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Geodetic satellite Doppler positioning and application to Canadian test adjustments†

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During 1974–6, the Geodetic Survey of Canada established a geodetic control network with spacing between points of about 200–500 km with the use of the satellite-Doppler method. For this application, a unique observation strategy and Doppler data reduction procedures have been developed, by using both precise and broadcast satellite ephemerides. The satellite-Doppler geodetic control has contributed greatly to the readjustment of the Canadian triangulation network, in particular to the datum orientation and positioning. The results have also been useful for geoid studies in Canada. Continuous satellite-Doppler tracking from the two Canadian Tranet stations provides additional information on polar motion and long-term variations of the satellite system, which are important for monitoring and maintaining the related geodetic datum.

Introduction

In Canada, satellite-Doppler positioning was introduced in 1968 by both Shell Canada Ltd and the Bedford Oceanographic Institute (Wells 1969). During 1969–70, simulation studies at the University of New Brunswick (U.N.B.) indicated potential accuracy at the 1 m level (Krakiwsky & Kouba 1970). In the autumn of 1970, the three agencies jointly carried out a field experiment in Eastern Canada using several navigation receivers (Hittel & Kouba 1971). The simulations and the experiment gave impetus to software development which started at U.N.B. and continued at Shell Canada Ltd.

In 1972, the Geodetic Survey of Canada, encouraged by additional field tests and a convincing U.S. Department of Defense report (D.O.D. 1972), embarked on its own field testing (with Canadian Marconi receivers) and software development. The original satellite-Doppler data reduction program, acquired from Shell Canada, was extensively modified and rewritten, resulting in the present GEODOP program package (Kouba & Boal 1975). Field production started in 1974; since then, more than 160 points with spacing between 200 and 500 km were observed (figure 1), allowing some simultaneous observation periods to increase relative accuracy. A detailed historical review can be found in Wells *et al.* (1977).

In 1974, the Earth Physics Branch, Department of Energy, Mines and Resources, established two permanent Doppler tracking stations located at the Polar Motion Observatories near Ottawa and Calgary under a cooperative agreement with the U.S. Defense Mapping Agency (D.M.A.). Both stations belong to the world-wide Tranet network, used for precise orbit determinations and satellite polar motion monitoring.

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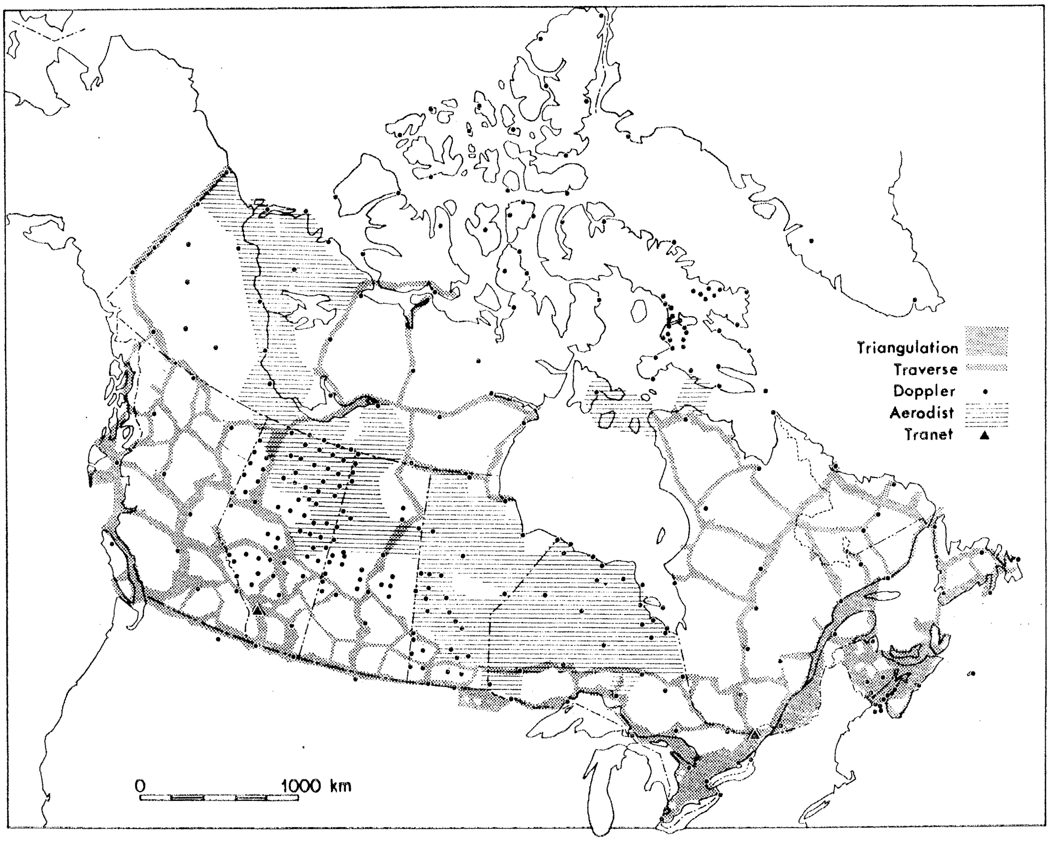

FIGURE 1. Horizontal control framework in Canada, to end of 1977.

GEODETIC APPLICATIONS

Doppler data collected by the Geodetic Survey of Canada since 1974 have been reduced by using the GEODOP program. The program is based on a semi-short arc method, utilizing either broadcast orbits or historical 'precise' satellite ephemeris generated by DMA Topographic Center. It employs the method of phase adjustment and comprehensive statistical testing for each satellite pass contribution. Three orbital (translation) biases and one timing bias are solved for each satellite pass. One frequency and one tropospheric refraction scaling bias are computed for each pass and station. The main program GEODOP requires several auxiliary programs for data preprocessing, file editing and manipulation (Kouba & Boal 1975).

Up to 15 stations are usually adjusted simultaneously, with the use of both precise and broadcast ephemeris, resulting in two types of solutions which include adjusted Cartesian coordinates and corresponding variance–covariance matrices. Since no common data and orbits are used in broadcast and precise solutions, they are largely independent. Both types of solutions (i.e. precise and broadcast) for the same group of stations are then combined, taking into account the variance–covariance matrices augmented in such a way that a translation is allowed for the whole figure ($\sigma = \pm 1$ m for precise and ± 5 m for broadcast ephemeris). This augmentation of the variance–covariance matrix is only approximate, as the error modelling does not allow for differential scale and rotation biases between various solutions of the same type. However, one scale and three rotation parameters are solved for broadcast into precise solutions for each group of stations.

Finally, such combined solutions for each figure are adjusted together. Overlapping stations provide the necessary redundancy for final analysis of the individual solutions, and increase the overall relative accuracy.

Canadian test adjustment

The geodetic datum positioning and orientation are derived from Doppler control points (Kouba 1976, 1978). The Doppler coordinate system has been referred to the Conventional International Origin (CIO) and the Bureau International de l'Heure (BIH) zero meridian by comparisons of the Doppler results with independent determinations based on very long baseline interferometry (v.l.b.i.), BC4 satellite triangulation, the U.S. Geodimeter Traverse, and the D.O.D. World Geodetic System 1972 (WGS 72). Table 1 lists the Doppler system orientation, position and scale, as adopted for the October 1977 test adjustment (Kouba 1978). Table 2 contains the same parameters as derived recently from comparison of Doppler and v.l.b.i. results (Hothem *et al.* 1978).

TABLE 1. OCTOBER 1977 TEST ADJUSTMENT, TRANSFORMATION PARAMETERS ADOPTED FOR DOPPLER (NWL 9D)

(ω is positive for counterclockwise rotation, as viewed looking toward the origin from the positive axes.)

orientation	$\omega_x = 0.00 \pm 0.15''$	origin	$\Delta x_0 = 0.0 \pm 2$ m
	$\omega_y = 0.00 \pm 0.15''$		$\Delta y_0 = 0.0 \pm 2$ m
	$\omega_z = -0.65 \pm 0.15''$		$\Delta z_0 = 0.0 \pm 2$ m

scale: -1.0 ± 0.1 part/10^6.

TABLE 2. RECENT ESTIMATES OF TRANSFORMATION PARAMETERS FOR DOPPLER (NWL 9D) TO A V.L.B.I. SYSTEM

(ω is positive for counterclockwise rotation, as viewed looking toward the origin from the positive axes.)

orientation	$\omega_x = +0.20 \pm 0.05''$	origin	$\Delta x_0 = 0.0 \pm 2$ m
	$\omega_y = +0.05 \pm 0.05''$		$\Delta y_0 = 0.0 \pm 2$ m
	$\omega_z = -0.80 \pm 0.10''$		$\Delta z_0 = 0.0 \pm 2$ m

scale: -0.5 ± 0.2 part/10^6.

Such an approach to geodetic datum determination has some advantages over the classical method with one local datum point fixed: namely, the accuracy of datum position and orientation is increased; combination of Doppler and terrestrial data is straightforward as transformed Doppler latitude and longitude are used with corresponding variance–covariance matrices in a Helmert-block type, two-dimensional adjustment. Another important aspect is the direct geometrical link to v.l.b.i. systems which currently provide perhaps the best inertial space orientation.

The datum orientation, position and scale are also implied by astronomical observations and the geoid used for reduction of terrestrial data to the ellipsoid. Though the accuracy is lower than can be achieved through Doppler, nevertheless both geoid and astronomical observations should be consistent with the calibrated Doppler and hence with the international conventions. For the October 1977 adjustment, the astronomical data were reduced to the CIO and BIH zero meridian (Vamosi 1977). The zero order correction and the centre of the geoid used,

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

GEM 8 (Goddard Earth Model no. 8), were checked by using the Doppler-derived ellipsoidal heights (Lachapelle 1978).

The October 1977 adjustment consisted of more than 5500 stations, 200 correlated Doppler points and 240 astronomical azimuths (Beattie *et al.* 1978). The adjustment was performed in blocks by using Helmert-block strategies, where transformed Doppler stations were entered at the highest level, providing the datum information as well. Apart from the combined adjustment of terrestrial and Doppler data, two additional geodetic adjustments were run: the first used only the terrestrial data with one point held fixed at a Doppler-derived value at Toronto; the second consisted of a two-dimensional adjustment of the Doppler data. The comparison of

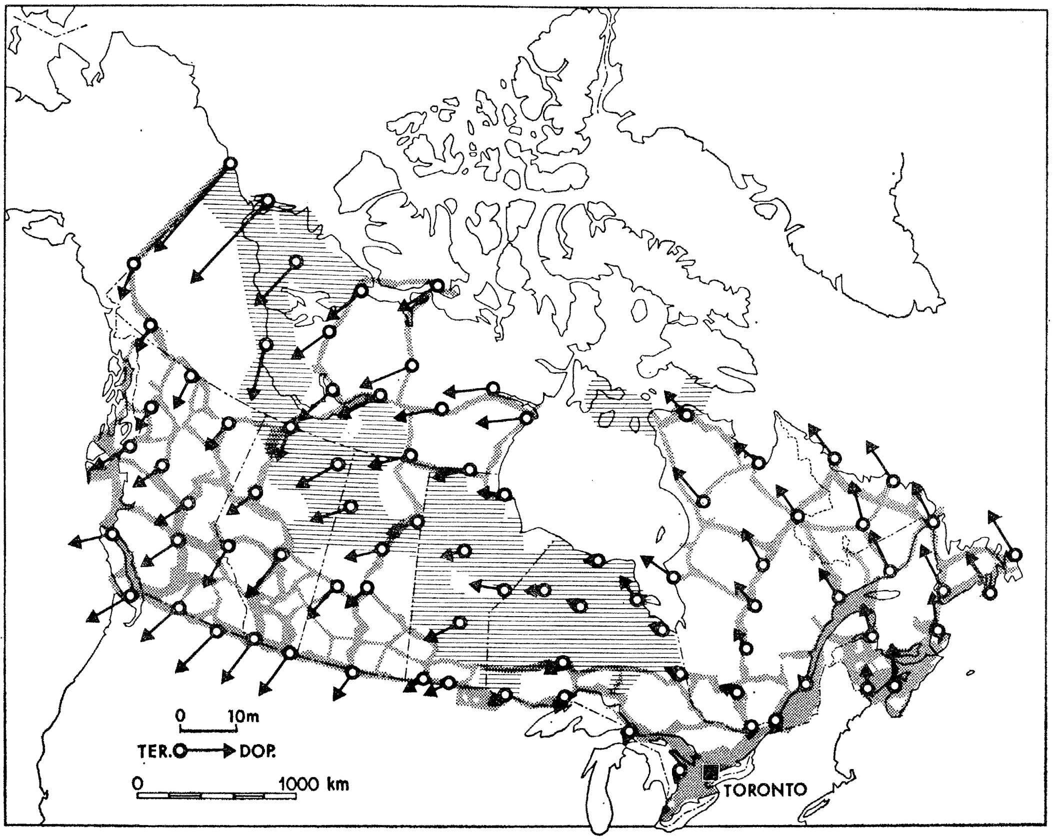

FIGURE 2. October 1977 adjustment for terrestrial and Doppler network differences.

the two adjustments is depicted in figure 2. A relatively good regional agreement with progressively growing systematic errors away from the fixed station can be observed.

A systematic azimuth difference of about 0.5″ is apparent, although both the Doppler and astronomic azimuths are presumed to be related to CIO and BIH. No difference would be present had Doppler longitude not been increased by 0.65″. This, however, contravenes recent findings by other authors (Hothem *et al.* 1978; T. Vincenty 1978, personal communication) which indicated that v.l.b.i. and the U.S. astronomical observations are consistent with the Doppler longitude (east) increased by about 0.8″. Since our Doppler is compatible with the U.S. solution at the sub-metre level (Kouba & Hothem 1978), the Canadian astronomical observations (longitude and azimuth) appear to be inconsistent with the U.S. astronomical

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

observations. Research and field programmes are being jointly designed with the cooperation of the U.S. National Geodetic Survey to solve this problem of incompatibility of our astronomical observations.

Other satellite-Doppler applications in Canada

In Canada, the existing Doppler and triangulation network is now densified by both private and government agencies, using both Doppler and the Litton Inertial Survey System (I.S.S.). The Doppler control provides the necessary information on scale and orientation and the I.S.S. is used to interpolate between the control points (Kouba 1977).

Another significant application employed in Northern Canada is determination of orthometric height from a combination of Doppler ellipsoidal heights and the satellite-derived geoid. The accuracy is limited to about 1–2 m, owing to the uncertainties of the satellite geoid, which is still better than the currently used barometric levelling.

Shell Canada has been using the Doppler for an ice-monitoring service in the Canadian Arctic (A. Hittel 1978, personal communication). This impressive, fully automated service consists of more than ten stations which are being remotely interrogated daily by a fixed winged aircraft. The data are transmitted via a communication satellite to the Calgary computing centre where, usually within 24 h, daily solutions of ice movements are obtained with 0.5 m resolution.

Satellite-Doppler tracking in Canada

Continuous satellite-Doppler tracking has been carried out from the Polar Motion Observatories of the Earth Physics Branch, located near Ottawa and Calgary, since 1976 (Orosz & Popelar 1976). It is part of the long-term geodynamic studies of polar motion, Earth rotation and crustal plate movements which had been based mainly on optical astronomical observations. Simultaneous Doppler and precise astronomical (PZT) observations are used to analyse the relation and long-term stability of the two systems. Of particular interest is their mutual orientation and analysis of site-related effects, such as crustal deformations, plate movements and the maintenance of the corresponding reference systems. Increased accuracy and time resolution of the Doppler pole determinations facilitate studies of short-term variations of polar motion.

From the geodetic point of view, these are important aspects which cannot be overlooked when establishing and maintaining precise geodetic control networks at a continental or world-wide scale. Time variations, due to both the Earth's dynamics and the reference system stability, will become increasingly important as the observational precision improves, and the permanent monitoring stations provide the link between present and future positioning systems.

During 1977–8, the Earth Physics Branch – together with York University, Geodetic Survey, National Research Council, U.S. National Geodetic Survey, D.M.A., University of Nottingham, U.K. Ordnance Survey and Military Survey – participated in a joint v.l.b.i.–Doppler experiment. Simultaneous v.l.b.i. and Doppler observations have been carried out at stations in Canada, the U.K. and U.S. during five week-long periods. Analysis of the data is expected to provide independent checks on accuracies and repeatability of both v.l.b.i. and Doppler results, as well as to allow a study of the relation between the two systems.

At present, the Earth Physics Branch is sponsoring a v.l.b.i. project to test the possibility of permanent monitoring of Earth rotation and polar motion. If this and similar experiments in the U.S. are successful, we expect to have a unique opportunity to analyse three independent and precise systems, namely astronomical PZT, v.l.b.i. and Doppler.

Summary

The basic Doppler control at 200–500 km has been completed and successfully used in the test adjustment of the Canadian geodetic network. Currently, the Doppler method is used for densification at station spacing below 100 km, and in conjunction with the Inertial Survey Systems.

A possible difference between Canadian and the U.S. astronomical observations has been encountered. Further research and field programmes are necessary to solve this problem.

Permanent Doppler monitoring is viewed as essential for geodetic datum maintenance and determination of time-related aspects of future precise geodetic networks.

The research in Canada is directed towards improvements and better understanding of the relation between the different methods of precise global positioning.

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