NEW RESULTS OF GEODETIC DATUM EVALUATION WITHIN SC-3 OF IAG

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Biography

Prof. Erwin Groten is Director of the Institute of Physical Geodesy and has been a full professor at Darmstadt Technical University (Germany) at the Institute of Technology since 1970. Prof. Groten is the author of over 200 scientific publications and several text books.

He is currently serving as president of the Special Commission on "Fundamental Constants" of the International Association of Geodesy (IAG). He is a former president of Section V „Geodynamics“ of IAG and serves currently as Vice-president of the National Committee of Geodesy and Geophysics of Germany. Moreover he is a member of a large number of scientific and professional international organizations.

His special fields of interest are geodesy, geodynamics, navigation and satellite positioning. He is affiliated with several other universities world-wide.

Abstract

The recent progress in determining global unified vertical geodetic datums within Special Commission 3 of the International Association of Geodesy is described. With increasing significance of sea level variations also the global interrelation of vertical datums being related to mean sea level globally becomes of increasing interest. New attempts to use satellite altimetry and the results obtained from combined applications of repeat GPS together with tide gauge data and gravity field information led to new and more dependable determinations of a unified global vertical geodetic datum to which all major vertical datums have been related. The attempts took profit out of existing oceanographic projects such as GLOSS, COST, WOCE and also of new altimetric satellites. With projects ahead in 2001 up to 2004, such as ENVISAT, JASON, GRACE, GOCE, etc. the reliability of such determination may increase so that the pioneer studies by SC-3 may then lead to a global vertical unified datum as badly needed by geodesy. Geodetic projects which may typically take profit out of those studies are the Western Pacific Geodynamic Project and similar approaches.

1. Introduction

In shallow off-shore areas the definition and implementation of maritime boundaries depends more and more on the definition and determination of mean sea level and its secular variations. Consequently, the use of one and the same up-to-date ellipsoidal systems is relevant to piecewise use of geodesics as realization of maritime delineations. Moreover, it would be appropriate to refer all boundary determinations to one and the same vertical geodetic datum. In other words we would need to refer all such maritime implementation and definitions to one global vertical reference frame.

Grafarend and associates have shown that the dimensions of the presently used ellipsoids in GRS 80 or WGS 84 deviate from the actually best approximation of the earth‘s best fitting ellipsoid by about half a meter. We know, that local and regional vertical geodetic datums deviate from mean sea level by up to 1.5 m and major geodetic vertical datums may deviate by about 1 m or so. We are now able to determine such deviations globally with accuracy of a few centimeters which is sufficient for any maritime purpose.

Bursa et al. (2001) have, in a series of global investigations, determined recently the deviations of all major geodetic vertical datums from mean sea surface where the latter was defined by its level surface W^0 with W being the geopotential and W^0 the constant W at geoid level which is best approximated by the aforementioned ellipsoid (Grafarend and Ardalan, 2000).

One central problem of modern global geodesy is now to incorporate the ocean surface as part of the earth's surface (being almost two thirds of it). The answer to this question has great impact on the determination of global parameters, the unification of vertical datums up to maritime boundaries. All present solutions to bridge the oceans via discrete networks involving islands and to be satisfied with a more or less undefined mean sea level (MSL) do not fulfill the requirements of $\pm 10^{-9}$-geodesy. For instance, secular changes of the MSL are not considered at all in most definitions and/or implementations of MSL (Le Meur and Huybrechts, 2001; Chao et al., 2000; Gross, 2001 a,b,c; Gross and Chao, 2001).

2. General Aspects

Currently, different types of global reference systems, such as IGS, ITRF, WGS 84, GRS 80, are being used in geodesy. Most of them are, more or less, interrelated. In theory, a Somigliana-Pizzetti system, such as GRS 80, should consist of four independent parameters. The ideal case would be for these parameters to be directly observable, in the sense that they can be directly observed. This is not the case in modern geodesy. Another deficiency is the fact that, even though attempts have been made or, at least considered, those global systems are not yet related to a global vertical (unified) datum. Moreover, the temporal changes of those fundamental parameters have not yet been sufficiently taken into account. Models of horizontal variations prevail. Discrete point fields related to standard tectonic plate models, assuming more or less continuous (with time) motion, are dominating. As far as the global shape of the earth is concerned, polyhedron type models are being used which do not sufficiently cover oceanic areas. Meanwhile the number of altimetric satellites is so large that, together with repeat GPS-controlled global tide gauge systems and substantially improved models for tidal and similar reductions, sufficient accuracy is achieved in deriving fundamental global parameters and their temporal variations. Whether or not ITRF should thus be related to a global vertical datum or an absolute geoid, GRS 80 should be replaced by an improved Somigliana-Pizzetti model etc. is a matter of practical relevance. However, first attempts in that direction by Rapp, Bursa, Grafarend and others indicate the possibility to derive substantially new global models as soon as results from new gravimetric satellite missions (CHAMP, GRACE, GOCE) are available. The details, which should be applied to make optimal models available, have to be discussed.

Global change and related variations are primarily and best evaluated from large and heterogeneous global data sets which need to be referred to precise reference frames and systems. Recent progress in that respect is such that a new generation of parameters can be derived, where global fundamental parameters are superior to discrete sets of regional or local data in view of their integrated global information.

With a triple of new LEO (=low earth orbiting)-satellites for a dedicated gravity field determination

CHAMP
GRACE
GOCE

now, more or less, at hand, we are going to meet the requirements of precise height determination as well as monitoring various mass transport processes at the earth's surface. With an enhanced family of altimeter satellites, enlarged by

ENVISAT
JASON etc.

improved global monitoring of sea and ice surfaces as part of the earth's surface will be available. We will thus achieve in the near future accuracies which correspond to those expected from navigation projects, such as GALILEO, GNSS I and II etc.; moreover the improved gravity field determination will lead to further improve geodetic quantities and parameters now being determined from global GPS or GLONASS observations.

Bursa (2000, 2001) and associates have demonstrated, after the pioneering work of Rapp, Kakkuri and others (see Mäkinen et al. 2000) that the combination of present data sets available in geodesy allow for accuracies of one (or two) decimeters in unifications of regional and global height systems with which global tide gauges etc. are connected. They used combinations of tide gauge, altimetric, gravimetric, levelling and other geodetic satellite information together with classical geodetic data.

In this way it became clear that the combined use of oceanographic together with geodetic and geophysical data and information is worthwhile, and promising in obtaining, in the future, substantial new global information which is not yet available at this time but will enhance the importance of cooperation of oceanographers, geodesists, meteorologists etc. in achieving novel high precision results of great interdisciplinary impact.

The quality of results expected from CHAMP-observations as well as simulation studies from GRACE and GOCE indicate a new quality of resolution of the gravity field as well as of its temporal changes. This leads to improved local and regional resolution as well as to substantially improved contribution to the determinations of global parameters which act as scale factors in determination of global parts of the earth. With two thirds of the earth being covered by oceans the role of atmosphere-ocean solid-earth interaction will become more important in the near future. In this way the interdisciplinary cooperation in dealing with a deformable earth in changing climate becomes crucial. Special Commission 3 (on: Fundamental Constants) of IAG (=Intern. Assoc. of Geodesy) sees a need for better, improved and more detailed cooperation between meteorologists, oceanographers and geodesists.

In putting large and complex masses of data of quite different nature together, the role of exact reference systems and high-precision scaling is of utmost importance to avoid systematic errors in the results. Moreover, many of the mathematical formulations in such data combinations represent inverse problems where non-linear „ill-posed“ problems in the Hadamardsense play a substantial role. This means that small errors in the „input“ imply large errors in the „output“ so that regularization, i.e. loss of information, is unavoidable. Consequently, external control, i.e. independent data control with redundant data is very important.

For the aforementioned interaction between solid and fluid earth, tectonic and post-glacial processes are relevant wherever long-term trends, as in case of climatic or green house (mean sea level uplift etc.) effects, are considered. The orientation of global reference systems which is now basically provided by satellite or other astronomical techniques (such as VLBI) is also a problem where stability and long-term aspects are crucial. Here again the field of interest of Special Commission 3 of IAG is under investigation and under consideration. Let us go somewhat more in detail:

3. Detailed Considerations

Beside exceptional areas, such as areas of postglacial isostatic readjustment, vertical changes (subsidence and uplift) are mainly of episodic behavior. Geodetic techniques to observe and monitor those height variations and associated deformations are of a relative type, which means that we get only differences, not absolute values of coordinates. Consequently, vertical and horizontal datums are necessary to which such relative measurements are referred. With two thirds of the earth’s of the earth’s surface being covered by ocean „dynamic heights“ or geopotential numbers and related potential values are relevant so that reference surfaces become available to which ocean dynamics and related variations of the earth surface are globally related. Again: potential cannot be directly observed but only deduced from sets of global parameters; in contrast potential differences

$$dW = g\ dh$$

can be observed or derived from gravity g and height differences dh. Absolute gravimetry is one of the few techniques where absolute values of g can be directly measured. Level surfaces W = const. thus play an eminent role in global description of mean sea level (MSL) etc. where again global parameters, such as the mass of the earth, or the volume of the geoid (being the level surface at MSL) are of utmost importance. The volume of the earth, v, differs from the volume of the geoid; the mass of the earth (being found by applying Kepler’s third law to satellite orbits) has to be specified in view of the mass of the atmosphere; it is usually given in terms of GM (=“geocentric gravitational constant“) where M is the mass of the solid + fluid earth without atmosphere and G = Newtonian Gravitational Constant. Here mass exchanges between ocean and atmosphere interact. Since GM and the volume of the geoid act as scale constants in various cases their exact determination is relevant. Quite often potential differences are sufficient (instead of geopotential itself) so that relative geoid sections can take the role of the geoid itself. Usually, the offset between both is denoted by N_o.

Wherever regional or national heights systems (together with their associated „vertical datums“) are unified to a global vertical datum, being related to the („absolute“) geoid W^o as the „zero reference“ surface from which geodetic heights are counted, we then need exact determinations of the aforementioned global parameters. Temporal changes of mass and volume of the earth thus affect such determinations. In order to go over from the earth’s volume to the geoidal volume we consequently need the (orthometric) heights of the points in a discrete station network representing the earth. This discretization is still insufficient at present.

By applying global satellite altimetry, GPS-equipped tide gauge stations and precise long-range positioning (SLR, VLBI, GPS ...) together with repeat gravimetry we can use the average sea surface represented by MSL to get mean volume parameters serving unification of height and elevation networks. Present attempts of that kind deliver accuracies of one or two decimeters at sea, so improved ocean tide models can still lead to improved results.

Geodesy, therefore, strongly depends on the interdisciplinary cooperation with oceanography, meteorology etc. in order to determine such global parameters related to mass and volume of the earth and their temporal variations.

The interaction of ocean and atmosphere in terms of mass and energy exchange, on the one hand, and between solid earth (ocean bottom) and ocean surface, on the other hand, are typical cases where such global parameters are affected. This applies to temporal as well as regional variations. Tidal ocean bottom deformations affecting ocean tides and ocean bottom topography affecting sea surface topography are good examples. In both cases higher accuracy is desired. Sea mounts and the effect of ocean bottom topography on ocean circulation are of similar importance.

In order to interrelate the different tide gauge stations in a unified reference system we need not only their locations in terms of Cartesian or ellipsoidal coordinates but also the geopotential at the tide gauge stations or, at least, the potential difference and related temporal changes. Here again tidal models interfere. In the first case of potential itself the absolute geoid (position and potential value W^o) is required, in the second case of relative positioning the relative geoid is needed.

However, the superiority of the absolute geoid is easily illustrated by the fact that we need, in various cases, gravity anomalies. They are reduced to the geoid using orthometric heights. Whenever, in different regions, they are related to different geoid sections (in the relative way, as is now often the case) instead of the actual geoid W^o, we unavoidably get offsets in the gravity anomalies Δg which differ from region to region and lead globally to serious, systematic errors (Groten, 2000).

Due to the problems described above most global reference systems, such as ITRF (=Intern. Terrestrial Reference Frame), IGS (=International GPS Service), WGS 84 (=World Geodetic System), GRS (=Geodetic Reference System of the Intern. Assoc. of Geodesy (IAG)) are not directly associated with a Vertical Datum and consequently not related to any MSL – or geoid value. The ellipsoid associated with spheroidal systems, such as WGS 84, GRS 80, is basically an artefact without substantial physical background. In the Somigliana or Somigliana-Pizzetti form (Grafarend and Ardalan, 1999) it is a level ellipsoid defined by four “independent” parameters, which, however, nowadays are no longer independent, as they are all basically deduced from the same satellite system. There are proposals and attempts to relate ITRF to a global vertical datum (Kouba, 2000). This would certainly be a good solution. This would basically imply to relate a geopotential at “zero-height” to ITRF in terms of W^o. However, to relate such a parameter to a Somigliana field would imply a fifth parameter which could also replace the semi-major, a, axis of the ellipsoid, as both, W^o and a, act as scale factors. In so far we may use the new satellite triple (CHAMP, GRACE, GOCE) for an improved determination of W^o in order to end up with a consistent parameter set.

4. Vertical datum and permanent tide

With increasing accuracy of modern global reference systems and related observations, such as VLBI (= very long base line measurements), SLR (=satellite laser ranging), GPS (=Global Positioning System), the interest in vertical coordinates has substantially gained. This is true in spite of the fact that, particularly for GPS, the vertical coordinate is weak. As a consequence of this gain of interest also the consistency of those fundamental systems was more carefully considered and minor inconsistencies are being removed. Recently, M. Kumar (priv. comm. 2001) of DoD (US Dept. of Defense) called the attention to apparent inconsistencies in ITRF which are basically related to the permanent tide effect. In view of resolution 16 of IAG which describes the application of permanent tide corrections (only the indirect effect of permanent tide, due to the tidal deformation should be preserved and all direct effects should be removed) he proposed to modify existing reference networks. This problem was, however already discussed earlier, at the GGG-Symposium of IAG at Calgary (Alberta) in August 2000. A modified relation of ITRF to a global vertical datum could easily resolve that and related problems. However, as mean sea level (MSL) is not in agreement with the tidal regimes mentioned above we basically need three different models of tide-reduced earth surfaces (mean, zero tide and tide-free) in order to fulfil different requirements of modeling. All three again differ from reality.

5. Conclusions

In spite of the numerous world-wide efforts of GLOSS, PSMSL, FAPSO, IAG, APSG, EOSS (IOC Group, 2001; Plag et al., 2000) etc. it would certainly be worthwhile to intensify, to some extent, interdisciplinary activities. It will certainly be possible to take profit from a substantially changed situation in geodesy, in a few years, as described above, to solve a variety of complex problems with relatively high precision which affect oceanography, geodesy, solid earth, geophysics, meteorology etc. Thus the progress of geodesy depends on cooperation with oceanography etc.

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