Report No. FAA-CT-81-160

EVALUATION OF THE NAVIGATION SATELLITE TIMING AND RANGING GLOBAL POSITIONING SYSTEM (NAVSTAR GPS) AS A ROTARY WING AIRCRAFT NAVIGATION AID USING THE MAGNAVOX "Z" SET

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PROJECT PLAN

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Prepared for

U. S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
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1. OBJECTIVES.

This project plan is designed as a series of task designated tests as scheduled in section 9 to be conducted with the primary objective to evaluate the suitability and accuracy of low-cost Navigation Satellite Timing and Ranging Global Positioning System (NAVSTAR GPS) receivers for helicopter area navigation operations. The results will be compared with total system requirements specified in Federal Aviation Administration (FAA) Advisory Circular (AC) 90-45A.

Data will be collected to substantiate the possible implementation of GPS as a future area navigation system for civil helicopter operations.

1.1 TASK I OBJECTIVES.

a. Develop recording and two-dimensional display interface hardware for Phase I GPS equipment.

b. Familiarization with GPS.

c. Develop generalized GPS test methodology.

d. Determine rotor modulation effects.

e. Initiate collection of operational performance data for helicopter area navigation using the following performance criteria:

1. Crosstrack error
2. Along track error
3. Airborne system error
4. Flight technical error

f. Postflight analysis of data collected will allow investigation of perturbational effects from the following anomalies:

1. Multipath
2. Satellite shielding
3. Ionospheric delay
4. Age of ephemeris data
5. Satellite configuration
6. User-satellite geometry
7. Position errors induced by vehicle dynamics
8. Receiver/processor software-hardware interaction
9. Radiofrequency (RF) interference

1.2 TASK II OBJECTIVES.

Expand the geographical coverage of GPS testing to expand the data base described in sections l.le and l.lf for en route area navigation for as yet unspecified routes in the following areas:

a. Northeast Corridor

b. New England

c. Appalachia

d. Gulf of Mexico

1.3 TASK III OBJECTIVES.

Expand the geographical coverage of GPS testing per Task II for nonprecision approach navigation tests.

1.4 TASK IV OBJECTIVES.

a. Develop hardware and software to generate three- and four-dimensional display navigation information.

b. Develop aided or quickened guidance information to compensate for low dynamic response of the GPS receiver/processor.

c. Collect data to determine system improvement per the performance criteria described in section l.le for the Task IV improved guidance information for en route, terminal, and nonprecision approach area navigation.

2. BACKGROUND.

There are over 6,000 helicopters in civil operation in the United States. Over half of these are in commercial operations, e.g., short haul transport of people and materials. The remainder are engaged in business/corporate activities and local, state, and Federal Government operations. The civil helicopter fleet is expected to double by mid-1980. The unique ability of helicopters to operate efficiently in applications at remote unprepared sites, either inland or offshore, and at low altitudes and steep glide slopes impacts on the availability of line-of-sight communications and navigation aides commonly used by fixed wing aircraft. The NAVSTAR GPS concept is designed to provide nonsaturable, passive, global, and three-dimensional navigation guidance independent of vehicle position with respect to the landing/takeoff site. This test plan is designed to evaluate low cost NAVSTAR GPS receiver/processors and the future potential of GPS as a rotary wing aircraft navigation aid.

2.1 NAVSTAR GPS.

NAVSTAR GPS is a joint service Department of Defense (DOD) navigation concept. Phase 1, the Concept Validation Program, verified the feasibility of determining precise user time and position from four ground aided satellites placed in 10,400 nautical mile radius, 12-hour circular orbits. Currently, and until 1984, six satellites will be positioned in two circular orbital planes at 55° inclination, with respect to the earth's equatorial plane, providing periodic 3- to 4-hour intervals of four-satellite coverage over selected geographical areas (reference figure 1). Eighteen to twenty-four satellites may be deployed by 1984 to provide full global coverage for three-dimensional navigation in the final program phase.

The NAVSTAR GPS is designed to provide high accuracy three-dimensional position data (±10 meters) for military missions and less accurate position data (±100 meters) for civil aviation use.

Four satellites are normally required for navigation. Ranges to the four satellites are determined by scaling the signal transit time with the speed of light. If the user clock is maintained precisely with GPS system time, only three satellites would be required for navigation. The fourth satellite is required to resolve the fixed bias ambiguity between the imprecise user's clock and the GPS system time. User position is determined by simultaneous solution of four equations involving four unknowns (three-dimensional position estimates and fixed user clock bias).

Several technical and nontechnical issues still remain to be resolved: the life and reliability of the satellites, the cost to implement a contingent of satellites for global coverage, hardware cost for individual receivers for civilian applications, and the level of precision ranging data accessible to civil aviation. A program plan to evaluate light weight, low cost GPS receivers suitable for civil aviation is outlined in this document. This FAA study will take place over the next decade, assuming resolution of all technical and nontechnical issues with resultant full deployment of GPS.

3. RELATED DOCUMENTATION/PROJECTS.

a. "Approval of Area Navigation Systems for Use in the U.S. National Airspace System," FAA Advisory Circular 90-45A.

b. "USCG/MARAD Static Tests of the GPS Navigation Set-Z (Low Cost)," U. S. Coast Guard, Report No. CG-D-18-90.

c. "NAVSTAR/GPS," FAA, Product Plan Project-100.

d. "Results of Joint Service Field Tests, Validation Phase 1 Concept Developmental Test and Evaluation," NAVSTAR GPS Joint Program Office documents.

e. Institute of Navigation, GPS Special Issue Summer 1978, Vol. 25, No. 2.

f. "Draft User's Manual (Computer Program) for User Equipment Set Z of the NAVSTAR Global Positioning System," Magnavox Government and Industrial Electronics Company.

g. "Computer Program Development Specification for the Z User Set of the NAVSTAR GPS User Equipment Segment Phase 1, Configuration Item 330C119," Magnavox Government and Industrial Electronics Company Specification No. CP-US-305.

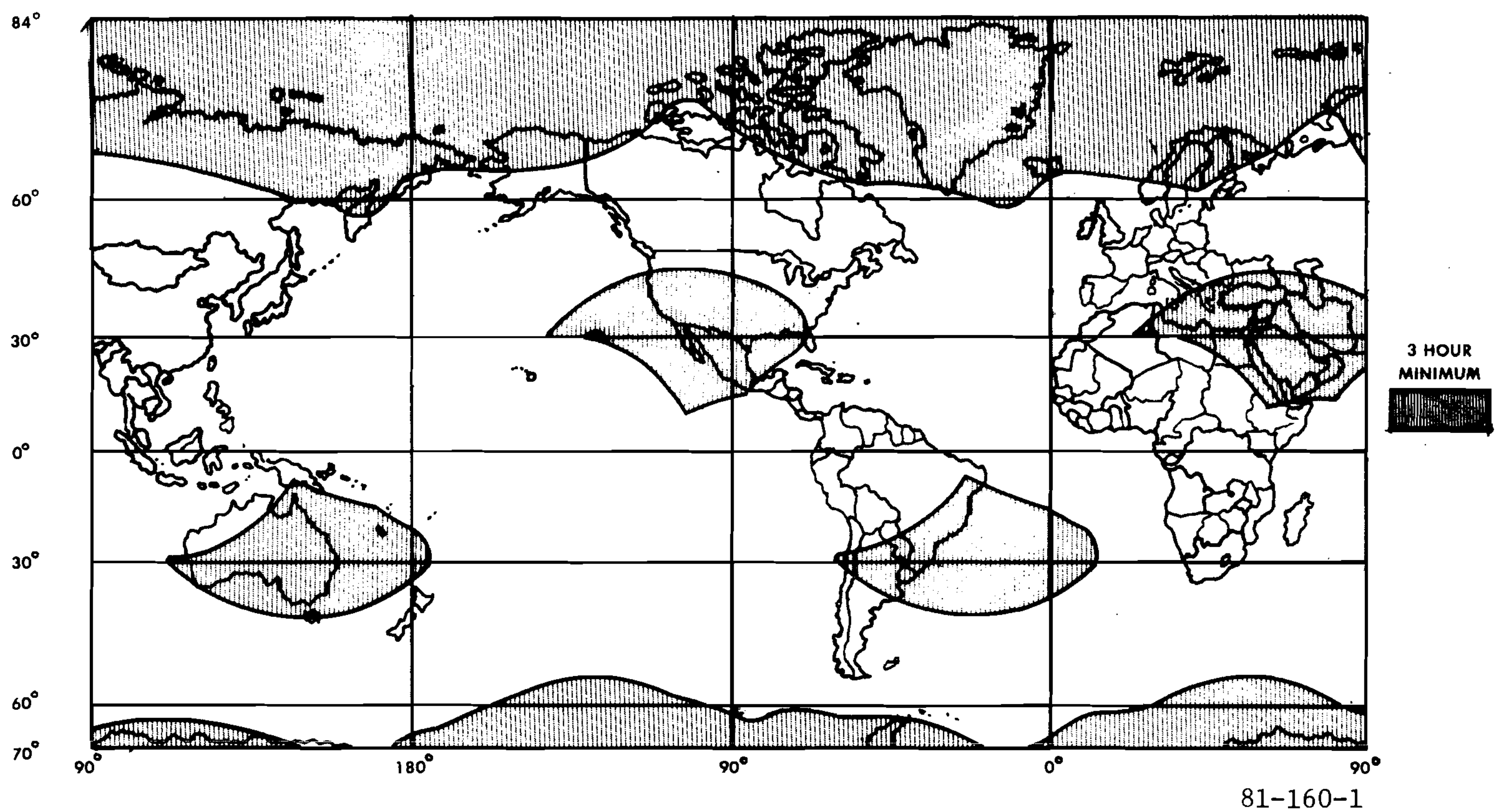

FIGURE 1. GPS CONSTELLATION CONTOURS (6 SATELLITES)

h. Lorge, Frank, "LORAN-C Nonprecision Approaches in the Northeast Corridor," FAA, Report No. FAA-CT-80-175, Project Plan, July 1980.

4. AIRBORNE SYSTEM EQUIPMENT.

All airborne data collected will be formatted for recording by the airborne Norden PDP 11/34M minicomputer.

4.1 VEHICLES.

a. Sikorsky twin-turbine CH-53 helicopter used for Tasks I, III, and IV tests.

b. Sikorsky S-76 helicopter used for Tasks II and III tests.

4.2 AIRBORNE DATA COLLECTION EQUIPMENT.

The airborne data collection equipment are interfaced as shown in figure 2 and listed as follows:

a. PDP 11/34M minicomputer

b. Magnavox GPS Z set

c. Dual Teledyne TDL-711 LORAN micronavigators

d. Litton LTN-51 inertial navigation system

e. Motorola Mini-Ranger III distance measuring unit

f. Canadian Marconi Company CMA-734 Omega receiver

g. Dual floppy disc drives

h. Magnetic tape recorder

i. GPS interface unit

j. Cockpit display (CDI for Tasks I, II, and III)

k. Aircraft systems coupler

l. Datametrics SP380 time code generator

m. Collins ADC-80F air data computer

4.3 MAGNAVOX Z SET.

One of six low cost Phase 1 prototype GPS receivers, the Z set manufactured by Magnavox Government and Industrial Electronics Company, has been delivered to the FAA Technical Center by the Joint Program Office for evaluation. The Z set will

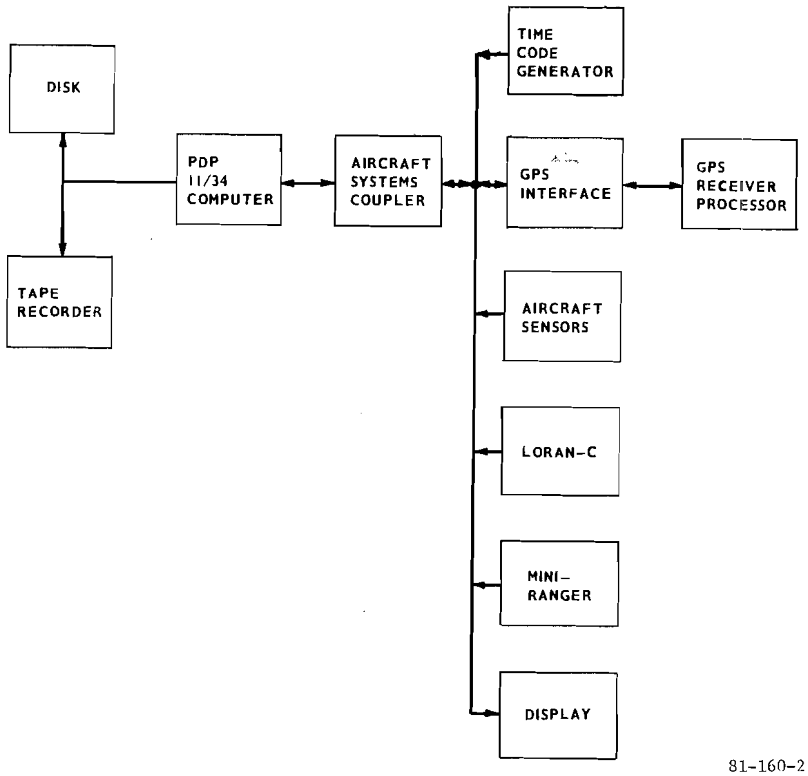

FIGURE 2. AIRBORNE DATA COLLECTION EQUIPMENT

be used for both rotary wing and fixed wing aircraft flight tests. The major components of the set are an L-band antenna, RF amplifier, receiver/processor, and a control indicator. The set is provided with an optional ZIM module to interface barometric altitude with the Z set for three satellite navigation, and a buffer box providing isolation and accessibility of the sets memory by an external data processor. Barometric altitude is used as a substitute range measurement only when less than four satellites are available for navigation. The Z set is a single channel sequential processing receiver, as contrasted with a four channel receiver, a concept sacrificing additional computer overhead and dynamic performance at a considerable savings in hardware. The set data is displayed on a single line readout (one parameter at a time displayed) selectable by the operator to monitor initial input conditions or set output parameters. The selectable parameters are:

a. Test mode

b. Estimated position error

c. Waypoint distance

d. Waypoint bearing

e. Latitude

f. Longitude

g. Altitude

h. Waypoint magnetic variation

i. Ground speed

j. True ground track

k. Day/time

l. Receiver/processor faults

Position data displayed by the set are referenced to the Department of Defense World Geodetic System 1972, commonly referred to as a WGS-72 ellipsoid surface. Throughput time is minimized within the Z sets central processor by computing only the display parameters selected with the control/indicator (C/I). The C/I will be installed in the cockpit for manual waypoint selection and display of range-to-go for Tasks I, II, and III tests.

4.4 GPS INTERFACE UNIT.

A bidirectional hardware interface unit will be designed and fabricated by ACT-100D to interface with the Z set's buffer box and the Norden computer.

Data transfer between the Z set's memory and the Norden computer is unidirectional unless in the receiver test mode (RTM), a mode that exists in order to use a single GPS satellite to drive all set functions in as near normal way as possible to extract receiver test data. Transfer of data from the Z set's memory occurs in the following sequence: (a) the Z set logically interrupts the Norden computer to signify that 1 of 31 possible events has been completed; (b) software routines within the Norden computer will identify the event by examining the Z set's events buffer and counter; (c) if data are required from the event, the Norden computer will initiate a direct memory access (DMA) transfer of data from the Z set's memory along with recording system time for storage on a magnetic tape recorder.

Crosstrack deviation will be computed from the GPS earth centered earth fixed (ECEF) position data and output to a digital-to-analog (D/A) converter for presentation on a course deviation indicator (CDI). A second D/A converter will be provided in the hardware interface for future expansion capability.

4.5 MINI-RANGER.

The Motorola Mini-Ranger III is a portable positioning system consisting of a transceiver installed on the helicopter and four ground reference stations positioned at precise locations. The airborne transceiver interrogates each reference station and measures the transit time of the return pulse to determine range to the receiver. Geographic position of each reference station is determined with the Navy Transit Satellite and a Doppler Survey Set, a system separate from the flight data collection package. The Doppler Survey Set uses the United States Navy navigation satellites as a reference to determine a precise three-dimensional position fix on the Earth's surface.

5. DATA COLLECTION.

Data collected onboard the aircraft are listed in table 1. The Magnavox Z set is the only available hardware representative of low cost GPS receiver technology. Future commercial versions may differ in hardware and software architecture. However, the basic data provided by the Z set (e.g., pseudorange, delta pseudorange, ECEF position, and rate data from which navigation information are derived) will be common to all receiver/processors. GPS data collection will consist primarily of that data for which generalized software analysis routines will be developed.

5.1 TASK I TESTS.

Task I tests are segregated into ground and flight tests designed to provide a data base for the objectives outlined in section 1.1.

5.1.1 Ground Tests.

Ground tests will be conducted to verify the functional operation of the recording system interface, gain familiarity with the operation of the Z set, and initiate the collection of data for Task 1.

5.1.1.1 Recording System Verification.

The functional operation of the recording system and data reduction software routines will be verified with data obtained from the following tests:

a. Comparison with Z set fixed memory locations (ROM).

b. Comparison of recorded and computed data with Z set C/I data at four surveyed locations approximately 1 mile apart at the Atlantic City Airport, N.J. (FAA Technical Center).

5.1.1.2 Static Tests.

GPS data will be continuously recorded for both the ZIM option enabled and disabled for approximately 2 to 3 hours each under the following conditions:

a. Test vehicle positioned statistically

b. Navigate mode enabled

The data will be analyzed for possible perturbational effects listed in section 1.1f.

5.1.1.3 Rotor Modulation Tests.

Concurrent with the initial verification and static tests, rotor modulation tests will be conducted. Rotor modulation tests were performed and reported in the Phase I GPS field tests (see section 3 of this project plan). Fresnel diffraction of the GPS signals with an antenna located beneath the rotor blade resulted in a 3 to 10 decibel (dB) loss of signal strength. The test results indicate received signal strength varies as an inverse function of the number of rotor blades and

TABLE 1. RECORDED DATA

1. Flight Parameters	Sample Rate (per sec)
a. Time	1/1.2 sec, 1
b. Pitch Attitude	1
c. Roll Attitude	1
d. Magnetic Heading	1
e. Altitude	1
2. LORAN-C Parameters	
a. Latitude	1
b. Longitude	1
c. Latitude	1
d. Longitude	1
e. Time Difference A	1
f. Time Difference B	1
g. Track Status	1
h. S/N Ratios	1
i. Crosstrack Distance	1
j. Along Track Distance	1
k. To Waypoint	1
l. From Waypoint	1
3. Mini-Ranger III Parameters	
a. Distance to Each of Four Beacons	5
4. Inertial Navigation System Parameters	
a. Latitude	1
b. Longitude	1
c. Groundspeed	1
d. True Heading	1
e. Wind Speed	1
f. Wind Direction	1

5. GPS Parameters

EVENT	DATA	SAMPLE/RATE
	Almanac data	1/FLT
6 to 9	Ephemeris data	Initially, then 5 to 15 min
4	Control/Indicator Output data, waypoint selection number and waypoint latitude and longitude	Variable
14	Common blocks of filter output data consisting primarily of the three earth centered, earth fixed, (ECEF) ranges and rates, time bias, time bias rate, GPS time, satellite ID, and receiver acquisition success/failure counters	1/1.2 sec
13	Common blocks of data including pseudorange and delta pseudorange measurements	1/1.2 sec
	Computed crosstrack error*	1/1.2 sec

*Derived within the Norden computer from ECEF position information decreases with proximity to the rotor shaft. The tests were conducted with a four channel receiver (X set) and a dual blade UH1H helicopter.

The Z set is a single channel sequential tracking receiver; the CH-53 is a 6 blade helicopter. Signal strength losses are expected to be more severe for the 6 blade helicopter and the single channel sequential tracking receiver.

Static ground tests with four satellite signals will be conducted for engine off and engine on (rotor turning) at three antenna locations (reference figure 3). The antenna and preamplifier will be mounted on a tripod with a 1-foot square ground plane. The receiver and filter output measurements will be examined for noise and bias for engine off and on conditions.

5.1.2 Flight Tests.

The aircraft instrumentation and Z set data described in section 5 will be recorded on board the CH-53A helicopter for postflight comparison with the Nike ground tracking data for the area navigation (RNAV) route depicted in figures 4 and 5. The course will be flown with a two-dimensional navigation display (range-to-go and crosstrack deviation derived from the GPS receiver/processor and the onboard Norden minicomputer). Range-to-go and waypoint selection will be generated and displayed on the Z set control/indicator. Crosstrack deviation will be displayed on a CDI. A total of ten 1-hour flights, each approximately 100 miles in length, will be flown from takeoff to approach and landing along the RNAV route segments described in figures 4 and 5 for navigation satellite configurations listed in table 2, with aided altitude as an active input for eight flights. Eight flights will be flown with at least a four-satellite configuration available for navigation. Two flights will be flown for equipment familiarization, checkout of the airborne hardware and software routines, and verification of postflight software analysis routines. Eight flights will be flown to collect data on various satellite configurations for postflight analysis. One of the checkout and evaluation flights will be flown with descent to 50-foot altitude over water for a 7-mile section of the RNAV segment TANGO to VICTOR (figure 4) to investigate possible multipath effects.

TABLE 2. TASK I FLIGHT TEST CONFIGURATION

	Initial Satellite Configuration				
Flights	4 Sat	4 Sat	4 Sat	4 Sat	3 Sat
1	c	a	b	a, d	a
2	c	a	b	a, d	a

a = Minimum possibility of satellite configuration change

b = Maximum possibility of satellite configuration change

c = Checkout and familiarization

d = ZIM option disabled

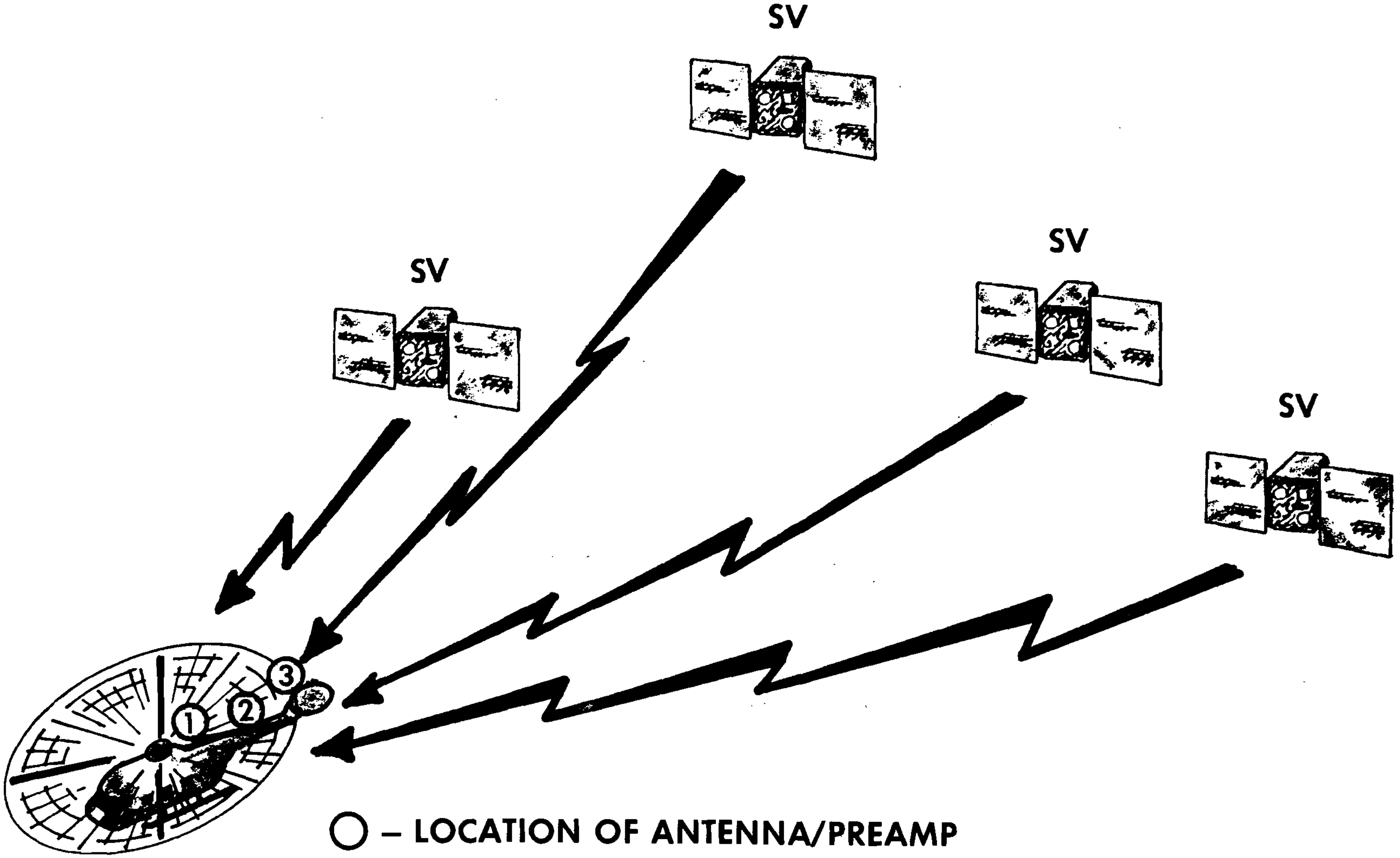

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FIGURE 3. HELICOPTER ROTOR MODULATION TESTS

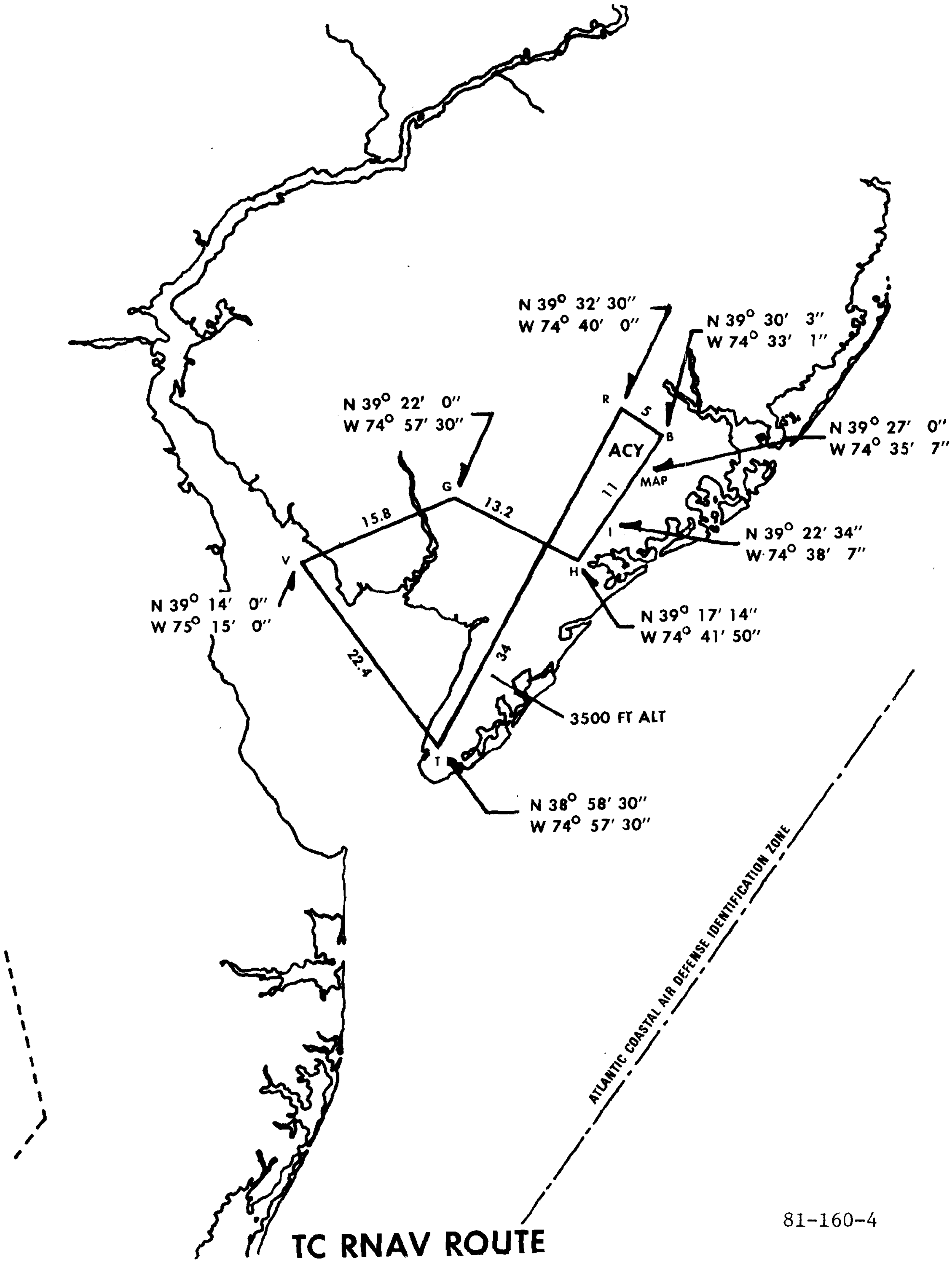


FIGURE 4. TC RNAV ROUTE

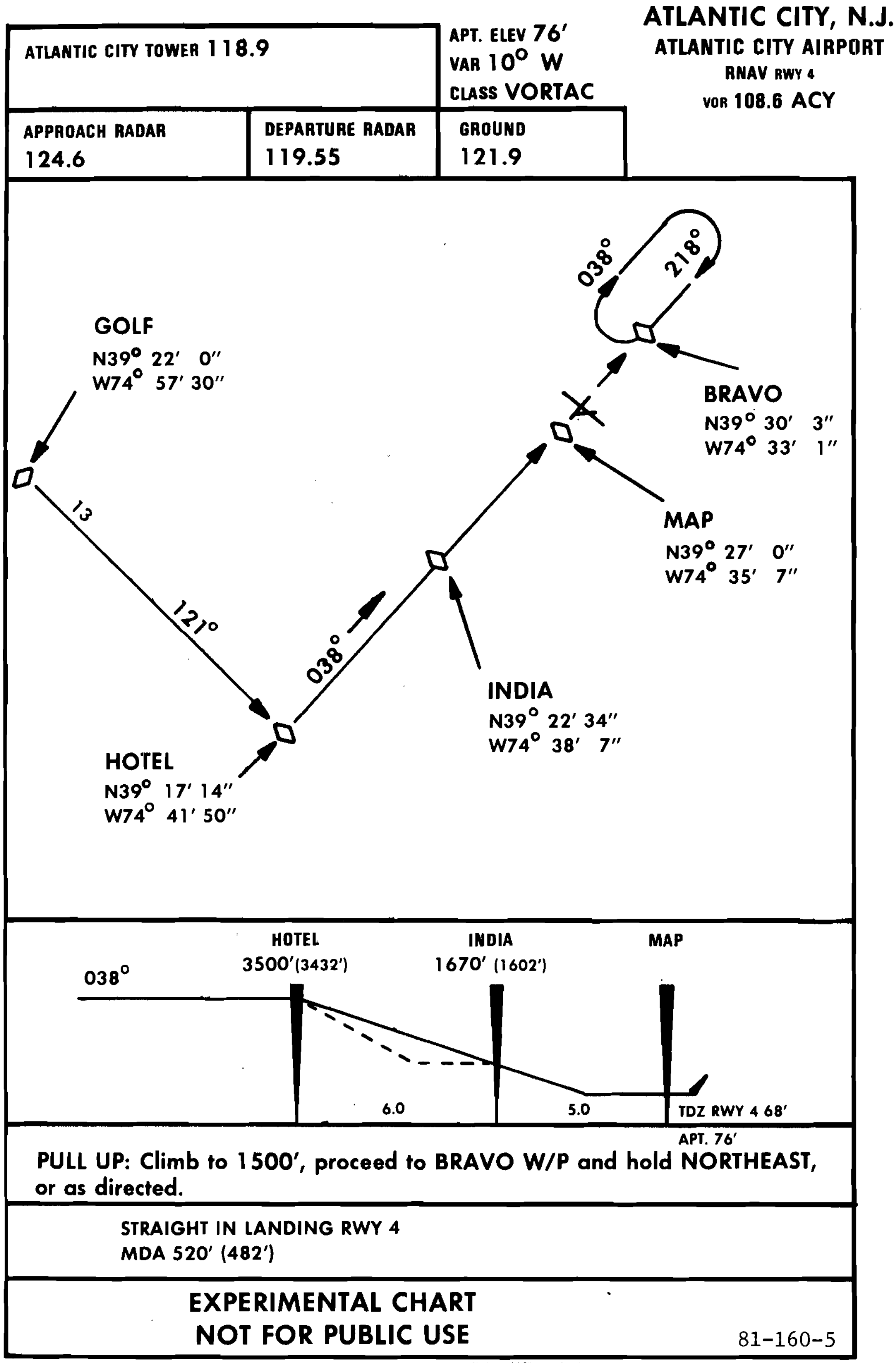


FIGURE 5. RNAV APPROACH PLATE FOR RUNWAY 4

5.2 Task II En Route Flight Tests.

A flight test matrix and en route flight path segments will be developed as a future addendum to this project plan. The Automated Radar Terminal Systems (ARTS) ground tracking facilities will provide ground tracking reference data for routes beyond the range of the FAA Technical Center's Nike/Hercules instrumentation radar. The en route flight segments will be limited to 2-hours duration because of satellite visibility.

5.3 Task III Nonprecision Approach Flight Tests.

A flight test matrix and approach patterns similar to the approach segments presented in report FAA-CT-80-175 will be included as a future addendum to this project plan. If the Z set is available and the recording interface is operational, data will be collected during the LORAN-C nonprecision approach tests in the Northeast Corridor. The primary ground tracking reference for this task will be the Mini-Ranger system.

5.4 Task IV Three- and Four-Dimensional Navigation Displays with Aided Guidance Information

Task IV is predicated on the assumption that other low cost GPS receiver/processors will not be available for testing at this time. The sequential receiver/processor Z set is a design compromise between data sample rate (0.83 samples per second) and cost (additional hardware). The low data sample rate which can be extended even longer (e.g., 3.3 to 8.2 seconds for a 10-second duration loss of satellite information) produces position data with poor dynamic response. Methods to increase the dynamic response of the GPS data and display additional navigation information, (e.g., vertical error, time-to-go, and automatic waypoint selection) will be investigated. A flight test matrix and flight profile patterns will be included as a future addendum to this project plan.

6. DATA REDUCTION AND ANALYSIS.

Ground reference tracking data will be obtained from the FAA Technical Center Nike/Hercules Precision Radar. The Nike/Hercules radar data will be time-correlated with the airborne data to provide precision position information over the test flight profile.

Mini-Ranger position information processing described in report FAA-CT-80-175 will be used as a secondary source of terminal area tracking information at the FAA Technical Center and as a primary source of terminal area reference position information for remote-base terminal area operations.

LORAN-C, Inertial Navigation System (INS), ARTS, and calibrated waypoint position information will be used as tracking information for en route RNAV remote base operations. LORAN-C and INS navigation systems have been tested for compliance with AC 90-45A. This data will be recorded concurrently with GPS data to permit direct comparisons.

Software routines will be generated to:

a. Plot satellite elevation angle and geometric dilution of precision (GDOP) time histories for specific geographic locations.

b. Conversion of GPS ECEF range and velocity data to:

(1) WGS-72 ellipsoid range and bearing
(2) Latitude and longitude
(3) WGS-72 altitude
(4) Ground speed and ground track

c. Analyze pseudorange and delta pseudorange process noise for rotor modulation and multipath effects.

d. Compute and plot time history of GDOP from vehicle and satellite ECEF coordinate data.

e. Plot time history of satellite identifications (ID's) included in the navigation constellation.

f. Plot altitude hold mode time histories (less than four satellites available for navigation).

g. Correlate flight time and position errors with age of ephereris data.

Flight data will be aggregated and presented graphically for the en route terminal and approach RNAV segments.

The measured ground and airborne data will be statistically processed for four basic performance measures defined as:

a. Total System Crosstrack Error (TSCT). This error is defined as the actual aircraft deviation perpendicular to the desired course in the horizontal reference plane. TSCT will be measured with the precision tracking radar at the FAA Technical Center used as a reference. Remote base operation reference measurements will be derived from merged combinations of Mini-Ranger, LORAN-C, INS, calibrated waypoints, and ARTS data.

b. Flight Technical Error (FTE). This error is defined as the indicated aircraft deviation perpendicular to the desired course in the horizontal reference plane.

c. Airborne System Error (ASE). This error is defined as the composite error contributed by all airborne navigation equipment, including sensors, receivers, computers, displays, and any calibration, scaling, or interconnecting errors peculiar to the system being evaluated.

d. Along Track Error (ATE). This error is defined as the actual aircraft deviation from the indicated position along the flight path. ATE results from the total error contributions of the airborne and ground equipment only. No FTE is used in determining the along track error. ATE will be measured with the precision tracking radar at the FAA Technical Center used as a reference. Remote base operation reference measurements will be derived from merged combinations of Mini-Ranger, LORAN-C, INS, calibrated waypoints, and ARTS data.

7. INSTRUMENTATION AND FACILITIES.

a. Precision Tracking Radar. Time correlated position information will be obtained from the FAA Technical Center Nike/Hercules instrumentation radar, an X-band tracking radar which provides azimuth, elevation, and slant range to a maximum range of 200 nautical miles.

The slant range is accurate within ±3 meters with a 1 sigma (1σ) standard deviation and the azimuth and elevation angle are accurate within ±0.15 milliradians (1σ). The antenna can track a target 360° in azimuth and from -5° to 90° in elevation.

b. ARTS Ground Tracking Facilities. Remote en route ground tracking data will be derived from the ARTS radars to obtain data relative to a 2-nautical mile course width. The ARTS tracking range is approximately 50 nautical miles. Error estimates increase with range from the ARTS antenna varying from 0.1 to 0.4 nautical miles for ranges of 10 to 50 nautical miles for ARTS III radars. Time correlation will be established between the airborne data recorded and the ground tracking (ARTS) facilities by using a "time hack" at various points along the flight path, utilizing countdown to time displayed on the air traffic control (ATC) ARTS radar display to initiate the time hack. This procedure has previously been used to obtain time correlation to within 1 second.

8. COORDINATION AND AREAS OF RESPONSIBILITY.

ARD-300 will provide overall Helicopter IFR Operations Evaluation Program management and coordinate various program aspects and equipment with the FAA Technical Center (ACT-100D and ACT-4).

ACT-100D will provide Center program and project management, engineering, air traffic control coordination, and other technical support available within ACT-100D. ACT-100D will be responsible for conducting the data flights; collecting, reducing, and analyzing the flight test data; and for writing the final report. Coordination will be accomplished between ACT-100D, ACT-50, ACT-600, ACT-700, and Air Traffic Service (ATS) for support of this project.

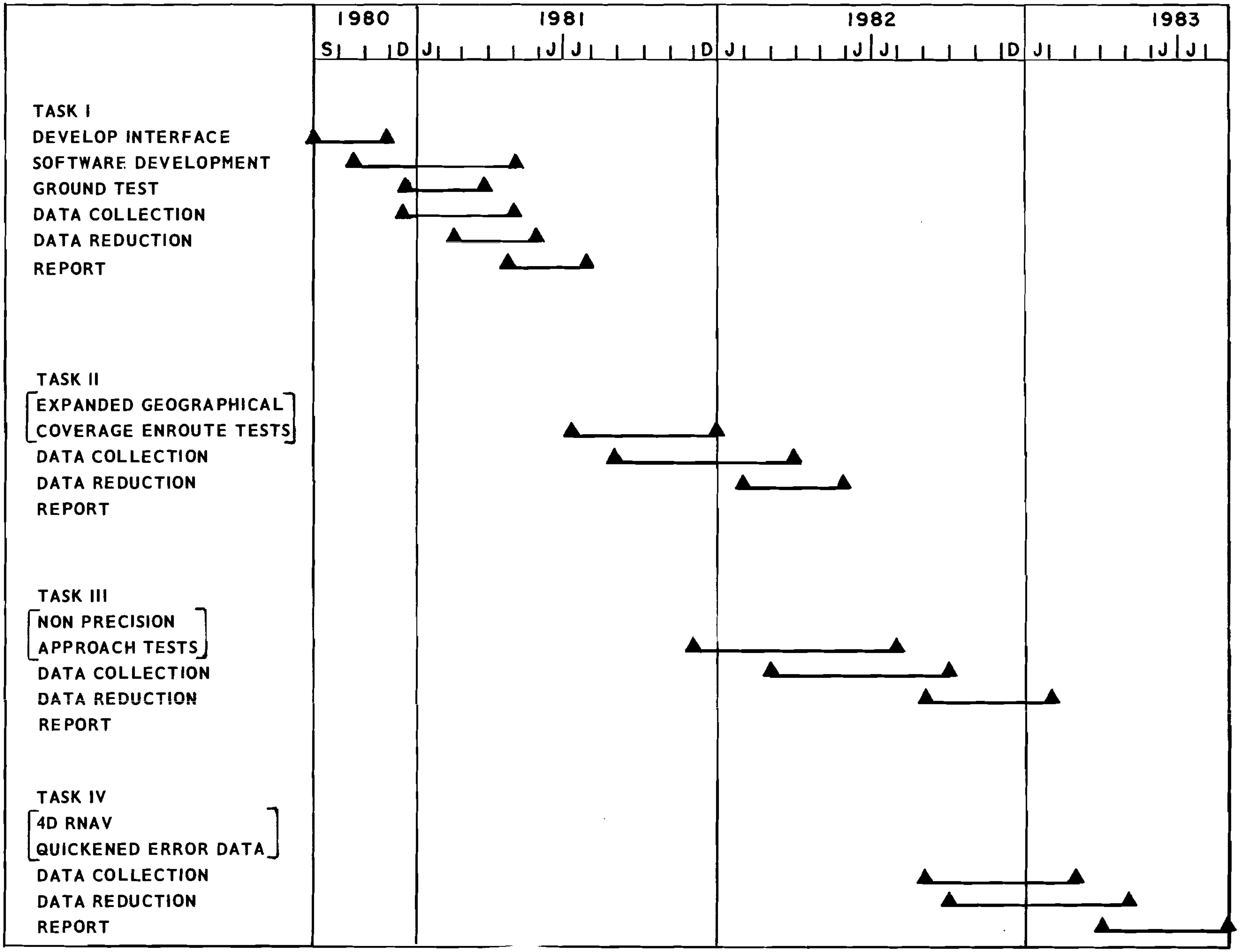
ACT-60 will be responsible for providing photography, technical illustrations, and printing services for this project, including final report processing. ACT-100D will be responsible for providing the requirements for these services.

ACT-600 will be responsible for providing project pilots, helicopter maintenance service, and for approving flight test scheduling. ACT-100D will be responsible for submitting a flight schedule.

ACT-700 will be responsible for operation of the Nike/Hercules facility and providing time correlated ground tracking data and computer services.

ATS will be responsible for providing air traffic control services for the helicopter flights. The Atlantic City Tower will be the facility for handling helicopter flights in the Atlantic City area.

9. SCHEDULE.


1980
1981
1982
1983
S D J J J D J J J D J J J
TASK I
DEVELOP INTERFACE
SOFTWARE DEVELOPMENT
GROUND TEST
DATA COLLECTION
DATA REDUCTION
REPORT
TASK II
EXPANDED GEOGRAPHICAL
COVERAGE ENROUTE TESTS
DATA COLLECTION
DATA REDUCTION
REPORT
TASK III
NON PRECISION
APPROACH TESTS
DATA COLLECTION
DATA REDUCTION
REPORT
TASK IV
4D RNAV
QUICKENED ERROR DATA
DATA COLLECTION
DATA REDUCTION
REPORT