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Possible Specification of a Local or Regional Vertical Datum

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Abstract

A local or regional vertical datum can be uniquely and precisely specified within the International Reference Frame (ITRF) by adopting a datum geopotential value W_0 (e.g., that best represents the mean sea level) and a global gravity field model, along with a set of well distributed, reference levelling points with precisely measured geopotential numbers and ITRF coordinates. The geopotential values at the selected reference points, computed from the adopted gravity model, are used to derive the mean geopotential offset, which best fits the geopotential numbers of the reference points, without fixing or favoring any single (datum) point. Then, the geopotential numbers, incremented by the mean geopotential offset, can be used to derive heights with respect to the reference geopotential W_0. Height determination by means of the mean geopotential offset is subject to a small, time invariant, bias - a datum height offset- with respect to the adopted W_0. Apart from measurement errors, this datum height offset depends only on the accuracy of the adopted gravity model and the density and coverage of the selected ITRF/levelling reference points. Like in the case of a classical vertical datum with a fixed datum point, the datum offset could be determined more precisely when new global gravity field models, that are more precise than the adopted one, become available. Such a modern vertical datum definition will be precise and stable in time, provided that the same (adopted) gravity field model and the same reference ITRF/levelling points (or replacement points in their vicinity) are used for datum realizations at all future epochs. Unlike the classical vertical datums, this modern vertical datum realization will also allow mm level monitoring (with respect to ITRF) of the normal (or orthometric height) changes at all the levelling points (including the reference stations, tide gauges, etc.). For example, a vertical datum for Iceland could be specified within ITRF2000, by adopting W_0=62 636 856.0 m^2s^{-2} and the EGM96 gravity field model along with a set of about 100 selected, well distributed GPS/levelling reference points for which precise geopotential numbers and ITRF2000 (GPS) coordinates are known (i.e., measured). Such a vertical datum would likely have a datum offset uncertainty of about 0.1 m with respect to the mean sea level, represented by the above W_0 and it should be stable in time (with respect to ITRF2000) at the mm level.

1 Introduction

This work was inspired by very interesting presentations and discussions at the Nordic Geodetic Commission workshop on Iceland's future national vertical datum, which was hosted by the National Land Survey of Iceland at Reykjavik in June 2005 (see ftp://ftp.lmi.is/GPS/Workshop-Heights-2005/). In many respects, Iceland is a unique and challenging country. This is also true from a geodesist's point of view, since the well-established classical approaches to horizontal and vertical datum definitions and realizations are not well suited for Iceland. Namely, no point can be considered stable, thus held fixed and used as an origin (or datum point) to which the levelling or horizontal networks can be referred.

Even modern geodetic datums (e.g., ETRS89, NAD83, etc.), which typically are defined with respect to the International Reference Frame (ITRF) (e.g., Boucher et al.2004) are not suitable for Iceland. This is so, since they are attached to a continental plate (exactly, by some conventional plate rotation values), so that all stable points, away from the plate margins, do not change their geodetic coordinates. However, Iceland spans two continental plates and most points are subjected to significant plate margin deformations, so that this approach cannot be used. Since these modern geodetic (3D) datums are defined within the ITRF, they also allow exact transformation to ITRF, enabling efficient and precise use of modern satellite techniques like GPS.

In a way, Iceland's situation resembles more to the whole Earth, where all points are moving and no point or continental plate can be held fixed. This is why the choice of ITRF as a (3D) geodetic datum for Iceland is likely the only sensible solution. As a matter of fact, Iceland's current (3D) geodetic datum, ISN93, is already based on ITRF (Rennen 2004). Clearly, a similar approach is needed for the new vertical datum realizations, i.e., physically meaningful heights (i.e., related to the mean sea level), expressed in a global vertical datum with no (datum) point held fixed. However, such a modern, vertical datum realization, directly traceable to ITRF, is currently also needed and applicable to all regional and national vertical datums, since it allows precise and consistent satellite based positioning as well as monitoring of all points within a datum, including the original datum point.

2 Global vertical datum and conventional local (national) vertical datums

The situation regarding vertical datums is not as advanced as that of modern (3D) geodetic datums. This is likely due to the fact that there is currently no conventional global vertical datum, not even a conventional specification of the mean sea level, or the geoid. Thus, global height determinations (within ITRF) is currently not possible with respect to a conventional mean sea level, though a need for it clearly exists, even for disciplines other than geodesy such as global (air) navigation, conventional atomic time realization, etc.

A new concept for the definition of a global vertical datum has recently been proposed by Burša et al. (1999a, b). This concept suggests that a (conventional) mean sea level (and geoid) be uniquely specified by adopting a geopotential value W_0, which best represents, in a mean sense, the world's oceans. Such a value for W_0 is nowadays easily accessible by using satellite altimetry and global gravity field models. Furthermore, as shown by Burša et al. (2005), W_0 is stable, (it practically does not change with time) and has virtually been the same for all the recent gravity models, including the latest ones based on the CHAMP (Reigber et al. 1999) and GRACE (Tapley et al. 2004) satellite gravity missions. In fact, a conventional value of W_0 = 62 636 856.0 m^2s^{-2} has already been implicitly adopted and used in 2003 by the International Astronomical Union (IAU) to derive a constant, required for relativistic time transformations and atomic time realization at mean sea level (Burša et al. 2005).

As proposed by Burša et al. (1999b), once a conventional W_0 is adopted for a global vertical datum, the individual vertical datums (e.g., each based on a unique datum point) can be related to the adopted W_0 by means of a global gravity field model, precise ITRF positions and levelled heights, which must allow a proper transformation into the corresponding geopotential numbers. These geopotential numbers referred to a unique datum point (with the zero geopotential number), are then compared, at levelling points with known ITRF positions, to the geopotential numbers evaluated from the global gravity field model. This comparison (or adjustment) yields an estimate of the datum geopotential (in an average sense). This estimated datum geopotential is then used to compute a datum geopotential (height) offset with respect to the adopted W_0 of the global datum. In this way, if there is a large number of ITRF/levelling points, covering a sufficiently large area (so that the resolution errors of the global gravity field will average down), it is possible to determine a local (national or regional) datum height offset with relatively high precision (a few cm). For example, the height offset of the North American Vertical Datum 1988 can be determined with cm precision (Burša et al. 1999a). Once known, the individual local vertical datum height offsets can be used to transform (relate) the respective local vertical datums (and the corresponding heights) to the adopted global vertical datum. Alternatively, a local vertical datum can be related to any other local vertical datum with a datum height offset known (i.e., determined) with respect to W_0.

3 A possible concept for local and regional vertical datum realizations

A modern vertical datum needs to be accessible, stable and compatible with modern methods of measurements (Makinen 2004). The new approach, proposed by Burša et al. (1999b), is both accessible and compatible with new methods of measurements (e.g., GPS), however, for a local/regional vertical datum, it lacks the high degree of stability needed for absolute height/geoid monitoring. This is so because once W_0 is adopted for a global vertical datum, future improvements of local vertical datum realizations, based on W_0 and more precise global gravity field models, will cause all the heights to be offset by a small amount, compromising the global height change monitoring with respect to ITRF. However, this new datum concept can also be made stable when the gravity field model and the ITRF/levelling points used to attach the local vertical datum are "frozen" in time (i.e., the same gravity field model and the same points are used to derive datum height offsets in all the future datum realizations).

In this way, the vertical datum is attached, in a unique and precise way, to ITRF at the reference points by means of the adopted gravity field model, in place of a classical datum point. The geopotential values are evaluated from the adopted gravity model at these selected reference points with known ITRF positions and then used to compute a mean geopotential offset that best fits the geopotential numbers of the reference points, without fixing or preferring any single (datum) point. Also note that the "measured" geopotential numbers could be referred to any (arbitrary/convenient) point. Then the measured geopotential numbers, increased by the above mean geopotential offset, can be used to derive physical (e.g. normal or orthometric) heights with respect to W_0. This height determination will be subject to a small (unknown) bias with respect to the adopted W_0. However, this height bias (datum offset), excluding the observational errors of levelling and ITRF positions, will be the same for all the future datum realizations, provided that the same gravity field and the same reference points are used. This is so since the errors of the adopted gravity field model at the same reference points remain exactly the same, thus the average of the gravity field errors, i.e., the unknown datum height offset, will also remain exactly the same. For example, assuming that a hundred well distributed reference points are selected with geopotential numbers and ITRF positions, both measured at the 1 cm precision level, then the new vertical datum will be stable (i.e., determined with respect to ITRF) at the mm precision level (1.4 mm, to be exact).

The magnitude of the unknown datum offset depends mainly on the accuracy of the adopted gravity model and the coverage area of the ITRF/levelling reference points. Much like for a classical vertical datum with a fixed datum point, this datum offset is in fact a tie to a future global vertical datum and can be determined more precisely later on when new precise global gravity field models (e.g., more precise than the adopted one) become available. As an example, if the EGM96 gravity field model is adopted for the Icelandic vertical datum, the datum offset uncertainty (with respect to the adopted W_0) is expected to be about 15 cm, which is the commission resolution error of EGM96 over an area with a radius of 200 km (NRC 1997).

4 Discussions

The above proposed vertical datum concept is essential for Iceland, since no geodetic or levelling point in Iceland can be considered stable and held fixed as a datum point. Nor is it possible to attach a datum to a single continental plate, since Iceland spans two continental plates (North American and Euroasia), which are spreading apart at about 2 cm/year. In addition, all the points are likely being subjected to plate margin deformations at varying degrees. Due to this unique situation, it is mandatory that any vertical datum in Iceland allows also a monitoring of absolute height and geoid changes (e.g., within a global reference frame, such as ITRF). This is important in particular for various geophysical studies and applications.

In the preceding vertical datum discussions only concepts were considered. However, for proper datum definition, apart from W_0, the adopted gravity field model and the reference points, additional choices need to be made, such as the height system (normal or orthometric), the tidal reference system (zero, mean or tide-free) as well as the associated constants and information needed to transform the geopotential numbers into the selected height system. For example, unlike orthometric heights, the normal heights, which are equivalent to geopotential numbers, require only 3 additional, already well-determined, constants. Namely the *GM*- the gravitational constant of the Earth, ω - the mean angular velocity of the Earth and J_2 – the second-degree zonal Stokes parameter, which defines the Earth's flattening (e.g., Burša et al. 1999b). Orthometric heights, however, require additional information/assumptions, models and/or approximations, related to the density distributions inside the Earth's topography (e.g., Tenzer et al. 2005)

Similarly, the assumed simultaneous observation and adjustment of the geopotential numbers and ITRF positions could be far from trivial, if not impossible to realize, in particular for the Icelandic environment of deformations and movements at all points. Some practical approximations and innovative modeling and adjustments will have to be employed in such cases. In particular, precise determination of geopotential numbers from gravity measurements and the corresponding levelled line segments, between two points with changing heights observed at different epochs, is unprecedented and truly quite challenging. Furthermore, non-linear, or even episodic height velocities should be expected at a number of points. If only a constant height velocity is used at each station, careful monitoring, robust outlier detection and close cooperation with the geophysical community will likely be needed to detect any episodic changes, etc. Simultaneous adjustment of height velocities from levelling together with frequent, or even continuous GPS position observations should help in this regard. However, even here, at least initially, some assumptions will have to be made regarding the height changes (e.g., assuming that orthometric or normal height changes are about 90% of the corresponding ellipsoidal height changes, observed by GPS (see e.g., Makinen et al. 2003). Even GPS height change observations represent a major challenge, as they often show significant systematic errors, mainly seasonal (due to e.g., snow coverage). For example, Makinen et al (2003) had to use only periods of integer numbers of years and delete winter observations, which were affected by snow, in order to get precise GPS height change solutions. Also, the GPS heights should be determined directly in ITRF, e.g., in a global solution or more conveniently by the popular and freely accessible Precise Point Positioning (PPP) with the IGS solution products (see e.g., Tetreault et al. 2005). Otherwise, GPS relative positioning taken at different epochs could be compromised due to movements and deformations at all observed points.

As mentioned above, for the sake of datum stability, it is essential that the same gravity model and the same reference points be used for all future datum realizations. However, it is unreasonable, or practically impossible to expect that all the reference points selected for the initial datum realization will survive, e.g., in Iceland's challenging and volatile environment. Fortunately, the global gravity field models have errors with long wavelength that are practically the same for all points within a few hundred meters, or even a few kilometers of a reference point. This means that any destroyed or lost reference point could be easily replaced by an alternate or a newly established point in the vicinity of the original (lost) reference point. In this way, the error from the adopted gravity field model will be the same at the replacement reference point as at the original (lost) reference point. Consequently, the datum height offset, i.e., the average of the gravity model errors at all the reference points, will still be the same, maintaining the datum stability despite the replacement of reference points.

Even though the adoption of a global gravity field model was proposed in this new vertical datum specification, any suitable and possibly more precise gravity field model or even a local geoid model could have been suggested. It is for the sake of simplicity, uniqueness (reproducibility) and even, because of the long wavelength gravity errors, that a global gravity model is preferred. More specifically, local geoid models tend to be updated frequently, not have unique or clear definitions and different computations/interpolations may give different results. Furthermore, the relatively short wavelengths of geoid errors would pose more stringent (and possibly unsustainable) constraints on the requirement that a replacement point be in the immediate vicinity (meters, rather than km) of any lost reference. For these reasons, a well defined, precise global gravity field model should be preferred. A local geoid or height corrector surface could, or even should be used, although not as a part of datum specification, for efficient determinations of orthometric or normal heights from ITRF positions, observed e.g., by GPS. In the future, a more precise global gravity field or a local geoid model could be used or even specified as part of a datum realization. However, if the datum continuity/stability is required, then the datum height offset would have to be determined as the average of the gravity model differences (the new - the original one) at all the reference points. Thus, even here, the originally specified gravity field model remains, at least implicitly through the datum height offset, a part of the new datum realization.

5 Conclusions

A modern, stable and easily accessible vertical datum that is also compatible with modern measuring techniques can be specified by selecting a geopotential value W_0, a global gravity field model and a large set of reference points with levelled heights (geopotential numbers) and ITRF positions. Such a datum definition is well suited for all national or regional vertical datums, as it does not require any fixed datum point and should allow for height and geoid monitoring directly within ITRF at the mm-precision level. This new datum specification is also sustainable, since it only requires that any reference point lost or damaged be replaced by an alternate or a new one, within the general vicinity (~ km) of the lost reference point. It is expected that by using this new datum concept, the current and future realizations could be made stable at the 1-mm precision level with a datum-offset uncertainty (with respect to the selected W_0) at about 0.1-m level. This compares quite favorably with the best classical datum realizations, which clearly cannot be used in a geodetically challenging regions, like Iceland, since all points are moving.

Only concepts were discussed here. The details regarding datum specifications, such as the choice of height system, the required constants and the tidal reference system (note that ITRF's tidal reference system is tide-free and is unlikely to change!) must be carefully considered from the accuracy/consistency point of view (see e.g., Makinen 2004). Also, the challenges and innovations (i.e. measuring and adjusting) required to obtain the geopotential numbers and the corresponding ITRF positions (heights) were not considered and discussed in any appreciable way. These, in the case of Iceland, are also major challenges that will require a high degree of innovation not yet seen in classical geodesy and surveying. No doubt, all these challenges by themselves will be worth further investigations and reports.

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