RELATIONSHIP BETWEEN TERRESTRIAL AND SATELLITE DOPPLER SYSTEMS

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ABSTRACT

Classical horizontal geodetic networks are commonly combined with space observations, mostly satellite Doppler, in order to optimize the accuracy of geodetic control points and, thus, satisfy as many types of users as possible. Since satellite Doppler observations refer to a fully defined three-dimensional reference system and terrestrial observations, through the presence of Laplace stations (astronomical longitude and azimuth), contribute also to the pole and longitude orientations, it is imperative to ensure the highest possible degree of compatibility between the astronomical and satellite Doppler systems to maintain optimization of the accuracy of control points. Since gravity and geopotential (in the form of spherical harmonics) data are usually combined to evaluate geoid undulations and deflections of the vertical which are in turn used to reduce terrestrial angular and range observations, it is equally imperative to ensure that the satellite Doppler system and that of the geopotential solution are truly geocentric and thus compatible with the gravity data which should refer to a single equipotential surface. In order to estimate the degree of compatibility in terms of longitude orientation between satellite Doppler and geodetic astronomical systems as realized by current observations, astrogeodetic (based on CIO pole, BIH longitudes, and NWL9D satellite Doppler system) and gravimetric deflections of the vertical were compared at several hundred stations of the Canadian geodetic framework and U.S. transcontinental traverse. It was found that, when using the U.S. data subset only, incompatibility between the zero geodetic meridian plane of the NWL9D system and the zero astronomic meridian plane of the BIH was of the order of $0\rlap{.}''8$, which is in good agreement with previous results. However, inter-comparisons between various North American subsets revealed inconsistencies between areas of up to $0\rlap{.}''8$ (between Canadian and U.S. geodetic astronomical longitude observations). These results are based on the assumption that gravimetric deflections are bias free. The geocentricity of the NWL9D system with respect to other systems such as the Goddard Earth Models and SAO Standard Earths is also analyzed by comparing satellite Doppler derived geoid undulati-

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ons with GEM and SAO SE undulations. An incompatibility of 4 m in Z (axis) exists between the origin of the NWL9D system and that of the other systems.

1. INTRODUCTION

Classical horizontal geodetic networks consist of terrestrial angle and distance measurements supplemented by astronomical observations which provide geodetic azimuth orientation through the well known Laplace equation

$$\alpha = A - (\lambda_a - \lambda_g) \sin \phi_g$$

where α is the resulting geodetic azimuth calculated from observed astronomical azimuth A and longitude λ_a, and derived geodetic longitude λ_g and latitude ϕ_g. The establishement of an earth fixed conventional geodetic reference system was traditionally done by specifying the geodetic coordinates of a point on the earth surface and the geodetic azimuth (through the use of astronomical observations) of a line from this point. This ensured the geodetic system to be compatible with the astronomical system (Star catalogue, pole, and zero meridian) used to reduce astronomical observations. Additional Laplace azimuth observations were made at other points to provide additional strength to the geodetic networks. This was the case with the North American Datum 1927 (NAD27) (Can. Inst. of Surv. 1974).

The advent of space techniques and, in particular, of satellite Doppler positioning, has provided geodesists with the capability of determining earth fixed geocentric three-dimensional positions with a sub-metre accuracy. Satellite Doppler data will be merged with classical horizontal geodetic networks to define the North American Datum 1983 (NAD83) (U.S. Dept of Commerce 1978). Several hundred satellite Doppler stations have already been established in Canada (Boal & Kouba 1978) and the U.S. (Strange & Hothem 1976) for this purpose. These North American satellite Doppler stations are estimated to be accurate and consistent at the 1 m level (Kouba & Hothem 1978). The station positions refer to the NWL9D (or, equivalently, NWL9Z) reference system (Anderle 1974, 1976) which was intended to be geocentric and to have its z axis coinciding with that implied by the Conventional International Origin (CIO pole). The longitude origin was specified to be consistent with the zero meridian of the Bureau International de l'Heure (BIH) within 1". In view of the merging of satellite and terrestrial data, it is necessary that terrestrial astronomical observations (used in Laplace azimuths) and satellite positions refer to the same astronomical pole and zero meridian, e.g., CIO pole and BIH meridian, otherwise network distortions will occur. It has already been established that the z axis of the NWL9D system is consistent with CIO pole within $0\rlap{.}''05$ (e.g., Hothem 1979). In view of this and of the fact that it would be difficult to study both pole and longitude origin from North American data only due to coupling between the pole x coordinate and $\partial\lambda$ (longitude origin), the present investigation deals with the longitude origin (Section 2) and geocentricity (Section 3).

It was decided among North American countries that NAD83 will be geocentric. Geocentricity will be realized through NWL9D satellite Doppler positions using an adequate datum definition (e.g., Kouba 1978). It is therefore important that the NWL9D satellite coordinate system be "as geocentric" as possible or that at least its position with respect to the true geocentre be as accurately known as possible in order to apply appropriate transformations. In addition, the NWL9D system should be compatible (in terms of geocentricity) with the geopotential model to be used to provide low harmonic components of geoid undulations and deflections of the vertical to be used to reduce terrestrial angle and distance measurements to the reference ellipsoid. The geocentricity of the NWL9D system was tested against other "geocentric" systems and results are reported in Section 3.

2. ZERO MERIDIAN OF NWL9D VERSUS BIH

The longitudes of NWL9D can be compared with those of BIH using either Very Long Baseline Interferometry (VLBI) or astrogravimetric techniques. Results using the VLBI technique, which is based on direct comparisons of satellite Doppler and VLBI data, are very consistent and indicate that NWL9D longitudes (East) should be increased by $0''.8$ ($\mp 0''.1$) to make the zero geodetic meridian plane of the NWL9D system parallel with the zero astronomical meridian plane of the BIH (Hothem 1979; Langley et al 1979). However, results using the astrogravimetric technique and data in North America are not consistent and suggest significant biases in the geodetic astronomical longitude data.

The astrogravimetric technique, which is described in detail in Kouba & Lachapelle (1979), consists of comparing (absolute) geocentric gravimetric prime vertical components η_g (of the deflection of the vertical) defined as angular differences between normals to the ellipsoid and to the geoid with astrogeodetic prime vertical components η_a defined as

$$\eta_a = (\lambda_a - \lambda_g) \cos \phi$$

where λ_a is the astronomical longitude referred to CIO pole and BIH zero meridian and λ_g the geodetic longitude based on the NWL9D system. Unless both BIH and NWL9D zero meridian planes are parallel, η_a will be biased and this bias will be the difference between η_g and η_a since both quantities should theoretically be the same. The additional presence of random errors in both η_a and η_g necessitates the use of several well distributed data points. It is also possible to determine additional biases such as offset parameters Δx, Δy, and Δz and pole coordinate differences δx and δy using meridian components ξ_g and ξ_a of the deflection of the vertical in addition to η_g and η_a in a least squares solution. However, Δx, Δy, and Δz are better determined through the use of

TABLE 1

COMPARISON OF NWL9D AND BIH LONGITUDES IN NORTH AMERICA USING THE ASTROGRAVIMETRIC TECHNIQUE

Solution No.	Description	δy^*	$\delta\lambda^{*\dagger}$	$\hat{\sigma}_o$
1	597 Canadian points East of long. 248^oE	$.01\mp.08$	$.34\mp.14$	1.10
2	142 Canadian points Laplace stations $\phi<60^o$, $\lambda>248^oE$	$-.14\mp.14$	$-.01\mp.21$	.83
3	628 U.S. points $\lambda>248^oE$	$-.30\mp.04$	$.76\mp.05$	.65
4	47 Canadian Laplaces $49^o<\phi<53^o$ $248^oE<\lambda<280^oE$	$-.27\mp.19$	$.16\mp.30$	.88
5	27 Canadian Laplaces as sol. No.4 with year $\geq$ 1968	$-.29\mp.22$	$.34\mp.34$	.75
6	101 U.S. points $46^o<\phi<49^o$ $248^o<\lambda<280^oE$	$-.19\mp.09$	$.46\mp.13$	.55

* In arcsecs
† With respect to NWL9D zero meridian plane

a worldwide data set (Cf. Section 3). In the present case, they were constrained to zero which implies that the geodetic coordinates λ_a and ϕ_a used to derive η_a and ξ_a refer to a geocentric system, i.e., NWL9D is geocentric. The non-geocentricity of NWL9D in the z axis reported in Section 3 will affect mostly δy but not $\delta\lambda$. δx is fixed to zero in view of the coupling effect mentioned earlier.

The η_g and ξ_g components for several hundred points in Canada and the U.S. for which η_a and ξ_a were available were predicted using a combination of geopotential coefficients (In this case, GEM10B - See Lerch & Wagner 1978) and surface gravity data (Lachapelle 1978) according to the method described in Lachapelle (1977). Canadian astronomical data used to derive η_a and ξ_a was partly reduced to conform with CIO pole and BIH zero meridian as described by Vamosi (1977). Canadian geodetic coordinates were obtained from the October 1977 test adjustment of the terrestrial and satellite Doppler data (Beattie et al 1978) and are related to the NWL9D system through a longitude correction of $0\overset{''}{.}65$ (Kouba 1978). U.S. η_a and ξ_a were provided by the National Geodetic Survey; the geodetic coordinates were obtained from an unconstrained adjustment of the transcontinental traverse and then converted to NWL9D (Gergen 1979); astronomical longitudes were referred to the BIH zero meridian.

Results are listed in Table 1. The $\delta\lambda$ values represent the amount (in arcsecs) which should be added to NWL9D longitudes to make these compatible with BIH longitudes. Differences between the various solutions of $\delta\lambda$ are due to regional biases in either or both gravimetric and astrogeodetic deflections of the vertical. Solution No. 3 is in agreement with VLBI results quoted earlier and with astrogravimetric results of White & Huber (1979) which are based on a limited U.S. data sample. Solution No. 2, which is in excellent agreement with an azimuth misorientation of 0".5 (which corresponds to the original -0".65 correction applied to the NWL9D longitudes for the October 1977 adjustment - See Kouba 1978) between terrestrial and combined terrestrial-satellite Doppler data solutions of the October 1977 adjustment (Beattie et al 1978), implies that Canadian geodetic astronomical and NWL9D longitudes are in agreement; this contradicts VLBI results and astrogravimetric results in the U.S. (Solution No. 3). However, Solutions No. 4, 5 and 6, which are made of data subsets from Solutions No. 2 and 3, show that results for $\delta\lambda$ vary significantly. If we assume that gravimetric components η_g and ξ_g are bias free, this indicates that North American geodetic astronomical longitude observations are not only incompatible between Canada and the U.S. but are also affected by significant regional biases. This could affect the new NAD83 unless adequate precautions are taken. The biases are larger than anticipated previously and are not fully understood at present.

Inconsistencies are also noted between the various solutions for δy. This could be due to either incompatibilities between astronomical latitude observations/reductions or/and biases in the gravimetric meridian components ξ_g of the deflection of the vertical. The negative sign trend for δy is consistent with the z axis offset of the NWL9D system from the geocentre reported in Section 3. A 4 m offset would amount to -0".09 in δy. The values of $\hat{\sigma}_0$ in Table 1 indicate that for all six solutions but No. 1 the estimated variances of either or both gravimetric and astrogeodetic deflection components were pessimistic. The estimated variances of the gravimetric deflection components were calculated according to Lachapelle (1977) and ranged from 1" to 2". The estimated variances of the astrogeodetic components were set to 0".7 (ξ_a) and $1''\cdot\cos\phi$ (η_a) respectively.

3. GEOCENTRICITY OF NWL9D

This was analysed by comparing satellite Doppler (NWL9D) derived geoid undulations N_D (N_D is h minus H where h is the satellite Doppler derived ellipsoid height and H, the sea level or orthometric height) with undulations derived from various geopotential models of the gravity field. Since all systems should, in principle, be geocentric, the first-degree harmonic of the geoid undulation,

$$N_1(\phi,\lambda) = \Delta x \cos\phi \cos\lambda + \Delta y \cos\phi \sin\lambda + \Delta z \sin\phi,$$

should be zero in both cases and a comparison solution in Δx, Δy and Δz between both sets of undulations should give zero for these translation parameters. A well distributed, worldwide set of undulations is required to obtain a meaningful solution. Such a solution, which also included a fourth parameter, namely N_0 the zero-degree harmonic of the geoid undulation (which provides information about the semi-major axis of the mean earth ellipsoid), was carried out by the U.S. Defense Mapping Agency Hydrographic/Topographic Center (DMAHTC) (Grappo 1979) using 290 globally balanced satellite Doppler stations. Geopotential models used for these comparisons were GEM10 (Lerch et al 1977) and GEM10B (Lerch & Wagner 1978). DMAHTC (Grappo, personal communication, July 1980) recently expanded comparisons to include GEM9 (Lerch et al 1977), Smithsonian Astrophysical Observatory (SAO) Standard Earth (SE) III (Gaposchkin 1973), SAO SE IV.3 (Gaposchkin 1976), SAO Global Gravity Field and WGS72(12,12). These results, summarized in Table 2, are more conclusive since GEM, SAO and WGS72 geopotential models are practically mutually independant. All solutions exhibit a fairly consistent Δz value of 4 m which is the z coordinate of the "geocentre" of NWL9D with respect to the "geocentre" of the geopotential models. This result is in agreement with that of (Hothem 1979) obtained from a direct comparison of satellite Doppler (NWL9D) and satellite laser ranging stations in the U.S. The high degree of consistency (in terms of geocentricity) between SAO and GEM geopotential models was also well demonstrated by Schaab & Groten (1979) using 10^o grid data sets for comparison.

TABLE 2

GEOCENTRICITY OF NWL9D VERSUS GEM, SAO SE AND WGS72 MODELS

(Using 290 globally balanced Doppler stations)

Geopotential Model	Δx^*	Δy^*	Δz^*	a^*
GEM9	0.9	-0.1	3.9	6378138.5
GEM10	0.7	-0.2	4.0	6378135.7
GEM10B	0.6	0.3	4.3	6378136.6
SAO SE III	0.6	-0.4	2.7	6378138.4
SAO SE IV.3	0.5	0.2	3.4	6378138.6
SAO GRAV. MODEL	1.2	0.1	3.3	6378138.2
WGS72(12,12)	0.8	-0.5	4.8	6378139.3

* In metres

The Δz value of 4.8 m obtained when using WGS72(12,12) geopotential model is interesting since WGS72 and NWL10E (which is used to calculate orbits for the NWL9D system) geopotential models are expected to be correlated and, thus, to have the same "geocentre". However, the above result is also consistent with Anderle (1980) who reports a Δz of 2.4 m when comparing GEOS-3 altimetric data (using orbits in NWL9D) with the NWL10E geopotential model. Also, Malyevac & Colquitt (1980) finds no significant difference between their SEASAT-1 orbit solutions using NWL10E and GEM10 geopotential models respectively. Yet, J.G. Marsh (Personal communication, March 1980) of NASA/Goddard Space Flight Center reports a 5 m difference between satellite positions using GSFC and NWSC (Naval Surface Weapons Center) orbits respectively. These findings suggest incompatibilities in station computation but compatibility (in terms of geocentricity) of the NWL10E geopotential model (which is used for the orbit computations in the NWL9D system) with GEM and SAO models. Since these models are independant and consistent (in terms of geocentricity), they can be assumed to be truly geocentric at the 1 m accuracy level. This implies that the NWL9D system is off the geocentre by about 4 m in z. Results reported by West (1980) are in disagreement with the above since comparisons between SEASAT-1 altimetric data (using orbits in NWL9D) and GEM10B and WGS72 geopotential models give Δz values between 0.0 and 0.3 m.

The results listed in Table 2 for the semi-major axis (a) of the mean earth ellipsoid will not be discussed in detail here. However, it is recalled that they are in agreement with the value of 6378137 m adapted by the International Association of Geodesy for Geodetic Reference System 1980 at its Canberra 1979 General Assembly following recommendations by Moritz (1979). The 4 m offset in the z axis of the NWL9D system is the cause for the best fitting semi-major axis of the mean earth ellipsoid obtained from North American data only (Lachapelle 1979; Grappo 1979) to be systematically 3 m lower than the above value of 6378137 m based on worldwide data.

4. CONCLUSIONS

The NWL9D system, which is used to calculate satellite Doppler positions worldwide, appears to be compatible with CIO pole at the 0″.05 accuracy level. Its longitudes (East) should be increased by 0″.8 (∓0″.1) to make its zero geodetic meridian plane parallel with the zero astronomic meridian plane of the BIH. z coorodinates should be increased by 4 m (∓1m) to make its centre coincide with the geocentre.

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