35	"	"	134

10 POINTS OVER :45

(#16)	7/25		
02:23	01	06	19
26	"	05	45
36	"	06	59
41	"	"	80
45	"	"	97
50	"	"	45
55	"	"	80
03:00	"	"	119
05	"	"	86
10	"	"	129
15	"	"	119
20	"	"	114

12 POINTS OVER :57

(#17)	7/26		
02:10	01	06	129
15	"	"	154
20	"	"	153
25	"	"	181
30	"	"	138
35	"	"	191
40	"	"	174
45	"	"	143
50	"	"	172
55	"	"	224
03:00	"	"	179
05	"	"	134
10	"	"	141
15	"	"	215
20	"	"	138

15 POINTS OVER 1:10

(#18)	7/30		
01:55	01	06	188
02:00	"	"	187
05	"	"	120
10	"	"	128
15	"	"	118
20	"	"	79
25	"	"	123
32	"	"	140
35	"	"	71
40	"	"	157
45	"	"	117
50	"	"	132
55	"	"	108
03:00	"	"	156
05	"	"	123

15 POINTS OVER 1:10

(#19)	7/31		
02:00	01	06	154
05	"	"	116
10	"	05	110
15	"	06	105
20	"	"	129
25	"	"	118
30	"	"	70
35	"	"	121
40	"	"	113
45	"	"	68
50	"	"	68
55	"	"	131
03:00	"	"	81

13 POINTS OVER 1:00

(#20)	8/29		
00:05	01	06	184
10	"	"	179
15	"	"	207
20	"	"	170
25	"	"	172
30	"	"	188
35	"	"	216
40	"	"	187
45	"	"	182
50	"	"	181
55	"	"	201
01:00	"	"	149
05	"	"	168
10	"	"	214

14 POINTS OVER 1:05

SUMMARY: THREE SATELLITE DATA, AFTER UPLOAD

(#1)	5/16	(100')	
08:06	01	06	*
08	00	"	*
12	01	"	9
14	"	07	9

(#2)	6/12	(240')	
06:21	01	07	*
25	"	"	29
30	"	"	20
35	"	06	-8
40	02	07	6
45	01	06	-13
50	"	"	-14

(#3)	6/18	(240')	
06:00	02	06	9
05	01	"	28
10	"	"	10

(#4)	6/19	(240')	
05:47	01	06	*
50	"	"	22
55	"	"	-6
06:00	"	"	-12
05	"	"	-8
10	"	"	-29
15	"	"	-32

(#5)	6/20	(240')	
05:50	01	06	*
55	"	"	57
06:00	02	"	-8
05	01	"	-24
10	"	07	0
15	"	06	-9
20	"	"	0

(#6)	6/21	(240')	
05:50	01	06	*
55	"	"	*
06:00	"	"	-12
05	"	07	-35
10	"	"	1
15	"	"	-10
20	"	06	-5

(#7)	6/22	(240')	
05:38	01	07	*
40	"	"	22
45	"	06	24
50	"	"	7
55	02	"	3
06:00	01	"	-12
05	"	"	-7
10	"	"	-16

(#8)	6/26	(220')	
05:20	01	06	*
25	"	"	*
30	"	"	*
35	"	"	*
40	"	"	-8
45	02	06	-10
50	01	"	2

(#9)	6/27	(220')	
05:25	01	06	48
30	"	"	15
35	"	"	1
40	"	"	-9
45	"	"	-19
50	"	"	2

(#10)	6/28	(220')	
05:18	01	06	*
20	"	"	19
25	"	"	17
30	02	"	-8

(#11)	6/30	(220')	
05:03	01	06	*
05	"	"	12
10	"	"	13
15	02	"	3
20	01	"	9
25	"	"	5
30	"	"	-6
35	"	"	-5

(#12)	7/3	(220')	
04:52	01	06	*
55	"	"	*
05:00	"	07	*
05	"	06	32
10	02	"	0
15	01	07	-20
20	"	06	-17

(#13)	7/4	(220')	
05:00	01	06	*
05	"	05	13
10	02	06	-5
15	01	"	-9
20	"	"	-29
25	"	"	-22
30	"	"	0

NOTE: Deviation from keyboard altitude input, rather than altitude readings, are shown. Altitude input is shown in heading.

*Indicates readout prior to resetting of altitude channel after 3-satellite transition.

(#14)	7/5	(220')	
04:50	01	07	*
55	"	"	8
05:00	"	"	-5
05	02	"	-17

(#15)	7/24	(220')	
03:37	01	06	*
40	"	05	*
45	"	06	18
50	"	"	-14
55	"	"	-4
04:00	"	"	-11
05	"	05	-3

(#16)	7/25	(220')	
03:25	01	06	*
30	"	"	*
35	"	"	2
40	"	"	-4
45	"	"	-12
50	"	"	-25
55	"	"	2

(#17)	7/26	(220')	
03:23	01	06	*
25	"	"	*
30	"	"	*
35	"	05	*
40	"	"	*

(#18)	7/30	(220')	
03:10	01	06	*
15	"	"	*
20	"	"	*
25	"	"	12
30	"	"	-2
35	02	"	11
40	"	"	-1

(#19)	7/31	(220')	
03:02	01	06	*
05	"	07	*
10	"	06	*

(#20)	8/29	(220')	
01:14	01	05	*
15	"	06	*
20	"	05	*

*Indicates readout prior to resetting of altitude channel after 3-satellite transition.

FOUR SATELLITE DATA, PRIOR TO UPLOAD

(#1) 5/16

NO DATA PRIOR TO UPLOAD

(#2) 6/12

04:43	00	07	344
44	"	06	300
46	"	"	279
48	"	"	256
50	"	"	232
55	"	"	228
05:00	"	05	147
05	"	"	237
10	"	"	126
15	"	"	97
20	"	"	70
25	45/59	"	0
30	"	"	-20
35	"	06	-32
40	"	"	-25
45	"	"	-100

UPLOAD OCCURS

(50	01	06	213)

(#3) 6/18

04:56	01	05	99

(#4) 6/19

04:20	01	06	138
25	"	05	80
30	"	06	89
35	"	05	73
40	"	06	105
45	"	05	118

(#5) 6/20

04:08	01	06	208
10	00	"	342
15	"	"	283
20	"	"	296
25	01	"	242
30	"	"	199
35	00	"	312
40	01	"	213
45	"	"	161
50	"	"	152
55	00	05	98
05:00	"	"	200

(#6) 6/21

04:06	01	06	84
10	"	05	87
15	"	06	154
20	"	"	147
25	"	"	140

(#7) 6/22

03:55	00	06	469
04:00	"	05	317
05	"	"	336
10	00	04	270
15	"	05	293
20	"	04	195
25	"	"	209
30	"	"	136
35	"	"	107
40	"	"	85
45	"	"	43

(#8) 6/26

03:50	01	06	258
58	00	05	294
04:01	"	"	216
05	"	"	253
10	"	04	201
15	"	05	187
20	"	04	158
25	"	"	160
30	"	"	112
35	"	"	102
40	"	"	90
45	"	"	62

(#9) 6/27

03:58	00	04	20
04:00	01	"	-63
04	"	"	-65
10	"	"	-36
16	01	"	-93
20	"	"	-92
24	00	"	-91
30	"	"	-118
35	"	05	-107
40	"	"	-82
45	"	04	-114

(#10) 6/28

03:40	01	05	134
45	00	05	153
50	01	"	102
55	"	"	148
04:00	"	04	38
05	00	"	25
10	"	05	51
15	01	"	21
20	00	"	9
25	"	"	-3
30	"	"	-50
35	"	"	-53
40	"	"	-5
45	"	"	-57

(#11) 6/30

03:34	01	05	170
40	"	"	212
46	"	"	221
50	"	"	164
56	"	"	172
04:00	"	"	167
05	01	"	134
10	00	"	146
15	"	"	91
20	"	"	100
25	"	"	59
30	"	06	65

(#12) 7/3

03:37	01	06	39
40	"	"	149

(#13) 7/4

03:30	00	05	365
35	"	"	262
40	01	"	268
45	00	"	262
50	01	"	198
55	00	"	171
04:00	00	04	159
05	"	"	96
10	"	05	113
15	"	"	136
20	01	07	35
25	"	"	74

(#14)	7/5		
03:05	45/59	08	966
10	"	06	677
15	"	"	683
20	01	06	120
25	"	"	39

(#15)	7/24		
02:00	03	07	-66
05	"	06	-204
10	"	07	-79
15	02	"	-61
20	"	"	-21
25	"	08	68
30	"	"	36
35	"	"	150
40	"	"	137
45	"	"	241

(#16)	7/25		
01:50	01	06	-47
55	"	"	18
02:00	"	"	-3
10	"	"	24

(#17)	7/26		
02:07	01	06	206

(#18) 7/30

NO DATA PRIOR TO UPLOAD

(#19)	7/31		
01:30	01	05	-49
35	"	06	4
40	"	05	60
45	"	06	65
50	"	"	55
55	"	"	57

(#20)	8/29		
00:01	01	07	230

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