Keynote Address

Inertial Methods in Mapping

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EDITOR'S NOTE. The KEYNOTE ADDRESS was delivered on March 14, 1962 following the end of the sessions of the American Congress on Surveying and Mapping and prior to the beginning of the sessions of the American Society of Photogrammetry. The place was the Main Ballroom of The Shoreham Hotel, Washington, D. C.

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The address as published in this Journal confirms exactly to that approved by Dr. Draper.

INTRODUCTION

MAPPING, the process by which regions of the actual world are described in terms of systematic scales or projections for lines drawn on convenient surfaces, is an art dating from the days of antiquity. The course of history itself has been paced by man's progress in making useful pictures of the earth and the sky. Early representations were often imaginative rather than correct, but today, generally available maps and charts leave little to be desired in either perfection or beauty.

Concepts of the earth and the heavens have changed with time and the instruments for measuring the quantities associated with these concepts have had to be greatly improved, but mapping of any region has continued to involve two basic elements. One of these elements is some reference space represented by a convenient set of coordinates. The other element is some physical quantity which is uniquely definable at each point of the region to be mapped. Linear distance from bench marks has been used for this quantity since the beginning of human travel. In later centuries, angles defined with respect to reference frameworks, have served to identify points.

The earth itself is a familiar example of a reference space often represented with latitude and longitude as surface coordinates. The earth's axis of rotation determines one basic direction for terrestrial space and is closely associated with the polar axis of celestial coordinates. The Greenwich meridian, an arbitrarily selected great circle on the earth, and the equator complete the usual definition of reference coordinates for points on the earth. A similar service for celestial space is provided by the *First Point of Aries* which is fixed by the line of intersection of the earth's orbit with the plane of the celestial equator on the side of the *Vernal Equinox*, the position of earth at the start of Spring.

Celestial coordinates are defined by lines of sight to properly selected stars and may be considered as representing a basic reference space for all mapping situations. Terrestrial coordinates, being fixed to the earth, share the rotation and translation of this planet among the stars, but the motions involved are so consistent and so well known that time and some knowledge of descriptive astronomy make it possible to transform freely between celestial space and terrestrial space. The ancient and now highly developed art of clestial navigation depends upon the routine realization of such transformations.

When a navigator uses his sextant to shoot lines of sight to selected stars, he is measuring the angles between the horizontal plane, which fixes the local vertical, and known directions in celestial space. If our planet did not rotate among the stars, sextant observations alone would be sufficient to locate points on the earth. The earth does rotate with respect to the celestial sphere, but this rotation may be related to the readings of a chronometer or the indications of some other means for accurately measuring sidereal time. Once the instant of observation is given in Greenwich time, the angular position of the earth with respect to the celestial sphere, that is the hour angle is known. It is a simple matter to use this angle for shifting instantaneous positions in celestial coordinates to corresponding locations in terrestrial coordinates.

The computations needed for fixing points on the earth by using the celestial sphere for reference purposes are relatively simple. A proper ephemeris to give celestial body locations, and logarithm tables supplied the needs of navigators for many years. In later times, improved presentations of information, more convenient means for carrying out computations, and simpler methods have appeared to help navigators of ships and aircraft. The trend toward automatic systems has also been very apparent, and it is reasonable to expect that automation will be used to guide substantially all the important missions of the future.

MAP MAKING AND NAVIGATION

Map making depends upon a great mass of data representing locations of many points of the region to be covered. These data must be expressed in terms of the reference coordinates to be used for the map. The methods used to build up the required information for a map could be those of celestial navigation which are usually applied to find the position of a vehicle on a map or chart. In the past, only bench marks have usually been established by reference to celestial space, while direct linear measurements, optical triangulations and microwave techniques have been applied to fill in details for the regions around the bench marks. These procedures are inherently difficult, slow, expensive, and have been effectively impossible for some regions such as inaccessible jungles, mountains, deserts, and the subsurface spaces of the oceans. Until recent years, the lack of maps for such places has not been important, and a certain lack of accuracy in various parts of other maps has been a tolerable defect.

This picture has changed during the last few years for both military and civilian applications. Long range missiles fired from marines well below the surface must have good initial position information if they are to be successful. Developments in new regions of the earth surely need accurate, detailed maps if the planning and execution of projects is to be most effective. The basic requirement is the same for all situations. A technique is needed for mapping that can rapidly provide accurate, complete, and detailed data for extensive regions without complete and continuous dependence upon optical, radio or sonic links to points outside of vehicle carried equipment. With such equipment on board a vehicle moving on the land, on the water, under the water, in the air, or above the atmosphere may be automatically constrained to move so that it covers all the essential points of the region to be mapped. Systems now feasible from state-of-the-art capabilities can accurately and automatically navigate a vehicle through any desired pattern. To acquire information for mapping purposes it is only necessary to record the navigational data and to associate these data with identified points on the earth. This identification may be photographic, based on natural landmarks or human works for the land, and in terms of sounded depths for the seas. With the positional and identification data continuously available from complete coverage patterns moved over by a suitable vehicle, complete mapping information for a given region may be made recorded during a short period of time. Any one of several techniques are available for accumulating this information in a form that may be automatically or semiautomatically applied in making maps of any desired type.

OPERATING COMPONENTS OF AUTOMATIC MAPPING SYSTEMS

Automatic mapping systems for the earth's surface must include operating components that provide seven essential functions.

1. Indication of Reference Coordinates.
2. Indication of Local Vertical.
3. Indication of Surface Altitude.
4. Identification of Points.
5. Monitoring of Information.
6. Accumulation of Information.
7. Mapping of Accumulated Information.

For all of these items an implied requirement is accepted under which mapping information must be rapidly accumulated by vehicle carried equipment, self-contained to the extent that continuous cooperation from external sources of radiation is not required. It is also implied that inaccuracies of not more than a few hundredths of a nautical mile are acceptable. In terms of angles between local verticals, one minute of arc corresponds to a mile on the earth's surface. This means that one hundredth of a nautical mile corresponds to slightly over one half second of arc.

Reference coordinate indications accurate to within the desired tolerance may be achieved by the use of inertial equipment based on high performance gyroscopic units controlling the torque motors driving three-degree-of-freedom gimbal systems. Local vertical indications of acceptable accuracy may be mechanized by means of servo-driven gimbals controlled by signals from damped pendulum units.

Because, under Einstein's law of equivalence, the effective force acting on a pendulum is the resultant of gravity and inertial reaction to linear acceleration, it is necessary to use special dynamics in eliminating the interference due to acceleration in systems for indicating the vertical. The dynamic characteristics used cause the vertical indication to rotate with an angular acceleration equal to the linear acceleration of equipment on the spherical surface of the earth, divided by the radius of this surface. When this condition exists, the vertical indication changes at its direction at the same rate as the change of direction of the time vertical and linear accelerations of the equipment do not introduce errors in indications of the vertical.

Systems which are free of errors because they behave in this way are said to have Schuler Tuning, a name chosen because Professor Schuler first worked out the theoretical background for vertical indicators carried by moving vehicles. In practice, Schuler Tuning results in a period of 84.4 for equipment to be used on the surface of the earth.

Indications of altitude for points on the earth's surface cannot be generated by inertial equipment by using the principles applied in finding positions. Pressure measurements in water or air by refined instruments may be interpreted in terms of altitude from sea level for the vehicle carrying mapping equipment. Altitudes for surface points must be found in terms of the distance from the equipment carrying vehicle to the surface. Various ways of measuring this distance are available. Sonic depth finders are routine instruments for vehicles that travel in or on the water, while radar type altimeters are in common use for aircraft. Signals from such devices as these may be recorded in the data accumulator for combination with other information when maps are drawn. Points on the earth may be identified by photography or other means synchronized with point location data.

Information from the various sources may be recorded on magnetic tape in the form of digital signals, it may also be typed on paper as groups of numbers and at the same time it may be drawn on automatic plotting boards for "quick look" monitoring purposes. Monitoring of this kind may use continuous comparison of current indications with previously available information in order to reveal malfunctions of equipment, and other discrepancies while runs are in progress. With this knowledge, the seriousness of difficulties may be judged, and proper corrective measures applied.

It is to be noted that with orientational and positional indications of high quality available, magnetic fields, gravitational fields, radiation fields, electrostatic fields and other physical quantities may all be measured in magnitude and direction as the collection of mapping data proceeds. The signals representing these field measurements may be accumulated as additional components in the record of information which is to later be reduced to maps and charts.

INERTIAL INDICATION OF REFERENCE COORDINATES

Reference, space, celestial, terrestrial, vehicular or of some other sort is always necessary for any mapping operation. The use of stars to establish celestial space coordinates is a familiar process in navigation and for the establishment of bench marks. Self-contained mapping equipment depends upon Newton's law of inertial reaction as this law is applied in the spinning rotors of gyroscopic units designed to provide accurate indications of reference coordinates. Gyroscopic principles have been thoroughly understood for over a century and orientational control instruments have been standard devices in aircraft for twenty years, but performance of inertial guidance quality has been available from production equipment for less than ten years. The necessary improvement from conventional aircraft bank and climb indicators to units of inertial quality performance is greater than three orders of magnitude. This improvement corresponds to differences between drift rates of about fifteen degrees per hour which are common for aircraft instruments, and the few seconds per hour needed for even marginally useful mapping equipment.

At the present time many different designs for gyroscopic instruments are either in production, under test or being developed. All of these designs depend on the fact that every rotor spinning at constant speed has an angular momentum vector of constant length associated with its motion. When a torque is applied to the rotor at right angles to this vector which is parallel to the spin axis, the spin axis changes its direction with respect to inertial space with an angular velocity proportional to the torque and inversely proportional to the magnitude of the angular momentum. Thus if a gyro rotor spin axis is free from all torque at right angles to itself it will hold a set direction with respect to inertial space. Thus, one gyro rotor with two-degrees-of-freedom will establish two directions in inertial space. A second such gyro rotor will establish the third direction needed to completely define the orientation of a three dimensional space. The same result may be realized by a set of three single-degree-of-freedom gyro units.

The practice of over forty years before 1950 found it impossible to realize three-degree-of-freedom gyroscopically stabilized members with performance in the seconds of arc region when the rotors themselves were used to resist disturbing torques. Within the last decade applications of electronic developments, servomechanism techniques, and modern technology have made it possible to design and build inertial reference members able to give stabilization performance with seconds of arc tolerances.

All gyro developments of importance have so far been sponsored by military projects with performance requirements matched to missile requirements rather than to the needs of mapping. It is certain that existing production gyro units are capable of providing inertial reference coordinates of mapping system quality. It is also very likely that that modifications to gyro designs would result in instruments of significantly improved performance.

The general objective of gyro unit design is to achieve instruments with the minimum disturbing torque per unit of rotor angular momentum. The principal line of attack has been to suspend a very closely balanced rotor system by bearings with the lowest possible friction. Although some units with quite high performance have been built, strong efforts are still being expended toward the development of many types of bearings. Journal bearings lubricated by gas, pressured air bearings, cyrogenic superconductors to give magnetic field support bearings, electrostatic bearings, floatation bearings, magnetic support bearings, permanent bearings, ball bearings, roller bearings, elastic supports and various other devices have been applied in the design of gyro units. As yet the evidence is not conclusive as to what type of gyro rotor support will finally be judged as superior to all others. Single-degree-of-freedom floated gimbal units with magnetic suspensions have proved to be satisfactory for ballistic missiles, aircraft and marine vessel applications. Many improvements in these units for mapping purposes appear to be possible. Proof of this opinion must wait on experience with actual systems.

In any case, gyroscopically established inertial reference coordinates are inherently non-rotating with respect to celestial space. So far as present knowledge is concerned, once the initial alignment of reference member is made with respect to celestial coordinates, a system of perfect gyro units will provide perfect indications of celestial space in the form of signals representing angles between internal parts of the mechanism. These indications may be derived directly from angles among mechanical parts or they may be computed from known calibrations of gyro units that actually rotate with respect to inertial space. In effect, the system contains a small, accurate and continuously available geometrical model of celestial space that may be used in the most convenient way for any given application.

Terrestrial coordinates may be indicated from an inertial reference member if sidereal time is used as an additional input. The simplest mechanical arrangement is to align the inner axis of the inertial reference member gimbal system with the polar axis of the earth. With this configuration a sidereal time drive between the inner gimbal and the next supporting gimbal causes the inner gimbal to rotate in synchronism with some meridian on the earth. This action makes it possible to use this gimbal as a terrestrial coordinate reference member for mapping points on the earth's surface. The same function may also be provided by computer transformations of angles without the need of a time drive within the system between mechanical parts.

Direct time drive systems and computer transformation systems have both been reduced to practice, and have given good results in practice so that either may be used by designers to meet the needs of particular operations.

PENDULUMS AND ACCELEROMETERS FOR MAPPING SYSTEMS

Instruments that produce output signals when they are subjected to linear acceleration inputs are commonly called *linear accelerometers* or merely *accelerometers*. Devices of this kind depend upon the force that acts on each particle of a body that is subjected to linear acceleration. This *inertia reaction body force* acts along the line of the acceleration but in the opposite direction with a magnitude proportional to the magnitude of the acceleration. Gravitational fields also produce body forces that are not directly distinguishable from inertia reaction forces so the sensing element of any acceleration really responds to the force per unit mass, that is the *specific force*, determined by the resultant inertial reaction and gravitational forces. The actions involved depend directly on Newton's Laws of Inertia and Gravitational Action. No hysteresis or saturation effects are involved so that for the gravity fields and accelerations involved in mapping operations simple *seismic elements*, that is bodies adapted to respond to specific force inputs, are perfectly satisfactory for receiving the basic inputs and producing force or torque as the essential output.

Specific force receivers differ among themselves in the means used to balance the outputs from their seismic elements and to produce signals representing input levels in terms of accurately known calibration levels. Elastic deflections of springs, effective components of earth's gravity, magnetic field restraints, eddy current forces, gyroscopic torque, electromagnetic torque based on feedback signals and various other methods have been applied to provide calibrated signals from specific force receivers. It is of interest to note here that various instruments have been designed, built, and tested to specifications that correspond well to the performance need for mapping system equipment.

Using available servo and electronic techniques, controlled members with their orientations determined by signals from specific force receivers can give angular indications of the vertical with inaccuracies less than one second of arc. By use of Schuler Tuning, performance of this kind should be maintained on vehicles moving through mapping patterns.

INERTIAL SYSTEMS FOR MAPPING

Inertial systems satisfactory for mapping purposes may surely be designed and built on the basis of currently available techniques and components. Gyro units, specific force receivers, ground clearance indicators, electromagnetic radiation systems for locating points, sonar equipments, pressure operated altimeters, etc., may all be more or less "taken off the shelf." However, it is probable that any system designed at the present time will be "sensor limited" because signal handling techniques and computers are so highly developed that performance at any level needed to avoid mapping errors from computer operation can surely be realized. The use of digitalized signals, digital computers, and digital recording on paper or tape not only insures satisfactory data handling capacity and performance, but allows the construction of equipment with reasonable size and reliability for field operations.

Sensing instruments can surely be improved for the purposes of mapping, so it is reasonable to expect that excellent over-all performance will be the reward for efforts spent on equipment based on inertial techniques.

Inertial techniques require that reference members be given initial orientational alignments. In practice also operating periods will be limited by errors accumulated because of gyro drift rates. The need for initial alignment carries with it the advantage of complete flexibility in the choice of reference system of coordinates to give the greatest possible convenience in practice. Drift effects may be minimized by periodic use of check points. For mapping purposes the interval between checks may have the order of hours so that gyro drift performance should not greatly hamper the development of automatic mapping equipment.

Finally, the advantages to be gained by the use of automatic mapping equipment are so great that it is reasonable to suggest that complete system studies be started and carried through to specific designs. These designs will surely benefit from starting from fundamental principles rather than from existing catalogue items. Once the possibilities and limitations of various arrangements are established, it will be time to decide what components to accept "off the shelf" and what components will benefit from reasonable amounts of development. With these decisions made, the steps to take in realizing equipment for new mapping techniques can be taken.