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MARINE APPLICATIONS OF THE GLOBAL POSITIONING SYSTEM

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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:

CONVENTIONAL AND SATELLITE GEODESY, INCLUDING GLOBAL POSITIONING SYSTEMS

Marine Applications of the Global Positioning System

(Submitted by the United States of America)**

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Marine Applications of the Global Positioning System

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Abstract

Due to its availability and accuracy, the NAVSTAR Global Positioning System (GPS) of navigation satellites may be exploited by the marine community to support a wide range of applications, the scope of which are only now being realized. Designed for navigation, GPS offers to provide an infrastructure for not only marine navigation, but also for a broad range of commercial, scientific and governmental activities which, in the future, may be accomplished with increased accuracy and timeliness. GPS, in conjunction with other key technologies, will contribute to new applications in many significant areas such as marine crustal dynamics. This paper provides a survey of some of the applications of GPS in the marine environment, contrasting, where possible, past or current technology with GPS capabilities.

Introduction

The NAVSTAR Global Positioning System is an all-weather navigation satellite system scheduled for full operational capability in 1993. The system uses the concept of passive satellite navigation based on highly accurate atomic frequency standards to enable the navigator to determine three-dimensional position, velocity and time instantaneously on a continuous worldwide basis. Range and range-rate measurements taken simultaneously from at least four satellites will be reduced to determine these states. A total of twenty-four satellites in six orbit planes will be available for navigation giving accuracies and availability far exceeding the Navy Navigation Satellite System which GPS was designed to replace. With the number of satellites in view always exceeding the number required for navigation, the user may select a subset of four based on criteria which optimize the geometric strength of the navigation solution.

Because of its advantages as a navigation system of high accuracy, GPS offers the marine community support for commercial, scientific and governmental initiatives where positioning or time are critical components. Table 1 presents some of the applications which are discussed in further detail below. In several of these applications, GPS is combined with other critical technologies to fully develop the capability. Where GPS is cited, its use either directly or in the higher accuracy differential mode is implicit.

Navigation-Related Applications

The primary function of GPS is to provide the navigator all-weather instantaneous position, velocity and time. In what follows, a broader interpretation for marine navigation will be considered to include not only surface ship navigation but undersea navigation, platform attitude determination and structural monitoring as well. Generally, surface marine navigation has an accuracy requirement varying from 10 to 1000 meters depending on its purpose. This may range from general cargo transport requiring less accuracy at sea to detailed geophysical surveys or underwater search and rescue operations which may require high positional accuracy. Navigational systems currently available include Loran-C, the Navy Navigation Satellite (or Transit) System and inertial navigation systems as well as GPS. However, GPS in a stand-alone mode or in an aided inertial configuration has the capability to provide accuracies of 3 to 100 meters in almost real-time where other systems generally provide position to perhaps 100 meters or more. GPS offers increased satellite availability and accuracy over Transit, and can potentially standardize navigation for a broad range of users with cost efficient and timely positional information. A broad spectrum of GPS equipment supporting surface ship navigation is commercially available.

Future undersea navigation will combine the surface ship navigation capabilities of GPS with underwater acoustical measurements to directly position either submersible vessels or seafloor transponder networks which will act as acoustic benchmarks for the submersible. Floating buoys equipped with GPS and acoustic transponders can act as a dynamic surface control grid for undersea navigation. Accurate placement of seafloor acoustic transponder networks using GPS and acoustic ranges will allow localized submarine navigation above these ocean floor grids with accuracies of perhaps better than 5 meters.

Another application of GPS is attitude determination for a surface platform. A single receiver with multiple antennas collecting GPS phase information allows the determination of platform attitude. For applications requiring the measurement of ship orientation, GPS alone or a GPS-aided inertial implementation can provide with great efficiency a cost-effective method for estimating three degree of freedom ship attitude previously available only with complex inertial systems.

Finally, highly accurate GPS phase observables, collected at multiple antennas sufficiently separated spatially on critical superstructure points, can potentially measure the flexure of ships or other large ocean structures for the purposes of monitoring structural integrity or adjusting operating conditions as necessary. Although GPS receiver technology capable of achieving the necessary accuracy is available, this engineering application is just beginning to be explored.

Tables 2 through 5 provide, as appropriate, past (pre-GPS) capabilities to support navigation-related applications and a view of activities of the future (and possibly of the present) where supported by GPS.

Mapping and Charting Applications

In this context, mapping and charting applications will consist of collecting data sets for the compilation or revision of standard map and chart products which are required for maritime operations, the new emerging requirement of mapping Exclusive Economic Zone areas, the establishment or enforcement of maritime political boundaries or commercial lease demarcations, and the collection of high resolution data for mapping the seafloor and for the acquisition of bathymetry. As a positioning resource GPS can greatly enhance the metric accuracy of imaging systems such as the Landsat multispectral system or Gloria type sonar swath collection from which map, chart and seafloor graphic products can be compiled. GPS has already performed such a role for the NASA Landsat program where GPS orbit determination provided image point locations in space to within 15 meters. Seafloor acoustic benchmark networks may provide enhanced positioning control for detailed local seafloor mapping projects of the future. Airborne laser profiling systems for acquisition of near-shore bathymetry will take advantage of positioning by GPS to control data collection and the subsequent bathymetric contours. GPS will also contribute to determining datum transformations which will allow local map products and survey control networks on islands to be related to a global reference frame.

For numerous data collection programs of the future which support the improvement of mapping and charting required by the marine community, and for related applications such as monitoring the environment, GPS will offer the positional control which will allow diversified data sources to be merged together on a common reference system in graphic display (Tables 6 and 7). Another related use of GPS is the establishment and legal enforcement of lines of demarcation, either political or commercial, within the marine environment. For example, Article 3 of the Agreement between The United States of America and The Union of Socialistic Republics on the Maritime Boundary between these two nations, ratified by the United States Senate in 1991, defines the Bering Sea boundary using a sequence of 87 geographic points in the World Geodetic System 1984. Monitoring position along such a complicated line, to ensure compliance for fishing rights or mineral exploration, would be facilitated using GPS. This is but one example where an accurate capability to determine position at sea may be critical from a legal perspective. Table 8 provides a summary of the application of GPS in support of the maritime boundary issues.

Geodetic and Geophysical Applications

Two important applications requiring accurate positioning from GPS will be the development of a seafloor positioning (SEAPOST) capability with geodetic accuracies in a global reference frame of from 1 to 10 meters and the use of such marine control points to monitor crustal dynamics in the ocean environment where an accuracy of 1 to 10 centimeters may be required.

Although transponders have been positioned by combining satellite Doppler measurements and acoustics, GPS with its increased versatility when combined with modern acoustics facilitates the problem of accurate positioning of seafloor benchmarks and instrumentation with greatly increased efficiency. With appropriate geometric configurations, simultaneous collections of GPS pseudoranges and acoustic transponder ranges can theoretically result in geodetic accuracy for a marine network. If equipped with the appropriate high frequency acoustic transponders, intersite measurements along the ocean floor can be periodically collected to monitor the network configuration with the aim of estimating the nature of crustal dynamics locally. Tables 9 and 10 provide summaries of these applications.

Geodetic and Oceanographic Applications

GPS will play a major role by increasing our understanding of the high frequency structure of the ocean geoid and variations in dynamic sea surface topography. Using GPS for ship navigation, geophysical surveys of the major oceans will continue to collect high frequency gravity data providing enhanced models for the geopotential and better insight into the structure of the oceanic crust. After extensive radar altimeter surveys from space by SEASAT and GEOSAT, detailed geoids with wavelengths down to 35 kilometers exist for most of the world's oceans. Current and future orbital missions tracking GPS may improve or densify existing altimeter data bases. Such missions as TOPEX and GEOSAT FOLLOW-ON intend to monitor dynamic sea surface topography including global tides, ocean sea-state, sea-level, and dynamic effects attributed to currents, eddies, temperature variations, weather and other causes. Precision orbit determination combining GPS on-orbit and GPS ground tracking from a global network will provide the accuracy necessary to measure these effects. Recent work has also demonstrated the effectiveness of GPS equipped buoys for measuring sea-level as a possible replacement for traditional tide gauges. Tables 11 and 12 provide further information on these GPS applications.

Time Transfer

Although time is available to the GPS navigator as part of a four satellite solution, the precise time and time interval community has developed specialized hardware and techniques to transfer precise time at the 5 nanosecond level using GPS observables. This time transfer technology is based on common view using one or more satellites, with observing sites at known geodetic positions. Such time transfer may have application within the marine community for certain experimental applications where precise time synchronization is critical. Table 13 provides additional information on this application.

Summary

The marine community has only begun to exploit the NAVSTAR Global Positioning System. The applications cited here offer several important examples where the contribution of GPS is great, but the list represents only a starting point. As the marine scientific and engineering community becomes more familiar with the potentials for GPS, an increased number of applications will find the support of this system.

TABLE 1: GPS MARINE APPLICATIONS
Surface Ship Navigation Structural Monitoring Platform Attitude Determination Undersea Navigation Time Transfer Seafloor Topography/Bathymetry Mapping and Charting Maritime Boundary Definition Oceanic Geoid Oceanographic Applications Seafloor Positioning Crustal Dynamics

TABLE 2: SURFACE SHIP NAVIGATION

DESCRIPTION:	POSITION DETERMINATION FOR INSTRUMENTATION OR VEHICLES INVOLVED IN ON- OR NEAR BOTTOM SEARCH AND WORK FUNCTIONS, GEOPHYSICAL SURVEY, BOTTOM SAMPLING, WASTE DISPOSAL, FISHING, BIOLOGICAL STUDIES SEA-FLOOR RESOURCE DEVELOPMENT, ETC., INCLUDING CARGO TRANSPORT		
	PAST	FUTURE	
REQUIREMENT:	GENERALLY 10-1000 METERS		
TECHNOLOGY DESCRIPTION:	LORAN-C INERTIAL NAVIGATION SYSTEMS TRANSIT SATELLITE SYSTEM	GPS & GPS AIDED INS	ADVANTAGE
CAPABILITY:	GENERALLY COVERS REQUIREMENT INTERVAL TO 100 METERS	3-100 METERS	INCREASED SATELLITE AVAILABILITY & ACCURACY STANDARDIZED NAV APPROACH ALL WEATHER CAPABILITY
ECONOMY:			TIME/COST(?)

TECHNOLOGY DEVELOPERS:	GPS NAVIGATION DEVELOPERS
TIME FRAME:	TECHNOLOGY CURRENTLY AVAILABLE
RELATED APPLICATIONS:	MARITIME BOUNDARY DEFINITION SEAPOST OCEANOGRAPHIC APPLICATIONS

TABLE 3: UNDERSEA NAVIGATION

DESCRIPTION:	PROVIDE POSITION DETERMINATION FOR UNDERWATER SUBMERSIBLE VEHICLES		
	PAST	FUTURE	
REQUIREMENT:	TO 1-5 METERS		
TECHNOLOGY DESCRIPTION:		BOUYS EQUIPPED WITH GPS AND ACOUSTIC TRANSPONDERS OR SEAFLOOR ACOUSTIC TRANSPONDER SYSTEMS	ADVANTAGE
CAPABILITY:		< 5 METERS	ACCURACY & AVAILABILITY ALL WEATHER AUTONOMOUS CAPABILITY
ECONOMY:			COST

TECHNOLOGY DEVELOPERS:	GPS RECEIVER MANUFACTURERS ACOUSTIC EQUIPMENT MANUFACTURERS
TIME FRAME:	NEXT SEVERAL YEARS
RELATED APPLICATIONS:	SEAPOST & SURFACE SHIP NAVIGATION

TABLE 4: PLATFORM ATTITUDE DETERMINATION

DESCRIPTION:	AS A FUNCTION OF TIME DETERMINE THREE-DIMENSIONAL ATTITUDE OF SURFACE PLATFORM		
	PAST	FUTURE	
REQUIREMENT:	VARIES WITH APPLICATION		
TECHNOLOGY DESCRIPTION:	INERTIAL NAVIGATION SYSTEMS	GPS OR GPS AIDED INERTIAL SYSTEMS	ADVANTAGE
CAPABILITY:	VARIABLE ACCURACY	CONTINUOUSLY AVAILABLE ACCURACY REQUIREMENTS YET TO BE SPECIFIED	GPS AVAILABILITY
ECONOMY:	REAL-TIME HIGH ACCURACY INS EXPENSIVE	NEAR REAL-TIME AND POST PROCESSED RESULTS	TIMELY & COST EFFECTIVE

TECHNOLOGY DEVELOPERS:	EXAMPLE: ASHTECH 3DF RECEIVER
TIME FRAME:	GPS HARDWARE/SOFTWARE SYSTEMS CURRENTLY AVAILABLE CIVIL USAGE MAY BE IMPACTED WITH A/S IMPLIMENTATION
RELATED APPLICATIONS:	SHIP FLEXURE

TABLE 5: STRUCTURAL MONITORING

DESCRIPTION:	MONITOR FLEXURE OF OCEAN STRUCTURES FOR PURPOSES OF STRUCTURAL INTEGRITY, ADJUSTING OPERATING CONDITIONS, ETC.		
	PAST	FUTURE	
REQUIREMENT:	TO BE SPECIFIED		
TECHNOLOGY DESCRIPTION:	N/A	GPS PHASE DATA FROM MULTIPLE ANTENNAS	ADVANTAGE
CAPABILITY:		TO BE DETERMINED	NEAR REAL-TIME MONITORING
ECONOMY:			
	TECHNOLOGY DEVELOPERS:	GPS RECEIVER MANUFACTURES	
	TIME FRAME:	NEXT SEVERAL YEARS	
	RELATED APPLICATIONS:	PLATFORM ATTITUDE DETERMINATION	

TABLE 6: MAPPING AND CHARTING

DESCRIPTION:	PRODUCTION AND REVISION OF MAP AND CHART PRODUCTS ASSOCIATED WITH MARITIME APPLICATIONS		
	PAST	FUTURE	
REQUIREMENT:	VARIES WITH MAP AND CHART TYPE (SEE DMA PRODUCT SPECIFICATIONS, FOR EXAMPLE)		
TECHNOLOGY DESCRIPTION:	**SHORE BASED RADIO NAVAIDS**	(1) REMOTE SENSING SYSTEMS SUPPORTED WITH GPS SUCH AS LANDSAT AND AIRBORNE LASER SOUNDERS (2) SHIP & LAUNCH ECHO SOUNDING (3) USE OF SEAFLOOR BENCHMARKS FOR CONTROL	ADVANTAGE
CAPABILITY:	**ACCURACY DEGRADING WITH DISTANCE FROM SHORE**	PROVIDES SUFFICIENT COVERAGE AND ACCURACY FOR MAP AND CHART PRODUCTION AND REVISION TO A SCALE OF 1:50,000	COVERAGE & AVAILABILITY
ECONOMY:		?	MAP/CHART SURVEY ANDPRODUCTION TIME AND COST

TECHNOLOGY DEVELOPERS:	TECHNOLOGY DRIVEN BY NASA, USGS, NAVY, DMA PROGRAMS
TIME FRAME:	CURRENT CAPABILITY
RELATED APPLICATIONS:	MARITIME BOUNDARY (EEZ) SEAPOST

TABLE 7: SEAFLOOR TOPOGRAPHY / BATHYMETRY

DESCRIPTION:	PROVIDE DETAILED OR ENHANCED MAPPING OF THE SEAFLOOR USING REMOTE SENSING, AIRBORNE LASER PROFILING AND BATHYMETRIC SWATH SYSTEMS		
	PAST	FUTURE	
REQUIREMENT:	VARIABLE WITH APPLICATION		
TECHNOLOGY DESCRIPTION:	SWATH SYSTEMS SHIP BATHYMETRIC PROFILING	GPS SUPPORTED: GLORIA SWATH SYSTEMS SATELLITE ALTIMETRY REMOTE SENSING	ADVANTAGE
CAPABILITY:		VARIES WITH TECHNIQUE	MULTI-SOURCE DATA COVERAGE SPEED POSITION (CONTROL) ACCURACY
ECONOMY:		COST	COST AND EFFICIENCY
	TECHNOLOGY DEVELOPERS:	NASA, NRL	
	TIME FRAME:	TECHNOLOGY CURRENTLY AVAILABLE	
	RELATED APPLICATIONS:	SURFACE SHIP NAVIGATION MAPPING AND CHARTING WORLD HEIGHT SYSTEM OCEANIC GEOID	

TABLE 8: MARITIME BOUNDARY DEFINITION

DESCRIPTION:	ESTABLISHMENT OF POLITICAL OR COMMERCIAL BOUNDARY LOCATIONS USING SURFACE REFERENCED SYSTEMS		
	PAST	FUTURE	
REQUIREMENT:	1-10 METERS OR AS SPECIFIED		
TECHNOLOGY DESCRIPTION:	(1) TRANSIT SATELLITES (2) SHORE-BASED SYSTEMS	GPS	ADVANTAGE
CAPABILITY:	(1) 30-150 METERS (2) 5-10 METERS	10-15 METERS ABSOLUTE (P-CODE) 1-3 METERS RELATIVE	ACCURACY/AVAILABILITY REAL-TIME CAPABILITIES INTERNATIONALLY AVAILABLE STANDARD
ECONOMY:	(1) SYSTEM AVAILABILITY (2) DISTANCE LIMITATIONS	NEAR REAL-TIME & LOW HARDWARE COST	SPEED & COST

TECHNOLOGY DEVELOPERS:	NUMEROUS GPS EQUIPMENT MANUFACTURERS
TIME FRAME:	TECHNOLOGY CURRENTLY AVAILABLE SA/AS IMPACTS EXPECTED FOR GENERAL USAGE
RELATED APPLICATIONS:	SURFACE NAVIGATION

TABLE 9: SEAFLOOR POSITIONING (SEAPOST)

DESCRIPTION:	DETERMINATION OF ACCURATE GEODETIC COORDINATES FOR DEEP OCEAN LOCATIONS IN A GLOBAL REFERENCE FRAME		
	PAST	FUTURE	
REQUIREMENT:	1-10 METERS		
TECHNOLOGY DESCRIPTION:	TRANSIT SATELLITE DOPPLER & UNDERWATER ACOUSTICS	GPS & UNDERWATER ACOUSTICS	ADVANTAGE
CAPABILITY:	10 METERS MULTI-PASS SOLUTION (1 WEEK)	1-2 METERS < 6 HOURS	ACCURACY
ECONOMY:	?	ENHANCED BY MULTI-SATELLITE AVAILABILITY	TIME & COST

TECHNOLOGY DEVELOPERS:	GPS NAVIGATION RECEIVER DEVELOPERS GPS ATTITUDE RECEIVER DEVELOPERS
TIME FRAME:	TECHNOLOGY CURRENTLY AVAILABLE SA/AS IMPACTS EXPECTED FOR GENERAL USAGE
RELATED APPLICATIONS:	PLATFORM ATTITUDE & NAVIGATION

TABLE 10: CRUSTAL DYNAMICS

DESCRIPTION:	MEASURE/MONITOR GLOBAL PLATE TECTONICS ON THE SEAFLOOR; MONITOR AND UNDERSTAND LOCALIZED MOTIONS DUE TO LOADING, EPISODIC SLUMPING, CURRENT-SEAFLOOR INTERACTION, ETC.		
	PAST	FUTURE	
REQUIREMENT:	1-10 CENTIMETERS		
TECHNOLOGY DESCRIPTION:	N/A	DIRECT ACOUSTIC MEASUREMENT BETWEEN OCEAN BOTTOM TRANSPONDERS SUPPORTED BY GPS SEAPOST	ADVANTAGE
CAPABILITY:		1-5 CM	ACCURACY & RECOVERABILITY
ECONOMY:			

TECHNOLOGY DEVELOPERS:	GPS RECEIVER DEVELOPERS ACOUSTIC TRANSPONDER DEVELOPERS
TIME FRAME:	1991-----FUTURE
RELATED APPLICATIONS:	SEAPOST

TABLE 11: OCEANIC GEOID

DESCRIPTION:	DETERMINE THE GLOBAL OCEANIC GEOID		
	PAST	FUTURE	
REQUIREMENT:	10 CM - 2 METERS OR AS SPECIFIED		
TECHNOLOGY DESCRIPTION:	(1) SATELLITE ALTIMETRY (2) SHIP GRAVITY SURVEY	(1) SATELLITE ALTIMETER REMOTE SENSING WITH GPS ORBITS (2) SHIP GRAVITY SURVEY WITH GPS NAVIGATION	ADVANTAGE
CAPABILITY:	(1) 1-2 M TO > 35KM (2) 0.5-2 M TO < 35KM	(1) < 1M TO >35KM (2) EQUIVALENT	SATELLITE ORBIT ACCURACY SHIP NAVIGATION ACCURACY
ECONOMY:	(1) RAPID COLLECTION (2) COSTLY.	SIMILAR	

	TECHNOLOGY DEVELOPERS:	GPS SPACE RECEIVER DEVELOPERS GPS NAVIGATION RECEIVER MANUFACTURERS
	TIME FRAME:	(1) TECHNOLOGY/OPERATIONAL CAPABILITY 1992 (2) TECHNOLOGY AVAILABLE
	RELATED APPLICATIONS:	OCEANOGRAPHIC APPLICATIONS MAPPING & CHARTING APPLICATIONS (GLOBAL VERTICAL DATUM)

TABLE 12: OCEANOGRAPHIC APPLICATIONS

DESCRIPTION:	ESTIMATE/MONITOR OCEAN TIDES, OCEAN SEA STATE, DYNAMIC SEA SURFACE TOPOGRAPHY, SEA LEVEL,ETC.		
	PAST	FUTURE	
REQUIREMENT:	VARIES ACROSS OCEANOGRAPHIC COMMUNITY/APPLICATION		
TECHNOLOGY DESCRIPTION:	SATELLITE REMOTE SENSING SEASAT/GEOSAT	GPS SUPPORTED SATELLITE REMOTE SENSING TOPEX/GEOSAT FOLLOW-ON	ADVANTAGE
CAPABILITY:	SUCCESSFUL TECHNOLOGY DEMONSTRATION	OPERATIONAL CAPABILITY WITH ORBIT ACCURACY VIA GPS	GLOBAL OCEAN MONITORING (DATA SET REPEATABILITY IN DAYS)
ECONOMY:	CAPABILITY TO MONITOR MAXIMIZED BY MISSION TYPE	CAPABILITY TO MONITOR EXTENDED BY MISSION TYPE USING GPS ORBITS	
	TECHNOLOGY DEVELOPERS:	NASA / US NAVY GPS SPACE RECEIVER DEVELOPERS (MOTOROLA)	
	TIME FRAME:	TECHNOLOGY AND OPERATIONAL DEMONSTRATION 1992-1995	
	RELATED APPLICATIONS:	OCEANIC GEOID MAPPING AND CHARTING	

TABLE 13: TIME TRANSFER

DESCRIPTION:	PROVIDE CLOCK SYNCHRONIZATION AT REGIONAL SITES		
	PAST	FUTURE	
REQUIREMENT:	TO 5 NANOSECONDS		
TECHNOLOGY DESCRIPTION:	(1) TRAVELING CLOCK (2) LORAN-C	GPS	ADVANTAGE
CAPABILITY:	(1) 5 - 100 nanosec	TO 5 NANOSEC	ACCURACY
ECONOMY:		COST	SPEED/COST

TECHNOLOGY DEVELOPERS:	STANFORD TELECOMMUNICATIONS INC.
TIME FRAME:	TECHNOLOGY CURRENTLY AVAILABLE
RELATED APPLICATIONS:	