

THE SPATIAL AGE AND THE NEW PARADIGMS IN GEODESY: IMPLICATIONS FOR SURVEYING AND MAPPING IN BRAZIL

*A Era Espacial e os Novos Paradigmas em Geodésia: Implicações nos
Levantamentos Geodésicos e Cartografia no Brasil*

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ABSTRACT

The satellite platforms allowed a very quick transition from local or regional Geodetic Reference Systems (GRSs) to the global ones. The evolution of methods also brought changes in the standards of precision and accuracy. Networks based on local Datums which had relative precision in the order of 1:100,000 to 1:150,000, like the classical networks in the Brazilian Geodetic System (BGS), could be easily replaced by networks constrained in geocentric Datums which reach relative precision of 1:10,000,000 or better and placed inside a concept of a Global Hierarchy. Besides the facilities for positioning, the modern satellite platforms of remote sensors are also applied for satellite altimetry, multi spectral imagery and on-board satellite gravimetry. This allows relevant geodetic information linked directly in global geocentric GRSs. Then, the modern orbital platforms changed completely the ability to capture, model and manage spatial data with strong implications in Geodesy and Cartography. The associated new data bases for Cartography have several new implications coming from the applied surveying methods and present paradigms of precision. Most of the implications come from the need of relating geometric and physical aspects. This happen due the necessary association of local measurements affected by the local gravity field to global oriented geocentric GRS. The modern Global Geopotential Models (GGMs) have a strong expectation for uses in the referred integration. In this paper are discussed the impacts of “spatial age” on the geodetic methods for surveying and mapping. The possible applications of GGMs for realizing fundamental geodetic networks, surveying and mapping are also discussed.

Keywords: Local and Global Geodetic Reference Systems; Gravity Field; Geodetic Surveying; Global Geopotential Models.

RESUMO

As plataformas orbitais permitiram uma rápida transição de Sistemas Geodésicos de Referência (SGRs) com caráter local ou regional para os globais. A evolução dos métodos geodésicos trouxe mudanças com grande incremento em precisão. Redes clássicas baseadas em orientação topocêntrica em *Data* locais, com precisões relativas na ordem de 1:100.000 a 1:150.000, tais como as redes clássicas do Sistema Geodésico Brasileiro (SGB), podem agora ser facilmente substituídas por redes globais com precisões relativas na ordem de 1:10.000.000 ou melhor, dentro de uma hierarquia global em vista do moderno conceito de *Datum* geocêntrico. Juntamente com o posicionamento geodésico, as modernas plataformas de sensores orbitais, tais como satélites altímetros, imageadores multiespectrais e sensores gravimétricos, propiciam diretamente informações em SGRs geocêntricos. Desta forma, mudaram totalmente a capacidade de aquisição, modelagem e gerenciamento de dados espaciais, com grandes implicações em Geodésia e Cartografia. As novas bases de dados espaciais em Cartografia sofreram grandes melhorias decorrentes dos novos produtos e dos paradigmas atuais de precisão decorrentes dos novos métodos geodésicos. Na abordagem clássica, as

implicações de ordem física nas redes entendidas como geométricas não eram, em geral, consideradas. No entanto, os levantamentos modernos têm exigências da integração de aspectos correlatos ao campo da gravidade visando ao melhor aproveitamento da potencialidade oferecida pela integração de levantamentos locais com as bases de dados globais. Sem dúvidas, os modernos Modelos Globais do Geopotencial (MGGs) têm boas perspectivas de aplicação para a referida integração. Neste trabalho são discutidas as mudanças que a “Era Espacial” produziu nos métodos de levantamentos geodésicos e que trazem implicações para a Cartografia. As possíveis aplicações dos MGGs para levantamentos geodésicos e Cartografia são também discutidas no trabalho.

Palavras chaves: Sistemas Geodésicos de Referência Locais e Globais; Campo da Gravidade; Levantamentos Geodésicos; Modelos Globais do Geopotencial.

1. INTRODUCTION

In the last four decades Geodesy continually developed in a quick form because the modern measurement techniques mainly those based on Earth satellites as well as computational methods. These conditions generated new ideas and allowed to put in practice global positioning methods. In consequence it is natural a strong transition in concepts mainly that related to Geodetic Reference Systems and Frames (GRSs and GRFs).

Nowadays, fundamental geodetic networks with relative precision in the order of 1:100,000 to 1:150,000 like classical triangulation and trilateration are considered old-fashioned. Local or regional classical geodetic networks must be replaced by densifications of global geodetic frames because the facilities given by the Global Navigation Satellite System (GNSS) technologies. Inside this consideration, it must be considered the present needs of accuracy related to data acquisition even for local geodetic and cartographic data basis. These needs happened mainly because the global referencing for geodetic and imagery data coming from orbital platforms. To take the best profit from these data it is necessary to keep their register characteristics in a global GRS, avoiding transformation for local classical GRF usually with worst relative precision and accuracy than the acquired data.

For keeping the characteristics from global GRF for complementary local surveys it is necessary to take into account physical variables linked to the Earth Gravity Field and the planetary dynamic. This happens, e.g., for surveying based on modern high performance Local Positioning System (LPS).

The mentioned aspects are in the present efforts of International Association of Geodesy (IAG) and *Fédération Internationale des Géomètres* (FIG). The IAG and FIG reorganized their commissions and services because the evolution for global approaches. They point out new needs for global GRFs and spatial data acquisition. Then, in the present there are considered three pillars of Geodesy (Figure 1): geometry and kinematics (geokinematics); Earth's gravity field; and Earth's rotation and orientation. Each one of the pillars is relevant for definition and realization of a modern GRS as well as for related data acquisition.

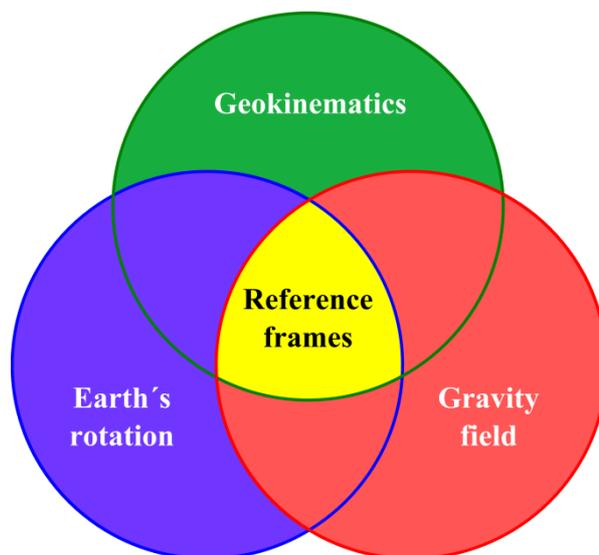


Fig. 1: The pillars of modern Geodesy. Source: Adapted from Plag et. al. (2009).

The concept of modern global GRS consider two components: the three-dimensional one that can be associated with an ellipsoidal reference surface; and the vertical associated with a global equipotential reference surface. Their realizations take into account each one of the pillars. According to FIG, the correct use of modern GRFs in surveying implies in to consider these characteristics. In consequence, we must classify the national, regional or local GRFs as densifications of a global GRF inside a hierarchy. In this sense the same definition of the global GRF must be kept for regional and local ones.

Considering the Brazilian Geodetic System - BGS (*Sistema Geodésico Brasileiro - SGB*) evolution to the context of SIRGAS (*SIstema de Referência Geocêntrico para as Américas*), two main problems related to the modern global GRFs in Brazil are discussed in this paper:

- What are the steps to be accomplished for the three-dimensional and vertical GRFs of BGS?
- How to integrate local surveys like leveling and Local Positioning Systems (LPS) based into the modern global concept?

The central role of the gravity field is considered as part of the answer to the questions. Because their

impact in Geodesy, the modern Global Geopotential Models (GGMs) are considered.

2. GEODETIC SURVEY AND THE EVOLUTION OF THE BRAZILIAN GEODETIC SYSTEM (BGS)

Due to different techniques and employed equipments, control geodetic networks are commonly divided into: horizontal; vertical; and three-dimensional. In a classical approach, horizontal networks (often mistakenly called planimetric networks, because, in fact, they are related to a curved reference surface) were established by triangulation, trilateration and traverse surveying. The evolution of these networks is in direction of a unique global network. In this sense each local, regional, national and continental network is considered as a densification of determined realization of the IERS Terrestrial Reference System (ITRS) being under the responsibility of IAG by its International Earth Rotation and Reference Systems Service (IERS). Nowadays, the vertical networks realizations follow the usual approach of spirit leveling around the world. However, there are several propositions related to overcome the expensive and tedious process of spirit leveling and for establishing a World Height System (WHS) or its realization World Height Frame (WHF). This process is coordinated by the Intercomission Project 1.2 (ICP1.2) of the IAG. This is pointed as an urgent task because the need of a unified global reference for heights to take profit from the registered data coming from spatial platforms.

2.1 Evolution of Brazilian Horizontal Network Towards a Densification of the ITRF/SIRGAS

Since the 1940's, the establishment of the horizontal network in Brazil was carried out mainly by triangulation technique, with the proposal of having a net of quadrilaterals at each 2°. The fundamental stations were established on ridges of hills to enable the visibility between them. Following international standards at the time, angular measurements were made with theodolites of 0.3" precision, the control baselines in the range of 1:500,000 and the relative ellipsoidal heights were determined by trigonometric leveling with precision in the order of the meter. The densification of the network was usually made by traverse surveying.

The used topocentric orientation at the Datum in classical networks were usually determined through six parameters: the coordinates of an origin point (latitude and longitude); orientation (azimuth); the geoid height $N = h - H$, where h is the ellipsoidal height and H is the orthometric height, and the components of deflection of the vertical (meridional component ξ and prime vertical component η). In practice, there were determined the astronomic coordinates at the origin point (Datum), the azimuth of a basis with origin in this point, and the values for the geoidal height and vertical deviation components were arbitrated or estimated. Thus, the

transformation between astronomical and geodetic coordinates could be processed by the following equations (GEMAEL, 1999):

$$\xi = \Phi - \varphi \quad (1)$$

$$\eta = (\Lambda - \lambda) \cos \varphi \quad (2)$$

$$\eta = (A_A - A) \cot g \varphi \quad (3)$$

where:

Φ , Λ , A_A : are respectively the astronomic latitude, the astronomic longitude and the astronomic azimuth;

φ , λ , A : are respectively the geodetic latitude, the geodetic longitude and the geodetic azimuth.

The equation (2) and (3) yields to the expression:

$$A = A_A - (\Lambda - \lambda) \sin \varphi \quad (4)$$

The (4) is known as Laplace's equation with which is possible to convert an astronomical azimuth into a geodetic azimuth.

In the 1970's, fundamental stations in the horizontal network of the BGS have been established with TRANSIT system, especially in the Amazon region. In the 1990's, Brazilian Institute of Geography and Statistics (*Instituto Brasileiro de Geografia e Estatística - IBGE*) began the extensive use of Global Positioning System (GPS) in the determination of the coordinates for fundamental horizontal network (COSTA, 1999); and from 1994 began to be deployed GPS high precision regional networks in several states of the Brazilian federation. Brazilian fundamental horizontal network underwent several adjustments over time, in view of developments in positioning techniques and different horizontal geodetic reference systems that were adopted for the BGS.

The *Córrego Alegre* system was officially adopted in the country from 1950 to 1970. A set based on the Hayford international ellipsoid of 1924 and with topocentric orientation in *Córrego Alegre* station, situated in *Minas Gerais* State (IBGE, 1996). *Astro Datum Chuá* is considered a provisional reference system between *Córrego Alegre* and SAD 69, where some maps of the systematic cartography were edited. The *Astro Datum Chuá* system was based on the Hayford ellipsoid with topocentric orientation in the *Chuá* station, situated in *Minas Gerais* State. It was established with the purpose to be an essay for supporting the definition of SAD 69 (IBGE, 2001).

The SAD 69 system was adopted for the BGS in the early of 1970's. It was based on the GRS1967 and with topocentric orientation in *Chuá* station (IBGE, 1998a). It is necessary to consider that the IAG and the International Astronomic Union (IAU) immediately after the GRS1967 adoption considered it not

completely adequate because the evidences for different values for the best fitted reference ellipsoid parameters (MORITZ, 1988), mainly the equatorial radius a and the angular velocity ω with implications in the flattening f .

For *Córrego Alegre* System the ellipsoid orientation was totally arbitrary, i.e. settling null values to the geoidal height and to the components of the vertical deviation at the Datum. This approach was the possible realization in practice at that time. In this way, the geodetic coordinates were equal to the astronomical ones at Datum. Due to the arbitrary orientation, there was an acceptable adaptation ellipsoid-geoid only in the region of *Minas Gerais* and *São Paulo*, but at North or South regions, far away from the Datum, the discrepancies were quite evident. In the SAD 69 the ellipsoid orientation was partly arbitrary, by estimating the values of the components of vertical deviation through gravimetric surveys around the Datum and looking for a better agreement between ellipsoidal and orthometric heights in geodetic stations at continental edges. It was considered the null value for the geoidal height in the Datum. By astronomical determinations in Chuá and by estimating the values of the components ξ and η it was possible to compute the geodetic coordinates in the Datum by means of (1) and (2).

The first adjustment of the Brazilian Horizontal Network performed in computational environment, aiming the establishment of the SAD 69, was conducted by the Defense Mapping Agency (DMA) of the United States (IBGE, 1996). In this adjustment, the Brazilian Horizontal Network was divided into 10 areas that were processed separately due to computational limitations (IBGE, 1996). The measurements of new surveys, made for the densification of the network, were adjusted considering fixed the coordinates of the existing stations. This procedure entered distortions in the coordinates of the stations, once systematic errors were propagated through the different adjustments (COSTA, 1999). In general, there are three factors that cause distortions in classical networks (IBGE, 1996):

- Poor geometry;
- Lack of an adequate geoidal model for the reduction of geodetic observations to ellipsoid, and;
- The used and misused strategies for adjustment.

Still related with the distortions in the classical network, according to Vaniček and Steeves (1996), the relative horizontal positioning is, as any measurement procedure, subject to random and systematic errors. Random errors are estimated during the adjustment process and these estimations must be made available to the user. The systematic errors in horizontal positioning are more difficult to be controlled. They are originated from systematic effects on measurement systems (e.g.: scaling error that results from the no calibration of the distance measurement system) and due to mismodeling (e.g.: neglecting the geoidal heights for reduction of

observations; not take into account the deflection of the vertical in the propagation of coordinates; the adjustment "by parts" of the network). Both error sources cause distortions on the horizontal networks. These distortions can easily reach tens of meters in classical networks of continental dimensions like in the Brazilian case. For example, an error of scale commonly found of 10 ppm (parts per million) in classical networks, distorts horizontal positions distant of 1000 km from the Datum in 10 m (VANIČEK and STEEVES, 1996).

In 1996, the horizontal network based on SAD 69 was submitted to a readjustment with a global character, i.e., all the network observations were adjusted simultaneously (horizontal directions, baselines, astronomical azimuths, etc.) and GPS long baselines observations were used as constraints according to their accuracies. This adjustment resulted in a new realization for SAD 69 system, with new coordinates for the horizontal network stations. According to IBGE (1996), with the obtained results it was drawn for the first time a consistent picture about the quality of the network. The quality of the network was improved due to the global treatment provided by the readjustment based on the long baselines. Since 1997, IBGE began to disclose only the coordinates and their precisions in the new realization of SAD 69, which gave to the user the knowledge about the quality of the stations coordinates. This approach was not possible previously. The mean value of the standard deviation after the adjustment was of 10 cm for the GPS stations and 50 cm for the classical network stations. According to IBGE (1996), the horizontal offset between the new and the old coordinates increases almost proportionally with the distance from the origin (Datum Chuá), reaching approximately 15 m at South Brazil and Northeast Brazil, and in some cases reaching differences of around 50 m on stations located in *Amapá* State, Northern Brazil.

The satellite positioning methods naturally provide the acquisition of three-dimensional (3D) coordinates related to a reference system with origin in the geocenter and with new paradigms of precision. Then, the classical systems which do not have compatible precision related to the satellite positioning techniques and each one with different topocentric orientation became old-fashioned. For each one it is necessary a set of transformation parameters and propagation of errors by different criteria. It is necessary to consider that in the process of transformation between GRSs the mandatory rule is that the worst precision is propagated for obtaining the related transformation parameters.

For South America and within a historical context, it must be mentioned the following facts:

- I. In the 1980's geodynamics control networks using GPS were established in some countries such as Venezuela, Ecuador, Peru and Chile;

- II. In June 1993 German Geodetic Research Institute (*Deutsches Forschungsinstitut Geodätisches* – DGFI), was responsible for a consult to the South-American countries about the interest in unifying their GRSs;
- III. In October 1993 was created the SIRGAS project with the initial purposes of: setting a geocentric GRS for South America (coordinate axes and Datum based on ITRS and its realizations and GRS80 ellipsoid parameters); and establish and maintain a reference network (ITRF densification in South America). These activities related to the definition and realization of SIRGAS are coordinated by the "Reference System" Working Group I and II (WG-I and WG-II) respectively;
- IV. In May 1995 was held the first GPS campaign with the aim of realize SIRGAS network. This is considered the first realization of SIRGAS (SIRGAS95), and it is composed of 58 stations distributed in South America and linked to ITRF94, at epoch 1995.4;
- V. From 1995 to 1997 data processing was performed by DGFI and by National Imagery and Mapping Agency (NIMA - USA);
- VI. In September 1997 was created the "Vertical Datum" Working Group (WG-III);
- VII. In May 2000 was held the second GPS campaign. This is considered the second realization of SIRGAS (SIRGAS2000), composed of 184 stations distributed in South America, Central America and North America, linked to ITRF2000 at epoch 2000.4;
- VIII. In January 2001 Cartographic Conference of the United Nations recommended the adoption of SIRGAS;
- IX. In February 2001 the title *Sistema de Referência Geocêntrico para a América do Sul* was changed to *Sistema de Referência Geocêntrico para as Américas*;
- X. In January 2005 SIRGAS was adopted as the new GRS for geodetic and cartographic works in Brazilian territory.

Each country in South America is going to integrate its individual geodetic network to SIRGAS reference network. This allows setting each national network as a densification of SIRGAS inside one hierarchy. In this sense, the responsible agencies of many countries have provided tools to the users for the conversion between the classical references and SIRGAS, like the ProGrid platform of IBGE (see IBGE home page). Today the emphasis is being given to the deployment of continuous monitoring networks. In this sense, the third realization of SIRGAS (SIRGAS-CON) is composed of more than 230 continuous monitoring stations, 47 of them are part of the global IGS network (International GNSS Service). The SIRGAS-CON

coordinates are processed weekly. These coordinates and the velocities of the stations are made available to users by the IGS Regional Network Associate Analysis Centre for SIRGAS (IGS-RNAAC-SIR) under responsibility of DGFI in Munich, Germany. These weekly coordinates refer to the same epoch of observation and reference system used by the IGS for the computation of final GNSS satellites orbits, which currently is the IGS08 which involves only GNSS stations of ITRF2008 network. In addition to the weekly solutions the users can access multi-year solutions referred to the current ITRF and with a particular reference epoch. The integration between different realizations of SIRGAS Network is possible through the transformation parameters between correspondents ITRF, associated with the coordinates reduction to the same reference epoch.

All the referred aspects related to the present structure of SIRGAS2000 in BGS must be considered for taking profit of its consistency with modern techniques for spatial data acquisition. It is the case for the optimization in integrating data coming from remote sensors, LPS, etc., for obtained spatial referencing of several kinds of relevant information. These aspects will be taken up in section 3.

Even considering local or regional data bases, nowadays their development are strongly based in the possibilities for capturing, modeling/processing and manage data, mainly those registered in global GRS, without lose of their precision and accuracy in positioning. The use of an old-fashioned GRS by transforming data coming from modern global acquisition system usually implies in unnecessary losing of precision and invested financial resources.

2.2 Evolution of Brazilian Fundamental Altimetric Network Towards a WHS

The Brazilian Fundamental Altimetric Network - BFAN (*RAFB – Rede Altimétrica Fundamental do Brasil*) is part of the BGS. Its realization began in 1945 in *Santa Catarina* State by spirit leveling. At that time the country had not yet an official vertical Datum. The connection between the vertical network with the tide gauge of *Torres, Rio Grande do Sul*, in 1946, enabled the computation of provisory heights to the bench marks. The Vertical Datum of *Torres* had a provisory character since it was defined with only one year of sea level observations (1919-1920). It was replaced by the Brazilian Vertical Datum of *Imbituba* (BVD-I) in *Imbituba* harbor, *Santa Catarina* State, southern Brazil. The BVD-I was established in 1958 with nine years of sea level observations (1949-1957) (ALENCAR, 1990). It is appropriate to mention the existence of a part of BFAN located at north of the Amazon River, in the *Amapá* State which is not referred to BVD-I. The width of Amazon River does not allow the connection between the two segments of the BFAN by conventional spirit leveling surveys. The heights in this network are linked to the Brazilian Vertical Datum of Santana

(BVD-S), situated in the harbor of *Santana*, *Amapá* state. The current configuration of the BFAN is shown in Figure 2, along with the Tide Gauge Network for Geodesy - TGNG (*RMPG - Rede Maregráfica Permanente para Geodésia*) with their new control tide gauges.

Today, the BFAN has approximately 69,000 stations and about 180,000 kilometers of leveled lines. The heights were obtained by spirit leveling, without the use of real gravity information and, therefore, it can not be displayed as a network with orthometric heights. The impacts of gravity information lack were partially reduced by the application of the correction related to the normal gravity derived from a Normal Earth Gravity Field Model (DE FREITAS and BLITZKOW, 1999). This kind of model is based on the reference ellipsoid, and assigns the same mass and the same angular velocity of the real Earth and its reference surface is considered equipotential. With this correction it is possible to consider only the effect of non-parallelism of the theoretical level surfaces, and thus the heights in this system are called normal-orthometric (LUZ, 2008).

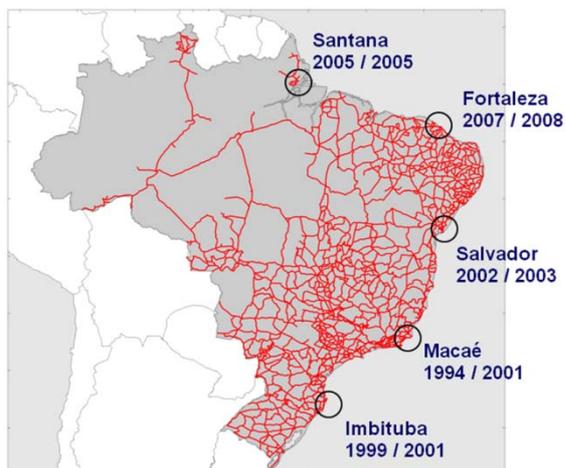


Fig. 2: Brazilian Fundamental Altimetric Network (BFAN) (red lines) and the present Tide Gauge Network for Geodesy (TGNG) (black circles). (LUZ, 2008).

Non-consideration of gravity information generates distortions in leveling networks due to anomalous effects of topographic masses and variations in the crust composition. The spirit leveling is a geodetic methodology which results are path dependent. These aspects are not predicted in the theoretical modeling. The only way for obtaining results in a holonomic system is its association with gravimetry (VANIČEK, 1982).

Both BVD, as already referred, were established in association with the mean sea level (MSL). However, effects linked to the shift between each local MSL from an equipotential surface W_0 best fitted to the global MSL were not taken into account. The relationship between each BVD and W_0 can be determined by each local gravity potential W_i .

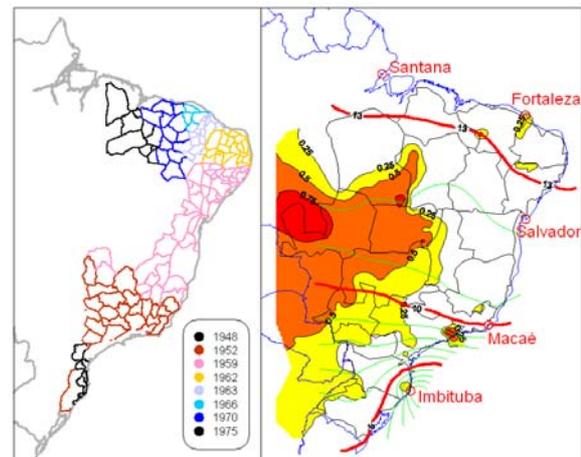
The potential difference $\Delta W = W_0 - W_i$ is related to the topography of the MSL related to the global

geoid, the so called Mean ocean Dynamic Topography (*MDT*). In each Datum region the *MDT* is given by:

$$MDT = \frac{\Delta W}{\gamma} \quad (5)$$

where γ is the normal gravity in the considered point. However, the computation of the potential difference ΔW is strongly affected by the local disturbing potential T not predicted in GGMs. The determination of these local components is part of the Geodetic Boundary Value Problem – GBVP. In the classical approach, like that used for obtaining the MAPGEO2010, the solution of GBVP is based on the use of gravity anomalies in the computations by Stokes' integral formula. This classical approach depends on the local vertical reference frame in a vicious process (HECK, 1990).

The sequential historic adjustments of the BFAN are represented in Figure 3; they have been evaluated by IBGE in 1993 with the conclusion of the first Global Preliminary Altimetric Adjustment (GPAA). Significant discrepancies were identified in this process of comparison. The shown discrepancies are still present in the new global network readjustment concluded in 6/20/2011 as an update of BFAN (IBGE, 2011).



The geopotential number in a point P (C_p) represents the potential difference between the geoid (W_0) and the equipotential surface passing through the point P (W_p). This geopotential number is equal to the geopotential variation and therefore expresses the work per unit of mass done by gravity in the path O-P. In practice it can be determined with sufficient accuracy based on leveling and gravimetry (DE FREITAS; BLITZKOW, 1999; GEMAEL, 1999):

$$C_p = W_0 - W_p = \int_0^P g dZ \cong \sum g_m \Delta Z^{obs} \quad (6)$$

In (6), g_m is the mean gravity observed in the extremes of a leveling section and ΔZ^{obs} is the observed level difference. If the geopotential number is divided by a specific value of gravity, it results in a distance. The geopotential number of a point P on the Earth surface is also equal to the work of gravity per unit of mass on an offset H along the plumb line between the geoid and P. This work is equal to the mean value of gravity $g_{G/P}$ between the geoid and P multiplied by the distance H. This implies in the definition of orthometric height of P:

$$H_p = \frac{C_p}{g_{G/P}} \quad (7)$$

The value $g_{G/P}$ can be only estimated, such that the orthometric height can only be determined based on hypothesis about the crust structure because the gravity value in the geoid is not known. Because these referred aspects the so called scientific heights are defined for keeping the physical meaning for heights at all, which are based on the (7), where the mean gravity value is estimated by any hypothesis and the path dependency is solved by the geopotential number C_p . Depending on the model or convention used to obtain in a consistent way the denominator of (7), it is possible to generate several kinds of Physical Height Systems. The kind of height or Height System depends only on the used gravity value which acts as a scale factor. If g in the geoid is determined by the Bouguer reduction the height is in the so-called **Helmert Height System**, which is adopted in North America. Other relevant height systems are: **Dynamic Heights System**, where the denominator of (7) is equal to a mean value of gravity, generally given by the value of normal gravity to latitude 45° . Once the gravity value is constant, this is the only height system where all points on a same equipotential surface will have the same height. This fact does not occur with orthometric height or with Helmert height. However, the use of an arbitrary constant divider introduces a scale distortion in the system. In the Molodenskii's **Normal Height System** the denominator is determined by the mean theoretical gravity between the ellipsoid and the point where the spheropotential has the same value than the geopotential in P. This kind of height preserves the physical meaning

of leveling survey and does not make use of reduction hypothesis. This is particularly useful for new concepts of altimetric surveying such as the association of GNSS with gravimetry (FERREIRA and DE FREITAS, 2010) because the possibilities for obtaining the disturbing potential at the Earth's surface.

Note that each of the reported physical height systems have as common characteristic the preservation of gravimetric information associated with the leveling operation. It must be emphasized that this information is contained in geopotential number C_p . This aspect does not exist in the present BFAN where the heights are in the so-called normal-orthometric system and the empirical relationship put equivalent information to a theoretical spheropotential number.

In the context of SIRGAS Project, the problem concerning the unification of vertical systems began to be discussed in 1997, with the creation of WG-III. The first recommendations of SIRGAS WG-III (IBGE, 1998b) indicated that:

- i) SIRGAS Vertical System would be defined through two sets of heights, a geometrical and a physical one, and their respective velocities;
- ii) SIRGAS Vertical System would be realized through a network of geodetic stations with GPS survey, spirit leveling and gravimetry;
- iii) The network cited previously would be established on the basis of SIRGAS95 network stations, with the addition of stations situated in the border of South American countries and in its major tide gauges – this network was effectively established by SIRGAS 2000 GPS campaign,
- iv) The geodetic authorities of the involved countries should organize the data necessary for the computation of geopotential numbers, with the purpose of obtaining physical heights.

Subsequently, GT-III recommended the adoption of normal heights as the physical component of the system (DREWES et al., 2002).

With respect to the recommendations presented earlier, it must be remarked that several activities are in course nowadays in South America. The main activities towards a modern height system according the most recent needs for users are:

- a) The geometric component of SIRGAS Vertical System (ellipsoidal heights) is well defined from the adoption of SIRGAS by South American countries, even including digital maps for velocities related to this component;
- b) Luz (2008) realized an extended analysis related to the BFAN including several propositions aiming its modernization and for giving to users better foundations for its needs;
- c) The computation of geopotential numbers has led countries to revise their first-order leveling networks, and verify the existing gravity information. In the Brazilian case a remarkable goal was a complete revision of survey manual registers and the building of a modern digital data base for the BFAN;
- d) The determination of a reference surface for

normal heights (quasigeoid) has led to studies based on GGMs derived from satellite missions as CHAMP, GRACE and GOCE, associated with terrestrial gravity data;

e) The BFAN is in a transitory process. In line with the present activities of readjustment realized by IBGE recently, several activities are in course for its modernization and for its link with a WHS. Some of these activities are presented in the next section.

3. PRESENT TOOLS OF GEODESY AND THEIR IMPLICATION ON GEODETIC SURVEY AND MAPPING

Geodesy is the science of measuring and mapping the Earth's geometry, orientation and the external gravity field in a three-dimensional time-varying space. In the scope of Geodesy, it is worthy of notice the gravity-dedicated satellite missions based on LEOs (Low Earth Orbit satellites) such as: CHAMP (CHALLENGING Mini-satellite Payload), GRACE (Gravity Recovery And Climate Experiment) and GOCE (Gravity field and steady-state Ocean Circulation Explorer). The main goal of these missions is to provide comprehensive global information of the Earth's gravity field associated to the mass distribution and its change in time. The global models and its derived functionals (e.g., geoid model, gravity anomalies and disturbances, components of deflection of the vertical - meridional component ξ and prime vertical component η , etc.) have an unprecedented spatial resolution in the history of Geodesy.

3.1 A New Generation of Global Geopotential Models

The gravity-dedicated satellite missions provide accurate data that can be converted into geopotential harmonic coefficients. These coefficients can be obtained from several sources of gravity information and are the bases of Global Geopotential Model (GGM, as plural GGMs). There are essentially three classes of GGMs:

- **Satellite-only GGMs:** are derived solely from satellite tracking data (analysis of satellites' orbits and gravity missions).
- **Combined GGMs:** are derived from a combination of a satellite tracking data, gravity data, satellite altimeter-derived gravity data in marine areas, and gravity information extracted from Digital Elevation Models (DEMs).
- **Tailored GGMs:** are derived by refining of existing (satellite-only or combined) GGMs using higher resolution regional gravity data which may have not been used previously.

Since the publication of the Earth Gravity Model 1996 (EGM96), cf. Lemoine et al. (1997), considerable

improvements on observation techniques resulted in better quality GGMs. These high quality new GGMs, cf. Arabelos and Tscherning (2010), are consequence of the improvements in the measuring techniques and systems which allowed obtaining new and more accurate data related to the gravity field even in areas with difficulties for conventional surveying techniques. Such data could be also obtained by improvements and reanalysis of old satellite altimetry data in association with new data as well as from the gravity-dedicated satellite missions.

Recently, improved models for the high degree combined solutions were made possible by the introduction of ellipsoidal harmonics. In addition, Jekeli (1988) proposed the conversion equations to transform ellipsoidal harmonics coefficients to spherical harmonic coefficients. Pavlis et al. (2006) have compiled a very high-resolution global topographic database and applied it in the computation of all terrain-related quantities. This kind of information is necessary for the pre-processing of gravity data and for the development and subsequent use of the Earth Gravitational Model 2008 (EGM2008) released by the National Geospatial-Intelligence Agency (NGA), cf. Pavlis et al., (2008). Such quantities include Residual Terrain Model (RTM) effects, analytical continuation terms (G_i), topographic/isostatic gravitational models, and the necessary models to convert height anomalies into geoid height.

The EGM2008 is considered the most consistent GGM produced until now. The EGM2008 is complete to spherical harmonic degree and order 2,159, and contains additional coefficients extending to degree 2,190 and order 2,159. EGM2008 includes improved 5'x5' gravity anomalies and has been enhanced from the latest GRACE based satellite solutions. EGM2008 also includes improved altimetry-derived gravity anomalies estimated by using PGM2007B and its implicit MDT model as reference. For the Collocation prediction of the final 5'x5' mean gravity anomalies, PGM2007B is used as reference model. It was also employed a formulation that predicts area-mean gravity anomalies which are effectively band limited.

3.2 Three-dimensional Geodetic Networks and LPS/GNSS integration

In the past, how mentioned in the previously sections, the three-dimensional (3D) geodetic networks were established as combinations of horizontal (2D) and vertical (1D) networks. In accordance with Hofmann-Wellenhof and Moritz (2006), the idea of a computation of a triangulation network in space dates back to H. Bruns in 1878. Hotine (1969), based in Bruns' ideas, presented the concept of a classical geodetic network in a rigorous three-dimensional way. Therefore, with the advent of GNSS technologies, especially the GPS, global scale networks have gained more and more importance. It is the case of the IERS Terrestrial Reference Frames realized in determined epoch yyyy (ITRFyyyy) which is the realization of ITRS where

several geodetic techniques are used. The ITRF2008 is the most recent realization of the ITRS. The IGS08 is a part of ITRF2008 composed only by GNSS stations.

Thus, today GPS is the best way to determine global rectangular coordinates $\{X, Y, Z\}$. However, in many practical surveys it is necessary to transform a global coordinate system F^* into a local coordinate system E^* , i.e., combine LPS and GPS. In doing so, it is necessary to know the Earth's gravity field for the association of GPS observations and Total Station observations because the vertical axes of the instrument coincides with the direction of the local gravity vector $\{\Gamma = \|\Gamma\|\}$. Deflection of the vertical components and height anomaly $\{\xi, \eta, \zeta\}$ at a point P on the Earth's surface provide the relationship between a curvilinear astronomical coordinate system $\{\Phi, A, H\}_\Gamma$ and a curvilinear ellipsoidal coordinate system $\{\varphi, \lambda, h\}$ at the same point P .

Grafarend and Awange (2005) determined deflection of the vertical by GPS and theodolite combinations thereof (Total Station), the referred LPS. The Procrustes solution emerges as an alternative to the solution of nonlinear equations. According to Awange (1999a), the *Partial Procrustes Problem*, in adjustment, is formulated as a problem of least squares. Given the coordinates of a Global Reference System (e.g. coordinates obtained by GPS) and coordinates in a Local Reference System (e.g. coordinates obtained by LPS) the Partial Procrustes Problem method may give a solution for the deflection of the vertical, as can be seen in (AWANGE, 1999a, 1999b). Considering F^* the Cartesian coordinates of the datum point in a global coordinate system and E^* Cartesian coordinates of that point on the local system, we have:

$$\mathbf{A} = \begin{bmatrix} x_2 - x_p & y_2 - y_p & z_2 - z_p \\ x_3 - x_p & y_3 - y_p & z_3 - z_p \\ x_4 - x_p & y_4 - y_p & z_4 - z_p \\ \vdots & \vdots & \vdots \\ x_n - x_p & y_n - y_p & z_n - z_p \end{bmatrix}_{E^*} \quad (8)$$

and

$$\mathbf{B} = \begin{bmatrix} X_2 - X_p & Y_2 - Y_p & Z_2 - Z_p \\ X_3 - X_p & Y_3 - Y_p & Z_3 - Z_p \\ X_4 - X_p & Y_4 - Y_p & Z_4 - Z_p \\ \vdots & \vdots & \vdots \\ X_n - X_p & Y_n - Y_p & Z_n - Z_p \end{bmatrix}_{F^*} \quad (9)$$

The partial Procrustes search exactly such a solution that:

$$\mathbf{B} = \mathbf{A} \cdot \mathbf{R} \quad (10)$$

A textbook treatment, which \mathbf{A} refers to the local system and \mathbf{B} to the global system to solve \mathbf{R} is described in Schönemann (1996):

$$\mathbf{S} = \mathbf{A}^T \cdot \mathbf{B} \quad (11)$$

$$\mathbf{S}^T \cdot \mathbf{S} = \mathbf{V} \cdot \mathbf{D}_s \cdot \mathbf{V}^T \quad (12)$$

$$\mathbf{S} \cdot \mathbf{S}^T = \mathbf{W} \cdot \mathbf{D}_s \cdot \mathbf{W}^T \quad (13)$$

\mathbf{V} and \mathbf{W} are obtained, for example, by *Schur decomposition*. The rotation matrix is obtained by:

$$\mathbf{R} = \mathbf{W} \cdot \mathbf{V}^T \quad (14)$$

This is the rotation matrix that relates \mathbf{A} and \mathbf{B} .

Other solution for Procrustes problem is given in Awange (1999a), with the peculiarity $\mathbf{A} = \mathbf{B} \cdot \mathbf{R}^T$ instead of (10):

$$\mathbf{A}^T \cdot \mathbf{B} = \mathbf{U} \cdot \mathbf{\Sigma} \cdot \mathbf{V}^T \quad (15)$$

$$\mathbf{T} = \mathbf{V} \cdot \mathbf{U}^T \quad (16)$$

The expression on the right-hand in equation (15) can be solved by decomposition in singular values. The matrix \mathbf{R} is obtained from:

$$\mathbf{R} = \mathbf{T}^T \quad (17)$$

Finally, it is calculated $\{A_p, \Phi_p, \Sigma\}_\Gamma$ through the extraction of elements of the matrix \mathbf{R} :

$$A_p = \text{atan} \left(\frac{r_{32}}{r_{31}} \right) \quad (18)$$

$$\Phi_p = \text{atan} \left(\frac{r_{33}}{\sqrt{r_{31}^2 + r_{32}^2}} \right) \quad (19)$$

$$\Sigma = \text{atan} \left(-\frac{r_{23}}{r_{13}} \right) \quad (20)$$

With the (18) and (19) it is possible to establish a *Local Astronomical System* for combine LPS with a GPS instead of a "Local Topographic System" (LTS). However, another system is necessary, in this case *Local Geodetic System* (LGS). This method is physically and geometrically more consistent with the systems related to LPS and GPS.

Another possibility with a good approximation for local surveys with short extension is given by using the moderns GGMs. From these models it is possible to derive the local/regional values of the components of deflection of the vertical (meridional component ξ and prime vertical component η). These values can be used for obtaining the astronomical coordinates Φ and A from geodetic coordinates as well as local bases improved orientation by using the GPS positioning and the equations (1) to (4). The relationship between the LPS local astronomical system and the GPS global GRS is shown in Figure 4.

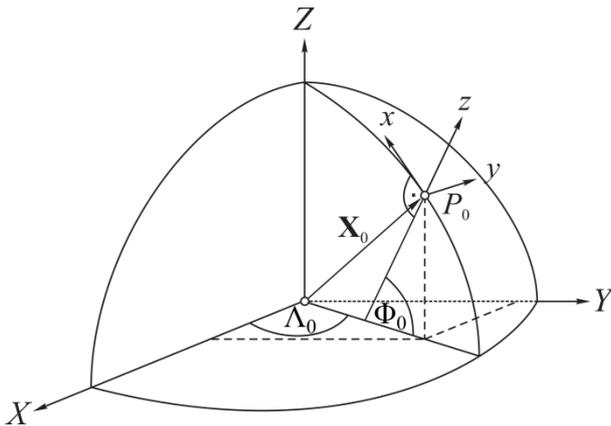


Fig. 4: The local Cartesian astronomical $\{x, y, z\}$ system and its spatial relationship with the Cartesian $\{X, Y, Z\}$ geocentric GRS.

The coordinates of a generic point $P_i \{x_i, y_i, z_i\}$ obtained in a local Cartesian astronomical system with origin in a point P_0 can be converted to a Cartesian geocentric GRS, with some approximation by using the following equation:

$$\begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} + R_3(180^\circ - \Lambda)R_2(90^\circ - \Phi)S_2 \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} \quad (21)$$

Where $\{X_0, Y_0, Z_0\}$ are the geodetic coordinates (e.g. that obtained with GPS) of the origin of the local astronomical system. R_2 and R_3 are the rotation matrix around the y-axis and z-axis, respectively, and S_2 is the reflection matrix related the y-axis. It must be remarked that the transformation is not rigorous because the astronomical coordinates are obtained considering constant values for the deflection of the vertical components which can vary slowly depending on the dimension of survey area and disregarding effects of the Earth's curvature.

3.3 Fundamental Altimetric Networks, Geoid/Quasigeoid and a World Height System

As mentioned in early section, the current extent of BFAN has about four times the distance around the world and it was dissociated of gravity observations. In this context the heights associated with the BFAN are the normal-orthometric heights because it was considered the non-parallelism of the normal equipotential surfaces. However, the adjustment of the leveling networks must be realized in a holonomic (path independent) height system. In this context, the natural holonomic vertical coordinate system is that one based on the geopotential numbers. Taking into account these above mentioned difficulties we can ask ourselves:

- Is it necessary re-leveling throughout the country by using spirit leveling associated with gravimetric observations?

- Is it possible to calculate definitely a geoid or quasigeoid model that achieves the precision required for such work?

In regarding to the first question we can mention that the spirit leveling is a very time-consuming, tedious and an expensive operation. Taking into account the second question, the geoid (quasigeoid) is still a topic of fundamental importance for emerging nations such as Brazil. Many regions around the world require improved gravimetric data bases to support a very accurate geoid (quasigeoid) modeling. This is essential for the modernization of height systems by employing the emerging GNSS technologies, in particular, the GPS. Geoid and quasigeoid computation have been of interest to many Geodesists such as Moritz (2011), Ardalán et al., (2010), Zhang et al., (2009), Flury and Rummel (2009), among others.

Most of the South American Datums are based on a determination of MSL at different tide gauges over a varying range of time intervals and at different epochs. However, each vertical datum is referred to a particular equipotential surface, associated with the MSL at tide gauge and reduced for a specific epoch. In general, these surfaces are not coincident with the global geoid. The ocean surface does not coincide with a level surface (e.g. the geoid) of Earth's gravity field because geostrophic effects which produce the Mean ocean Dynamic Topography – MDT already mentioned in section 2.2. Figure 5 displays the MDT around the BVD-I.

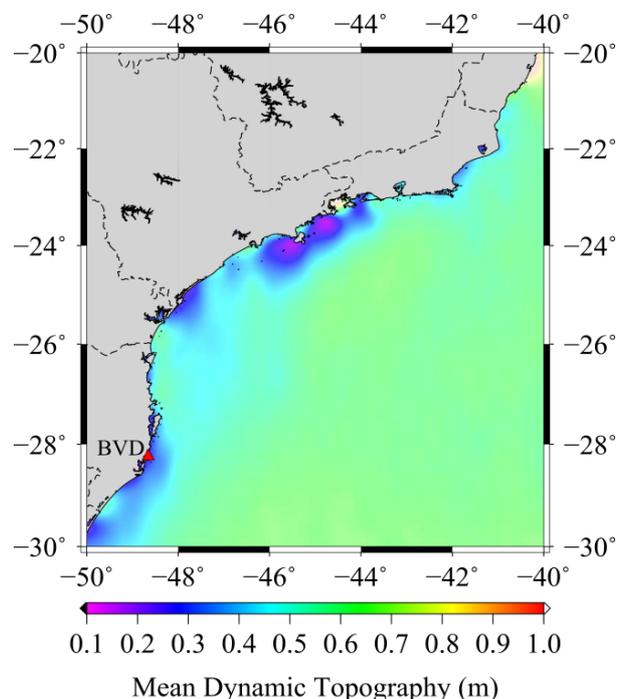


Fig. 5: Mean Dynamic Topography at a region around of the Imbituba Brazilian Vertical Datum.

According Andersen and Knudsen (2009) a MDT model gives a global mean sea level bias related

to a global geoid. However, Ferreira et al. (2010) found that the MDT at the BVD-I is -0.31 ± 0.01 m. We must emphasize that the used methodology for determining the offset of the BVD-I related to a World Height System (WHS) (or its realization World Height Frame, WHF) did not use the computation of local geoids approach and, in consequence, not contains error propagation related to those models (FREITAS et al., 2010).

De Freitas et al. (2011) showed that the MDT reflected in the Paraná state portion of the BFAN, or the Brazilian zero-reference is about -0.35 ± 0.01 m under a global zero reference. They used GPS positioning integrated with disturbing potential information refined by Residual Terrain Model (RTM), in the context of the Fixed Geodetic Boundary Value Problem (FGBV). The used approach was asked to be introduced in the SIRGAS project, WGIII, for linking vertical networks in South America.

Another consistent value for the shift of the zero height of BFAN related with a WHS was obtained by Melo (2011). In his study they were used several GGMs available in the International Center for Global Earth Models (ICGEM) of IAG and the MAPGEO2010 produced by IBGE. The considered parameter for analysis was the geoid height in reference stations obtained from the models minus the difference $h - H$ obtained from the BGS, where h is the ellipsoidal height determined with GPS on bench marks and H is the normal-orthometric height from BFAN. It is possible to see in Table 1 that the mean discrepancy obtained in 21 stations from all analyzed GGMs is 0.34 m above the BGS. The MAPGEO2010 has a discrepancy in opposite sense. It must be remarked that in the study area the MAPGEO2010 presents the largest discrepancies in Brazil.

Table 1: Discrepancies of geoid height obtained for several GGMs and MAPGEO2010 and the value obtained from GPS/leveling in the BGS

Model	Min	Max	Ampl	Mean	RMS
	(m)				
GO CONS GCF2 TIM	0.002	0.964	0.962	0.300	0.419
AIUB-GRACE03S	0.028	1.195	1.167	0.258	0.455
EGM2008_2190	-0.054	0.696	0.750	0.362	0.411
EGM2008_720	-0.058	0.690	0.748	0.360	0.404
EGM2008_360	-0.022	0.662	0.683	0.359	0.404
EIGEN_05C	-0.015	1.596	1.611	0.384	0.511
MAPGEO2010	-0.060	-1.081	-1.021	-0.517	0.578

Recently, IAG by its Inter-Commission Project 1.2: Vertical Reference Frames (Idhe, 2009) proposed a program of activities related to the study of regional vertical systems and their relations to a WHS/WHF. The practical applications are among the main objectives. This goal is proposed to be achieved until 2012. This proposal is in according of SIRGAS WGIII statements

for linking South American Vertical Networks. There is a tendency among South American countries in to monitor and integrate the vertical networks according to SIRGAS project statements for taking profit of modern space geodetic observations in a continental basis. A unified vertical datum in South American is important for monitoring common problems related to environment, hydrodynamics and energy of transporting mass, engineering, natural resources, land management, and so on.

Montecino et al. (2011) proposed three approaches for connecting the two portions of BFAN linked respectively to the Datums of Imbituba and Santana. These approaches are based in determining the shift between the two Datums with basis in a regional quasigeoid model. Then, the height anomaly ζ in each Datum is determined according the following models:

a) Satellite only model derived from the GOCE mission givem by the GO_CONS_GCF_2_TIM_R2 GGM (ICGEM, 2011):

$$\zeta(\varphi, \lambda) = \zeta_{GOCE}^{N_{240}}(\varphi, \lambda) \quad (22)$$

b) Same model used in the precedent approach but complemented by RTM:

$$\zeta(\varphi, \lambda) = \zeta_{GOCE}^{N_{240}}(\varphi, \lambda) + \zeta_{RTM}^{>N_{max}}(\varphi, \lambda) \quad (23)$$

c) In addition to the precedents approaches by introducing the mean wave lengths in the geopotential harmonic spectrum information given by the EGM2008:

$$\zeta(\varphi, \lambda) = \zeta_{GOCE}^{N_{240}}(\varphi, \lambda) + \zeta_{EGM08}^{N_{240-2190}}(\varphi, \lambda) + \zeta_{RTM}^{>N_{max}}(\varphi, \lambda) \quad (24)$$

Geopotential numbers, cf. Eq. (6), are still very important in the calculation of physical heights for practical use such as dynamic, Helmert/orthometric, and normal heights. Hofmann-Wellenhof and Moritz (2006, p. 318), Idhe (2009), and others have suggested to apply the disturbing potential on the Earth's surface associated with the normal potential at the same point to calculate the geopotential numbers. Technical details on how to develop geopotential numbers from such a model must be worked out, so as to develop other types of heights (Roman et al, 2010). In this modern concept, to carry out time-consuming leveling such as spirit and trigonometric is not required any more. Nonetheless, from Molodenskii's theory, which provides the disturbing potential T at point P on the Earth's surface, we have:

$$W(\varphi, \lambda, h) = U(\varphi, \lambda, h) + T(\varphi, \lambda, h) \quad (25)$$

where $W(\varphi, \lambda, h)$ is the geopotential required by:

$$C(\varphi, \lambda, h) = W_0 - W(\varphi, \lambda, h) \quad (26)$$

The geopotential numbers $C(\varphi, \lambda, h)$ are computed in a direct way from gravity data. See Eq. (6) for

comparison with (23). It is more general than the geometric determination of the normal height from ellipsoidal height associated with the quasigeoid model.

All countries in South America can benefit from the methodology discussed here, mainly Paraguay and Bolivia. Due to geographical limitation (landlocked countries) their vertical networks have no direct connection with the MSL. The velocity component related to temporal variation of the geoid is one aspect to be considered in the BFAN, as well as in all leveling network in South America. The BFAN should be planned as kinematic height network. This goal could be achieved by using combination of the SIRGAS-CON permanent station network, the repeated leveling surveys, repeated gravity measurements, tide gauge measurements along the Brazilian coast lines as well as the gravimetric quasigeoid model and GRACE data.

3.4 Tide System and its Influence in Geodetic Observations

Nowadays, it is necessary to consider the permanent earth tide phenomena in several problems related to Geodesy because the present standards of precision. It is the case, e.g., for long baselines determination with GNSS, leveling associated with geopotential numbers, local and regional vertical datums connections. Considering in special the fundamental altimetric networks connection problem, it is important that all measurements are reduced to the same tide system. Then, GPS positioning, gravity measurements and local height systems must be reduced to the same permanent tide system (POUTANEN et al., 1996). There are three approaches for dealing with the permanent tidal effects on the geopotential and the Earth's shape (MÄKINEN and IHDE, 2008):

- In the *mean-tidal system*: the mean permanent effect of tides is not removed from the shape of the Earth.
- In the *tide-free or non-tide system*: the permanent deformation is eliminated from the shape of the Earth as well as the direct and indirect effects of the potential associated with the tides.
- In the *zero-tidal system* only the direct effects of the potential associated with tides are removed. Only the indirect effect is keep.

Conforming to the IAG Resolutions No 16 adopted in Hamburg in 1983, gravity related components are given in a zero tidal system as well as the handling of the gravity data. However, the ITRFyy coordinates are given in the tide-free system, the same holds for the EGM2008. In doing so, SIRGAS coordinates systems follows the same tide system related to the ITRF. Contrary to this, the BFAN heights (normal-orthometric heights) are given in the mean-tidal system since the tidal corrections were not applied to the leveling observations.

In Ekman (1989) are presented equations to transform heights and gravity values among tidal systems. The transformations between a height difference ΔH_z above the zero geoid, a height difference ΔH_m above the mean geoid, and a height difference ΔH_n above the non-tidal geoid, between a northern and southern station, are given by (EKMAN, 1989):

$$\Delta H_m - \Delta H_z = 29.6(\sin^2 \varphi_N - \sin^2 \varphi_S) \quad (27)$$

$$\Delta H_z - \Delta H_n = 29.6(\gamma - 1)(\sin^2 \varphi_N - \sin^2 \varphi_S) \quad (28)$$

$$\Delta H_m - \Delta H_n = 29.6\gamma(\sin^2 \varphi_N - \sin^2 \varphi_S) \quad (29)$$

Where φ_N and φ_S are the geodetic latitudes of the northern and southern points respectively and γ is a constant $\gamma \approx 0.68$ (EKMAN, 1989). And for gravity values, the differences between zero gravity g_z , mean gravity g_m and non-tidal gravity g_n are given by (EKMAN, 1989):

$$g_m - g_z = -30.4 + 91.2 \sin^2 \varphi \quad (30)$$

$$g_z - g_m = (\delta - 1)(-30.4 + 91.2 \sin^2 \varphi) \quad (31)$$

$$g_m - g_n = \delta(-30.4 + 91.2 \sin^2 \varphi) \quad (32)$$

Where δ is an arbitrary constant ≈ 1.53 (EKMAN, 1989).

4. SUMMARY

The Spatial Age brought new possibilities for Geodesy and Cartography. The modern orbital platforms changed completely the ability to capture, model and manage spatial data. Associated to these facts, new paradigms of precision must be considered. Then the classical geodetic networks based in terrestrial methods became old-fashioned. Now the global GRS must be adopted in all stages of the georeferencing.

The transition from local geodetic systems is a real need today for taking profit from the modern technologies. In the Brazilian case it is possible to obtain 3D positioning with accuracy on the centimeter level all over the country based in the SIRGAS-CON network. However, the survey needs the adequate integration of LPS and GPS reference systems. In this case aspects linked to the gravity field must be considered.

The BFAN still remain with its classical conception. The heights are in a non holonomic system. Its link with a WHS it is possible only by introduction of gravity information along with leveling lines.

The modern GGMs allowed several possibilities for facing the absence of gravity information in practical applications, but sophisticated effects like permanent tides must be now considered.

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