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MARINE GEODESY IN THE DEPARTMENT OF DEFENSE (USA)

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INTRODUCTION

Marine geodesy during and since World War II has occupied a significant place in the military whenever precise positioning or distance measurements were required. Applications of geodetic principles in coastal and deep ocean marine environments have been of perhaps greater importance to the Naval Oceanographic Office (NAVOCEANO) and the Defense Mapping Agency (DMA) in DoD. The Army Corps of Engineers depends also on accurate geodetic control in the conduct of hydrographic survey and dredging operations in United States harbors and inland waterways. Accurate absolute positions are critical for Air Force global operations using electronic navigation systems referenced to the World Geodetic System (WGS). Even the Department of State depends on DMA and the National Ocean Service (NOS) for Doppler-derived island positions and computed geodesics to determine Exclusive Economic Zone (EEZ) 200-mile limits from continental baselines and median lines between U.S. and foreign territories. Other navigational problems demanding precise geodetic control are associated with radioactive waste disposal and missile-firing evaluations.

The aim of this paper, therefore, is to review major marine geodetic requirements, relevant applications, and major developing systems, some of which are being developed for DMA through the Naval Ocean Research and Development Activity (NORDA).

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EVOLVING CONCEPTS

Background

In the 1940's, classical geodetic survey methodology embraced astronomic observations for calculating latitude, longitude, and azimuth, plus gravity measurements for determining deflection of the vertical, followed by base line length measurements, vertical leveling to bench mark referenced to mean sea level, and theodolite angle observations through a network of area-wide triangles. Computations based on these efforts yielded geographic positions of various orders of relative accuracy oriented to a local, national, or regional datum. They also provided the framework to which secondary or tertiary control stations were linked and, ultimately, all off-shore depth measurements and features positioned.

In later years, medium- and long-range electronic surveying systems were introduced and used to produce point position coordinates, all of which can now be tied-in to precise, absolute positions obtained by the most important technologically advanced Doppler navigation/survey system. This system with receivers is known as the Navy Navigation Satellite System (NNSS) or TRANSIT.

Techniques and equipment used in the earlier hydrographic survey operations still persist — especially in developing countries. But over the past 40 years, many changes have been made, and by the late 1980's other major new technologies will be on line. The most significant new positioning system for Mapping, Charting, and Geodesy (MC&G) programs will be the NAVSTAR Global Positioning System (GPS).

SENUS [1] and GRUNTHAL [2] have adequately described GPS as being a Department of Defense (DoD) system which is expected to provide the solution to most off-shore navigation and positioning problems. GPS is a passive, worldwide, all-weather, space-based radio-positioning system. When fully operational, in late 1988, it will provide 24-hour, highly accurate three-dimensional positions, velocity, and time information to an unlimited number of suitably equipped users. Dynamic (navigation) accuracy of about 16 meters is expected for users having access to the Precise Positioning Service (PPS); 100 meters, for users with the Standard Positioning Service (SPS). Suitable techniques may provide in two to four hours absolute global point positioning with an accuracy of about one meter relative to WGS, as compared with the 2-3 days of observations using the NNSS.

GPS operating in a dynamic mode on board survey vessels is expected to replace eventually (post 1990) the NNSS primary positioning control system and to revolutionize hydrographic surveying logistics. A significant advantage in possessing an external coordinate-fixing capability aboard survey ships collecting geophysical data such as gravity is that vector corrections relative to course made good are tracked more effectively. According to DUNN and HIGGS [3], annual savings over current costs of operating two Navy coastal survey ships by using GPS are estimated to be $4.2 million and include considerably more efficient use of the ships.

Requirements

From the military mapping, charting and geodesy (MC&G) viewpoint, it is essential that regional or theater-wide requirements be identified mainly by the principal users — the Unified and Specified Commands; e.g., Commander-in-Chief Pacific (CINCPAC), the Military Departments, Department of State, Maritime Administration (MARAD), and individual merchant marine vessels. Stated requirements are reviewed carefully by DMA for validation and resource allocation purposes. The process includes analyses of available data and products to ensure DMA indicates that requirements can be satisfied with present inventory resources or that additional efforts will be undertaken. Requirements are weighed against assessments of current capabilities in terms of evaluated products and data on hand. The net result is that portions of highest priority goals are programmed for achievement with available DMA resources to reduce the level of total requirements within established milestone periods.

Validation of a requirement recognizes the need for a particular product or service. Geodetic accuracy requirements to support military operations involving weapons systems, e.g., missile-firing, mandates initiating action by DMA to ensure that different areas are referenced to the same three-dimensional datum. DMA's primary mission includes development of modern geodetic earth reference models and maintenance of a network of Doppler tracking stations in order to compute precise ephemerides for geodetic satellite orbits and subsequent determination of point position coordinates. An enormous effort is also required of DMA to convert thousands of control points based on various datums worldwide in order to refer them to the global reference system — WGS.

If more accurate or complete geodetic surveys are required, priority of effort is assigned and passed to a DMA Component (the Hydrographic/Topographic Center at Washington, D.C., the Inter-American Geodetic Survey (IAGS) at San Antonio, Texas) or to NAVOCEANO at Bay St. Louis, Mississippi. World geodetic model parameters for WGS updates, as well as assistance with NNSS and GPS software developments, continue to be provided by the Naval Surface Weapons Center (NSWC) at Dahlgren, Virginia. Coordination of geodetic surveys is also arranged by DMA with the National Geodetic Survey, National Ocean Service, NOAA and countries with which DMA has agreements.

The most important geodetic requirement that confronts DMA is associated with datum establishment and adjustments on a global scale which impact not only on MC&G products, but also on land, air and sea military operations. Of equal importance are the spin-off benefits that accrue to civil maritime users who receive virtually the same navigational products. For the past thirty years, global datum updates have been made in each decade. The World Geodetic System of the 1960's was superseded by WGS 72. The latter was approved as a chart reference system in 1983 by Member States of the International Hydrographic Organization (IHO) with full knowledge of the planned update to WGS 84 effective in early 1985. For mapping and charting purposes, the differences between WGS 72 and WGS 84 are negligible, being a − 0.24 second of longitude shift which is approximately 7 meters on the ground and, consequently, insignificant at chart scales smaller than 1:10,000.

APPLICATIONS OF MARINE GEODESY

Datum Conversion Guidance

The DMA Table of Transformation Parameters for Geodetic Datums to WGS 72, complete with conversion formulae, was recently submitted to the International Hydrographic Organization at Monaco and issued under IHO Circular Letter 44, September 1983, to all 52 Member States. The table, while equally applicable to topographic maps and aeronautical charts of the same regions, was released to the international chart community to enable geodesists/cartographers in various hydrographic offices to make the necessary datum conversions. As a result, navigators using NNSS or radio navigation systems oriented to WGS can apply their corrected coordinate positions directly to charts that are still based on national or regional datums.

With increased use of earth-centered datum-related navigation systems, it is not difficult to perceive the difficulties in which navigators would find themselves if ship or aircraft navigation instrument readouts and coordinate plots did not relate to charted geographic features and projected tracks. For this reason, the Defense Mapping Agency has already produced hundreds of maps and aeronautical charts at scales of 1:250 000 and larger referenced to WGS. Also, as of August 1983, more than 345 DMA nautical charts at various scales have been produced on WGS-72, and 1750 charts either carry datum shift notes or the datum tie exists to allow them to be referenced to WGS. The remainder of the charts (totalling 1300) at scales of 1:500 000 or larger, will be investigated for feasibility of datum correction; those selected will be programmed for referencing to WGS by one means or another by 1989.

Although it is essential that up-to-date and complete charts reflect correctly symbolized, color-coded and textually described information, nothing is more crucial to users than the chart's geodetic framework. It provides the required positional accuracy on which the portrayed data must depend. For this reason, geodesists and cartographers concentrate on accurate computations and clearly understood procedures to ensure users' understanding of chart datum and change relationships. The paramount task — always — is to promote the safety of lives and property at sea and in airspace.

Data Collection Systems Used for Global Gravity Modeling

Radar altimetry data from GEOS-3 and SEASAT satellites have contributed significantly to the upgrade of the geoidal model over the open ocean areas of the world as well as an improved earth gravity model. Similar data from GEOSAT will be obtained in 1985 and integrated with earlier data to provide for an improved global gravity model and verification data in support of WGS 84. DMA also has a long term program to develop and deploy a moving-base gravity gradiometry system designed for ground and airborne surveying.

Organized Studies on Marine Geodesy

A most useful and interesting study to identify requirements for marine geodetic applications in support of national objectives in ocean science, engineering and operations over the next two decades was initiated in 1980 by the Marine Technology Society (MTS) and is summarized by SAXENA [4].

The study established a broad definition of marine geodesy to form a base for several applications of marine geodesy, such as (1) marine gravity, geophysics, and geology, (2) shallow water hydrography, (3) deep ocean bathymetry, (4) positioning and navigation, (5) plate tectonics/sea floor spreading, (6) ocean surface topography, mean sea level, tidal variations and (7) tsunamis. The role of geodesy in each of these fields is clearly discernible.

Most of the national objectives that require supporting marine geodetic applications bear direct mission interest of the DoD although some of the recommendations appear to be more within the interest range of civil agencies and scientific institutions. For familiarization purposes in this paper, the definition of the term marine geodesy and its inter-disciplinary fields has been retained as follows :

> Marine geodesy is the science which defines and establishes control points in and/or on the ocean, and the shape of the ocean including its floor. It includes those maritime activities that depend on determination of position or accurate measurements on, under, and above the ocean surface. The areas covered under this inter-disciplinary field, among others, include : bathymetry, positioning (ocean floor and surface), gravity, plate tectonics, seafloor spreading, geoidal undulation, tsunami research, mean sea level, and tidal variation.

One can also refer to the classic definition of geodesy, defined for navigators in BOWDITCH [5], as that science concerned with the exact positioning of points on the earth; also, the study of the earth's gravity variations, and the application of these variations to exact measurements on the earth. In actuality, therefore, the science of marine geodesy does not differ from geodesy *per se* except for specialized techniques that are necessary to achieve required positioning accuracies to locate ships, projects and features in the ocean environment.

Marine geodesy needs and opportunities on the ocean bottom were investigated in the Report entitled *Seafloor Referenced Positioning* issued in 1983 by the Panel on Ocean Bottom Positioning, a group of scientists meeting under the aegis of the National Research Council [6]. The five-member Panel comprised three scientists from Scripps and Woods Hole Institutions of Oceanography and two from industry. DMA provided a liaison member; three others represented NOAA, NASA, and USGS.

Five requirements were generated by demanding situations found in the study (see Figure 1). It is appropriate that they be included in this paper to emphasize the increased use of seafloor for position-locating functions using acoustic transponder systems tied to an appropriate global coordinate system or to nearshore radio positioning systems.

Problems	Accuracy	Range	Lifetime
1. 3-D seismic survey	10 cm	10 km	1 month
2. Missile-firing evaluation	10 m	10,000 km	1 month
3. Radioactive waste disposal	10 m	10 km	10^5 yr
4. Geodynamic-spreading centers, transform faults, slump zones	1-10 cm	10 km	10 yr
5. Geodynamics - subduction, interplate motion, intraplate deformation	1-10 cm	1,000 km	10 yr

FIG. 1. — (From *Seafloor Referenced Positioning*, Panel on Ocean Bottom Positioning, NRC, 1983).

With reference to navigation requirements, the Panel's conclusion was that, while all of the goals appear to be achievable, none is currently met by validated operational systems. However, with regard to navigation requirements, most seafloor-oriented navigation problems can be solved with systems capable of precision of the order of 1 part in 10,000. The major conclusion is that current capabilities, including seafloor acoustic transponders and a variety of radio positioning systems, can meet the 1 part in 10^4 requirements, if carefully used.

Where seafloor related geodetic positioning requirements involve boundary marking and geodynamics, the former lead to accuracy requirements in the 10 m range which can be met under the sea with near bottom acoustic transponder systems and tied-in to nearshore radio positioning systems. In offshore ocean regions, only GPS can be expected to achieve the desired accuracy. (KUMAR *et al.* [7] reaffirm the latter claim in their efforts on error analysis for marine geodetic control using GPS.) Within the geodynamic context, tectonic plate action, slumping of thick sediment columns, and earthquake-induced crustal motions lead to more stringent requirements which are in the 1-10 cm accuracy range.

The Panel also concluded that marine physics (particularly underwater acoustics and optics) must play a major role in seafloor-oriented geodesy. Most of the investigators who understand marine physics and carry out innovative work in it are supported by groups within the U.S. Navy whose primary interests do not include either geodesy or geodynamics (NAVOCEANO's hydrographic and oceanographic surveying missions were overlooked.) Traditional geodetic activities are centered in the Defense Mapping Agency (DMA) and the National Geodetic Survey (NGS). (It is true that DMA has no requirement to date for ocean floor surveys at an accuracy of 1-10 cm.) NGS is primarily concerned with requirements for terrestrial control, leaving only minimal resources at this time for marine problems. (Report ignores extensive marine geodetic survey efforts by NOS.) The most comprehensive fundamental geodynamics research programs are those of the National Science Foundation, whose interest in geodesy, either on land or sea, is quite small. The National Aeronautics and Space Administration, with its focus on application of space-oriented techniques, has become the major supporter of geodesy in the geodynamics context but has not to date sponsored any related major undersea programs. The U.S. Geological Survey has been involved in geodesy in a geodynamic context in connection with earthquake-related research, but again this has been primarily a land-based effort. (Beginning with 1984, however, USGS became involved in sonar side-scan surveys of the seafloor in the outer reaches of the U.S. West Coast EEZ. These surveys, which were recently completed, are Loran-C controlled.)

DMA Hydrographic Research and Development for the 80's

BODIE [8] provides a succinct description of DMA projects plus those of other agencies, which are aimed at exploiting space, airborne, and surface sensors to develop rapid, cost-effective, large-area coverage data collection systems and associated assimilation and processing techniques. Priority is given to increasing data acquisition efficiencies and to automation in the data handling and analysis processes. The program is structured to address airborne, satellite and surface hydrographic data acquisition and subsequent data processing. Virtually all the project results, where positioning data is integral to the systems employed, will depend on marine geodetic applications based on either NNSS or GPS positioning control and referred, of course, to WGS. DMA, in conjunction with NASA, NOAA and USGS, is developing a GPS geodetic receiver (GEOSTAR TI4100) for precise geodetic applications.

Improved analysis tools and in some cases interactive work stations to analyse data collected from space sensors as the Multi-spectral Scanner (MSS) flow aboard the LANDSAT series and the Thematic Mapper on LANDSAT 4 and 5, SEASAT and aircraft Synthetic Aperture Radar (SAR) imagery and Shuttle Imaging Radar (SIR-A and B) are being developed by DMA to improve the exploitation of these materials for its hydrographic program. All of these sensors are intended to yield data concerning either ocean surface expressions and/or correlation with bottom features.

Surface sensors such as multi-beam sonars and sector-scan sonars and the Hydrographic Information Handling System (HIHANS) will concentrate on collecting data on depths and physical features on the ocean floor for digitizing and using on DMA products.

Airborne sensors, mainly the Multi-spectral Active/Passive Scanner (MAPS), the Hydrographic Airborne Laser Sounder (HALS) and the Extremely Low Frequency Electromagnetic (ELF/EM) system are all aimed at rapidly collecting data over a wide area with accurately positioned aircraft or space craft. DMA is closely monitoring the Australian Laser Airborne Depth Sounder (LADS) and the Canadian Light Detection And Ranging (LIDAR) developments in association with HALS and MAPS.

SUMMARY

Geodetic surveys conducted and managed by DoD agencies such as NAVOCEANO and DMA are concerned with straightforward control establishment techniques using both conventional and sophisticated advanced equipments. The resultant geodetic control, along with that obtained from other sources, is used to produce a host of DMA graphic and digital products required for military operational support and for general use by the merchant marine worldwide.

Gravity surveys are a vital adjunct to geodetic surveys, and they are required to attain one or two milligals accuracy in coastal and oceanic regimes where data is used primarily to improve the earth gravity model and to support various weapons systems.

Requirements for geodetic survey control data (point positioning) in area theaters are normally generated by major military command users. Transregional or worldwide requirements are generally initiated by DMA who is in the best position to be aware of datum deficiencies, for example, the African Doppler Survey (ADOS) program is aimed at computing observed Doppler stations in 55 African countries to provide a zero-order geodetic network for WGS compatibility.

The most modern geodetic survey capabilities currently exist with the Navy Navigation Satellite System (NNSS) and in the future, the DoD NAVSTAR Global Positioning System (GPS). DMA coordinates many of its geodetic surveys with other federal government survey organizations and countries with which DMA has agreements.

DMA has contributed the means for IHO Member States to orient their own charts to WGS. As of 1983, DMA had related 62 percent (2095) of its 3400 nautical charts to WGS and is proceeding toward completion of the task by 1989.

Marine geodesy is now being applied to surveys of the ocean bottom; for example, missile test firing evaluations and political boundary survey projects. Other surveys, not yet attainable in the undersea environment, require 1-10 cm accuracy for geodynamic plate tectonics and other localized motions.

DMA possesses a well-trained professional personnel complement, along with a sophisticated array of data collection and processing technologies, with more under development for use beginning in the late 1980's.

DoD's MC&G requirements and production challenges must be met by anticipating crises while, simultaneously, planning better utilization of technology for long-term production.

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