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REVIEW OF THE LATEST TECHNOLOGY IN CARTOGRAPHIC DATA ACQUISITION, MANIPULATION, STORAGE AND PRESENTATION, WITH SPECIAL EMPHASIS ON POTENTIAL APPLICATIONS IN DEVELOPING COUNTRIES: AERONAUTICAL CHARTING

GPS/GIS integrated systems to benefit all phases of aircraft navigation

Paper submitted by United States of America**

Summary

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** Prepared by Ronald M. Bolton, National Ocean Service, National Oceanic and Atmospheric Administration.

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INTRODUCTION

The U.S. Department of Defense Global Positioning System (GPS) program was born in 1973 from the initial efforts by the U.S. Navy to develop an all weather global radionavigation system. GPS is a multibillion dollar satellite positioning and navigation network. Its use has been extended to civilian land, marine and air navigation, providing incredibly accurate, worldwide navigation and positioning capabilities. GPS can be accessed by U.S. and international users and requires no user fees.

GLOBAL POSITIONING SYSTEM DESCRIPTION

GPS consists of 21 satellites and 3 operational spares. The satellites orbit at 10,900 miles above the earth and complete each orbit in approximately 12 hours. The GPS satellites constantly transmit their position in space and reference time; the time is accurate to one second in 30 years. With this accurate time and position data, GPS receiver systems compute very accurate positions at anytime without interference by weather conditions.

GPS receiver systems must obtain signals from a minimum of three satellites to resolve the latitude and longitude of a point, and four satellites to determine the latitude, longitude and elevation of a position. The GPS receiver generally can lock on to the satellite signals and provide two dimensional fixes in 2 to 3 minutes and three dimensional fixes in 3 to 4 minutes. Once the receiver has resolved its initial position, it can provide position and time updates in a matter of seconds.

GPS NAVIGATION CAPABILITIES AND IMPLEMENTATION STATUS

GPS, even without augmentation, can still be used for accurate navigation for most purposes. The GPS basic signal provides very accurate navigation positioning. Compared with other navigation systems, GPS, in its most elementary form, is one or two magnitudes more accurate than conventional systems as depicted in Table 1.

Table 1: Navigation System Comparison*

System	Position Accuracy (m)	Velocity Accuracy (m/sec)	Range of Operation	Comments
GPS	15 (SEP) 3-D	0.1 (RMS per axis	Worldwide	Operational worldwide with 24-hour all-weather coverage. Specified position accuracy available to authorized users.
Loran-C (Note 1)	180 (CEP)	No velocity data	U.S. Coast, Continental U.S., selected overseas areas	Operational with localized coverage. Limited by skywave interference.
Omega (Note 1)	2,200 (CEP)	No velocity data	Worldwide	Operational worldwide with 24-hour all-weather coverage. Degraded performance in polar areas.
Std INS (Note 2)	1,500 max after 1st hour (CEP)	0.8 after 2 hrs (RMS per axis)	Worldwide	Operational worldwide with 24-hour all-weather coverage. Degraded performance in polar areas
TACAN (Note 1)	400 (CEP)	No velocity data	Line of sight (present air routes)	Position accuracy is degraded mainly because of azimuth uncertainty which is typically on the order of +/-1.0 degree.
Transit (Note 1)	200 (CEP)	No velocity data	Worldwide	The interval between position fixes is about 90 minutes. For use in slow moving vehicles. Better position fix accuracy is available with dual frequency measurements.

NOTES: 1. Federal Radio Navigation Plan, March 1982
2. ENAC-77-IV, Characteristic for a Moderate Accuracy Inertial Navigation System, August 1979

Used with assistance from geostationary satellites, local area differ-ential systems, and wide area augmentation systems, GPS can provide aircraft sufficient integrity, accuracy and availability to support enroute, landing and departure operations.

DoD declared GPS operational in the U.S. on December 8, 1993. FAA subsequently has granted approval for U.S. civil operators to use GPS equipment as a primary means of navigation in oceanic airspace and certain remote areas. GPS equipment may be used as a supplemental means of Instrument Flight Rules (IFR) navigation for domestic enroute, terminal operations and certain instrument approach procedures (IAPs). FAA has authorized the use of GPS in a manner that is consistent with current navigation requirements and approved air carrier operation specifications.

FAA has approved the use of GPS for IFR aircraft navigation in the U.S. National Airspace System (NAS) with certain stipulations:

- Oceanic - The GPS installation meets the requirements of TSO C129 and replaces one of the approved means of long range navigation, such as dual Inertial Navigation Systems (INS) or dual Omega systems. A single GPS installation with a type of GPS equipment which provides

receiver autonomous integrity monitoring (RAIM)* may be used for short oceanic routes which are approved for utilization with only one means of long-range navigation.

- Enroute and terminal area - GPS domestic enroute and terminal IFR operations can be conducted as soon as proper avionics equipment is installed in an aircraft and general requirements for flight are met. The avionics necessary to receive all the ground-based facilities appropriate for the route to the destination airport and alternate airport must be installed and operational. Ground-based facilities necessary for these routes also must be operational.

- Instrument approaches - Published GPS Approach Overlay IAPs and Standalone IAPs are authorization for pilots to use with GPS avionics under IFR; however, these approaches must be included in the receiver's database or the approach is not authorized.

Aircraft navigators worldwide are demanding full GPS implementation. Expected benefits are reduced travel time, more efficient travel paths, and reduced delays (especially in poor weather conditions)--all of which are made possible by flight procedures supported by more accurate GPS navigation systems, airborne and ground-based databases, and reliable surveillance equipment augmented by GPS.

*The GPS receiver verifies the integrity of the signals received from the GPS constellation through receiver autonomous integrity monitoring (RAIM) by ensuring that a satellite is not providing corrupted information. At least one satellite, in addition to the four required for navigation, must be in view of the aircraft to have RAIM function.

LONG RANGE PLANS FOR GPS

The *Federal Radionavigation Plan (FRP) 1994*, published by the U.S. Department of Defense and Department of Transportation, left no question as to the long range plans for GPS. The FRP stated that, "GPS has broad potential for satisfying current civil user needs or for responding to new requirements that present systems do not satisfy. It could ultimately become the primary worldwide system for military and civil navigation and position location." The FRP cited evidence that there was increased interest and use of GPS for air navigation since the 1994 approval of unaugmented GPS as a primary system for oceanic and remote airspace navigation. The 1994 FRP designated the GPS Wide Area Augmentation System (WAAS)as a candidate for certification as a primary aircraft navigation system. Table 2, published in the 1994 FRP, clearly shows the aviation community has embraced GPS as the navigation system of the future.

Table 2: Estimated Current Radionavigation System User Population

Systems Users	0 50 100 150 200
ILS/Air	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
*Loran/Air	XXXXXXXXXXXXXXXXXXXXXXXXXXXX
Loran/Land	XXXXXXXX
Loran/Maritime	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX. . .530
Omega/Air	XXXXXX
Omega/Land	XX
Omega/Maritime	XXXX
*GPS/Air	XXXXXXXXXXXXXXXXXXXXXXXXXX
GPS/Land	XXXXXXXXXXXXXXXXXXXXXXXXXXXX
GPS/Maritime	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX. . .275
VOR/Air	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
DME/Air	XXXXXXXXXXXXXXXXXX
TACAN/Air	XXXX
RBN/Air	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
RBN/Maritime	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX. . .490
Transit/Maritime	XXXXXXXXXXXXXXXX

Number of U.S. Users in Thousands

*Includes a large number of receivers that are not certified for IFR use, including handheld receivers.

GPS AND AUGMENTED GPS ACCURACIES

The positional accuracies listed below of GPS and augmented GPS explain government and aviation interest in these systems:

Kinematic Accuracies

- GPS Precise Positioning Service (PPS)
  - 15 meters (95%)
- GPS Standard Positioning Service (SPS)
  - 100 meters (95%)
- Wide Area Augmentation System (WAAS)
  - maximum test errors determined by Stanford University and Stanford telecommunications: vertical error was 9 meters and horizontal error was 6 meters. Over the whole continent, the average was under 2 meters.
- Local Area Augmentation System (LAAS)
  - instrument approach test errors: Ohio University using differential GPS achieved error rates under 2 meters, Stanford University making approaches using carrier phase corrections and integrity beacons had error in the .1 meter range.

A quick review of these accuracies achieved in the kinematic mode reveals that GPS and augmented GPS can meet all requirements for enroute, terminal, approaches (including categories I, II and III), and departure operations.

INTEGRATION OF GPS AND DATABASES TO SUPPORT AIRCRAFT NAVIGATION AND AIR TRAFFIC MANAGEMENT SYSTEMS

Aircraft of the future will include significant enhancements in communication, navigation and surveillance capabilities. The majority of communications between aircraft and air traffic management (ATM) systems will be conducted by redundant, high speed data links. GPS navigation signals, augmented by WAAS enroute and LAAS during the approach and landing phases, will provide highly accurate position and universal time standards. Automated Dependent Surveillance - Broadcast (ADS-B) equipment on board aircraft will provide position and other important data to the cockpit displays, nearby aircraft, as well as controllers in the ATM system.

These systems, as described above, will interface with the pilot through controls and displays that may be similar to the latest generation "glass" cockpits available now; however, the next generation of cockpit equipment will be more capable than current systems. The pilot will be supported by databases, processors, and networks that will provide storage, manipulation, display, and external/internal communications involving massive volumes of data; these pilot support systems will be capable of processing all essential or critical flight information. Future advanced automated functions will include data for:

- Area navigation (lateral and vertical)
- Auto loading of flight plans, flight trajectories, winds, and temperatures
- Data link communications - including air-to-air, ground-to-air, and air-to-ground
- Separation assurance from terrain, obstacles, special use airspace and other aircraft
- Weather information - graphic and digital
- Flight management data - waypoints, altitude and informative text (enroute, approach and departure)
- Airport data - gates, surface movement, runways, taxiways, lighting, etc.
- Collision avoidance data
- Aircraft operation information and warnings
- Display data for moving maps/charts - navaids, controlled airspace boundaries, route data, magnetic variation, obstacles, VFR chart depictions, flight path position, etc.

In the near term, these automated functions will immediately require supporting databases such as those key data sets listed below:

- Controlled Flight into Terrain (CFIT) Protection - Many of these functions will require current and projected future positional data supplied by GPS. GPS data will be critical in Obstacle and Ground Collision Avoidance Systems. Predictive systems will use GPS and terrain/obstacle data to provide advisory or automatic thrust/climb management as well as graphic terrain surface displays.
- Airport Surface Operations - GPS data combined with airport data (i.e., runways, taxiways, buildings, etc.) will assist in avoiding accidents, especially in low visibility conditions.
- Flight Management Systems (FMS) - Flight Management Systems use GPS, inertial, and Loran C navigation systems coupled to databases containing fix, waypoint, and altitude data for enroute, terminal, approach, landing, and departure phases of flight. These FMS databases will need to be linked/integrated with other databases -- especially the CFIT Avoidance System.
- Controlled Airspace (CA) and Special Use Airspace (SUA) - CA and SUA databases will be required for efficient aircraft and ATM operations. The SUA data would allow planes to transit these areas at approved altitudes when they are inactive.

AVIONIC COMPANIES USING GPS AND DATABASES FOR CHART AND MAP DISPLAYS

The concept of combining GPS data with integrated databases to display fix and moving maps/charts to enhance situational awareness and improve aircraft navigation has been embraced by avionics manufacturing companies† and chart producers. Many operational systems are in operational use now that offer some or all of the following features:

- Position and altitude display/control
- Map/chart displays
- Weather data and displays
- Enroute, approach, departure, and visual chart displays
- Video displays
- Waypoint sequencing
- Minimum safe altitude data
- Political boundary data
- Coastline data
- CFIT displays and warnings
- Airport graphics and/or data

These are the key databases being linked with GPS to provide navigation improvements and enhanced situational awareness for aircraft and better information for ATM.

GPS, CHART, DATABASE, FMS, ATM SYSTEMS INTEGRATION AND QUALITY CONTROL

FAA and the International Civil Aviation Organization (ICAO) are working with RTCA, Inc. and SAE International Aerospace, the key standards groups for the aviation industry, to assure proper standards and procedures are developed and implemented to allow safe aircraft operations in the NAS and worldwide. The ATM system, the aircraft navigation system, and the pilot must be supplied the same consistent, accurate, operational information in a form that facilitates navigation and enhances situational awareness. Without technical standards and proper certification procedures, the integrated GPS/database systems might not contribute to safe and efficient flight in an optimum manner. In any case, the aviation community must be supplied charts, FMS databases, and ATM data and displays that are certified as accurate and consistent; otherwise, the advantages of GPS and integrated database systems will be negated and even might become a hazard to aircraft navigation.

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†A few of the avionics, navigation systems, and chart producers active in this area include: Jeppesen, Collins, Trimble, Bendix/King, II Morrow, Smith Industries, Honeywell, Megellen, and Allied Signal, Inc.

IMPACT ON AERONAUTICAL CHARTS AND RELATED PRODUCTS

The use of GPS in the U.S. NAS has created significant impacts on aeronautical charts and related products. Enroute charts have been modified to include geographic positions (GPS information for use in flight computers), Off-Route Obstruction Clearance Altitudes (OROCAs) have been added, and the IACC has changed the U.S. High and Low Enroute charts from two colors to four colors to give pilots and navigators enhanced situational awareness as they increasingly choose to fly off-route in a more dynamic mode.

In the instrument approach chart area, the impact has been very dramatic. Over 3,347 charts have been published that allow the approaches to be made with traditional navaids "or" GPS. Seven hundred and ninety seven GPS (standalone) approaches have been published; thus, over one half of all U.S. published approach charts are associated with GPS.

Future impacts for chart producers will be even more extensive and dramatic:

- Instrument approach charts will be reformatted and be produced in both digital and paper analog forms.
- Enroute charts will be reformatted and a companion product for off route enroute area navigation will be produced as a new series of charts. (The IACC has started deliberations on the specifications for this new enroute series.) Enroute charts will be published in digital and paper analog forms.
- Publications that supplement and augment IFR and VFR products will be issued in analog and digital forms.
- Databases will be created and issued for use in "value added" cockpit navigation systems.

BENEFITS OF UTILIZING GPS/GIS INTEGRATED SYSTEMS

Technological change in the aviation industry in the last 5 years has been rapid and will continue to accelerate dramatically well into the next century. The enhanced computers, improved data storage devices, advanced digital and graphic display systems, and GPS have enabled the industry to develop improved cockpit avionics, more accurate navigation capability, real time access to flight information, better communication networks, and improved air traffic management (ATM).

Near term benefits derived from GPS/GIS integrated systems include fewer traffic restrictions, better navigation capabilities, increased NAS user flexibility, and increased NAS capacity. Longer term benefits will include an improved ATM system with enhanced automation and mature supporting infrastructure that will allow aviators to fly optimized routing.

A unique development that will impact and benefit the airborne and ground based segments of the NAS is the Automated Dependent Surveillance - Broadcast (ADS-B). The ADS-B will allow aircraft equipped with traffic displays to see other ADS-B equipped aircraft and allow ATM to know the GPS

derived position of the equipped aircraft. Thus, this improved surveillance technology will provide more accurate position reports for use by controllers, pilots, and automated systems in the function of aircraft separation assurance.

GPS will allow accurate aircraft navigation in all types of weather; thus, many current weather-related flight delays will be avoided. Augmented GPS will also bring an end to the necessity for ground based navigation and landing systems for aircraft. Integrated GPS/GIS systems will provide substantial cost savings to the aviation industry.

The greatest benefit of these systems will be increased safety for the aviation community through better situational awareness provided to both pilots and the ATM system managers by GPS/GIS integrated systems.

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