MODERN GEODETIC REFERENCE FRAMES FOR PRECISE SATELLITE POSITIONING AND NAVIGATION

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ABSTRACT

The NAD83 and WGS84 reference coordinate frames were established more than a decade ago to satisfy most mapping, charting, positioning and navigation applications. They are consistent at the 1-2 metre level on a continental and global scales respectively, reflecting the limitations of available data and techniques. With rapid improvements in positioning accuracy, mainly due to GPS, submetre navigation has become practical and reference frames at the cm to mm level are required by the most demanding users. The IERS Terrestrial Reference Frame (ITRF) was established in 1988 by the International Earth Rotation Service (IERS) to facilitate precise monitoring of the Earth Orientation Parameters (EOP) based on state-of-the-art techniques such as Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR). With the establishment of the International GPS Service for Geodynamics (IGS) in 1994, the ITRF is directly accessible to users world-wide by means of precise global GPS satellite orbit/clock solutions and a large number of IGS monitoring stations. The most recent ITRF solutions, designated ITRF92 and ITRF93, are based on space geodetic observations including GPS up to the end of 1993 providing global consistency at the cm level. The Canadian Active Control System (CACS) facilitates access to ITRF through active participation in IGS and VLBI. Fiducial VLBI points included in NAD83 provide a direct link to ITRF and make it possible to upgrade NAD83 coordinates in order to satisfy positioning and navigation requirements with cm precision in the future. CACS facilitates the most efficient connections to the ITRF and NAD83 reference frames for high precision positioning by GPS as well as for general spatial referencing needs in Canada.

1. INTRODUCTION

In geodesy a reference coordinate frame implies a scale, orientation and coordinate origin as part of a reference system which also includes Earth planetary models and constants necessary for satellite orbit determination, geodynamic and geophysical data analysis. Satellite navigation systems made it possible to establish a truly global geocentric reference system which was quickly adapted for precise geodetic positioning, especially over long distances. For the first time it was possible to determine distortions and misorientation of classical geodetic networks around the world. The U.S. Navy Navigation Satellite System (NNSS), also called Transit or simply Doppler (Kershner and Newton, 1962) became the basis for the U.S. Department of Defense World Geodetic System 1972 (WGS72) and later WGS84 which define global geocentric reference frames consistent at about the 1-2 metre level. To upgrade and correct distortions of the classical North American Datum 1927 (NAD27), a readjustment of the geodetic networks in Canada, USA, Mexico and Greenland was jointly undertaken. This new datum, designated NAD83, was nominally made compatible with WGS84 by being geocentric and oriented according to transformed Doppler positions, but in addition the NAD83 adjustment included VLBI (Very Long Baseline Interferometry) baselines. Thus both, WGS84 and NAD83, are consistent at about one metre, mainly due to the limitations of the Doppler techniques (Kouba, 1993). GPS and other space based techniques such as VLBI and Satellite Laser Ranging (SLR) provide data with higher precisions to support studies of crustal dynamics and polar motion which require a more accurate global reference frame. The IERS Terrestrial Reference Frame (ITRF) was established in 1988 and is updated on an annual basis by the International Earth Rotation Service (IERS) to keep it current and to improve knowledge of station velocities which are necessary for maintaining the accuracy of this global reference frame. NAD83 can be related to ITRF precisely for a given epoch by a transformation based on common VLBI stations. The Canadian Active Control System (CACS) provides the most efficient method to upgrade NAD83 coordinates in Canada in order to meet positioning and navigation requirements with cm precision in the future.

2. NORTH AMERICAN GEODETIC DATUM: NAD83

The North American Datum 1927 (NAD27) was established at the beginning of this century using continental triangulation with a centrally located datum point at Meades Ranch in Kansas, USA (Ross, 1936). Satellite geodesy in the 60's and 70's detected the approximately 100 m offset of the NAD27 origin with respect to the geocenter as well as distortions exceeding tens of meters in some parts of the geodetic control network (Mueller, 1974). A new reference frame was required to facilitate use of efficient and precise satellite geodetic techniques in surveying and navigation. Satellite Doppler positions and several VLBI baselines which had been established before the end of 1986, were used to provide a framework and to define the geodetic datum in a new way. The North American Datum 1983 (NAD83) was based on Doppler station coordinates transformed to conform with the international convention for geocentric origin, scale and orientation of the reference ellipsoid (NOAA, 1989). Classical geodetic observations for more than 260,000 control points have been re-adjusted and integrated within the framework to provide the NAD83 coordinates of the horizontal control network monuments for practical use. Thus, NAD83 in its original version provides a reference frame for horizontal positioning with accuracies at the one meter level corresponding to satellite Doppler precision somewhat diluted by errors in the classical triangulation arcs included in the NAD83 network adjustment. At this level of precision there was no need to introduce station velocities and NAD83 is considered to be attached to the North American tectonic plate. The NAD83 reference frame satisfies most practical needs for mapping, charting, navigation and spatial referencing in North America where sub-meter accuracy is not required.

However, today the increased precision of geodetic GPS measurements requires a reference frame consistency at a cm level which would facilitate studies of crustal dynamics related to plate tectonics and natural hazards associated with seismic or volcanic activities, etc. The accuracy of the VLBI baselines which contributed to the definition of NAD83 not only provides an effective way to relate NAD83 to more accurate reference frames at a 2cm level (Soler et al., 1992) but also facilitates precision upgrades using accurate geodetic space techniques. Such an approach will assure continuous improvements of positioning accuracy as well as traceability to NAD83 which is of great practical importance.

3. WORLD GEODETIC SYSTEM: WGS84

WGS84 is a global geodetic reference system which has been established and maintained by the U.S. Department of Defense to facilitate positioning and navigation world wide (DMA, 1991). The terrestrial coordinate reference frame corresponding to WGS84 has been updated to keep pace with increasing precision of GPS positioning and navigation technology in general use.

3.1 ORIGINAL WGS84 TERRESTRIAL REFERENCE FRAME

WGS84 world wide terrestrial reference frame was initially based only on satellite Doppler coordinates transformed in the same way as for NAD83. However, a different set of Doppler stations was used and no VLBI baseline measurements were included in the network adjustment. This approach produced a globally homogeneous geodetic reference frame with an accuracy of 1-2 m reflecting the limitations of the Doppler technique. Station velocities were ignored as they were of little importance. Although the Doppler WGS84 reference frame is comparable with that of NAD83 in North America, the lack of precise VLBI framework makes it impossible to relate WGS84 to current, more accurate reference frames with a precision better than 1m. Significant improvement can be achieved if the WGS84 framework adopted for GPS operations is considered. This WGS84 (GPS) terrestrial reference frame is based on WGS84 coordinates of 10 GPS tracking stations used by the U.S. DoD for generation of operational (broadcast) satellite orbits and clock parameters.

3.2 REVISED WGS84(G730) TERRESTRIAL REFERENCE FRAME

The WGS84 (GPS) coordinates of the 10 GPS tracking stations have been revised using several weeks of GPS observations from a global network of 32 stations (10 DoD + 22 IGS) in a simultaneous adjustment of satellite orbits and station coordinates; the coordinates of 8 IGS stations were constrained to the values adopted by the International Earth Rotation Service (IERS) and the IERS value of the geocentric constant of gravitation was used. This improved reference frame for GPS, designated WGS84 (G730) to refer to GPS week 730, shows global consistency at about the 10cm level and uses NUVEL-1 plate motion model for station velocities (Swift, 1994; De Mets at al., 1990). Since the beginning of 1994, DMA has used WGS84 (G730) in post- processing and it is expected to be adopted for the computation of operational (broadcast) GPS satellite orbits in the near future (Malys and Slater, 1994).

4. IERS TERRESTRIAL REFERENCE FRAME: ITRF

In order to facilitate precise Earth rotation and polar motion monitoring by modern space geodetic techniques the Bureau International de l'Heure (BIH) established in 1984 the BIH Terrestrial System (BTS84) based mainly on VLBI, SLR and satellite Doppler observations. In 1988 when BIH was superseded by IERS the IERS Terrestrial Reference Frame (ITRF88) was created to meet the following requirements (Boucher, 1990):

(a) it is geocentric with the origin at the center of mass of the whole Earth including the oceans and the atmosphere;
(b) its orientation is consistent with the BIH Earth Orientation Parameter (EOP) series for the epoch 1984.0;
(c) the station velocity model shall not produce any residual rotation with respect to the Earth crust;
(d) the scale corresponds to the local coordinate system of the Earth in the sense of the relativistic theory of gravitation.

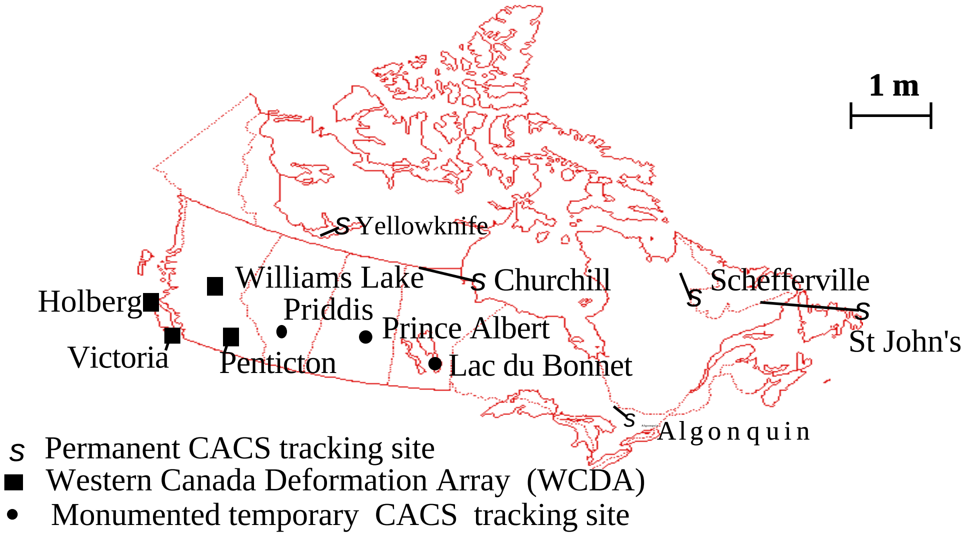

Figure 1. Residual differences between NAD83 and ITRF92 (1994.0) for the CACS monitoring stations.

Since 1988, an ITRF solution has been produced on an annual basis to incorporate new observations and stations as appropriate to satisfy the above requirements. The tectonic plate motion model NUVEL-1 was used to derive

Table 1. Consistency of VLBI and GPS global solutions included in ITRF92

Solution	N	Weighted 2D	RMS [cm] 3D
VLBI(GIUB)	7	0.6	0.7
VLBI(GSFC)	70	0.4	0.6
VLBI(JPL)	7	1.1	1.5
VLBI(NOAA)	55	0.3	0.5
VLBI(USNO)	15	0.7	0.7
GPS(CODE)	12	0.4	0.7
GPS(CSR)	24	1.2	1.3
GPS(EMR)	17	0.4	0.6
GPS(ESA)	32	3.1	3.4
GPS(JPL)	39	0.6	0.7
GPS(SIO)	40	1.3	1.8

station velocities while enforcing the no residual rotation requirement. This combined with the somewhat uneven global distribution of the ITRF stations produced a 0.2 mas/year rotation between ITRF and IERS EOP (IERS Annual Report 1992) which accumulated by 1992 to a significant misalignment of about 1 mas. The NUVEL-1 model station velocities were revised to take into account observed VLBI and SLR station velocities where available, to produce ITRF92 which included about 150 stations. GPS observations offer the most efficient technique for the densification of ITRF when integrated in the VLBI framework which maintains the absolute orientation and scale. Mean station position errors for VLBI and GPS networks included in ITRF92 are summarized in Table 1 which shows cm level consistency for the global solutions (Boucher at al., 1993). Improvements in determination of station velocities and further densification to obtain more homogeneous coverage on all continents will be critical for maintaining and increasing the ITRF accuracy in the future.

5. TRANSFORMATION BETWEEN TERRESTRIAL REFERENCE FRAMES

Practically useful transformations between different terrestrial reference frames are based on their most accurate common set of stations which are then used to determine seven transformation parameters and provide basic RMS information on the consistency of the relationship. Residual systematic differences can be mapped or represented analytically if they exceed significantly the RMS value of the coordinate differences after the transformation. The residual differences between NAD83 and ITRF92 (epoch 1994.0) positions for the Canadian Active Control System (CACS) monitoring stations are shown in Figure 1. However, such deviations should be investigated and corrected if they represent accumulation of systematic errors. Revisions of this kind provide natural upgrade path for any terrestrial reference frame and enhance significantly its practical importance by gradually eliminating unacceptable errors. The WGS84 (G730) reference frame is an example of a comprehensive revision in response to practical needs of GPS applications.

Table 2 lists the 7 transformation parameters between the terrestrial reference frames discussed above and ITRF92 (epoch 1988.0). The global consistency of the terrestrial reference frames has improved by almost two orders of magnitude over the last decade as evident from Table 2. It has been achieved by a meticulous application of the complementary techniques of VLBI and satellite geodesy. The maintenance of the cm level terrestrial reference frame consistency requires systematic monitoring of crustal and terrain dynamics including monument stability. Continuous monitoring of the Earth rotational

Table 2. Transformation parameters with respect to ITRF92(epoch 1988.0)

Ref. Frame	DX	DY [cm]	DZ	RX	RY [mas]	RZ	SCL [ppm]	RMS [cm]
NAD83	-94	198	54	27.5	15.5	10.7	-0.005	2
WGS84	-6	+52	+22	-18.4	-0.3	-7.0	0.011	<200
WGS84(GPS)	-4	-1	-28	4.2	-4.0	-15.6	-0.218	94
WGS84(G730)	0	-3	4	-2.6	-2.5	-0.4	0.000	6
ITRF93	0.2	0.7	0.7	-0.39	0.80	-0.96	-0.0012	<1

dynamics by VLBI is necessary for high precision applications of satellite positioning and navigation systems which have made this rapid progress in global geodesy possible.

6. ACCESS TO MODERN TERRESTRIAL REFERENCE FRAMES

The high precision, global scope and dynamic nature of space techniques, particularly GPS in general use today, demand new approaches to the maintenance and access to terrestrial reference frames. As pointed out above, the modern terrestrial reference frames must be connected to the best available realization of the inertial frame provided by VLBI and must facilitate determination of station velocities in the geocentric coordinate system. This is presently accomplished by a combined solution for a global network of fiducial VLBI stations augmented by SLR and GPS stations for which geocentric coordinates and velocities are obtained from series of observations and geodynamic models; the solution defines a "control network" for a given epoch, e.g. 1988 for ITRF. Monitoring of "control station" velocities and the Earth rotation parameters (ERP), needed for inertial reference, requires continuous observation at some of the "control network stations" which creates an Active Control System (ACS). Such reference system offers two complementary modes of access to its terrestrial reference frame and supports real-time high precision global positioning and navigation.

6.1 CANADIAN ACTIVE CONTROL SYSTEM - CACS

The Geodetic Survey Division (GSD), Geomatics Canada in collaboration with the Geological Survey of Canada (GSC) has established CACS as an essential component a modern fully integrated spatial reference system to support geodetic positioning, navigation and general purpose spatial referencing. CACS represents the Canadian contribution to the International GPS Service for Geodynamics (IGS) and facilitates direct integration of Canadian stations within ITRF. The CACS network configuration (Fig. 1) augmented by about l8 globally distributed IGS stations provides continuous data for daily precise GPS satellite orbit and clock offset determination constrained by about 13 fiducial VLBI stations to facilitate positioning with highest precision for geodetic control networks and crustal dynamic studies as well as generation of high quality orbit predictions for

Table 3. IGS Combined Orbit Summary, week 0758 (July 17 - July 23, 1994)
Mean and standard deviations of transformation parameters.
WRMS - orbit RMS weighted by the orbit accuracy codes.
Units: meters, mas, ppb, nano-sec, nano-sec/day.

CENT	DX	DY	DZ	RX	RY	RZ	SCL	RMS	WRMS	TOFT	TDRFT	RMS
cod	.01	.02	-.01	-1.66	-1.44	.08	.0	.13	.11	-3.1	1.7	75.4
	.01	.01	.01	.58	.33	.32	.2			3.4	6.5	
emr	.02	.00	-.01	-1.73	-1.08	.17	-.1	.13	.13	-417.1	-30.8	1.5
	.01	.01	.01	.58	.43	.10	.2			67.3	8.9	
esa	.00	.00	-.01	-1.56	-1.38	-.24	.0	.20	.18	-15.4	.1	2.9
	.01	.01	.01	.41	.41	.31	.2			13.2	22.2	
gfz	-.04	.02	-.02	-1.70	-.92	-.36	-.1	.14	.11	-411.5	-24.3	9.8
	.01	.01	.01	.72	.27	.13	.1			65.8	10.0	
jpl	.00	-.01	.01	-1.86	-1.76	-.18	.2	.11	.11	-412.5	-30.5	3.0
	.01	.01	.01	.56	.37	.16	.1			67.3	9.0	
ngs	.05	-.01	-.03	-1.91	-.67	.58	1.1	.29	.27	-2.9	1.9	75.4
	.03	.01	.03	.81	.48	.35	.3			3.1	6.6	
sio	.00	-.04	.10	-1.94	-.95	.85	-.3	.20	.18	.0	.0	.0
	.01	.01	.02	.68	.20	.17	.1			.0	.0	

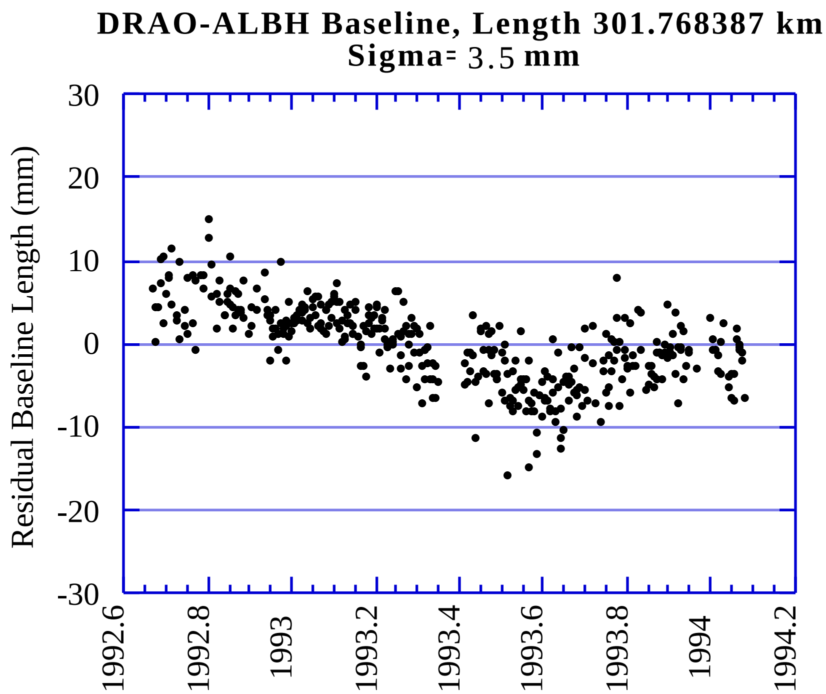

Figure 2. Variations in the DRAO (Penticton) -ALBH (Victoria) baseline length solutions (after Dragert at al., 1994).

real-time applications. The quality of the CACS results in comparison to the other IGS Analysis Centers can be seen in Table 3. GSD is also responsible for coordination of the IGS Analysis Centers and combination of their results into the official IGS products (Beutler at al., 1993). Three strategies have been developed for the integration of regional GPS stations and networks in ITRF or related terrestrial reference frames, e.g. NAD83, WGS84. The first strategy uses sequential global processing for addition of data from regional stations to the system of normal equations and obtain updated global solution with coordinates of the regional stations. The second strategy uses the CACS/IGS precise orbits in baseline double-difference processing to establish high precision regional networks for special geodetic and geodynamic applications with mm or ppb precision (Fig. 2). The third strategy uses the CACS/IGS precise satellite ephemerides and clock offset data and undifferenced GPS observations for single point positioning with accuracy corresponding to the pseudorange measurement precision of the GPS receiver used. This rather simple approach can satisfy wide range of spatial referencing and navigation requirements with one meter or better precision (Fig. 3). Real-time wide area differential GPS (WADGPS) service can only be supported by an active control system like CACS which assures continuous, efficient and economical access to the reference frame. In this way all activities and operations can be related to a common, accurate and reliable global spatial reference frame by means of GPS. CACS satisfies both requirements of a modern terrestrial reference frame: maintains a network of fiducial reference stations and provides continuous monitoring and updating of all variable system parameters which are necessary for precise and consistent user positioning.

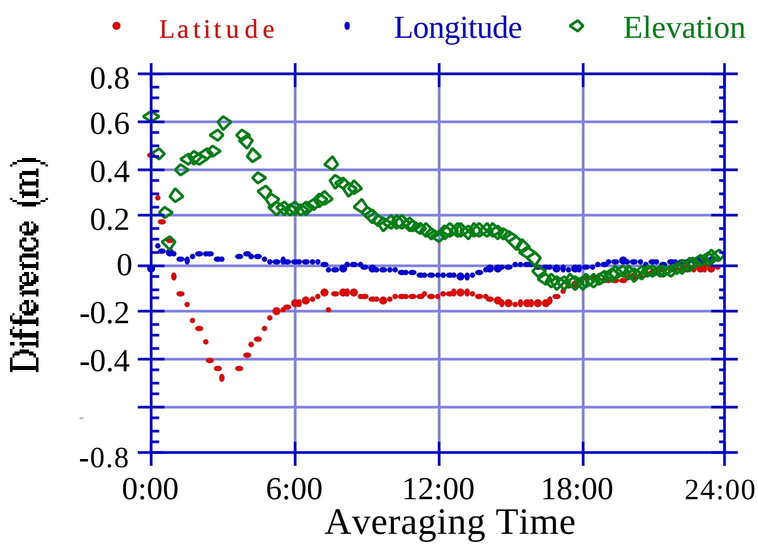

Figure 3. CACS USER POSITIONING INTERFACE: Initial convergence tests based on CACS post-processed orbits/clocks and a single receiver pseudorange/phase data.

6.2 CANADIAN BASE NETWORK - CBN

The traditional method of access to a reference frame is based on differential positioning with respect to control stations with "known" coordinates in the required reference frame. These are determined either during the reference frame definition or the later integration of so called control surveys. Such an approach was necessary due to the elaborate and time consuming procedures used in the past to obtain reference station coordinates with required accuracy. Nevertheless, the need to maintain an accurate terrestrial network of monumented reference stations in addition to an active control system is twofold. Firstly, it provides control points for tecniques other than GPS and facilitates calibration and performance analysis of survey instrumentation and procedures. Secondly, it densifies the network of active control points while providing direct connections to classical geodetic horizontal and vertical control networks. Station spacing is generally greater and special considerations are required for site selection and monumentation to support higher precision and efficiency of operations. The determination of station velocities requires regular reoccupations and systematic analysis of monument stability and crustal dynamics. The Canadian Base Network (Fig. 4) is to play an important role in the integration of the horizontal and vertical geodetic control networks and support studies of crustal deformations and seismic hazards in Canada.

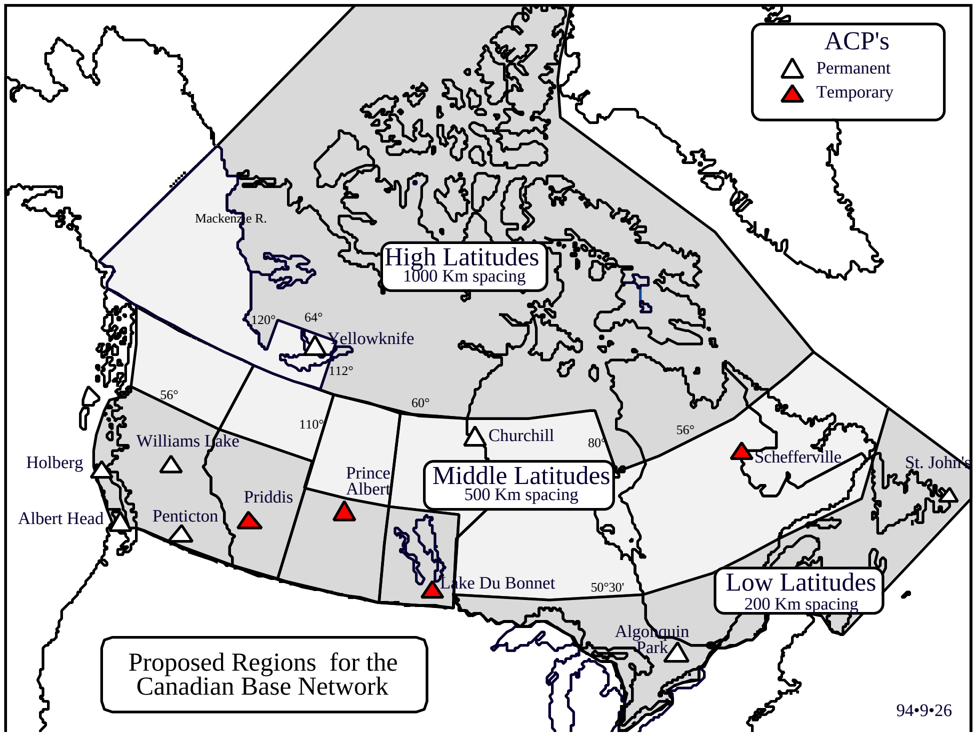

Figure 4. Proposed station spacing for the Canadian Base Network (CBN).

7. CONCLUSIONS

GPS technology offers users the most versatile, accurate and economical system for geodetic positioning, navigation and general purpose spatial referencing to date. In order to maximize system performance and effectiveness, GPS applications depend on continuous monitoring of the GPS satellites with respect to conventional terrestrial and celestial reference frames. Modern terrestrial reference frames are based on the space-time coordinate system centered at the geocenter and must take account of Earth tectonic plate motion and deformation to provide a cm level accuracy potential. ITRF has been implemented and maintained to satisfy the highest accuracy positioning requirements on the global scale. NAD83 has been implemented to satisfy mapping, charting and navigation applications where sub-meter accuracy is not required; however the VLBI framework provides an upgrade path to a cm accuracy NAD83 reference frame rigidly connected to the North American plate. The transformation parameters (Table 2) facilitate transformations between the reference frames to accommodate user needs. The active control system (ACS) provides efficient and economical direct access to the terrestrial reference frames with the required accuracy and facilitate real-time high precision spatial referencing and navigation.

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