SATELLITE NAVIGATION FOR HELICOPTERS

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Abstract

The Department of Defense of the United States is in the process of implementing a satellite-based navigation system called Navstar GPS (Global Positioning System). This system will have 24 satellites orbiting in three different orbits, with 8 satellites in each. Full implementation is planned for the mid to late 1980's. Partial use of the system should be possible commencing in the early 1980's. GPS can provide many unique features of particular benefit to helicopters, such as highly accurate airborne area navigation (RNAV) capability; accurate approach and landing guidance solely by reference to the airborne RNAV system; ability to function on a worldwide basis without the need for ground based navigation aids; unlimited capacity. Numerous benefits in addition to highly accurate navigation will accrue from civil application of GPS, including capability for automatic position reporting and air-to-air separation assurance. Cost benefits make application of GPS to civil aircraft in general, and particularly helicopters, highly attractive.

1. Background

Technological advances during the past several years are providing the capability to implement a satellite-based navigation system concept with enormous potential benefits to aeronautical, maritime and terrestial civilian users. The U. S. Department of Defense (DOD) is now in the process of implementing its Navstar Global Positioning System (GPS) which represents a potential utility for an order of magnitude performance improvement for navigation and exploitable utility for precise time transfer, system synchronization, collision avoidance and guidance.

The GPS satellite system concept is an outgrowth of numerous experimental and developmental satellite techniques and proposed implementations. These include such satellite systems as: TRANSIT, the U. S. Navy's Navigation Satellite System; the TRANSIT Improvement Program, TIPS; the TIMATION and 621B development experiments; the NASA Position Location and Communication Equipment (PLACE) experiment; the Maritime Satellite Program of the U. S. Department of Commerce's Maritime Administration; the U. S. Department of Transportation (DOT) and Federal Aviation Administration (FAA) Aeronautical Satellite Program; the DOT's Advanced Air Traffic Management System Concept (AATMS); and the FAA's ASTRO-DABS Concept.

GPS navigation signals are transmitted by the satellites on two L-band frequencies; L_1 which is centered at 1575.42 MHZ and L_2 which is centered at 1227.6 MHZ. The L-band frequency provides all-weather operation with minimal ionospheric group delay propagation errors. Military users may employ two-frequency operation at L_1 and L_2 to precisely calibrate ionospheric delay. The signal waveform structure which is impressed upon the L-band carrier frequency is a composite of two pseudo-random-noise (PRN) phase shift-keyed (PSK) code signals transmitted in phase quadrature. These two signals are termed the precise or P-code, and the Coarse/Acquisition or C/A-code. The P-code provides high precision navigation accuracy for military users which can be encrypted or altered to provide a secure code for selective denial purposes, and is also resistant to jamming and multipath distortion.

For the civil user, the C/A-code provides a ranging modulation which consists of a PRN sequence of binary "chips" biphase modulated on the carrier at a chip rate of 1.023 Mbps. Each C/A PRN chip duration is equivalent to approximately 978 nanoseconds or a range duration of 293 meters. The C/A code has a 1023 bit linear gold code pattern generated by the module-2 sum of a selected pair of maximal PN codes from a 10-stage shift register generator. Each satellite has a unique C/A-code which is obtained by inserting a different time displacement (i.e., code address) between the maximal code pairs. The C/A code has a period of 1023 chips, or exactly 1 millisecond at chip rate of 1.023 Mbps. The repeating 1 millisecond long code duration provides unambiguous ranging equivalent to about 300 kilometers between the satellite and the user, which is compatible with the 10,900 nautical mile orbit altitude of the satellites.

The following table illustrates the qualititive military/civil rankings of navigation satellite system significant characteristics.

It is considered that GPS meets these rankings for a common military/civil navigation system in a highly satisfactory manner.

Navigation System Characteristics	Military Significance	Civilian Significance
Worldwide Coverage	Essential	Essential
Precision Accuracy	Essential	Desirable
Common Grid Capability	Essential	Essential
Passive non-transmitting Users	Essential	Essential
Unlimited Number of Users	Essential	Essential
Freedom from Ambiguities	Essential	Essential
High Anti-Jam Immunity	Essential	Desirable
Selective Denial to Unauthorized Users	Essential	Minimal
Continuous Navigation Availability in real-time	Essential	Essential
Operation with High Dynamic Users	Essential	Desirable
Minimal Frequency Allocation Needs	Essential	Desirable
All Weather Operation	Essential	Essential
Minimum Propagation Limitations	Desirable	Desirable
Satisfactory Form Factor, size, weight	Essential	Desirable
Minimal User Equipment Cost	Essential	Essential
Autonomous Ground Control from U.S. Territory	Desirable	Minimal
Compatibility with other navigation systems	Desirable	Essential
Evolutionary transition into Operational Capability	Desirable	Essential
Provide world-wide Time and System Time Synchronization	Desirable	Desirable

2. GPS Implementation

The operational GPS satellite segment will employ 24 satellites in 12 circular orbits. The Final Operational Capability (FOC) of GPS is now scheduled to take place in the 1986-1987 time period. These satellites will be equally spaced in three orbital planes so that six to eleven satellites are always in view to a user on or near the surface of the earth. Average visibility for all locations on the earth and at all times is eight to nine satellites visible above 5° elevation angle from the horizon, and six, seven or eight above 10°. Since only four or less satellites are needed for civil navigation, the users generally will have twice as many satellites available from which to select the best geometry.

The selection of a spread spectrum code modulation for GPS provides significant advantages for a satellite-based passive navigation system. Spread spectrum code modulation provides several essential system characteristics such as: Single frequency allocation for satellite transmissions with code-division multiple access to each individual satellite, precision ranging measurement on the code modulation in continuous real-time, significant processing gain against signal interference, and inherent multipath discrimination.

Other distinct features have been incorporated to benefit the potential user community. The GPS concept utilizes one-way ranging to the satellites with no active transmission from the users. This passive navigation approach can therefore support an unlimited number of military and civil users. A user employing an inexpensive time reference can be computationally synchronized to the GPS system time base by utilizing at least four satellite signals from the global coverage, or only three if altitude or times are known. System time is maintained within a few nanoseconds at the GPS satellites by a Control Segment which tracks the satellite and detemines the individual ephemeris and satellite clock parameters. All resultant navigation solutions are thus referenced to a common grid, the Department of Defense World Geodetic System.

Several types of user equipment have been developed to satisfy the requirements of highly dynamic aircraft, slow moving aircraft, surface ships, submarines and the field soldier. Overall test results to date have been extremely successful.

Navstar GPS offers real time, worldwide, all weather navigation with accuracies previously unachievable. Furthermore, it appears that GPS receivers can be made available at a low enough cost to make their use attractive to a wide variety of civil, government and commercial users. The possibility thus exists for reducing the existing mix of military and civil navigation systems. The cornerstone of the reduced mix is a highly reliable satellite based system not restricted by the limitations in accuracy, coverage, and timeliness that are inherent in present radionavigation systems.

3. GPS Accuracy

As stated earlier, the satellites will transmit two signals: a C/A signal for coarse acquisition and a P signal for precision navigation. The accuracy achievable from these signals can be controlled from the ground. The P signal will provide high accuracy (10 m (CEP) or better), high jam resistance and will be protected for U. S. and Allied military use only. The C/A signal can be used by any appropriately equipped user. It had been estimated that the location accuracy of the C/A signal would be between 100m and 200m (CEP). However, based on limited navigation tests, it appears that the actual accuracy which may be expected by GPS civil users (C/A code) is apparently as follows:

	POSITION (METERS)	VERTICAL (METERS)	VELOCITY (M/S)
50% of Time	20 to 30	30 to 40	0.2
90% of Time	30 to 38	50 to 60	0.3

4. Area Navigation (RNAV)

From an operational civil aviation point of view, the GPS should be considered as an Area Navigation (RNAV) system. The FAA's Advosory Circular 90-45A (in process of being updated) sets forth basic considerations involved in introducing RNAV into the National Aviation System (NAS). At present, the great majority of the RNAV systems in use are based on VOR/DME (VORTAC).

Other navigation systems which currently may be considered to have RNAV capability include Loran C, VLF/Omega, TACAN and INS/ Doppler. These systems may be approved by the FAA for Instrument Flight Rules (IFR) operation enroute, in terminal areas and for instrument approaches provided they equal or exceed the VOR/DME RNAV accuracies as specified in AC 90-45A.

There are three basic categories of RNAV systems:

(1) 2-D - Whereby the pilot may determine his cross-track and along-track position (x-y coordinates).

(2) 3-D - Whereby the pilot may determine his x-y coordinates plus his z (altitude) coordinate.

(3) 4-D - Whereby the pilot has the ability to arrive precisely at a point in space at a desired altitude on a desired track and at a desired time (x-y-z-t coordinates).

(4-D RNAV also permits arrival at a desired touch down zone (TDZ) on an airport or heliport at a desired time.)

Because of the angular divergence of the VOR radials, VOR/DME (VORTAC) RNAV route widths may be in excess of 4.0 nm on either side of the route centerline in an angular splay, depending upon distance from the reference facility. Inasmuch as such facilities are subject to line-of-sight (radio horizon) limitations VOR/DME (VORTAC) RNAV instrument approaches are not authorized at locations more than 25 nm from the reference facility. Under the best of conditions, VOR/DME (VORTAC) RNAV instrument approach minimums generally are not less than MDA (Minimum Descent Altitude) 500' and visibility 1 nm. Helicopter visibility minimums may be half of those approved for fixed wing aircraft instrument approaches.

All RNAV instrument approaches today are classified as "non-precision". A "precision" approach according to current FAA definition can only be made with an ILS (or future MLS) or a precision approach radar (PAR/GCA) at the point of intended landing. A Category I precision instrument approach facility provides minimums of 200' and $\frac{1}{2}$ nm; Category II 100' and 1200' RVR (Runway Visual Range), and Category III in three gradations down to 0 - 0. Based on helicopter flight tests conducted by the U.S. SAMSO (Satellite and Missiles System Office) at its Yuma, Arizona, GPS test facility, it would appear that GPS RNAV instrument approaches for helicopters could have minimums in the order of Category I or Category II "precision" approach and landing aids.

5. Displays

Since the primary operational function of a GPS receiver will be to serve as an RNAV system, a suitable control and display unit (CDU) will be needed to interface between pilot and receiver. It will be relatively simple to integrate the GPS RNAV system with the FAA's RNAV planning. Since waypoints are used to define a desired RNAV route, including an RNAV instrument approach, the waypoints may be expressed either in rho/theta with reference to a VOR/DME (VORTAC) facility, or in terms of lat/lon. The FAA is now well underway in identifying RNAV waypoints in both rho/theta and lat/lon.

Since the GPS receiver will use lat/lon inputs to define waypoints, a GPS CDU will need to be designed to receive lat/lon inputs (similar to INS). The CDU can be designed in various degrees of sophistication such as different capacity levels of waypoint storage; 2-D, 3-D or 4-D operational application; parallel track offset; time to go; ground speed; and so on. Various GPS CDU concepts with relative design pricing are being studied.

The simplest cockpit navigation display unit for the pilot will be today's CDI/HSI. For track guidance, the vertical track bar will be used and for vertical guidance (if a 3-D GPS system is used) the glide-slope horizontal bar or bug. More sophisticated CRT displays can be included, along with preprogrammed flight data storage units. To the pilot everything will be the same in the cockpit of the aircraft to which he is accustomed, insofar as flight technique is concerned.

If time referenced navigation (4-D) is used, "T" display capability would be needed to reference desired time of arrival to a particular waypoint (in space or on the surface), together with a fast-slow indicator. It is contemplated that the GPS outputs could interface with such sophisticated systems as flight directors and autopilots. Its outputs also could provide improved cockpit instrumentation such as absolute altitude, and highly accurate rate of climb/descent and velocity.

As with the CDU input device, various levels of cockpit displays (output) need to be examined, with alternate pricing and operational scenarios analyzed. This phase of further study should include sophisticated CRT multi-function displays (MFD) on which many functions can be shown, such as the GPS RNAV tracks and waypoints, own aircraft position, other aircraft positions as a type of CAS (Collision Avoidance System), weather contours, and so on.

6. GPS Communication

An essential function for implementing any Air Traffic Control System is the requirement for providing communications. The GPS communications capabilities are considered to be:

(1) Provide information exchange using coded, non-voice digital signals.
(2) Provide data link for air-to-ground information transfer in the local ground, approach and departure, terminal, and enroute regions of flight sufficient to accomplish ATC surveillance functions.
(3) Provide data link for ground-to-air information transfer for the same regions of flight sufficient to accomplish ATC executive control functions.
(4) Provide data link capability to perform air-to-air infor-

mation transfer compatible with identification and collision avoidance requirements.

No existing or proposed communication data link system meets these requirements. The current communication function is accomplished by VHF voice channels operating with associated control centers such as the Air Route Traffic Control Centers (ARTCC's) and the Terminal Radar Control Centers (TRACON's).

7. Time Division Multiple Access

Concerns for the communication function design are motivated by the necessity of conserving spectrum allocations and usage since only a finite frequency band is available to accomodate the numerous potential users and the large volume of exchanged data. GPS navigation has the singular utility of providing for the incorporation of a data link communication technique which is based on time division multiplexing, or Time Division Multiple Access (TDMA). The timing accuracy of the GPS provides a concept of TDMA with guard band times of one micro-second. This one micro-second timing compares with a required 600 micro-seconds per 100 nautical miles of propogation delay encountered in a one-way data link. Such highly accurate timing from GPS makes the TDMA appear to be most fruitful for pursuing. A planned military TDMA secure communication system, the Joint Tactical Information Distribution System (JTIDS) uses a similar precisely clocked time slot concept but is not available to civilian users.

8. GPS Collision Avoidance System

Basically a GPS/CAS would involve the use of an airborne data link (D/L) which would transmit the x-y-z coordinates of an aircraft derived from its airborne GPS receiver. These transmissions would be monitored by any other aircraft in a given area of concern, a feature particularly important in offshore and remote area helicopter operations. When in airspace under Air Traffic Control jurisdiction, these transmissions could be monitored by ground ATC facilities to provide automatic position reporting, thus augmenting or supplanting radar.

In the application of GPS/CAS, different degrees of sophistication could be achieved. For example, a minimum installation would not require a cockpit display. In this case, such aircraft's presence would be detected by other aircraft with a suitable cockpit display, but the pilot without a GPS/CAS display would not have this capability.

A simple cockpit display would be one which would give the pilot minimum avoidance maneuvering indications, such as "fly up", "fly down" etc. A more sophisticated display could be a CRT type Cockpit Display Traffic Indicator (CDTI). With this category of airborne collision-avoidance instrumentation, the pilot would be provided with a real world display of the traffic situation in his immediate area of concern.

Based on such air-derived information, the pilot can assess a given traffic situation and maneuver his aircraft accordingly. Or, in cooperation or coordination with the ATC System, the pilot may carry out directly - by reference to the CDTI - certain functions to "unload" the ground ATC System, and at the same time increase airspace/airport/heliport capacity. These include:

- Station-keeping, which involves flying within specified close proximity to other aircraft.
- In-trail spacing at optimum distances from other aircraft departing, enroute, and landing.
- Passing (going around) aircraft being overtaken.
- Avoiding crossing traffic.

9. Helicopter Development Status

Today, there are something over 6,000 helicopters in the U.S. civil aircraft fleet. Of this number over 55% currently are engaged in commercial operation, about 30% in business/corporate activities and 15% in government-type work. Civil helicopter production now has a 12% annual growth rate. By the mid 1980's, the U.S. expects to have about 10,000 helicopters of which some 5,000 will be IFR capable. Some 10,000 to 15,000 U.S. military helicopters also may be expected to be in operation.

A basic criterion related to helicopter operational environments is "weather", e.g. VFR (under Visual Flight Rules) or IFR (under Instrument Flight Rules). Because of the unique capabilities of the helicopter to reduce speed and hover when necessary, it is possible to fly in weather conditions below normal VFR limits. This type of operation, known as helicopter special VFR (HSVFR) can be accomplished as long as the pilot can maintain visual contact with the surface and identify position, desired flight path, and reporting points. In such circumstances navigation requirements are minimized, although navigation still remains an important flight performance feature.

The question has been raised many times "Why go IFR?" The helicopter operators say "What does it buy me?", "What are the advantages?". Public officials - operators of airports, airways and the air traffic control system - ask "Why should we change or modify the present fixed-wing (CTOL) method of handling air traffic without a demonstrated need shown by helicopter users?". Some answers to these questions follow.

10. Improving Safety

A survey of U. S. helicopter accidents involving fatalities and/ or substantial or total destruction of the helicopter made recently by the author in cooperation with the U. S. National Transportation Safety Board, the Helicopter Association of America, and Bell Helicopter Textron, indicates that a significant number of these accidents were caused by operational factors such as:

- Attempting to continue under VFR into adverse (IFR) weather conditions.
- Initiating VFR flight in the face of existing IFR weather conditions.
- Flying at night (no horizon).
- Spatial disorientation.
- Whiteout (terrain snow covered).

All of the accidents resulting from the above basic operational situations ended in a collision (controlled or uncontrolled) with the surface or with man made obstructions. None of the helicopters were IFR equipped and none of the pilots were IFR rated. It is logical to presume that had these operations been conducted in accordance with IFR the related accidents would not have occurred.

11. Increasing Helicopter Productivity

With the significant investments involved in a modern helicopter, it is essential that the vehicle be operated at the highest possible level of productivity. The scheduled airlines and most business aircraft operators long ago learned that, for economic reasons, they had to have a high productivity level for their fixed wing aircraft, and that such productivity could only be achieved by having virtually all-weather (IFR) capability. The same situation applies today to helicopters, whether they are flying off-shore, in remote areas, or whether they are being used for business/executive/commuter/police/ or rescue purposes.

12. Expanding Air Service

Because of the small landing/takeoff area needed by a helicopter, the potential for developing helicopter service virtually is unlimited. Where surface locations are not available, heliports may be elevated, such as on rooftops, over railroad yards, above warehouse areas, as well, of course, as on off-shore platforms. To provide really reliable helicopter service to the many potentially desired landing/takeoff areas, all-weather (IFR) capability is essential.

13. Helicopter Operational Categories

In addition to the two basic weather criteria, helicopter operations may be categorized also by area or type of operation. Operational requirements for off-shore operators may involve special controlled airspace extending out to sea several hundred miles and down to the surface in some instances, requiring adequate navigation and communication coverage.

The remote area category generally applies to such locales as Alaska or the North Sea where there is a great dearth of facilities and particularly difficult flying conditions. IFR operational capability is considered a must for virtually all the flights.

Operations in the Continental United States constitute the third category of helicopter areas of application. Interface with the ATC System is a principal consideration in this area.

The trend is now underway to move helicopter operations more and more into the ATC environment as a result of increasing IFR operational requirements. In this respect, one of the fastest growing segments of the helicopter fleet is that involved in business and executive operations. From an operational requirements point of view, helicopters in this category will need to at least match the weather minimums of the scheduled airlines as they will be providing, in many instances, a complementary or connecting type service.

14. Navigation Goals

What are the implications of the foregoing requirements on helicopter navigation goals?

A fundamental goal is to have a high accuracy navigation system with global coverage, capable of providing area navigation without the need for point reference navigation aids. Signal coverage should be down to the surface without the constraints of line-of-sight limitations.

The navigation system should be capable of providing narrow, discrete helicopter routings to facilitate segregation of helicopters and conventional take-off and landing (CTOL) aircraft. Similarly needed are discrete instrument approach and missed approach procedures to heliports, helipads at CTOL airports and points-in-space, requiring a minimum of airspace.

Thus, it should be possible to operate helicopters without interference to or from airlines and other conventional aircraft, in many cases sharing the same landing areas, but not the same runway. The potential of helicopters cannot be achieved if they are to be handled in the ATC system as fixed-wing, conventional aircraft, particularly in high traffic density areas. For optimum IFR helicopter operational flexibility, and particularly in the application of discrete IFR helicopter routings and approaches, an RNAV system of some sort is needed.

15. The Case for an Improved RNAV System

The increasing use of civil IFR helicopter operations has focused sharp attention on the deficiencies of the present VOR/DME (VORTAC) navigation system. These basically are the lack of precision navigation guidance, line-of-sight limitations for low altitude flight, and unavailability of stations off-shore and in remote areas. Other types of navigation available today similarly have various types of limitations for optimum helicopter use.

As stated earlier the present national navigation system permits "precision" instrument approaches only where an ILS (future MLS) or PAR (Precision Approach Radar) system is installed. There are about 13,000 aircraft landing facilities in the United States and its possessions, including nearly 3,500 heliports, of which about 300 are elevated, yet precision instrument approach facilities are available for less than 500 conventional airports, and none for heliports.

The present nav system limitations become even more pronounced when considering the growing need for precision or "semi-precision" approaches to virtually an infinite number of landing/takeoff areas for IFR-capable helicopters and other VTOL's now being developed.

16. Navigation System Requirements

The ideal helicopter navigation and positioning concept would be one which would have all of the following capabilities in an integrated system:

- Highly accurate three-dimensional (lateral, longitudinal, vertical) area navigation guidance.

- Four-dimensional (4-D) guidance adding time referenced navigational capability to 3-D guidance with extremely high time positioning accuracy.

- Sufficiently accurate approach and landing guidance by the airborne RNAV system so that minimums approaching "precision" instrument approaches could be achieved to any pilot-selected point on the surface, or in space, without the need necessarily to have an electronic landing aid at that location.

- Ability to function without line-of-sight (radio horizon) limitations.

- Vertical velocity measurement accuracy in the order of 0.1 feet/second; horizontal velocity measurement accuracy in the order of 0.1 knot.

- Imperviousness to atmospheric conditions for noninterrupted operations.

- Non-saturable capacity.

- Service availability to all classes of airspace users on a worldwide basis.

- System outputs capable of inputting advanced multi-function cockpit displays, including displays of navigational and traffic situation information, as well as existing conventional cockpit displays.

- Data link capability to transmit x-y-z coordinates for automatic position reporting and air-to-air separation assurance.

- Be cost-effective based on life cycle cost analyses, with the system design such that it can have various levels of sophistication and thus will be affordable to all classes of airspace users.

17. Benefits

Assuming the successful implementation of a navigation and positioning system meeting the requirements outlined above, numerous benefits for helicopters can be visualized along the following broad lines:

- More efficient use of the airspace.
- More efficient use of Heliports as well as CTOL and STOL airports.
- Greater flexibility in the availability of landing/takeoff areas for instrument approaches.
- Increased safety.
- Increased efficiency in the air traffic control system.
- Savings to the government (i.e., to the Federal Aviation Administration, in the context of this paper) as a result of eventually decomissioning facilities now in use (i.e. VOR/DME) and reducing the need for numerous local landing facilities (e.g. MLS/ILS).
- Savings to the airspace users as a result of eliminating

the need for certain airborne avionics equipment (e.g., VOR/DME; ADF; RMI; INS; Omega/Doppler; and perhaps ILS/MLS for some operations.)

18. Conclusions

(1) Helicopters have become, and are becoming more and more, a vital element in the total air transportation system.

(2) Due to the unique characteristics of helicopters (and future VTOL's), discrete routes and approach procedures are needed in many instances to provide segregation of this type of air traffic from CTOL traffic, thus necessitating highly accurate navigation capability down to the surface.

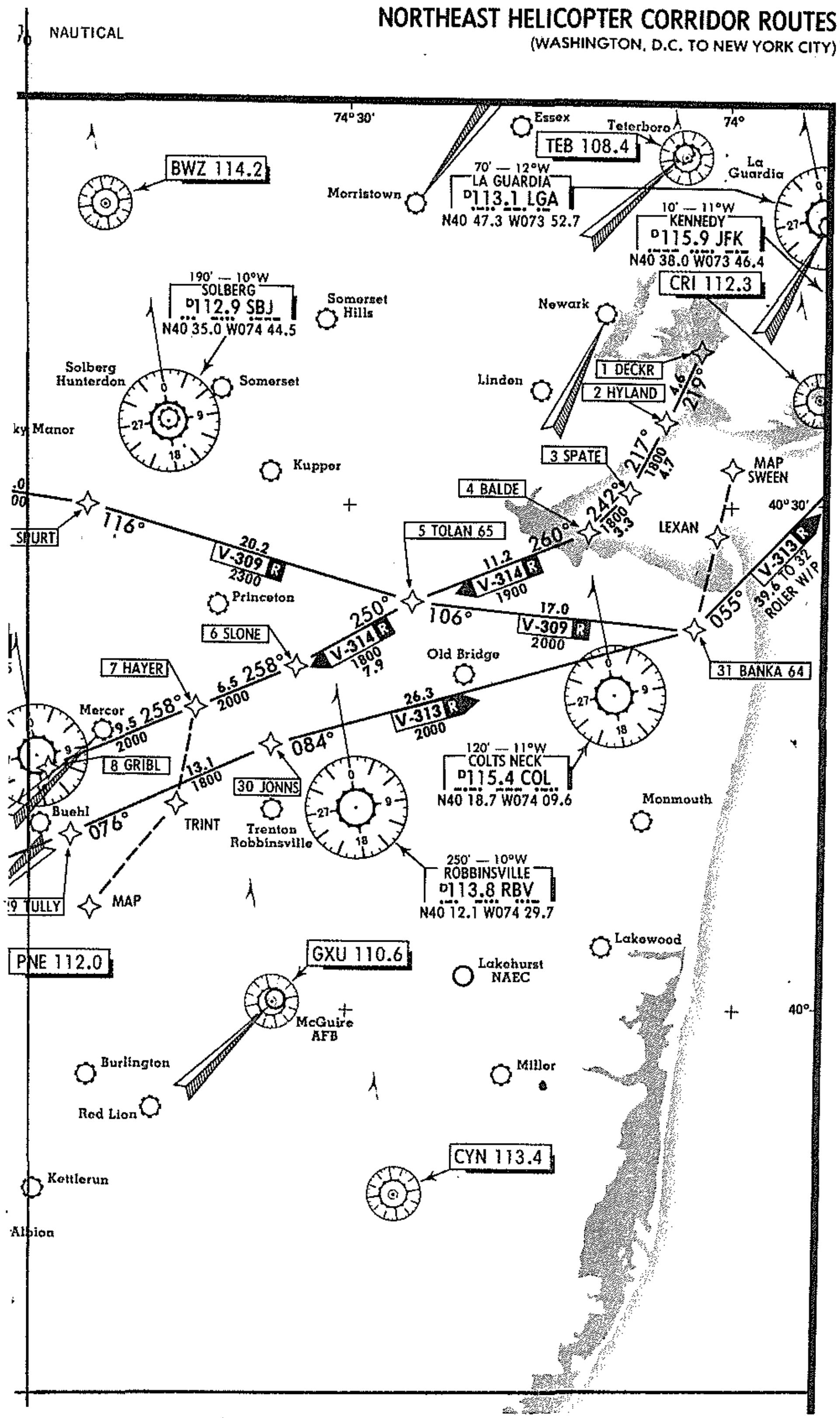
(3) Instrument approach capability is needed to serve an infinite number of locations (both on the surface and elevated), off-shore, in remote areas and on-shore without the need to necessarily have an electronic aid at each such location.

(4) Area navigation (RNAV) is a must for successful helicopter IFR operations, and also is exceedingly useful in VFR operations.

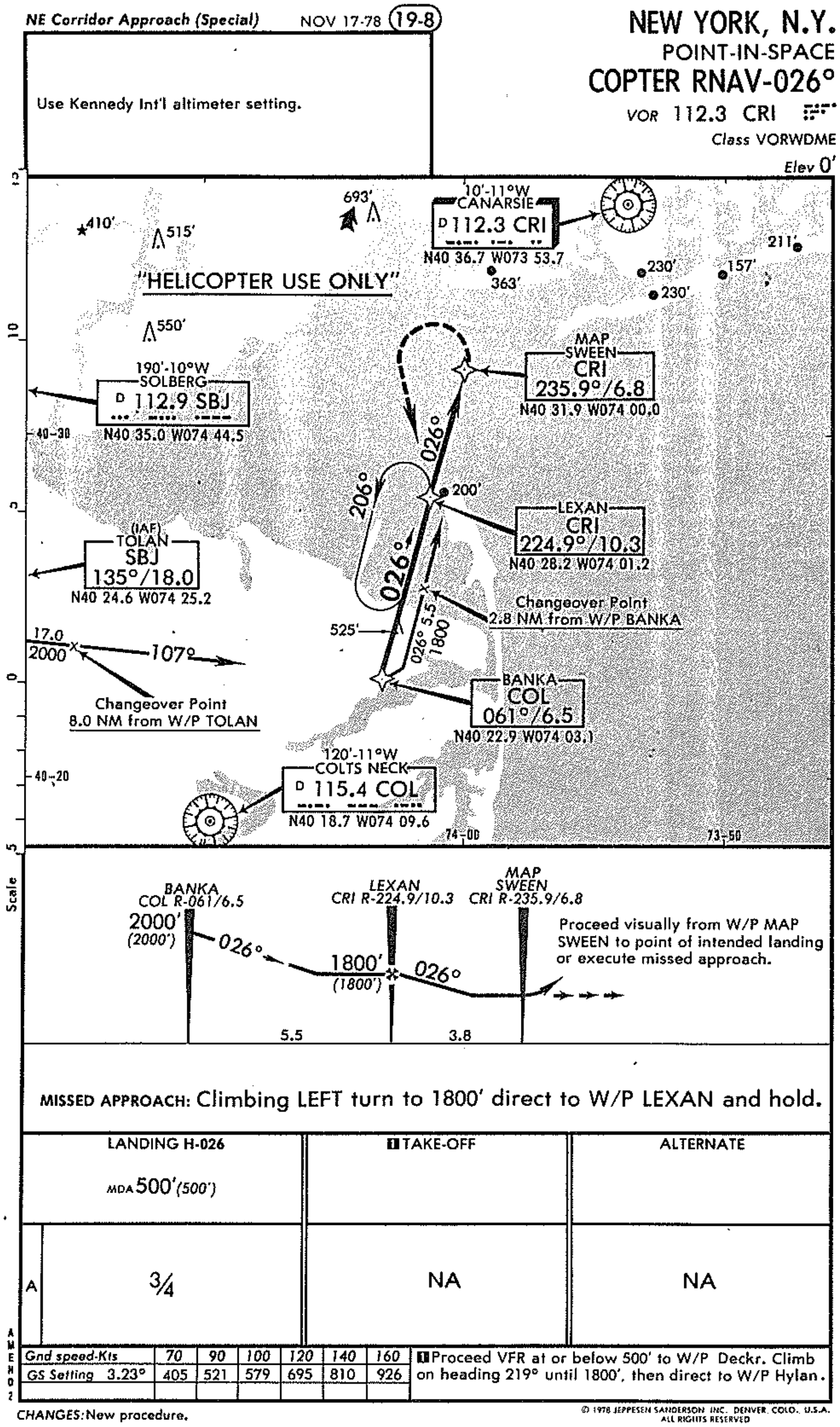
(5) Current RNAV systems do not fully meet helicopter navigation goals.

(6) GPS appears to be the most logical candidate for a future helicopter RNAV and guidance system, as well as for other types of aircraft.

(7) The GPS may be expected to be an advantageous replacement for the VOR/DME (VORTAC) system by the end of this century. Its worldwide coverage, fail-safe features and signal reliability have distinct advantages over Loran C. Its excellent accuracy and immunity to atmospheric disturbances are obvious advantages over Omega. However, due to the long transitional process needed to introduce a new civil aviation navigation system, the rapid replacement of the VOR/DME (VORTAC) system is not envisioned. Rather, a gradual, evolutionary transition to a GPS civil aviation navigation/collision avoidance/communication/surveillance system is visualized, beginning in the early to mid 1980's.



Portion of U. S. Northeast Corridor connecting Washington and Boston by discrete helicopter RNAV routes. GPS RNAV would provide highly accurate, narrow route widths on this type of RNAV route structure.



Helicopter Point-In-Space RNAV instrument approach procedure for flight from the south/southwest into the New York area. GPS RNAV would permit highly accurate flight paths, a low MDA, and minimum airspace requirements for both approach and missed approach procedures.

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