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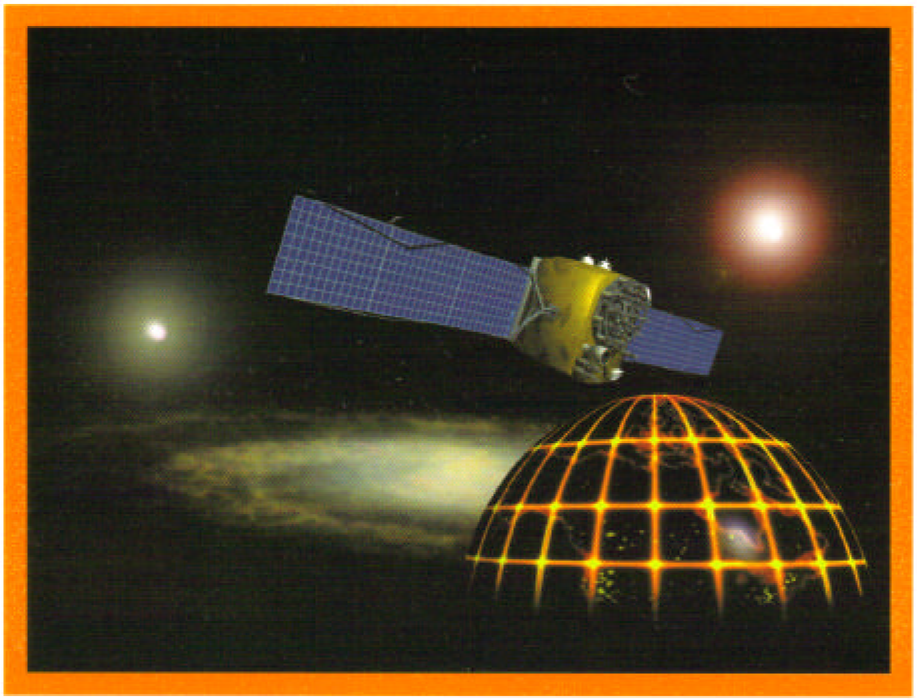
GEOMATICA



CANADIAN SPATIAL REFERENCE SYSTEM

SYSTÈME CANADIEN DE RÉFÉRENCE SPATIALE

CANADIAN INSTITUTE OF GEOMATICS
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GEOMATICA

FEATURES / ARTICLES DE FOND

The Canadian Expedition Beta Team at the Mars Desert Research Station in Utah. (see Field Notes & Office Memos page 222 / voir page 222)

DEPARTMENTS / CHRONIQUES

ANNOUNCEMENTS / ANNONCES

Geomatics is a field of activities which, using a systemic approach, integrates all the means used to acquire and manage spatial data required as part of scientific, administrative, legal and technical operations involved in the process of the production and management of spatial information.

La géomatique est un champ d'activités qui intègre, selon une approche systémique, l'ensemble des moyens d'acquisition et de gestion des données à référence spatiale requis pour effectuer les opérations scientifiques, administratives, légales et techniques dans le cadre du processus de production et de gestion de l'information sur le territoire.

Robert Duval

CANADIAN SPATIAL REFERENCE SYSTEM INTRODUCTION

Robert Duval, Geodetic Survey Division, Natural Resources Canada

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Ever wanted to be in two places at once? We all know it isn't possible and we can hardly believe that we could be misled to think so. But in this modern world, where spatial geo-referencing using coordinates (latitude, longitude, and height) is becoming ubiquitous, the likelihood of being confused by different coordinates being associated to a same location is increasing. Obviously, merging or integration of geospatial or georeferenced information works best when a point or an object can be associated to a single coordinate.

Nowadays, GPS receivers are finding their way to almost everywhere and expanding georeferencing capabilities far beyond the traditional geomatics community: transport and taxi companies use them to track vehicle locations; they are used in farming and forestry operations for autonomous platform guidance for crop harvesting and other robotic field operations; and cars use them for navigation, with some systems even able to alert emergency services to your exact location if you've been involved in an accident! GPS technology is making positioning easier than ever before and consequently impacting how we organize information, coordinate activities, and manage assets. To be useful though, positions must be compatible with one another, otherwise their utility is compromised and confusion follows. It is a bit like time! Imagine the chaos within a city, a province, or nation if we all operated with different time "systems" and had no means of reconciling them? A standard time system used by all ultimately ensures that the activities of a society are synchronized and organized in a way that allows it to function coherently.

Today, the Canadian Spatial Reference System (CSRS) provided by the Earth Sciences Sector (ESS) of Natural Resources Canada (NRCan) continues to respond to the Order in Council that created the Geodetic Survey of Canada in 1909 and tasked the then Minister of Interior "to determine with the highest attainable accuracy the positions of points throughout the country… which may form the basis of surveys for all purposes, topographical, engineering or cadastral, and thereby assist in the survey work carried on by other departments of the Dominion Government, by Provincial Governments, and by municipalities, private persons or corporations." This statement, though nearly 100 years old, continues to capture the essence of the fundamental role played by the CSRS today. Not unlike the time standard analogy, the CSRS provides the fundamental reference values (or the starting coordinates) to ensure that positions anywhere in Canada can be determined uniquely and remain compatible with one another regardless of when they were determined or their originators. The resulting frames of reference, propagated through provincial and municipal networks as well as other governmental services, serve as standards which ensure the compatibility of Canadian georeferenced information.

Over the last 20 years, in order to respond to the needs of diverse user groups and to adapt to technological changes, several new geodetic (or spatial) reference systems have emerged, each time introducing a new reference frame [*a "geodetic reference system" is a theoretical concept and consist of a collection of prescribed principles, fundamental parameters, and specifications to quantitatively describe the positions of points in space; in contrast, a "reference frame" is much easier to relate to, as it is the materialization or 'realization' of such a prescription*]. In addition, although the theoretical definition of these reference systems did not change, new realizations were introduced as measurement accuracy improved. This adds to the potential for some confusion within the user community as to what the basis for their coordinates should be.

Traditionally, a reference frame consisted of ground-based geodetic control monuments with adopted coordinates. In Canada, to ensure nationwide coordination and consistency, the establishment of primary horizontal and vertical networks of geodetic control points has traditionally been a federal responsibility. To facilitate downstream user access, provincial, municipal, and other governmental agencies have further densified the network "fabric," establishing a hierarchical structure. For most of the last century, surveyors "connected" to these control points using classical techniques to integrate their surveys within the adopted reference frame, the standard ensuring the compatibility of Canadian georeferenced information.

Today, with the advent of Global Navigation Satellite Systems, and currently GPS in particular, the means for connecting to the reference frames have evolved significantly. A variety of tools and data products are now available to maximize the efficiency and the benefits of these modern technologies. Additionally the widespread availability of low-cost GPS equipment in the consumer market is rapidly increasing the user base for georeferenced information. Along with these changes comes the increased potential for incompatible coordinates due to the diversity of reference frames available. It is therefore important not only to facilitate the user's access to these reference frames but also to provide information about them, including their time-evolution and the related impacts on their georeferenced information. This is an objective of this Special Issue of *Geomatica*.

In concert with these new developments, the possibility of integrating directly into a stable global reference frame is also becoming reality through applications such as Precise Point Positioning. Although this new ability is appealing, the requirement to maintain consistency with the adopted reference systems for Canada, the North American Datum of 1983 (NAD83) and the Canadian Geodetic Vertical Datum of 1928 (CGVD28), continues to be a priority. The legacy left by the monumented geodetic infrastructure still requires that relationships between old and new reference frame realizations be clearly established to maintain coordinate traceability over time. Additionally, the desire to maintain stable coordinates for control points that are monumented on the surface of our "restless planet" requires that reference frame options be available to minimize disruption to the general users while also meeting the needs of more demanding user communities.

Another fundamental role also played by the CSRS is its contribution to the determination of underlying dynamic parameters of the Earth such as its orientation and rotation rate in space as well as its gravity field. These parameters, determined from the collective effort of the international geodetic community, are not only critical to the efficient exploitation of modern space-based technology for positioning and navigation but are also enablers behind the technology itself. Furthermore, monitoring variations in both the Earth's geometry and its gravity field, essential to the maintenance of the reference frames, also contributes to a better understanding of regional and global geophysical processes linked to natural hazards and global change.

The use of reference frames provided through the Canadian Spatial Reference System has extended from traditional applications in mapping and cadastral surveys to monitoring sea level rise, rectifying remote sensing imagery, measuring crustal uplift and subsidence, and interpreting seismic disturbances. However, the fundamental role the CSRS plays has not changed much over the years, and today it continues to provide the means to ensure we can only be "in one place at one time!" In this Special Issue, papers authored mainly by personnel from NRCan address different aspects regarding the evolution of geodetic reference systems in Canada as well as provide a look forward.

Space Geodetic Techniques and the CSRS - Evolution, Status and Possibilities looks at the evolution of technology over the past century, with particular emphasis on the advent of navigation satellites during the past decades, and the impact this technology has had on reference frame accuracy and access. Now that the positions (or, in a general sense, the orbits) of navigation satellites are continuously estimated with centimetre accuracy and subsequently made publicly available through the Internet, a geodetic control network has in essence been created in the sky. As a result, our dependence on an infrastructure of ground-based monuments is increasingly being lessened. This new capability is also giving rise to the development of new methodologies for end users to achieve greater efficiency and enhanced accuracy of their positioning information with respect to a common reference system.

In ***The Evolution of NAD83 in Canada***, the reader will be provided insights into our national horizontal reference system including: the evolution of NAD83 from a horizontal to a three-dimensional reference frame, how it is now linked to the dynamic International Terrestrial Reference Frame (ITRF), and how it is maintained using active control points and episodic measurements of the Canadian Base Network. The improvement in NAD83 accuracy that came along with GPS is shown. Crustal movements driven by geophysical processes, observed at regional and national scales and capable of affecting reference frame stability, are now apparent and their impacts are also discussed.

A Gravimetric Geoid Model as a Vertical Datum in Canada gives readers a glimpse of how the vertical control network has developed nationally over time and how the advent of space geodesy has led the Earth Science Sector to initiate the "Height Modernization" project towards the adoption of a gravimetric geoid model as the new vertical datum in Canada. The improvements in geoid modelling, in part attributable to the availability of data from recently launched (CHAMP and GRACE) and upcoming (GOCE) satellite gravimetry missions, as well as the centimetre accuracy available for ellipsoidal height determination from precisely processed signals from navigation satellites, are the major enablers behind this new direction. The anticipated operational benefits that stem from not having to physically connect to a benchmark for precise height determination are appealing from the perspective of both the user and the provider of height information.

While geodetic reference frames underpin the measurements of the motions and slow deformations of the Earth's crust, these geophysical processes also systematically affect the reference frames provided as standards for geodetic surveys. In ***Crustal Motion and Deformation Monitoring of the Canadian Landmass,*** some of NRCan's efforts to monitor contemporary crustal dynamics across Canada are reported. Progressing from continental to smaller regional scales, the rationale, techniques, and results are outlined in this paper. While the required observational data and interpretations are fundamentally dependent on the Canadian Spatial Reference System, they in turn also contribute to the incremental improvement of its definition and maintenance.

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Robert Duval

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SYSTÈME CANADIEN DE RÉFÉRENCE SPATIALE

INTRODUCTION

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Avez-vous déjà souhaité être à deux endroits en même temps? Nous savons tous que c'est impossible et avons du mal à croire qu'on pourrait intentionnellement nous le faire accroire. Pourtant, en ce monde moderne où le géoréférencement spatial à base de coordonnées (latitude, longitude et hauteur) est très répandu, il est de plus en plus possible qu'on attribue des coordonnées différentes au même endroit. Évidemment, l'intégration ou la fusion de données géospatiales ou géocodées fonctionne mieux lorsque le point ou l'objet n'est associé qu'à une seule coordonnée.

De nos jours, les récepteurs GPS sont de plus en plus omniprésents et leurs capacités de géoréférencement sont beaucoup plus avancées qu'auparavant. Les compagnies de taxi et de transport les utilisent pour suivre leurs véhicules; les compagnies forestières et agricoles, pour le guidage de plates-formes autonomes pour la récolte des cultures ou pour les opérations robotisées sur le terrain. Ils se retrouvent aussi dans plusieurs véhicules automobile à des fins d'aide à la navigation. Certains de ces systèmes peuvent même avertir les services d'urgence et leur fournir votre situation géographique exacte en cas d'accident! La technologie GPS rend le positionnement encore plus facile qu'auparavant et a des répercussions sur la façon dont nous organisons l'information, coordonnons les activités et gérons nos avoirs. Cependant, afin d'être réellement utilisables, les coordonnées doivent être compatibles les unes avec les autres sinon leurs utilité en serait compromise et s'ensuivrait une confusion générale. C'est un peu comme le temps! Imaginez le désastre si dans une ville, une province ou un pays, on utilisait tous des systèmes différents pour mesurer le temps et n'avions aucune façon de les concilier? L'utilisation d'un système commun de mesure du temps permet de s'assurer que toutes les activités d'une société sont synchronisées et organisées de façon à ce qu'elle fonctionne de manière cohérente.

Aujourd'hui, le Système canadien de référence spatiale (SCRS), sous la gouvernance du Secteur des sciences de la Terre (SST) de Ressources naturelles Canada (RNCan), continue à répondre au décret qui a créé les Levés géodésiques du Canada en 1909 et demandait alors au ministre de l'Intérieur de « déterminer, le plus précisément possible, la position des points partout au pays… qui pourraient former la base de levés à toutes sortes de fins (topographiques, cadastrales ou d'ingénierie) et aideraient ainsi tous les autres ministères du Dominion du Canada, les gouvernements provinciaux, les municipalités, les personnes et les entreprises à mener leurs travaux d'arpentage ». Cet énoncé, bien qu'âgé de près de cent ans, continue à saisir toute l'importance du rôle fondamental joué par le SCRS aujourd'hui.

Tout comme pour notre exemple du temps, le SCRS nous offre des valeurs de référence fondamentales (ou des coordonnées de départ) afin de s'assurer que les positions de partout au Canada soient déterminées de sorte qu'elles soient uniques par rapport à ces points de référence et demeurent compatibles entres elles peu importe la date ou la source qui les a déterminées. Le cadre de référence, transmis par les réseaux provinciaux et municipaux ainsi que par d'autres services gouvernementaux, sert de norme qui assure ainsi la compatibilité de toutes les données géoréférencées au Canada.

Au cours des deux dernières décennies, on a eu besoin de s'adapter à divers changements technologiques; plusieurs systèmes de référence géodésique (ou géospatiale) ont été créés afin de répondre aux besoins des différents groupes d'utilisateurs, en y ajoutant à chaque fois, un nouveau cadre de référence *un « système de référence géodésique » est un concept théorique qui consiste en un ensemble de principes, de paramètres fondamentaux et de spécifications pour décrire la position de points dans l'espace de manière quantitative. En comparaison, un « cadre de référence » est beaucoup plus facile à concevoir puisqu'il s'agit de la matérialisation ou de la réalisation d'un tel concept.* De plus, de nouvelles réalisations ont été introduites au fur et à mesure que la précision des mesures s'améliorait, bien que la définition théorique de ces systèmes de référence n'ait pas changé. Ce qui ajoute à la confusion probable de la communauté d'usagers sur la nature de la base de leurs coordonnées.

Traditionnellement, un cadre de référence était constitué de points physiques de contrôle terrestre auxquels on attribuait des coordonnées. Au Canada, afin de s'assurer de la coordination et de la cohérence, le gouvernement fédéral était responsable des réseaux géodésiques primaires de points de contrôle horizontaux et verticaux. Ensuite, afin de faciliter l'accès aux usagers, les gouvernements provinciaux et municipaux et d'autres organismes gouvernementaux ont densifié le réseau, établissant ainsi une structure hiérarchique. Au cours de la majorité du siècle dernier, les arpenteurs se sont rattachés à ces points de contrôle en utilisant des techniques traditionnelles pour que leurs levés s'intègrent au cadre de référence adopté; la norme qui permet d'assurer la compatibilité de toutes les données géocodées au pays.

Aujourd'hui, avec l'avancée des systèmes mondiaux de navigation par satellite, et du GPS en particulier, les moyens de se rattacher aux cadres de référence ont évolué de manière significative. Il existe bon nombre d'outils et de produits pour nous aider à manière l'efficacité et les avantages de ces technologies modernes. La base d'usagers de données géoréférencées s'agrandit très rapidement, le matériel GPS étant de plus en plus disponible, et à faible coût, aux consommateurs moyens. Le risque de coordonnées incompatibles augmente donc à cause du nombre de cadres de référence disponibles. Il est donc important qu'on facilite non seulement l'accès des usagers à ces cadres de référence mais aussi qu'on leur fournisse des renseignements à leur sujet, incluant leur évolution temporelle et les répercussions sur les données qui leur sont géoréférencées. C'est précisément l'objectif de ce numéro spécial de *Geomatica*.

La possibilité de s'intégrer directement dans un cadre de référence global stable devient aussi réelle par des applications telles que le positionnement par points précis. Bien que cette nouvelle capacité soit intéressante, la priorité demeure d'assurer la cohérence avec les systèmes de référence canadiens : le Système de référence nord-américain de 1983 (NAD83) et le Système de référence altimétrique géodésique de 1928 (CGVD28). L'héritage laissé par cette infrastructure géodésique de points de contrôle nécessite une relation claire entre les réalisations du nouveau et de l'ancien cadres de référence afin d'assurer la traçabilité des coordonnées dans le temps. Puisqu'on désire maintenir des coordonnées stables pour des points de contrôle physiques sur notre planète en pleine effervescence, nous aurons besoin d'options pour ces cadres de référence afin de minimiser les dérangements pour les usagers moyens tout en rencontrant les besoins des communautés d'usagers plus spécialisés.

Le SCRS joue un autre rôle essentiel en contribuant à la détermination des paramètres dynamiques fondamentaux de la Terre comme son orientation, sa vitesse de rotation dans l'espace ainsi que son champ gravitationnel. Ces paramètres, déterminés à partir d'un effort collectif de la communauté internationale géodésique, sont non seulement essentiels à l'opération efficace de la technologie moderne spatiale pour le positionnement et la navigation mais aussi pour soutenir la technologie elle-même. On doit aussi surveiller les variations à la géométrie et au champ gravitationnel terrestres afin d'assurer la pertinence des cadres de référence. Cette opération permet aussi de mieux comprendre les processus géophysiques régionaux et globaux reliés aux risques naturels et aux changements mondiaux.

L'utilisation des cadres de référence du Système canadien de référence spatiale a permis d'étendre les applications traditionnelles de la cartographie et des levés cadastraux à la surveillance du niveau des océans, à la rectification d'images de télédétection, à la mesure du soulèvement ou de l'affaissement de la croûte terrestre et à l'interprétation des secousses sismiques. Le rôle principal du SCRS n'a cependant pas beaucoup changé au fil du temps et il continue aujourd'hui à s'assurer que nous ne soyons qu'à un seul endroit à la fois! Les articles de ce numéro spécial ont été principalement écrits par du personnel de RNCan. Leurs articles touchent à divers aspects de l'évolution des systèmes de référence géodésique au Canada ainsi qu'une vision de l'avenir.

L'article sur les ***Techniques géodésiques spatiales et le SCRS - Évolution, état et possibilités*** nous offre un regard sur l'évolution de la technologie au cours du siècle dernier, en mettant particulièrement l'accent sur l'avancement des satellites de navigation au cours des dernières décennies et les répercussions de cette technologie sur la précision et l'accessibilité du cadre de référence. Maintenant que les positions (c.-à-d., au sens général, les orbites) des satellites de navigation sont constamment évaluées à une précision d'un centimètre et ensuite offertes au public par Internet, un réseau de contrôle s'est en quelque sorte créé dans le ciel. Notre dépendance envers une infrastructure fondée sur des points terrestres diminue conséquemment. Cette nouvelle capacité a aussi ouvert la porte à l'élaboration de nouvelles méthodes pour les usagers finaux leur permettant d'obtenir des coordonnées plus précises et plus efficaces par rapport à un système de référence commun.

Dans l'article sur ***L'évolution du NAD83 au Canada***, le lecteur aura droit à un aperçu de notre système de référence horizontal national incluant l'évolution du NAD83 d'un cadre de référence horizontal à un cadre de référence tridimensionnel, comment il est maintenant relié au Repère international de référence terrestre (ITRF) et comment il est maintenu par l'utilisation de points de contrôle actifs et la prise de mesures périodiques du Réseau de base canadien. La précision du NAD83 a été améliorée grâce au GPS. Le mouvement de la croûte terrestre résulte des processus géophysiques observés à l'échelle régionale et nationale et peut se répercuter sur la stabilité du cadre de référence. Ce mouvement est aujourd'hui perceptible et on discute de ses répercussions.

L'article intitulé ***Un modèle gravimétrique du géoïde comme système de référence altimétrique au Canada*** donne au lecteur un aperçu de la façon dont le réseau de contrôle vertical s'est établi à l'échelle nationale et comment les avancées en géodésie spatiale ont mené le Secteur des sciences de la Terre à lancer le projet « Modernisation des hauteurs » qui visait l'adoption d'un modèle gravimétrique du géoïde comme nouveau système de référence altimétrique au Canada. Cette nouvelle direction a été rendue possible grâce aux avancées en modélisation du géoïde, attribuables en partie à la disponibilité de données des nouveaux satellites (CHAMP et GRACE) et du futur satellite (GOCE) en missions gravimétriques et le niveau de précision, au centimètre près, des hauteurs au-dessus de l'ellipsoïde obtenues à partir des signaux très précis envoyés par les satellites de navigation. Les avantages opérationnels anticipés de cette initiative, qui nous évite d'avoir à se rattacher physiquement à un point géodésique vertical pour déterminer la hauteur précise, sont intéressants pour les usagers et pour les fournisseurs des renseignements sur la hauteur.

Alors que les cadres de référence géodésique soutiennent les mesures des mouvements et des lentes déformations de la croûte terrestre, ces processus géophysiques modifient aussi systématiquement les cadres de référence qui servent de normes aux levés géodésiques. Dans l'article sur la ***Surveillance du mouvement et des déformations de la croûte de la masse continentale canadienne***, on parle de certains des efforts de surveillance de la dynamique contemporaine de la croûte terrestre au Canada par Ressources naturelles Canada. La justification, les techniques et les résultats sont décrits dans cet article, de l'échelle continentale à l'échelle régionale. Alors que les données d'observation et les interprétations nécessaires dépendent essentiellement du Système canadien de référence spatiale, elles contribuent aussi à l'amélioration progressive de sa définition et à sa maintenance.

À notre ère des technologies globales, les cadres de référence modernes doivent s'arrimer à une « norme » globale. Le Repère international de référence terrestre, fruit des efforts conjugués des agences géodésiques de partout au monde sous la supervision de l'Association internationale de géodésie (AIG), répond à ce besoin. L'AIG reconnaît la nécessité de mieux coordonner les efforts internationaux afin de répondre à nos besoins à long terme et a donc lancé l'initiative du système global d'observation géodésique [Global Geodetic Observing System (GGOS)] et a fondé un groupe de travail spécifiquement pour élaborer une stratégie qui visera à intégrer et à maintenir le réseau géodésique d'instruments de base et l'infrastructure qui le soutient d'une façon durable. L'article sur le ***Système global d'observation géodésique - Aspects importants de l'infrastructure du réseau géodésique***, propose un processus d'intégration global qui comprend l'élaboration d'un réseau de stations de base, des techniques géodésiques de colocalisation et des liens entre les systèmes déterminés avec précision. La conception de ce réseau permettrait de profiter des forces de chaque technique et minimiserait leurs faiblesses, autant que possible. Cet article présente donc un survol de l'état actuel de l'infrastructure et un aperçu des futurs réseaux, services et produits géodésiques globaux.

En conclusion, je tiens à remercier tous les auteurs, incluant ceux dont les articles ne seront pas publiés dans ce numéro spécial. Ces derniers paraîtront peut-être dans de prochains numéros de *Geomatica,* du moins je l'espère. Je souhaite aussi remercier plus particulièrement Pierre Héroux pour avoir coordonné les efforts au sein de la Division des levés géodésiques. Sans lui, ce numéro n'aurait pu être publié. Finalement, je tiens aussi à remercier Kelly Dean, rédactrice en chef de *Geomatica* et Carol Railer, responsable de la production et de la publicité, d'avoir facilité la publication de ce numéro spécial, et ce, malgré un échéancier très serré, et d'avoir été si coopératives à l'occasion des étapes finales de mise en page de ce numéro. ❑

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In this era of global technologies, modern reference frames require alignment with a global "standard." Collectively realized by geodetic agencies around the world under the auspice of the International Association of Geodesy (IAG), the International Terrestrial Reference Frame provides this foundation. Recognizing the need for better coordination of international efforts to satisfy long-term requirements, the IAG has initiated the Global Geodetic Observing System (GGOS) project and has specifically tasked a working group to develop a strategy to further integrate and maintain the fundamental geodetic network of instruments and supporting infrastructure in a sustainable manner. In ***Global Geodetic Observing System – Considerations for the Geodetic Network Infrastructure***, a global integration process is proposed that includes the development of a network of fundamental stations with co-located geodetic techniques and precisely determined inter-system relationships. The design of this network would exploit the strengths of each technique and minimize the weaknesses where possible. The paper summarizes the present state of the infrastructure and provides a roadmap to future global geodetic networks, services, and products.

In closing, I would like to thank all contributing authors, including those whose papers were not selected for publication in this Special Issue. For the papers not presented here, I look forward to their possible publication in future issues of *Geomatica*. Special thanks to Pierre Héroux who has taken on the coordination of this effort within the Geodetic Survey Division and without whom this issue would have not materialized. Finally, I would like to extend my thanks to Kelly Dean, Editor, *Geomatica* and Carol Railer, Production and Advertising Manager, for facilitating the publication of this special issue and, despite a very tight schedule, for being so accommodating at the final editing stages of this production. ❑

SPACE GEODETIC TECHNIQUES AND THE CANADIAN SPATIAL REFERENCE SYSTEM EVOLUTION, STATUS AND POSSIBILITIES

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Over the last two decades a revolution has taken place in the field of positioning and navigation. The availability and accuracy of signals from Global Navigation Satellite Systems (GNSS), combined with advances in microelectronics, have greatly improved our ability to georeference information. While positioning was traditionally the business of professionals in the field of surveying and geodesy, it has now become a commodity readily available to a wide range of users, from professional surveyors to recreational amateurs.

The Canadian Spatial Reference System (CSRS) has been evolving over this time to facilitate access to the reference frame with innovative products. These new products and associated tools are taking advantage of the widespread availability of navigation satellite signals and the popularity of the Internet to respond to Canadians in a way that enables seamless integration of their geospatial data, on location and in real-time. The move to space geodetic techniques for delivery of the CSRS is presented in this paper.

Au cours des deux dernières décennies, nous avons traversé une révolution dans le domaine du positionnement et de la navigation. L'accessibilité et la précision des signaux des systèmes mondiaux de navigation par satellite (GNSS), en plus des avancées en microélectronique, ont grandement amélioré notre capacité à géocoder les données. Alors qu'auparavant, le positionnement relevait de professionnels des levés et de la géodésie, il est maintenant accessible à une grande variété d'usagers, qu'ils soient des arpenteurs-géomètres ou des amateurs de plein air.

Le Système canadien de référence spatiale (SCRS) a évolué au cours de ces années afin de faciliter l'accès au cadre de référence par des produits innovateurs. Ces nouveaux produits et outils connexes tirent profit de l'accessibilité globale aux signaux des satellites de navigation et de la popularité de l'Internet afin de répondre aux Canadiens d'une façon qui permet l'intégration parfaite, instantanée et sur place de leurs données géospatiales. Dans cet article, nous vous présenterons la transition du SCRS vers ces techniques géodésiques spatiales.

THE EVOLUTION OF NAD83 IN CANADA

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The North American Datum of 1983 (NAD83) is the national spatial reference system used for georeferencing by most federal and provincial agencies in Canada. The physical realization of this system has undergone several updates since it was first introduced in 1986. It has evolved from a traditional, ground-based horizontal control network to a space-based 3D realization fully supporting more modern positioning techniques and the integration of both horizontal and vertical reference systems. After a brief review of previous reference systems

used in Canada, the original definition of NAD83 and its subsequent updates are described, focusing on the definition of the current implementation NAD83(CSRS) and its relationship with other reference systems. Official transformation parameters between NAD83(CSRS) and ITRF (including WGS84) are provided for use throughout Canada. Possible future reference systems for Canada and North America are also examined.

Le Système de référence nord-américain de 1983 (NAD83) est le système de référence spatiale national utilisé pour la géoréférence par la plupart des agences fédérales et provinciales au Canada. La réalisation physique de ce système a nécessité plusieurs mises à jour depuis son entrée en vigueur en 1986. Le système a évolué d'un réseau de contrôle horizontal terrestre à une réalisation spatiale tridimensionnelle comprenant des techniques de positionnement plus modernes et intégrant les systèmes de référence horizontale et verticale. Après une brève revue des systèmes de référence utilisés au Canada, la définition originale du NAD83 et ses mises à jour subséquentes sont décrites, en se concentrant sur la définition de la mise en oeuvre actuelle du NAD83 (SCRS) et sa relation avec d'autres systèmes de référence. Les paramètres officiels de transformation entre le NAD83 (SCRS) et l'ITRF (incluant le WGS84) sont accessibles aux usagers pour tout le Canada. On examine aussi d'autres systèmes de référence possibles pour le Canada et l'Amérique du Nord à l'avenir.

A GRAVIMETRIC GEOID MODEL AS A VERTICAL DATUM IN CANADA

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The need for a new vertical datum in Canada dates back to 1976 when a study group at the Geodetic Survey Division (GSD) of Natural Resources Canada investigated problems related to the existing vertical reference system (CGVD28) and recommended a redefinition of the vertical datum. The US National Geodetic Survey and GSD cooperated in the development of a new North American Vertical Datum (NAVD88). Although the USA adopted NAVD88 as its datum in the early 90s, Canada did not follow suit because unexplained discrepancies of about 1.5 m were still present between east and west coasts. GSD continued to maintain and expand the vertical datum using the spirit levelling technique; however related cost and inherent deficiencies to this technique has forced GSD to rethink its approach for the delivery of the height reference system in Canada. Meanwhile, advances in space-based technologies and new developments in geoid modelling have emerged and now offer an alternative to spirit levelling. A new project to modernize the vertical datum is currently in progress in Canada. GSD is planning the adoption of a geoid model as the new vertical datum, which will allow users of space-based positioning technologies access to an accurate and uniform vertical datum everywhere across the Canadian landmass and surrounding oceans. Furthermore, this new vertical datum will be less sensitive to geodynamic activity, local crustal uplift and subsidence, and deterioration of benchmarks.

Le Canada a senti le besoin de se doter d'un nouveau système de référence altimétrique en 1976 alors qu'un groupe d'étude à la Division des levés géodésiques (DLG) de Ressources naturelles Canada étudiait des problèmes liés au système de référence altimétrique existant

(CGVD28) et avait recommandé une nouvelle définition du système de référence altimétrique. Le National Geodetic Survey des États-Unis et la DLG ont travaillé ensemble à l'élaboration d'un nouveau système de référence altimétrique nord-américain (NAVD88). Bien que les États-Unis aient adopté le NAVD88 et comme système de référence altimétrique vers le début des années 1990, le Canada ne l'a pas adopté à cause de lacunes inexpliquées d'environ 1,5 mètre entre les côtes Est et Ouest. La DLG a continué à maintenir et à améliorer le système de référence altimétrique en utilisant le nivellement de précision (à bulle). Cependant, à cause des défauts et des coûts associés à cette technique, la DLG a dû trouver une autre façon d'établir le système de référence altimétrique au Canada. Entre temps, les technologies spatiales et la modélisation du géoïde ont connu des percées importantes et offrent maintenant une alternative intéressante au nivellement de précision (à bulle). Ce projet est d'ailleurs déjà lancé au Canada. La DLG planifie l'adoption d'un modèle de géoïde en tant que système de référence altimétrique, ce qui permettra aux usagers des technologies de positionnement spatiales d'y accéder pour partout sur le continent canadien et les océans qui nous entourent. De plus, ce nouveau systtème de référence altimétrique sera moins sensible à l'activité géodynamique, au soulèvement ou à l'affaissement local de la croûte terrestre et à la détérioration des repères de nivellement.

CRUSTAL MOTION AND DEFORMATION MONITORING OF THE CANADIAN LANDMASS

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The science of geodesy and the corresponding reference systems it develops have increasingly been applied to measuring motions and slow deformations of the Earth's crust driven by plate tectonics. Improvements to geodetic methodologies have therefore enabled better understanding of the Earth's systems, including improved modelling and forecasting of changes that may affect society. These geophysical processes also systematically affect the reference frames used as standards for geodetic surveys. Reference frames therefore must not only define the system of coordinate axes (including orientation, origin, and scale), but also characterize the time-evolution of spatial coordinates on the Earth's surface. When evaluating the effect on reference standards within a given area, it is also important to realize that geodynamic processes operate on various spatial scales. In this paper we summarize some of NRCan's efforts to monitor contemporary crustal dynamics across Canada. Progressing from continental to smaller regional scales, we outline the rationale, techniques, and results. The observational data and interpretations presented are fundamentally dependent on the Canadian Spatial Reference System yet in turn also contribute to the incremental improvement of its definition and maintenance.

La science de la géodésie et les systèmes de référence correspondants ont été de plus en plus utilisés pour mesurer les mouvements et les lentes déformations de la croûte terrestre causés par les plaques tectoniques. L'amélioration des méthodes géodésiques nous a donc permis de mieux comprendre les systèmes de la Terre en nous permettant, entres autres, de mieux modéliser et prévoir les changements qui risquent de nous toucher. Ces processus géophysiques modifient aussi systématiquement les cadres de référence qui servent de normes aux levés géodésiques. Les cadres de référence doivent alors non seulement définir le système des axes des coordonnées (incluant l'orientation, l'origine et l'échelle), mais doivent aussi définir l'évolution temporelle des coordonnées spatiales sur la surface terrestre. Lorsqu'on évalue leur effet sur les normes de référence dans une zone donnée, il est aussi important de réaliser que les processus géodynamiques se produisent à plusieurs échelles spatiales. Dans cet article, nous résumerons certains des efforts de surveillance de la dynamique contemporaine de la croûte terrestre canadienne par Ressources naturelles Canada. De l'échelle continentale à l'échelle régionale, nous présenterons un survol du besoin, des techniques et des résultats. Les données et les interprétations observationnelles présentées dépendent fondamentalement du Système canadien de référence spatiale tout en contribuant à l'amélioration de sa définition et à sa maintenance.

GLOBAL GEODETIC OBSERVING SYSTEM—CONSIDERATIONS FOR THE GEODETIC NETWORK INFRASTRUCTURE

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Properly designed and structured ground-based geodetic networks materialize the reference systems to support sub-millimetre global change measurements over space, time, and evolving technologies. The Ground Networks and Communications Working Group (GN&C WG) of the International Association of Geodesy's Global Geodetic Observing System (GGOS) has been working with the IAG measurement services (the IGS, ILRS, IVS, IDS and IGFS) to develop a strategy for building, integrating, and maintaining the fundamental network of instruments and supporting infrastructure in a sustainable way to satisfy the long-term (10 to 20 years) requirements identified by the GGOS Science Council.

Activities of this Working Group include the investigation of the status quo and the development of a plan for full network integration to support improvements in terrestrial

reference frame establishment and maintenance, Earth orientation and gravity field monitoring, precision orbit determination, and other geodetic and gravimetric applications required for the long-term observation of global change. This integration process includes the development of a network of fundamental stations with as many co-located techniques as possible, with precisely determined intersystem vectors. This network would exploit the strengths of each technique and minimize the weaknesses where possible. This paper discusses the organization of the working group, the work done to date, and future tasks.

Des réseaux géodésiques terrestres bien conçus et structurés permettent de matérialiser les systèmes de référence afin de prendre en compte les changements mondiaux dans l’espace, le temps et les nouvelles technologies à un niveau inframillimétrique. Le groupe de travail sur les communications et les réseaux terrestres (Ground Networks and Communications Working Group (GN&C WG)) du Système global d’observation géodésique (GGOS) de l’Association internationale de géodésie (AIG) a travaillé avec les services de prises de mesures de l’AIG (l’IGS, l’ILRS, le SIR, l’IDS et l’IGFS) afin d’élaborer une stratégie pour édifier, intégrer et maintenir le réseau essentiel d’instruments et d’infrastructures de façon durable afin de répondre aux besoins à long terme (10 à 20 ans) cernés par le Conseil des sciences du GGOS.

Le Groupe de travail se prête notamment à l’évaluation du statu quo et à l’élaboration d’un plan pour l’intégration complète du réseau afin de comprendre les améliorations à l’élaboration et au maintien du cadre de référence terrestre, la surveillance de l’orientation et du champ gravitationnel terrestres, la détermination précise de l’orbite et d’autres applications géodésiques et gravimétrique nécessaires à l’observation des changements mondiaux à long terme. Ce processus d’intégration comprend l’élaboration d’un réseau de stations principales intégrant autant de techniques conjointes que possible et de vecteurs, déterminés avec précision, entre les systèmes. Ce réseau exploiterait les forces de chacune des techniques et minimiserait leurs faiblesses. Cet article présente l’organisation du groupe de travail, le travail accompli à ce jour ainsi que ses prochaines tâches.

THE EVOLUTION OF NAD83 IN CANADA

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The North American Datum of 1983 (NAD83) is the national spatial reference system used for georeferencing by most federal and provincial agencies in Canada. The physical realization of this system has undergone several updates since it was first introduced in 1986. It has evolved from a traditional, ground-based horizontal control network to a space-based 3D realization fully supporting more modern positioning techniques and the integration of both horizontal and vertical reference systems. After a brief review of previous reference systems used in Canada, the original definition of NAD83 and its subsequent updates are described, focusing on the definition of the current implementation NAD83(CSRS) and its relationship with other reference systems. Official transformation parameters between NAD83(CSRS) and ITRF (including WGS84) are provided for use throughout Canada. Possible future reference systems for Canada and North America are also examined.

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Introduction

The Geodetic Survey Division (GSD) of Natural Resources Canada has a mandate to establish and maintain a geodetic reference system as a national standard for spatial positioning throughout Canada. In general terms, a reference system is an abstract collection of principles, fundamental parameters, and specifications for quantitatively describing the positions of points in space. A reference frame is the physical manifestation or realization of such a prescription. Traditionally, a reference frame consists of a network of geodetic control points on the ground with adopted coordinates that other surveys can be tied and referenced to. Since the introduction of the Global Positioning System, this paradigm has been changing.

Mapping, GIS, scientific and other organizations make large investments in georeferenced data and demand that the integrity of the reference system be maintained and enhanced to keep pace with the way they obtain their positioning data. Consequently, GSD is constantly improving the reference system and periodically publishes new coordinates effectively representing updated realizations of the reference system. Such updates usually result from densification of the network of control points, elimination of blunders and distortions, improvements in accuracies, and the introduction of new positioning methodologies like GPS. At the same time, continuity must be maintained to ensure legacy data, based on previous reference systems and realizations, can be incorporated into the current reference frame.

The current reference system adopted as a national georeferencing standard by most federal and provincial agencies in Canada and endorsed by the Canadian Council on Geomatics [*CCOG* 2006] is the North American Datum of 1983 (NAD83). NAD83 has undergone several updates since its first realization in 1986. This paper describes these changes, focusing on the current implementation and its relationship with other reference systems. It also briefly examines possible future reference systems for Canada and North America.

Original Realization of NAD83 – NAD83(Original)

The first continental reference system for North America was the North American Datum of 1927 (NAD27). It was defined as a reference ellipsoid that was positioned and oriented using classical astronomical observations to best fit North America. The realization of this reference system consisted of a network of thousands of geodetic control monuments (physical makers in the ground) spaced about 20 to 100 km apart at locations chosen for intervisibility but which were usually inconvenient to access. This was only a horizontal network originally built up primarily from triangulation surveys in which systematic errors accumulated resulting in widespread distortions throughout the network. Because of the limited computational resources at the time, densification of the reference frame was performed in a piece-wise fashion by holding existing control points fixed to their published values. This further propagated the accumulation of errors by distorting newer, often more accurate data. For more information about NAD27, see *Junkins and Garrard* [1998].

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In a cooperative effort to reduce the distortions in the reference frame and to obtain a system more compatible with new space-based positioning technologies, Canada, the US, Mexico, and Denmark (Greenland) began a readjustment of the entire continental network using a new reference system called the North American Datum of 1983 (NAD83). The NAD83 system was based on a global reference system known as the BIH Terrestrial System 1984 (BTS84) together with the reference ellipsoid of the Geodetic Reference System 1980 (GRS80). BTS84 was an earth-centred (geocentric) reference frame produced by the Bureau International de l'Heure (BIH) using spaced-based data from lunar laser ranging (LLR), satellite laser ranging (SLR), very long baseline interferometry (VLBI) and the satellite Doppler system. It was the most accurate reference frame available at the time.

Using a relatively dense framework of new Doppler stations across the continent, the NAD83 reference frame was brought into alignment with BTS84 using an internationally adopted transformation between BTS84 and the Doppler reference frame NWL 9D [*Boal and Henderson* 1988]. About a dozen VLBI stations in Canada and the US were also included to provide a connection to the celestial reference frame. As we shall see below, these VLBI sites provide the only link between NAD83 and more modern, stable reference frames. The continental network was then readjusted in 1986 using a stepwise methodology known as Helmert blocking. This initial realization is denoted here as NAD83(1986).

Densification

Although the US included their entire hierarchy of networks in the NAD83(1986) adjustment, from highest accuracy geodetic to the lowest-order municipal networks, Canada included only its primary control network of about 8000 stations. This framework was then densified through subsequent so-called secondary integration adjustments in cooperation with the provincial geodetic agencies [*Parent* 1988]. The first of these was the 1989 Eastern Secondary Integration Helmert Block Adjustment (ESHIBA, now referred to as just SHIBA), that included provincial networks from Ontario eastward. Only a 374-station primary network was included in the Maritimes which had adopted their own new reference system (see below). Shortly after, the Western Secondary Integration Helmert Block Adjustment (WSHIBA) was completed in 1990 with the western provinces. The same year, NAD83 was proclaimed the official geodetic reference frame for federal government operations [*EMR* 1990]. To assist incorporating legacy NAD27 data into NAD83, an official transformation and distortion model called the National Transformation (NT) was developed [*Junkins* 1988].

Immediately after the completion of WSHIBA, some western provinces began major GPS surveying campaigns to densify and improve their networks. There were also many new federal networks in the northern territories. Rather than create confusion by adopting WSHIBA results and subsequently updating them shortly after, it was decided to redo the western adjustment with the new data. This new adjustment, completed and made public in 1993, was called the Network Maintenance Integration Project of 1993 (NMIP93).

The ESHIBA and NMIP93 realizations of NAD83 were the last of the major federal-provincial cooperative adjustment projects and are collectively referred to as NAD83(Original). This network is shown in Figure 1. Based on the ESHIBA and NMIP93 realizations of NAD83, an improved transformation from NAD27 was developed. Known as the National Transformation Version 2 (NTv2) [*Junkins* 1990], this new transformation provided much improved distortion modelling that adapted to the variations in the spatial density of network points.

Limitations

At about the same time as these traditional adjustment projects, a major advancement was taking place in GPS technology and in the realization of global reference frames. It was at this time that the International GPS Service (IGS), through the cooperative efforts of GSD and several other geodetic agencies around the world, began producing precise GPS satellite orbits that enabled centimetre-level positioning accuracies in 3D [*Beutler et al*. 1999]. These orbits were computed using a collection of permanent GPS tracking stations on the ground, including several in Canada that became the Canadian Active Control System (CACS) [*Duval et al*. 1997]. The number of federal tracking stations has since increased to nearly 50, resulting in even greater improvements in the accuracy of the GPS orbits and positioning results based on them. In essence, the geodetic control network was shifting to the GPS satellites in space (see *Héroux et al*. [this issue]).

At the time of its initial realization, NAD83 (and BTS84) was intended to be a geocentric system and was compatible with the other geocentric systems of the time, including the original realization of WGS84. However, due to the use of more accurate techniques, it is now known that NAD83 is offset by about 2 m from the true geocentre.

Another limitation of the original realizations of NAD83 was that access to it was provided mainly through a horizontal control network. Today, many applications of GPS require a 3D reference frame. Yet another problem revealed by GPS was the limited accuracy of conventional horizontal control networks. The significant accumulation of errors in both the observations and methods of network integration were being revealed by the use of new GPS survey techniques. Figure 2 illustrates these errors at points across Canada by comparing NAD83(Original) coordinates to those based on high accuracy GPS surveys tied almost directly to the fundamental reference frame of NAD83. Errors in the horizontal network are about 0.3 m on average but can exceed 1 m in the northern parts of many provinces.

3D Realization of NAD83 – NAD83(CSRS)

In light of the above limitations of NAD83(Original), a more accurate, true 3D realization of the NAD83 reference frame was clearly needed which enabled users to relate their positions more directly to the fundamental definition of the NAD83 reference frame. Together with a high accuracy geoid (see *Veronneau et al*. [this issue]), a complete 3D reference frame would also enable the convergence of traditional horizontal and vertical reference systems into a single unified system able to support all aspects of spatial positioning (see *Héroux et al*. [this issue] and *Veronneau et al*. [this issue]).

Figure 1: Traditional horizontal control network comprising the original realization of NAD83.

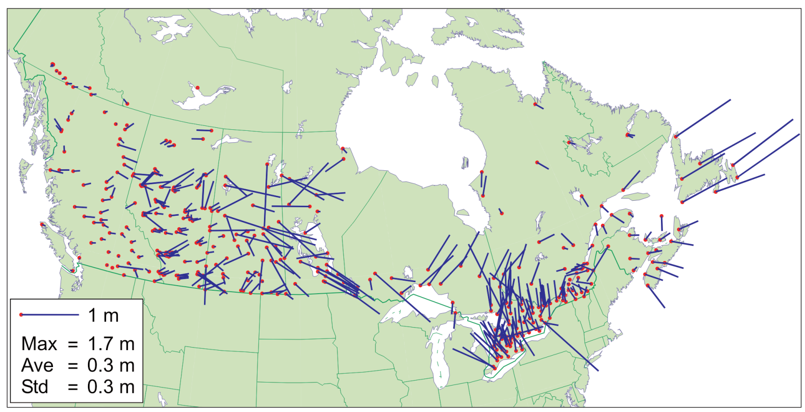

Figure 2: Errors in NAD83(Original) as revealed by high accuracy GPS observations in NAD83(CSRS).

Since 1990 the most accurate and stable reference frames available are the successive versions of the International Terrestrial Reference Frame (ITRF) produced by the International Earth Rotation and Reference Systems Service (IERS). Individual realizations are denoted by ITRFxx, where xx represents the last year for which data was included in a particular solution. These reference frames are based primarily on SLR, VLBI, GPS and a system called DORIS (Détermination d'Orbite et Radiopositionement Intégré par

Satellite) [*Boucher and Altamimi* 1996]. A key difference with previous reference systems is the dynamic nature of the reference frame. Coordinates for stations are valid for a specific date (epoch) and are accompanied by velocity estimates for propagating coordinates to other epochs.

During the first several years, new realizations of ITRF were introduced on a nearly annual interval as significant amounts of new data were added. Now that well over 15 years of data are available, the realizations of ITRF have stabilized to about a centimetre. Consequently, new versions are released less frequently. Presently, the last two releases were ITRF97 and ITRF2000 [*Altamimi et al*. 2002]. A new ITRF2005 is due sometime this year and is likely to be the last official public version for several years. Scientific updates are expected to be released more frequently to densify the reference frame and improve velocity estimation for new stations.

Realizing the benefits of using such a highly stable global reference frame, at the 20th General Assembly of the International Union of Geodesy and Geophysics in 1991, the International Association of Geodesy (IAG) adopted Resolution No. 1 which, among other things, made the following two recommendations [*IAG* 1992]:

> "1) that groups making highly accurate geodetic, geodynamic or oceanographic analysis should either use the ITRF directly or carefully tie their own systems to it"

> "4) that for high accuracy in continental areas, a system moving with a rigid [tectonic] plate may be used to eliminate unnecessary velocities provided it coincides exactly with the ITRS at a specific epoch"

Unfortunately …Canada and the US chose different methods of updating the transformation to new ITRF realizations.

Considering recommendation (4), it was assumed that recommendation (1) also allowed for the use of other systems such as NAD83 providing they are carefully tied to the ITRS. Note that the ITRF coordinates of points are constantly changing due to the motions of the individual tectonic plates. It is therefore necessary to specify which epoch ITRF coordinates refer to and to account for tectonic motion when propagating coordinates to other epochs.

Rather than abandon NAD83 altogether in favour of ITRF (as some countries have done), it was decided to define NAD83 by its precise relationship with ITRF which would comply with the IAG resolution. A precise connection between ITRF and NAD83 was made possible by the common VLBI stations in both systems. This allowed for the determination of a conformal 3D seven-parameter similarity (Helmert) transformation between the two reference frames. The transformation effectively provides a more accurate realization of the fundamental NAD83 3D reference frame in terms of the ITRF. It also provides any user with convenient and nearly direct access to the highest levels of the NAD83 reference frame. This enables users to determine accurate positions that are highly consistent across the entire continent. Moreover, GPS orbits can be transformed to NAD83 allowing users to position themselves directly in NAD83 through applications such as Precise Point Positioning (PPP) [*Héroux et al*. this issue].

1996 Realization – NAD83(CSRS96)

The first ITRF-NAD83 transformation adopted by both Canada and the US was determined with respect to ITRF89 in the early 1990s [*Soler et al*. 1992]. The scale of ITRF, derived in part from VLBI stations in Canada and the US, was adopted for compatibility with more recent versions of WGS84 by setting the estimated scale parameter to zero. This realization of the NAD83 reference frame was denoted as NAD83(CSRS96), where "96" indicates the year the transformation was introduced (not any particular coordinate epoch). The transformation was used to produce NAD83 coordinates for CACS stations and allowed for GPS orbits to be generated in NAD83.

Unfortunately, following the adoption of this first ITRF-NAD83 transformation, Canada and the US chose different methods of updating the transformation to new ITRF realizations. Canada used the official incremental transformations between different versions of ITRF as published by the IERS. The US, on the other hand, recomputed the transformation for each new ITRF, adopting the slightly different scale of each ITRF. Consequently, the updated transformations differed slightly, mainly in scale. This resulted in ellipsoidal height discrepancies of about 5 cm along the common borders by the time ITRF96 was introduced in 1998.

1998 Realization – NAD83(CSRS)

In order to reconcile the slightly different realizations of NAD83 in Canada and the US arising from these different ITRF-NAD83 transformations, a new common NAD83 transformation was derived with respect to ITRF96, the most recent at the time. The data used in determining the transformation were the NAD83(Original) and ITRF96 coordinates at 12 VLBI stations in Canada and the US (see Figure 3). These are the only fundamental points in the original definition of NAD83 with 3D coordinates in both NAD83 and ITRF96.

Using the ITRF96 coordinates at epoch 1997.0, a new seven-parameter similarity (Helmert) transformation was determined [*Craymer et al*. 2000]. The scale of ITRF96 was adopted for this realization of NAD83 by setting the scale parameter to zero after estimation. This ensures the scale of NAD83 will be compatible with the more accurate scale defined by ITRF96 and used by other systems such as WGS84. The estimated parameters are given in Table 1.

In order to correctly account for the tectonic motion of the North American tectonic plate when transforming from/to ITRF96 positions at any arbitrary epoch, the NNR-NUVEL-1A plate motion model was adopted [*DeMets et al*. 1994] as recommended by the IERS [*McCarthy* 1996]. *Larson et al*. [1997] had shown NNR-NUVEL-1A to be in relatively good agreement with velocities estimated from GPS in North America at that time (based on more data it is now known to be slightly biased). The effect of this motion can be treated as additional rotations of the reference frame defined by

$$\begin{bmatrix} R_X \\ R_Y \\ R_Z \end{bmatrix} = \begin{bmatrix} 0.0532 \\ -0.7423 \\ -0.0316 \end{bmatrix} \text{mas/y} \qquad (1)$$

where R_X,R_Y,R_Z are rotations about the geocentric Cartesian coordinate axes in units of milliarcseconds per year (mas/y).

To ensure a consistent application of the transformation to other ITRF realizations, both Canada and the US also agreed to adopt the most current IERS values for transforming between ITRF96 and other ITRF reference frames. The only exception was the incremental transformation between ITRF96 and ITRF97 where the GPS-based IGS transformation was used to account for a systematic bias in the GPS networks used in ITRF97.

This new realization of NAD83 was originally denoted as NAD83(CSRS98) to distinguish it from the 1996 realization. Like the 1996 realization, "98" refers to the year it was adopted and not to any coordinate epoch. However, because the NAD83(CSRS96) realization saw very limited use, the name of the new realization has since been shorted to just NAD83(CSRS).

The main advantage of this improved NAD83(CSRS) realization is that it provides almost direct access to the highest level of the NAD83 reference frame through ties to the CACS and collocated VLBI stations that form part of the ITRF network. These stations effectively act as both ITRF and NAD83 datum points for geospatial positioning, thereby enabling more accurate, convenient, and direct integration of user data with practically no accumulation of error typically found in classical horizontal control networks.

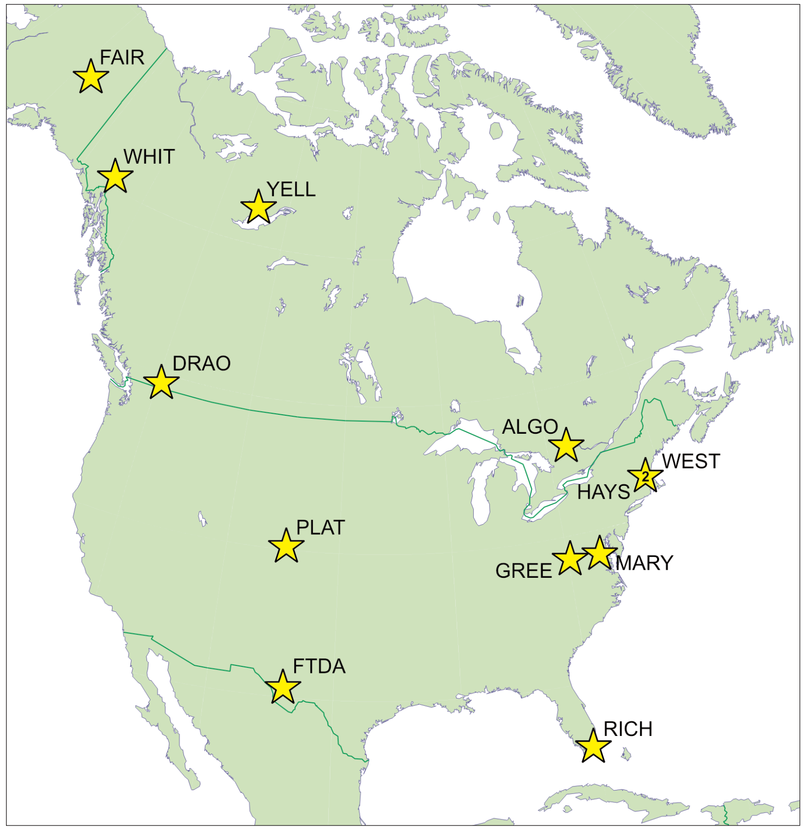

Figure 3: VLBI stations included in NAD83(Original) and used in the ITRF96 transformation.

It is important to bear in mind that the NAD83 reference system itself has not changed. It is only the method of physically defining or realizing it that has been updated to make NAD83 more accurate and stable, and more easily accessible to more users. Any differences between NAD83(Original) and NAD83(CSRS) reflect primarily the much larger errors in the original. Each successive update is generally more accurate than, but fully consistent with, previous realizations.

Hierarchy of NAD83(CSRS) Networks

The new NAD83(CSRS) realization was accompanied by a transition to a new reference frame structure for Canada (see Figure 4). The traditional horizontal network hierarchy that constituted the original realization of NAD83 was replaced with a more modern framework that takes advantage of advanced GPS methods and enables more

Table 1: ITRF to NAD83 transformation parameters at an epoch of 1997.0 and their rates of change (mas = milliarcsec, ppb = parts per billion).

	T_X m dT_X m/y	T_Y m dT_Y m/y	T_Z m dT_Z m/y	R_X mas dR_X mas/y	R_Y mas dR_Y mas/y	R_Z mas dR_Z mas/y	DS ppb dDS ppb/y
ITRF88	0.9730 0.0000	-1.9072 0.0000	-0.4209 0.0000	-25.890 -0.053	-9.650 0.742	-11.660 0.032	-7.400 0.000
ITRF89	0.9680 0.0000	-1.9432 0.0000	-0.4449 0.0000	-25.790 -0.053	-9.650 0.742	-11.660 0.032	-4.300 0.000
ITRF90	0.9730 0.0000	-1.9192 0.0000	-0.4829 0.0000	-25.790 -0.053	-9.650 0.742	-11.660 0.032	-0.900 0.000
ITRF91 WGS84(G730)	0.9710 0.0000	-1.9232 0.0000	-0.4989 0.0000	-25.790 -0.053	-9.650 0.742	-11.660 0.032	-0.600 0.000
ITRF92	0.9830 0.0000	-1.9092 0.0000	-0.5049 0.0000	-25.790 -0.053	-9.650 0.742	-11.660 0.032	0.800 0.000
ITRF93	1.0111 0.0029	-1.9058 -0.0004	-0.5051 -0.0008	-24.410 0.057	-8.740 0.932	-11.150 -0.018	-0.400 0.000
ITRF94 WGS84(G873)	0.9910 0.0000	-1.9072 0.0000	-0.5129 0.0000	-25.790 -0.053	-9.650 0.742	-11.660 0.032	0.000 0.000
ITRF96	0.9910 0.0000	-1.9072 0.0000	-0.5129 0.0000	-25.790 -0.0532	-9.650 0.7423	-11.660 0.0316	0.000 0.000
ITRF97	0.9889 0.0007	-1.9074 -0.0001	-0.5030 0.0019	-25.915 -0.067	-9.426 0.757	-11.599 0.031	-0.935 -0.192
ITRF2000 WGS84(G1150)	0.9956 0.0007	-1.9013 -0.0007	-0.5214 0.0005	-25.915 -0.067	-9.426 0.757	-11.599 0.051	0.615 -0.182

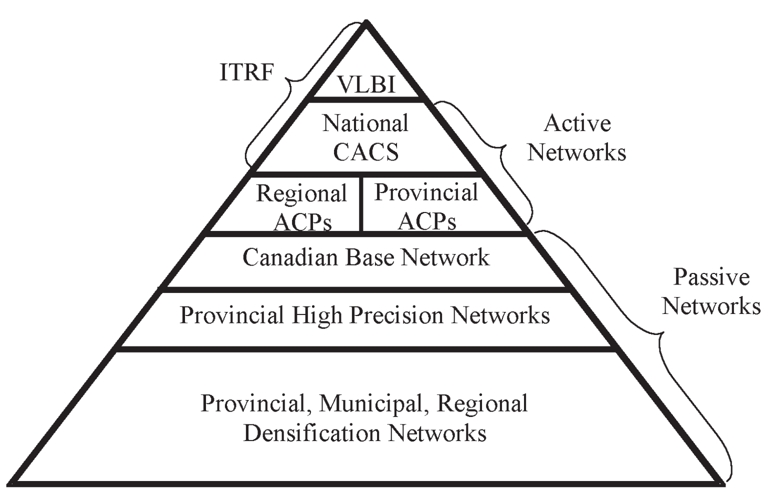

Figure 4: Hierarchy of NAD83(CSRS) reference frame.

accurate and more convenient access to the NAD83(CSRS) reference frame.

This new reference frame hierarchy is divided into active and passive components as illustrated in Figure 4. The active component consists of networks of continuously operating GPS receivers and products derived from them, such as precise orbits and broadcast corrections. The passive component is comprised of more traditional monumented control points that users can occupy with their own equipment.

Active Component

At the top of the “active” reference frame hierarchy are the VLBI and CACS stations that are part of the global ITRF reference frame. Using the adopted transformation, the ITRF coordinates for these stations can be converted to NAD83 without any loss of accuracy or continuity with previous ITRF or NAD83(CSRS) realizations. Moreover, the data for these GPS stations are available to the general public thereby enabling users for the first time to tie directly to the highest level of NAD83 reference frame. In the old hierarchal network structure, users were generally only able to connect to control points in the lower levels of the network hierarchy with their attendant lower accuracies.

At the level below the CACS sites are additional continuously operating GPS receivers, collectively referred to as regional ACPs. These regional ACP networks were installed in support of specific local and regional projects to determine crustal motions and monitor sea level rise. They can be considered a densification of the ITRF and IGS global networks. Some examples of these regional networks are the Western Arctic Deformation Network (WARDEN) and the Western Canada Deformation Array (WCDA) (some of these regional ACPs have recently been incorporated into the ITRF global network) See *Henton et al.* [this issue] for more discussion of these networks.

In addition to the federally operated CACS stations, some provinces have implemented their own network of active GPS stations that provide data and DGPS corrections to the general public. Some examples of such systems can be found in British Columbia, Quebec, and soon New Brunswick. A few private companies have also installed DGPS system in various regions. Most of these services charge a fee for access to the DGPS corrections. Although the provincial systems generally tie their DGPS stations to NAD83(CSRS), not all private systems do. Some systems have only been tied to the original realization of NAD83 and thus their accuracies will be degraded by any local distortions. In some areas the distortions are fairly coherent enabling accurate relative positioning (cf. Figure 2). However, problems might arise if using such services across areas where the distortions are quite different.

Note that a Canada-wide DGPS Service (CDGPS) has also been created through collaboration between all the provincial and federal geodetic agencies based on NRCan's wide-area GPS Corrections (GPS•C). Broadcast nationwide via Canada's own MSAT communication satellite, this service provides sub-metre positions directly in NAD83(CSRS) nearly everywhere in Canada. For more information about CDGPS and GPS•C see *Héroux et al*. [this issue] and the CDGPS web site at *www.cdgps.com*.

In addition to providing the link to the global reference frame, the CACS stations and some regional ACPs contribute to the International GNSS Service (IGS) efforts to produce, among other products, the most accurate GPS orbits available. Although computed in the ITRF reference frame of date, these orbits are easily transformed to NAD83(CSRS) like any other coordinates using the adopted ITRF-NAD83(CSRS) transformation. By using such precise IGS orbits, users can determine point positions directly in NAD83(CSRS). For more information about these products see *Héroux et al*. [this issue]. In essence, the satellites themselves have effectively become an extension of the NAD83(CSRS) reference frame available to users.

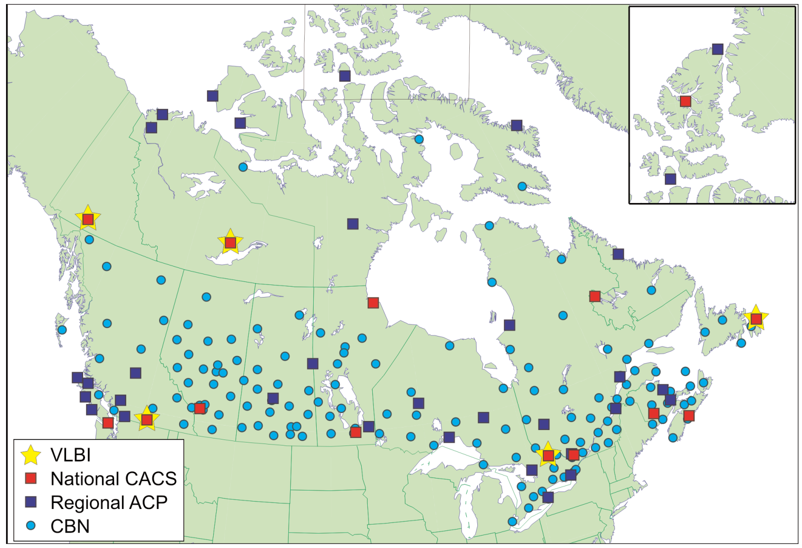

Figure 5: Federal component of the NAD83(CSRS) reference frame.

Passive Component

In order to assist with the integration of the older horizontal control networks into NAD83(CSRS) a new, much sparser but more stable network of "passive" control points was established and tied directly to the CACS stations (see Figure 5). Called the Canadian Base Network (CBN), this network forms the next level of the reference frame hierarchy below the CACS. It is the highest level of the passive component of the CSRS reference frame.

The CBN consists of approximately 160 highly stable, forced-centering pillars. This network was originally conceived as an interim measure or transition during the move to a CACS-only reference frame. However, the CBN has proven to be invaluable for monitoring the on-going deformation of the Canadian landmass for scientific studies and the long-term maintenance of the reference frame. To date, there have been three complete measurements of the CBN. The quality of these surveys has been held in high regard by many scientists because of the unprecedented spatial detail the results have revealed about the motions of the Earth's crust (see *Henton et al*. [this issue]). Public interest has also been very high as indicated by much media interest [*AP* 2004; *CanWest* 2004; *The Globe and Mail* 2004; *The Guardian* 2004; *The Independent* 2004; *The New Scientist* 2004; *UPI* 2004; *The Washington Post* 2004].

During the establishment of the CBN, the provincial agencies began densifying the network for their own requirements. These densifications are often referred to as a provincial high precision networks (HPNs). High accuracy ties between the CBN and various HPNs were made during the first measurement campaign of the CBN enabling the provinces to integrate their traditional networks into NAD83(CSRS).

The 8000 stations of the primary horizontal control network were not entirely abandoned by this new reference frame structure. Rather the provinces assumed the responsibility for their maintenance and integration into NAD83(CSRS). Most provinces have readjusted this data together with their own (secondary) horizontal control networks. These networks provided the main source of information for the development of NTv2 distortion models for converting large holdings of georeferenced data from NAD83(Original) to NAD83(CSRS).

Relationship to Other Reference Frames

ITRF

The transformation between NAD83(CSRS) and any realization of ITRF at any arbitrary epoch (t) can be obtained by combining the definitive ITRF96-NAD83 transformation previously described together with the incremental between-ITRF transformations and the NNR-NUVEL-1A rotations defining the motion of the North American tectonic plate. The resulting Helmert transformation can be written as [*Craymer et al*. 2000]

$$\begin{bmatrix} X_N \\ Y_N \\ Z_N \end{bmatrix} = \begin{bmatrix} T_X(t) \\ T_Y(t) \\ T_Z(t) \end{bmatrix} + \begin{bmatrix} 1+DS(t) & -R_Z(t) & R_Y(t) \\ R_Z(t) & 1+DS(t) & -R_X(t) \\ -R_Y(t) & R_X(t) & 1+DS(t) \end{bmatrix} \begin{bmatrix} X_I(t) \\ Y_I(t) \\ Z_I(t) \end{bmatrix} \quad (2)$$

where

X_N, Y_N, Z_N are the geocentric Cartesian coordinates in NAD83(CSRS)

$X_I(t), Y_I(t), Z_I(t)$ are the geocentric Cartesian coordinates in ITRF at epoch t

$T_X(t) = T_X + dT_X \cdot (t\text{-}1997.0)$ m

$T_Y(t) = T_Y + dT_Y \cdot (t\text{-}1997.0)$ m

$T_Z(t) = T_Z + dT_Z \cdot (t\text{-}1997.0)$ m

$R_X(t) = [R_X + dR_X \cdot (t\text{-}1997.0)] \cdot k$ rad

$R_Y(t) = [R_Y + dR_Y \cdot (t\text{-}1997.0)] \cdot k$ rad

$R_Z(t) = [R_Z + dR_Z \cdot (t\text{-}1997.0)] \cdot k$ rad

$DS(t) = DS + dDS \cdot (t\text{-}1997.0)$ ppb

t = epoch of ITRF coordinates

$k = 4.84813681 \times 10^{-9}$ rad/mas

All these parameters are time-dependent due to tectonic plate motion and the rates of change of some of the incremental transformation parameters between different ITRFs. Note that the rotations in these expressions are given as positive in a clockwise direction following the non-standard convention used by the IERS. Table 1 summarizes these parameters for all ITRF realizations available at the time of this paper (ITRF2005 is expected to be released this year). See also *Soler and Snay* [2004] for further discussion of the ITRF2000-NAD83 transformation.

In addition to transforming coordinates, it is also possible to transform GPS baseline vectors. Because vectors contain no absolute positional information, the translational part of the transformation is not used. Only the rotations and scale change are applied to the vector coordinate differences as follows:

$$\begin{bmatrix} \Delta X_N \\ \Delta Y_N \\ \Delta Z_N \end{bmatrix} = \begin{bmatrix} 1+DS(t) & -R_Z(t) & R_Y(t) \\ R_Z(t) & 1+DS(t) & -R_X(t) \\ -R_Y(t) & R_X(t) & 1+DS(t) \end{bmatrix} \begin{bmatrix} \Delta X_I(t) \\ \Delta Y_I(t) \\ \Delta Z_I(t) \end{bmatrix} \quad (3)$$

where

$\Delta X_N, \Delta Y_N, \Delta Z_N$ are the geocentric Cartesian coordinate differences in NAD83(CSRS)

$\Delta X_I(t), \Delta Y_I(t), \Delta Z_I(t)$ are the geocentric Cartesian coordinate differences in ITRF at epoch t

Although the effect of the rotations and scale change on baseline vectors is relatively small (of the order of 0.1 ppm) and may be neglected in some cases, they systematically accumulate throughout a network and can amount to a significant error in some situations. Because the application of the transformation is relatively simple, it is recommended to always transform baseline vectors unless one is sure they will never be assembled to construct larger networks.

Velocities in ITRF can also be transformed into NAD83(CSRS). This involves only the rates of change of the transformation parameters defined in eqn. (2) and Table 1. These parameters represent the NNR-NUVEL-1A velocity for the North American plate and some small drifts in the origin, orientation, and scale of different realizations of the ITRF. The transformation can be expressed as

$$\begin{bmatrix} V_{X_N} \\ V_{Y_N} \\ V_{Z_N} \end{bmatrix} = \begin{bmatrix} V_{X_I} \\ V_{Y_I} \\ V_{Z_I} \end{bmatrix} + \begin{bmatrix} dT_X \\ dT_Y \\ dT_Z \end{bmatrix} + \begin{bmatrix} dDS & -dR_Z \cdot k & dR_Y \cdot k \\ dR_Z \cdot k & dDS & -dR_X \cdot k \\ -dR_Y \cdot k & dR_X \cdot k & dDS \end{bmatrix} \begin{bmatrix} X_I(t) \\ Y_I(t) \\ Z_I(t) \end{bmatrix} \tag{4}$$

where

$V_{X_N}, V_{Y_N}, V_{Z_N}$ are the geocentric Cartesian velocities in NAD83(CSRS)

$V_{X_I}, V_{Y_I}, V_{Z_I}$ are the geocentric Cartesian velocities in ITRF at epoch t

These ITRFxx-NAD83(CSRS) transformations have been implemented in software available from GSD and the US National Geodetic Survey (NGS). GSD's software is called TRNOBS and will transform input data files of positions and position differences for GSD's own GHOST adjustment software as well as for the commercial GeoLab™ software. For US users, the HTDP (Horizontal Time Dependent Positioning) software will transform data files of positions and velocities in NGS Blue Book format. On-line versions and Fortran source code for both TRNOBS and HTDP are available at the respective agency's web sites.

WGS84

The World Geodetic System 1984 [*NIMA* 2004] is a global reference frame originally developed by the US Defense Mapping Agency (subsequently renamed the National Imagery and Mapping Agency (NIMA) and now called the National Geospatial-Intelligence Agency (NGA)). It was used for mapping campaigns around the world and is the "native" reference frame used by GPS.

WGS84 is unique in that there is no physical network of ground points that can be used as geodetic control. The only control points available to the public are the satellites themselves, defined by the broadcast orbits. Because of the relative inaccuracy of these orbits and further degradation prior to May 1, 2000 due to the implementation of selective availability (S/A), public users could not get true WGS84 positions to better than about 10-50 m. Accuracies improved to about 3-5 m when S/A was turned off and even better accuracies of a metre or less can now be achieved with correction services such as the Wide Area Augmentation System (WAAS). It was at this time that many users began to notice a systematic bias between WGS84 and NAD83 of about 1.5 m in the horizontal and a metre in the vertical.

Originally, WGS84 was defined in a similar manner as NAD83. It used a global network of Doppler stations to align itself with the same BTS84 reference frame used by NAD83. Thus, WGS84 was identical with NAD83 in the beginning. Based on this original realization, NIMA determined simple average geocentric Cartesian coordinate shifts (translations) between WGS84 and many local datums around the world. Because NAD83 and WGS84 were defined by the same BTS84 reference frame, the shift between these systems was zero [*NIMA* 2004].

Several years later, in an effort to improve its stability and accuracy, WGS84 was redefined in terms of ITRF [*Slater and Malys* 1998; *NIMA* 2004]. In doing so, the WGS84 reference frame was shifted by about two metres and rotated slightly to align it with the ITRF reference frame. Figure 6 illustrates the differences between this new WGS84 and NAD83 in Canada for both horizontal and vertical components. This realignment with ITRF occurred three different times [*Slater and Malys* 1998; *Merrigan et al.* 2002; *NIMA* 2004; *NGA* 2004]. These WGS84 realizations are denoted with a "G" followed by the GPS week the frame was put into use. Table 2 lists the different ITRF-based realizations of WGS84 giving the particular version of ITRF used and the dates they were put into use. Of particular importance to GPS users are the dates used to produce the broadcast orbits. Users can transform WGS84 positions or baseline vectors to NAD83 by simply using the parameters for the associated ITRF.

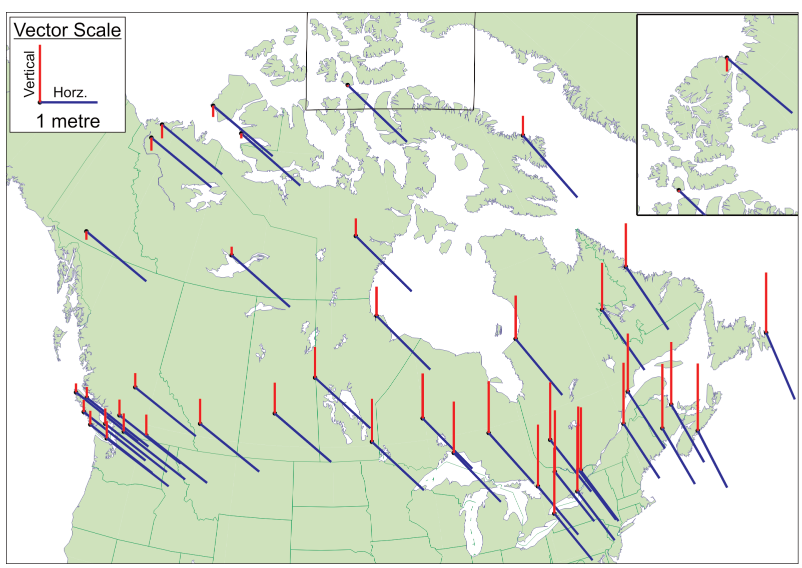

Figure 6: Horizontal (blue) and vertical (red) differences between NAD83(CSRS) and WGS84 in the sense NAD83(CSRS) minus WGS84.

Table 2: ITRF-based realizations of the WGS84 reference frame.

Version	Based on	Implemented at NIMA	Implemented in Orbits
WGS84(G730)	ITRF91	1994-01-02	1994-06-20
WGS84(G873)	ITRF94	1996-09-29	1997-01-29
WGS84(G1150)	ITRF2000	2002-01-20	2002-01-20

Unfortunately, NGA still considers the G-series realizations of WGS84 to be identical with the original realization. Thus, the zero transformation with respect to NAD83 has never been revised in spite of the bias being clearly measurable. This has created problems when using WGS84-based correction services and trying to convert results to NAD83. Most receiver manufactures include only the original NIMA coordinate shifts (translations) in their receiver firmware, which are zero for NAD83. Consequently, many receivers are producing so-called NAD83 coordinates that are actually still in WGS84 and biased by 1.5 to 2 metres with respect to the true NAD83 reference frame. Great care must therefore be exercised when using the transformations built into receiver firmware and post-processing software.

NAD83(Original)

To assist in the conversion of large amounts of data tied to the original realization of NAD83 and in cases where it is impractical or impossible to readjust existing NAD83(Original) networks in NAD83(CSRS), many provinces have developed NTv2-type distortion models to convert such data to NAD83(CSRS). This task first involved the readjustment of provincial networks in NAD83(CSRS). This provided coordinate discrepancies between the original and CSRS realizations of NAD83 with a greater spatial density to better model the distortions. In some cases it was necessary to perform surveys to provide additional connections between the old and new realizations.

It is important to emphasize again that NAD83(Original) and NAD83(CSRS) do not represent different reference systems. NAD83(CSRS) is essentially an updated physical realization (network) of the same NAD83 reference system, fully consistent with NAD83(Original) but with much greater accuracy. The provincial NTv2 distortion models therefore do not reflect any changes in the reference system. Rather they represent the errors (distortions) in the networks comprising the original realization of NAD83. Because these distortions are about half a metre on average, users should consider the accuracy of their georeferencing before deciding whether data holdings need to be converted from NAD83(original) to NAD83(CSRS).

NAD27/CGQ77/ATS77

For similar reasons, transformations to NAD83(CSRS) have also been developed for other older reference systems. The system with the greatest amount of legacy data was NAD27 and so an NTv2 to NAD83(Original) transformation and distortion model was developed as discussed earlier. This transformation can also be used for NAD83(CSRS). This is because the differences between the original and CSRS versions of NAD83 are insignificant compared to the relatively low accuracy of the NAD27-NAD83(Original) transformation. These minor differences can therefore be safely ignored without introducing any systematic bias in the results.

In order to reduce the distortions in NAD27, Quebec performed a readjustment of their provincial networks based on the NAD27 reference frame several years before NAD83 was introduced. This realization was denoted as NAD27(CGQ77) or CGQ77. Quebec developed their own NTv2-compatible transformations and distortion models between NAD27, CGQ77, NAD83(Original), and NAD83(CSRS) which are implemented in their SYREQ software.

At about the same time CGQ77 was implemented, the Maritime Provinces introduced yet another reference system called the Atlantic Terrestrial System of 1977 (ATS77) [*Gillis et al*. 2000]. Unlike CGQ77, this was a geocentric system. It was adopted in New Brunswick and Nova Scotia in 1979 and continued to be used after the introduction of the original realization of NAD83. An NTv2-based transformation between NAD27 and ATS77 was developed as was a transformation between ATS77 and NAD83(Original). However, the latter used only the federal primary control stations in the Maritimes. When the 1998 realization of NAD83(CSRS) was introduced in 1998 it was soon adopted or was used unofficially for most positioning applications. New Brunswick, Nova Scotia, and Prince Edward Island have since developed their own NTv2-compatible transformations and distortion models between ATS77 and NAD83(CSRS).

Maintenance of NAD83(CSRS)

In general, geodetic reference frames and networks need periodic maintenance or updating of their coordinates for a variety of reasons. Some of these include the addition of new densification networks, the correction of survey blunders, unstable or disturbed monumentation, the effects of crustal motion both locally and regionally, and to keep pace with ever increasing accuracy requirements.

Crustal motions are especially troublesome along the west coast and in central and eastern Canada (see *Henton et al.* [this issue]). Vertical movements up to 2 cm/y due to post-glacial rebound can quickly make positions outdated. In the case of NAD83(CSRS), it is now known that the NNR-NUVEL-1A plate motion used in the defining ITRF-NAD83 transformation is in error by about 2 mm/y (see Figure 7). Over several years this can accumulate to well over a centimetre which becomes problematic for high accuracy and scientific applications.

In an effort to ensure the NAD83(CSRS) reference frame keeps pace with future requirements, coordinates are periodically updated as new versions of the ITRF are released. New ITRF coordinates for Canadian stations are transformed to NAD83(CSRS) using the adopted transformation. This periodic updating of the reference frame is sometimes referred to as a semi-dynamic approach to maintenance where positions are valid for only a defined period of time.

Another method of reference frame maintenance is a purely dynamic approach where positions are assumed to be dynamic and are valid only for a specific epoch. Estimated velocities are then used to propagate the positions to any other date. Such an approach is often required for scientific applications demanding the highest accuracies. The ITRF is the prime example of a dynamic global reference frame as is the new Stable North American Reference Frame (SNARF) discussed below.

Evolving from NAD83

To many, our current NAD83(CSRS) spatial reference system appears to be adequate for most positioning activities in North America. However, history has repeatedly shown that reference systems need to evolve to keep pace with the ever-increasing accuracy with which we are able to locate points on and near the Earth, and to enable the proper integration of georeferenced data from various sources and from different times.

As previously mentioned, it is now known that NAD83 is offset from the true geocentre by about two metres. It is therefore incompatible with the newer realizations of WGS84, the native reference frame for GPS. As discussed above, this can cause problems when treating the two frames as the same. In addition, the adopted NNR-NUVEL-1A plate motion model overestimates the magnitude of the rotation of the North American plate (see Figure 7). This can accumulate to magnitudes that are detectible in high accuracy GPS surveys. Finally, intra-plate crustal deformations such as post-glacial rebound can cause coordinates to quickly go out of date.

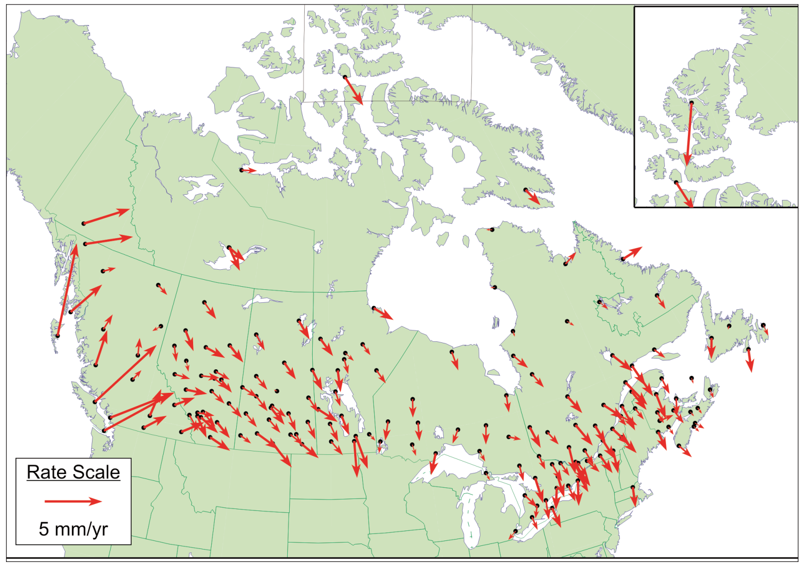

Figure 7: GPS horizontal velocities from repeated high accuracy GPS observations with respect to the NNR-NUVEL-1A plate motion estimate for North America. The coherent pattern reveals a bias in NNR-NUVEL-1A of about 2 mm/y.

One option of dealing with these problems is to simply use the most recent ITRF realization as done in some countries (e.g., South America). The advantage of this is that it would be completely compatible with the WGS84 system used by GPS. However, the relentless movement of the North American continent due to plate tectonics will slowly but surely ensure that all coordinates systematically change by about 2.5 cm/y. This amounts to a quarter of a metre in only 10 years. If this motion is not accounted for it would result in coordinate discrepancies at a level unacceptable for most users.

The accumulating coordinate discrepancies due to tectonic motion could be somewhat reduced by simply updating the ITRF coordinates on a regular basis following the semi-dynamic approach to maintenance. However, it would still be difficult to relate data from different time periods. At the very least, this approach would require significant efforts to inform and educate the public.

Another approach would be to adopt a version of ITRF at a specific epoch and to keep this realization fixed to North America as recommended by the *IAG* [1992]. Such coordinates can be related to ITRF coordinates at any other epoch using an estimate of the motion of the North American tectonic plate as done for NAD83(CSRS). This is the approach recently used to define the so-called Stable North American Reference Frame (SNARF) [*Blewitt et al*. 2005; *Craymer et al.* 2005]. Under the joint auspices of UNAVCO, Inc. in the US and IAG Sub-Commission 1.3c for North America, a working group was established with the goal of defining such a regional reference frame that is consistent and stable at the sub-mm-level throughout North America. This reference frame fixes ITRF2000 to the stable part of North America to facilitate geophysical interpretation and inter-comparison of geodetic solutions of crustal motions.

The SNARF reference frame is essentially defined by a rotation vector that models the tectonic motion of North America in the ITRF2000 reference frame. The rotations transform ITRF2000 positions and velocities at any epoch into the SNARF frame fixed to the stable part of North American. Thus, just like NAD83(CSRS), SNARF is defined in relation to the ITRF. The advantage of SNARF is that it is truly geocentric and also uses a rotation vector that more accurately models the motion of stable North America. Previous plate rotation estimates have used stations in areas of intra-plate crustal deformations which can bias the estimation of the rotation vector.

The SNARF plate rotations were determined using ITRF2000-based velocities of 17 stations in geophysically stable areas. The following are the rotations adopted for SNARF v1.0 which transform ITRF2000 coordinates into the SNARF frame:

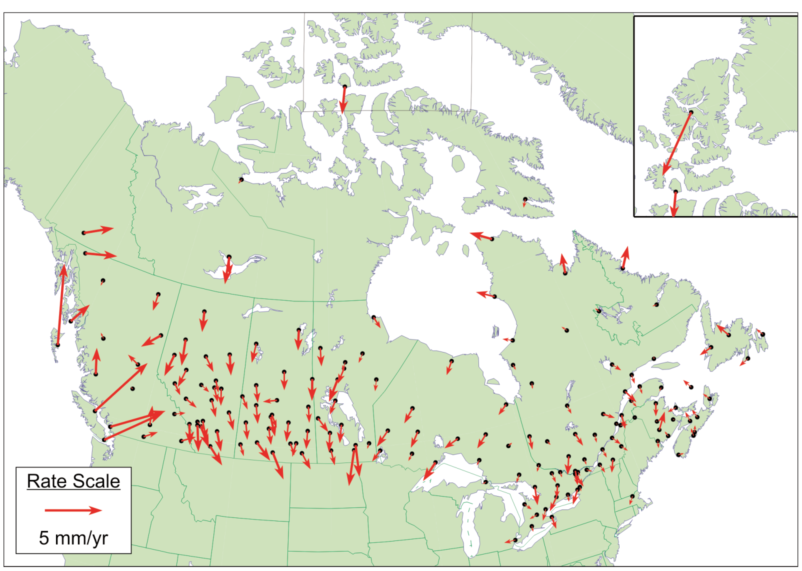

Figure 8: GPS horizontal velocities from repeated high accuracy GPS observations with respect to the SNARF 1.0 plate motion estimate for North America.

$$\begin{bmatrix} R_X \\ R_Y \\ R_Z \end{bmatrix} = \begin{bmatrix} 0.06588 \\ -0.66708 \\ -0.08676 \end{bmatrix} \text{mas/y} \quad (5)$$

This rotation vector is equivalent to a horizontal surface velocity of about 2 cm/y in Canada.

Velocities of CBN stations with respect to the SNARF reference frame are plotted in Figure 8. In this reference frame the expected outward pattern of intra-plate horizontal velocities from post-glacial rebound is small but clearly visible. This model of plate motion is an improvement over NNR-NUVEL-1A for North America (compare Figures 7 and 8).

The first release of SNARF also includes an empirical model of post-glacial rebound based on a novel combination of GPS velocities with a geophysical model. It has been adopted as the official reference frame for the Plate Boundary Observatory of the EarthScope project along the west coast of North America. Over the next few years SNARF will be incrementally improved and refined and could become a de facto standard for many applications. Sometime in the future it is possible that, after further analysis and consultation with stakeholders, SNARF or some variation of it may eventually replace NAD83 as the official datum for georeferencing in both Canada and the US.

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Disclaimer

Any reference to commercial products in not intended to convey an endorsement of any kind.

References

Altamimi, Z., P. Sillard and C. Boucher. 2002. ITRF2000: A new release of the International Terrestrial Reference Frame for earth science applications. *Journal of Geophysical Research*, Vol. 107, No. B10, DOI: 10.1029/2001JB000561.

Associated Press (AP). 2004. Scientists say Chicago sinking a millimeter a year. *The Associated Press State and Local Wire*, May 20.

Beutler, G., M. Rothacher, S. Schaer, T.A. Springer, J. Kouba and R.E. Neilan. 1999. The International GPS Service (IGS): An Interdisciplinary Service in Support of Earth Sciences, *Advances in Space Research*, 23(4), pp. 631-635.

Blewitt, G., D. Argus, R. Bennett, Y. Bock, E. Calais, M. Craymer, J. Davis, T. Dixon, J. Freymueller, T. Herring, D. Johnson, K. Larson, M. Miller, G. Sella, R. Snay, and M. Tamisiea. 2005. A Stable North American Reference Frame (SNARF): First Release, Proceedings of the Joint UNAVCO/IRIS Workshop, Stevenson, WA, USA, June 9-11.

Boal, J.D. and J.P. Henderson. 1988. The NAD 83 Project - Status and Background. In J.R. Adams (ed.), *Papers for the CISM Seminars on the NAD '83 Redefinition in Canada and the Impact on Users*, Canadian Institute of Surveying and Mapping, Ottawa, pp. 59-78.

Boucher, C. and Z. Altamimi. 1996. International Terrestrial Reference Frame. *GPS World*, 7(9), September, pp. 71-74.

Canadian Council on Geomatics (CCOG). 2006. CCOG Resolution S05-10: National Standard for Integrated Surveys. CCOG Spring Meeting, Ottawa, April 6-7.

CanWest. 2004. Satellite shows North America bulging upward. *CanWest News Service*, May 15.

Craymer, M., R. Ferland and R. Snay. 2000. Realization and Unification of NAD83 in Canada and the U.S. via the ITRF. In R. Rummel, H. Drewes, W. Bosch, H. Hornik (eds.), *Towards an Integrated Global Geodetic Observing System (IGGOS)*, IAG Section II Symposium, Munich, October 5-9, 1998, International Association of Geodesy Symposia Volume 120, Springer-Verlag, Berlin, pp. 118-121.

Craymer, M., G. Blewitt, D. Argus, R. Bennett, Y. Bock, E. Calais, J. Davis, T. Dixon, J. Freymueller, T. Herring, D. Johnson, K. Larson, M. Miller, G. Sella, R. Snay and M. Tamisiea. 2005. Defining a Plate-Fixed Regional Reference Frame: The SNARF Experience. Dynamic Planet 2005, IAG/IAPSO/IABO Joint Assembly, Cairns, Australia, August 22-26.

DeMets, C., R.G. Gordon, D.F. Argus and S. Stein. 1994. Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions. *Geophysical Research Letters*, 21(20), pp. 2191-2194.

Duval, R., P. Heroux and N. Beck. 1997. Canadian Active Control System—Delivering the Canadian Spatial Reference System. Presented at GIS'96, Vancouver, March 1996 (revised).

Energy, Mines and Resources, Department of (EMR). 1990. New Reference System of Latitudes and Longitudes for Canada - Notice of Adoption. *Canada Gazette*, Part I, Vol. 124, No. 21, May 26, pp. 1808-1809.

Globe and Mail, The. 2004. Canada is rising. *The Globe and Mail*, June 1.

Guardian, The. 2004. The earth moves, and you can watch. *The Guardian* (U.K.), May 20.

Gillis, D., A. Hamilton, R.J. Gaudet, J. Ramsay, B. Seely, S. Blackie, A. Flemming, C. Carlin, S. Bernard and L.-G. LeBlanc. 2000. The Selection and Implementation of a New Spatial Reference System for Canada's Maritime Provinces. *Geomatica*, 54(1), pp. 25-41.

Henton, J., M. Craymer, H. Dragert, S. Mazzotti, R. Ferland and D.L. Forbes. 2006. Crustal Motion and Deformation Monitoring of the Canadian Landmass. *Geomatica*, this issue.

Héroux, P., J. Kouba, N. Beck, F. Lahaye, Y. Mireault, P.Tétreault, P.Collins, K. MacLeod and M. Caissy. 2006. Space Geodetic Techniques and the CSRS Evolution, Status and Possibilities. *Geomatica*, this issue.

IAG. 1992. International Association of Geodesy Resolutions adopted at the XXth IUGG General Assembly in Vienna. In "The Geodesist's Handbook". *Bulletin Geodesique*, 66(2), pp. 132-133.

Independent, The. 2004. Chicago feels chill of the ice age as geologists say Windy City is sinking. *The Independent*, London, The Independent, May 22.

Junkins, D.R. 1988. Transforming to NAD 83. In J.R. Adams (ed.), *Papers for the CISM Seminars on the NAD '83 Redefinition in Canada and the Impact on Users*, Canadian Institute of Surveying and Mapping, Ottawa, pp.94-105.

Junkins, D.R. 1990. The National Transformation for Converting Between NAD27 and NAD83 in Canada. In D.C. Barnes (ed.), *Moving to NAD '83: The New Address for Georeferenced Data in Canada*, The Canadian Institute of Surveying and Mapping, Ottawa, pp. 16-40.

Junkins, D. and G. Garrard. 1998. Demystifying Reference Systems: A Chronicle of Spatial Reference Systems in Canada. *Geomatica*, 52(4), pp. 468-473.

Larson, K.M., J.T. Freymueller and S. Philipsen. 1997. Global plate velocities from the Global Positioning System. *Journal of Geophysical Research*, Vol. 102, No. B5, pp. 9961-9982.

McCarthy, D.D. (ed.). 1996. IERS Conventions. 1996. Technical Note 21, International Earth Rotation Service, Paris Observatory, Paris.

Merrigan, M.J., E.R. Swift, R.F. Wong and J.T. Saffel. 2002. A Refinement to the World Geodetic System 1984 Reference Frame. *Proceedings of the ION GPS 2002*, September 24-27, pp. 1519-1529.

New Scientist, The. 2004. Canada's on the up – US is going down. *The New Scientist*, May 20.

NGA. 2004. *Addendum to NIMA TR 8350.2: Implementation of the World Geodetic System 1984 (WGS 84) Reference Frame G1150*. National Geospatial-Intelligence Agency.

NIMA. 2004. Department of Defence World Geodetic System 1984: Its Definition and Relationship with Local Geodetic Systems. Technical Report 8350.2, Third Edition, Amendment 2, National Imagery and Mapping Agency (NIMA), Bethesda, MD.

Parent, C. 1988. NAD83 Secondary Integration. *CISM Journal ACSGC*, 42(4), pp. 331-340.

Slater, J.A. and S. Malys. 1998. WGS 84 - Past, Present and Future. In F.K. Brunner (ed.), *Advances in Positioning and Reference Frames*, IAG Scientific Assembly, Rio de Janeiro, Brazil, September 3-9, 1997, International Association of Geodesy Symposia Volume 118, Springer-Verlag, Berlin, pp. 1-7.

Soler, T., J.D. Love, L.W. Hall and R.H. Foote. 1992. GPS Results from Statewide High Precision Networks in the United States. *Proceedings of the 6th International Geodetic Symposium on Satellite Positioning*, The Ohio State University, Columbus, OH, March 17-20, pp. 573-582.

Soler, T. and R.A. Snay. 2004. Transforming Positions and Velocities between the International Terrestrial Reference Frame of 2000 and North American Datum of 1983. *Journal of Surveying Engineering*, 130(2), pp. 49-55.

United Press International (UPI). 2004. Researchers see North America moving. *United Press International*, May 14.

Véronneau, M., R. Duval and J. Huang. 2006. A Gravimetric Geoid Model as a Vertical Datum in Canada. *Geomatica*, this issue.

Washington Post, The. 2004. Chicago is sinking! In Coast to Coast: A national briefing of people, issues and events around the country. *The Washington Post*, May 30.

Wessel, P. and W.H.F. Smith. 1998. New, improved version of the Generic Mapping Tools released. *Eos Trans. Amer. Geophys. U.*, 79(47), p. 329.

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SPACE GEODETIC TECHNIQUES AND THE CANADIAN SPATIAL REFERENCE SYSTEM EVOLUTION, STATUS AND POSSIBILITIES

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Over the last two decades a revolution has taken place in the field of positioning and navigation. The availability and accuracy of signals from Global Navigation Satellite Systems (GNSS), combined with advances in microelectronics, have greatly improved our ability to georeference information. While positioning was traditionally the business of professionals in the field of surveying and geodesy, it has now become a commodity readily available to a wide range of users, from professional surveyors to recreational amateurs.

The Canadian Spatial Reference System (CSRS) has been evolving over this time to facilitate access to the reference frame with innovative products. These new products and associated tools are taking advantage of the widespread availability of navigation satellite signals and the popularity of the Internet to respond to Canadians in a way that enables seamless integration of their geospatial data, on location and in real-time. The move to space geodetic techniques for delivery of the CSRS is presented in this paper.

Au cours des deux dernières décennies, nous avons traversé une révolution dans le domaine du positionnement et de la navigation. L'accessibilité et la précision des signaux des systèmes mondiaux de navigation par satellite (GNSS), en plus des avancées en microélectronique, ont grandement amélioré notre capacité à géocoder les données. Alors qu'auparavant, le positionnement relevait de professionnels des levés et de la géodésie, il est maintenant accessible à une grande variété d'usagers, qu'ils soient des arpenteurs-géomètres ou des amateurs de plein air.

Le Système canadien de référence spatiale (SCRS) a évolué au cours de ces années afin de faciliter l'accès au cadre de référence par des produits innovateurs. Ces nouveaux produits et outils connexes tirent profit de l'accessibilité globale aux signaux des satellites de navigation et de la popularité de l'Internet afin de répondre aux Canadiens d'une façon qui permet l'intégration parfaite, instantanée et sur place de leurs données géospatiales. Dans cet article, nous vous présenterons la transition du SCRS vers ces techniques géodésiques spatiales.

1. Introduction

The Canadian Spatial Reference System (CSRS) is an abstract collection of principles, fundamental parameters, and specifications for quantitatively describing the positions of points in space, as described by *Craymer* [this issue]. The reference frame is the physical manifestation or realization of such a prescription. Traditionally, a reference frame consisted of a network of ground-based geodetic control points with adopted coordinates that other surveys were connected and referenced to. Since the introduction of space geodetic techniques, this paradigm has been changing.

Nowadays, the ability to acquire georeferenced data and merge layers of geospatial information with ever increasing accuracy to establish spatial relationships and extract knowledge has been greatly improved and is becoming everyday business in many organizations. As our ability to associate coordinates to objects of our physical environment improves along with the precision of our techniques, efficient access to an accurate reference frame must be provided and maintained. If relationships are to be established between objects regardless of their spatial separation or date of observation, a consistent reference frame with sufficient density is required to identify and analyze spatio-temporal processes of interest. The failure to maintain this capability would lead to a reference frame that cannot fulfill its fundamental purpose. In practical terms, the failure to unify under a common reference frame or the inability to inter-relate reference frames eventually leads to the existence of different coordinates referencing a single object, confusing the modern coordinate-based users to think that they can be in two places at once!

This paper briefly looks back over the past century and describes the improvement of measuring techniques for the establishment of geodetic control networks and how they have evolved and moved from 'ground to space.' It describes the impact of technology on precision and reference frame realization and access. The approach used to upgrade the CSRS and respond to modern user needs with 'active control networks' and innovative products created through international cooperation are explained. Finally, future possibilities for real-time georeferencing with respect to a consistent reference frame are considered.

2. The Evolution of Geodetic Control Networks

Looking back over the past century, precision has evolved with technology over three major eras that are referred here as classical (optical and electronic) and space-based (see Figure 1). The classical era includes the period when optical instruments were used to observe angles between control points and combine them with baseline measured sparsely along triangulation chains to transfer coordinates from a reference point. With the limitations of angular measurements and the difficulty of maintaining orientation using astronomical means, systematic errors accumulated as triangulation chains were assembled to extend the network. These factors led to the realization of a continental reference frame, known as the North-American Datum of 1927 (NAD27), that we now know was affected by distortions of several tens of metres and offset from the Earth's centre of mass by a few hundred metres [*Junkins and Garrard* 1998]. This original geodetic fabric underpinned small-scale mapping programs throughout most of the 20th century.

The introduction of electronic distance measuring (EDM) instruments mid-way through the last century significantly improved the precision of geodetic surveys by taking advantage of the synergy

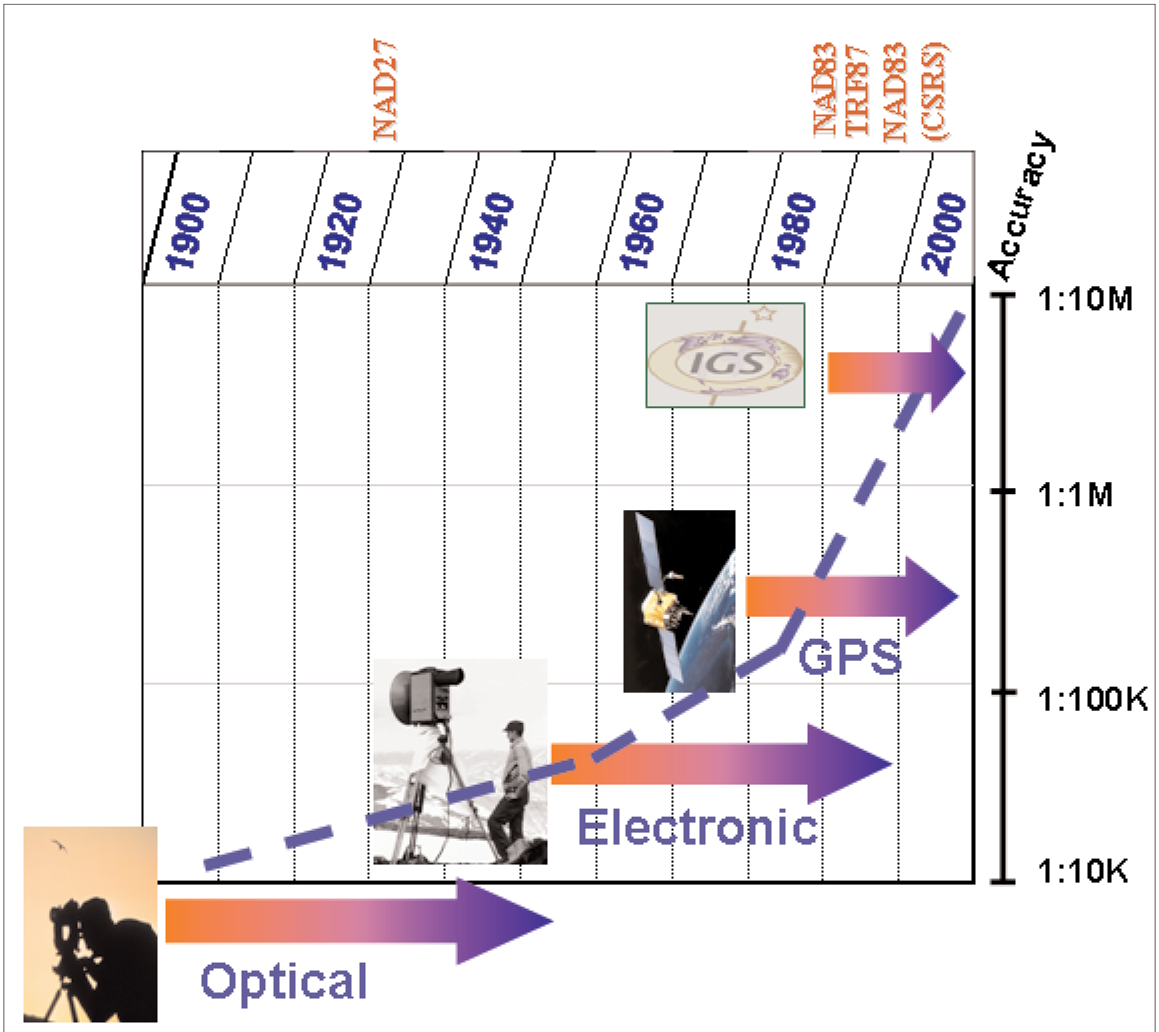

Figure 1: The evolution of geodetic technology and precision.

between angle and distance measurements. This combination of ground-based measurements was used to form trilateration chains and gradually improve the NAD27 network. It was soon recognized that fixing coordinates of the NAD27 realization to constrain these more precise measurements was detrimental to network improvement, leading to the decision to perform a re-adjustment. All observations of the primary national network, supplemented with a few stations with Doppler observations from the emerging TRANSIT satellite navigation system, formed the basis of the NAD83 project. Coordinated with North-American partnership and adopted in 1986, this new reference system realization was originally believed adequate to satisfy georeferencing requirements for many decades. With a nationwide average accuracy of 0.3 m and better than 1 m in the northern parts of many provinces, this reference frame had an overall relative precision of about 20 ppm [*Craymer* this issue]. Then, navigation satellites from the Global Positioning Satellite (GPS) constellation appeared on the scene in the early 1980's.

2.1 The Advent of Space Geodetic Techniques

While station coordinates were being adjusted by national geodetic organizations for NAD83 realization in the early 1980's, an international scientific initiative known as the Crustal Dynamics Project, led by NASA, was establishing global observatories that used modern space geodetic techniques, mainly Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR), to validate the geological evidence for global plate tectonics [*Smith and Baltuck* 1993]. This scientific initiative eventually led to the first realization of the International Terrestrial Reference Frame (ITRF) released by the International Earth rotation and Reference systems Service (IERS).

The early 1980's also saw the first GPS satellites being launched. The new navigation satellites were expected to supersede TRANSIT and become the tool of choice for global navigation. GPS also quickly became a promising technology for geodetic applications given the quality of its coded L-band signals and anticipated low cost of future user equipment. Midway through the decade, its relative precision of a few parts per million over baselines of a few tens of kilometres was demonstrated using geodetic processing techniques [*Goad* 1985]. GPS was soon adopted for control surveys and Natural Resources Canada's (NRCan) Geodetic Survey Division (GSD) acquired its first GPS units in 1985. While GPS was limited by the precision of its broadcast orbits, it presented the operational advantage of not requiring inter-visibility between ground stations, greatly facilitating the operational logistics of field surveys and allowing for the establishment of control points in locations of convenient physical access for user occupation. The adoption of GPS by the geodetic community quickly revealed the limitations of the recently adopted NAD83 realization and led to the realization of NAD83(CSRS), first materialized at active control points and subsequently densified with the establishment of the Canadian Base Network (CBN) of about 200 passive monuments [*Craymer* this issue].

Sharing the common goal of improving GPS satellite orbits to respond to the needs of the Earth sciences community, in particular in the field of geodynamics, the International GPS Service (IGS) was formed in the early 1990's [*Beutler et al*. 1999]. With the objective of providing precise GPS orbit products on a continuous basis in a globally consistent reference frame, the IGS stimulated the development of a network of globally distributed tracking stations and the creation of regional and global Data Centres (DCs) for public access. With voluntary contributions from a number of Analysis Centres (ACs) and a cooperative, although competitive, model for product combination, the quality of GPS satellite orbits and clocks estimates improved progressively over the last decade, reaching today's centimetre level precision. These new global products overcame the limitations of the GPS broadcast orbits and now support positioning with accuracies approaching a few parts per billion on a global scale. They have also offered a reliable means for users to directly connect to the global reference frame using the GPS data they collect from a single receiver, anywhere on Earth. This new possibility is effectively changing the way modern GPS users operate.

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2.2 From Regional to Global Reference Frames

The traceability of coordinates over time and space requires knowledge about the reference system in which they were computed. Technologies applied to realize a reference system determine the accuracy of some of its fundamental parameters [*Pearlman et al*. this issue]. For example, accurately establishing a global reference frame origin has always been difficult because of the relative insensitivity of classical near-Earth measurements to the location of the Earth's centre of mass. The advent of space geodetic techniques has now provided the ability to pinpoint the average location of the

...GPS users could unknowingly be operating within a reference frame that is arbitrarily set by the operator of a local GPS service.

Earth's centre of mass with centimetre precision. This new capability brings along the option to choose a single geocentric reference frame with a well defined coordinate system origin.

Historically, different technologies were applied as they became available for new reference frame realizations, resulting in the creation of a number of reference frames having different origins. This has been confusing to users who see apparent coordinate shifts as they move between reference frames. Although these shifts can be accounted for in part by applying transformations that improve compatibility, the recent availability of a global reference system to which national reference systems can be related is changing the way in which reference frame are accessed amd maintained [*Craymer* this issue].

2.3 From relative to "absolute" accuracy

Until the advent of space geodetic techniques, systematic errors accumulated in control networks as their spatial coverage was extended. The difficulty in controlling the propagation of these errors resulted in the inability to provide absolute accuracy estimates (i.e. accuracy with respect to the reference frame). Therefore coordinates were qualified in terms of their relative accuracy (or precision), usually given with respect to neighbouring control stations. Today, using signals from navigation satellites, precise orbit products and geodetic processing techniques, it is possible to determine coordinates of stations separated by long distances with very high precision. Consequently, precision and accuracy estimates now compare favourably and separation between markers is less of a factor. Actually, users anywhere on Earth can now position themselves relative to the Earth's average centre of mass with centimetre precision and therefore qualify their coordinates in term of "absolute" accuracy.

2.4 Options for Integrating Positions into a ReferenceFrame

Traditionally, occupation of monumented control points was the only method for integration of positioning results within a specific reference frame, with published reference coordinates providing the connection.

With coordinates of navigation satellites now readily available as either broadcast or post-processed orbits, users now have the option to connect directly through the satellites. In this case, reference coordinates are provided for the centre of mass of the satellites which effectively become control points that extend the realization of the reference frame. For instance, autonomous GPS positioning, through the GPS broadcast orbits directly connects users to the WGS84 reference frame with a global consistency of a few metres.

The accuracy of the coordinates for the selected control point (ground or satellite) characterizes the quality of the realization of the reference frame and directly affects the quality of end-user coordinates. Therefore, the control point (satellite or ground) must be carefully selected, along with the necessary observations and processing strategy, to meet the user's required precision. Not surprisingly, this is often overlooked since the overwhelming majority of GPS users operate in stand-alone mode, relying blindly on the reference frame realization of the satellite broadcast orbit. The main limitation of operating in this mode is that user-positioning precision is limited by the quality of the predicted satellite orbits.

Users seeking higher precision have generally chosen a relative positioning method and differenced satellite observations made simultaneously at one or more surrounding control points with predetermined (adopted) or user-assigned coordinates. In the later case, despite the control point coordinate potential uncertainties, a very precise local solution can still be obtained as long as the control point and satellite coordinates are compatible within a few metres, which corresponds to the current broadcast orbit precision. This is so because the error in the coordinates of the satellites and control point cause systematic errors in relative positioning that are a function of the ratio between the distance separating the user from the control point and the satellite elevation. Therefore, a combined satellite-station coordinate error of a few metres translates into a relative systematic error of a few centimetres over a 100 km baseline, which may satisfy the need for local to regional reference frame consistency for many applications. However, while local to regional consistency may be achieved, the option to loosely assign control point coordinates gives rise to the possibility of creating a multitude of reference frames with varying levels of compatibility. Nowadays, with the growing availability of continuously operating reference stations, this risk is increasing and GPS users could unknowingly be operating within a reference frame that is arbitrarily set by the operator of a local GPS service. This may significantly impact users who generally want to work in a reference frame that does not change or that ensures traceability of coordinates over time. This issue may become significant as datasets collected using different local reference frames are combined.

While GPS orbit predictions broadcast in real-time have metre-level precision, they can now be estimated in post-mission with centimetre precision.

Therefore, a global reference frame can now be accessed through precise orbit and clock products without explicitly assigning coordinates to ground control points in the user solution. This new possibility is an alternative that significantly impacts the users as well as geodetic agencies that have traditionally provided coordinates of ground control.

3. Enabling Geodesy from Space

As a result of advances in positioning and communication technologies, mainly the advent of GPS and Internet, the Canadian Active Control Systems (CACS) was conceived and proposed in the early 1980's. This novel idea at the time suggested that we could eventually replace dense traditional geodetic control networks, based on 'passive' survey markers, with a sparse network of 'active' sensors or tracking systems operating continuously (see Figure 2). As opposed to passive networks that required users to physically occupy monumented markers to integrate into the reference frame, active networks could give users access to the reference frame through their observed data. Based on signals from space, the 'active' concept only requires that common space objects be simultaneously visible from both the user location and 'active' sensor. With navigation satellites visible from locations thousands of kilometres apart, the active control concept offered the possibility to significantly reduce the number of monumented control points along with their high cost of maintenance. This possibility was particularly appealing to GSD who at the time was maintaining thousands of control markers across Canada. In addition, maintenance of NAD83 could be linked to the most recent realizations of the ITRF.

3.1 The VLBI Component

GPS was always envisioned as the technology users would adopt to access the CSRS through related data and products, as widespread availability of affordable user equipment was anticipated. Nevertheless, the desire to sustain a reference frame that would offer long-term stability required that Very Long Baseline Interferometry (VLBI) be part of the overall solution. While offering an additional level of redundancy, the fundamental role VLBI plays is to connect the celestial and terrestrial reference frames through estimates of all Earth Orientation Parameters [*NASA* 2002]. This is essential for ongoing support of reference frame delivery through orbits of navigation satellites. Now that navigation and Earth monitoring satellites broadcast signals with millimetre resolution and that

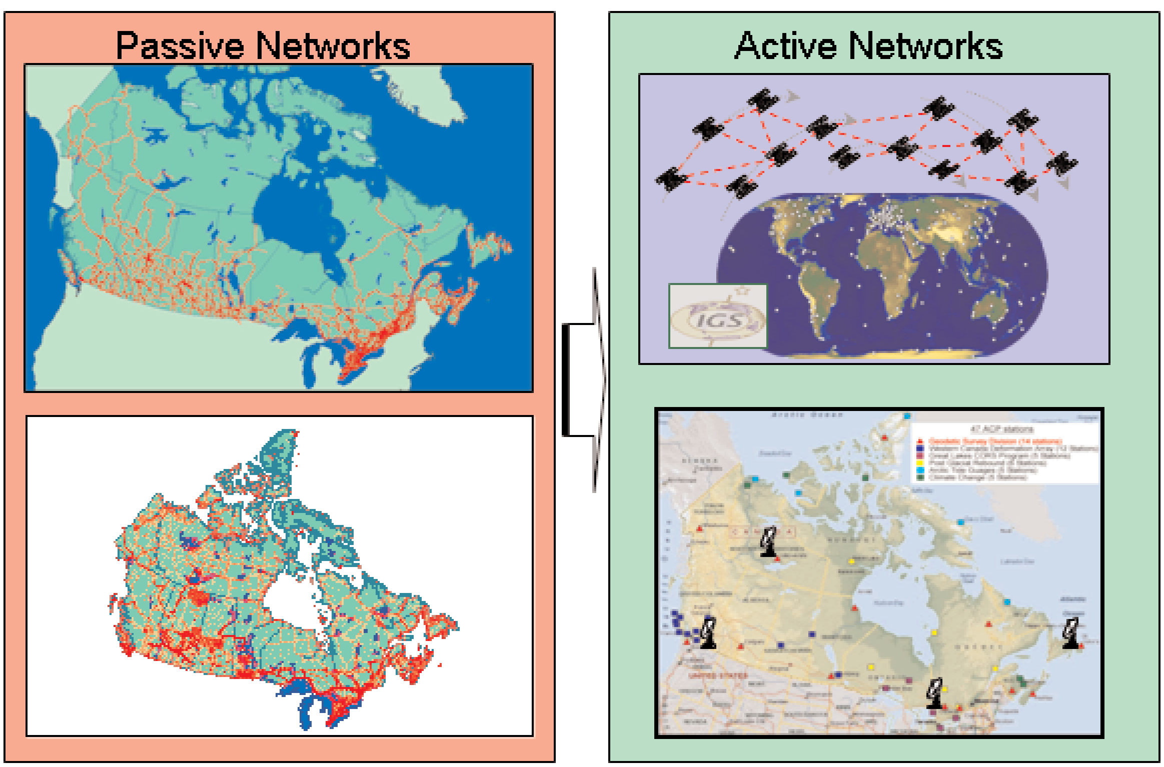

Figure 2: From passive to active control networks.

global reference frames can be realized with centimetre accuracy, the requirement to monitor the alignment between the two systems has become more important, as stated in the Global Geodetic Observing System (GGOS) project proposal [*Pearlman et al*. this issue]. Because the GPS satellite orbits are conveniently made available in ITRF, a reference frame that is fixed to the Earth and rotates with it, it is easy to forget that satellites orbiting in the Earth's gravity field are also sensitive to the Earth's spatial orientation and various forces acting upon them. Therefore, unless orbit computations are linked to the inertial celestial reference frame, the connection between GPS orbits and the earth-fixed reference frame cannot be precisely maintained in time. VLBI is the sole space technique that can provide reference frame scale and orientation with sufficient precision and stability over the long term [*Altamimi et al.* 2002].

GSD contributes weekly to the core network of the global VLBI initiative coordinated by the International VLBI Service (IVS). The 46 metre VLBI antenna in Algonquin Park is the most active Canadian observatory and is complemented with a smaller antenna in Yellowknife and a transportable system that has been deployed mainly at the Dominion Radio Astrophysics Observatory in Penticton and in St-John's over the past 10 years. These fiducial points are the anchors of the CSRS.

3.2 The GPS Component

By the early 1990's, NRCan's GSD began implementing the GPS component of CACS (see Figure 3). The implementation of CACS was in part influenced by the formation of the IGS. It is worth mentioning that the IGS came along when individual countries recognized their inability to achieve their goals without a global cooperative endeavour. At the time, this was important mainly to scientists in the field of global geodynamics who had adopted GPS as their instrument of choice to measure plate tectonics with centimetre precision. However, they lacked an accurate and stable global reference frame on which to express their results. This effort also created the opportunity for geodetic agencies to connect their geodetic networks to the ITRF using GPS, leading to further integration and densification of the global geodetic fabric, at an unprecedented level of accuracy.

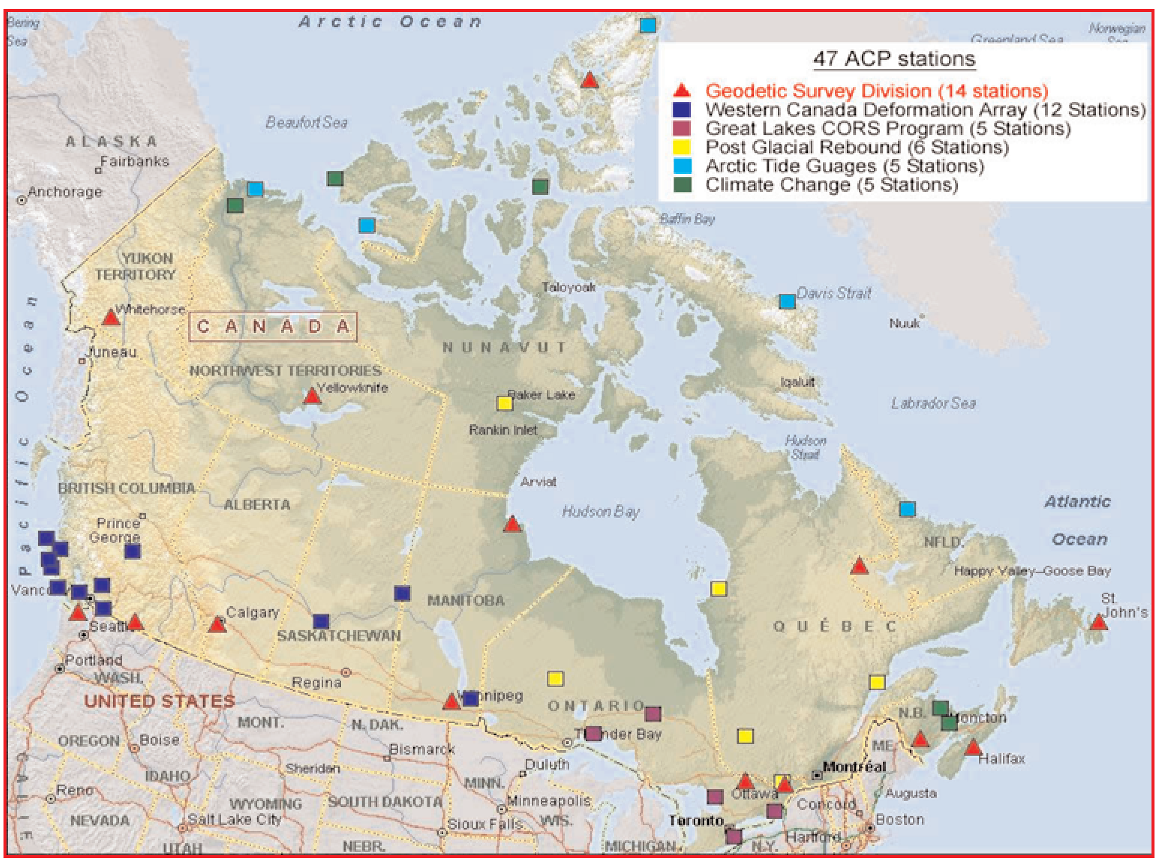

Figure 3: Continuously operating GPS tracking stations of the CACS.

In an effort to take full advantage of the synergies between VLBI and GPS technologies, the first continuously operating GPS Active Control Points (ACPs) in Canada were deployed at the Algonquin Park and Yellowknife sites where permanent VLBI antennas were in place. Soon after, ACPs were also installed at the VLBI sites in St-John's and Penticton. In late 1993, this initial deployment of four ACPs ready for the IGS pilot phase provided minimal spatial distribution of GPS tracking stations over the Canadian territory, but significantly contributed to the original global IGS network designed to track GPS satellites continuously through their complete orbit, given Canada's geographical size.

As the core stations of a national GPS network were being established, the development of the Western Canada Deformation Array (WCDA) was initiated to address the particular requirements of geodynamic studies along Canada's west coast [*Dragert et al.* 1995]. The CACS and WCDA initiatives had different objectives, the former providing continuous GPS data for orbit estimation while the latter focused on analyzing tectonic movements in a seismically active area. Nevertheless, they were strongly linked through GPS orbit products which are essential to the recovery of relative station velocities with mm/year accuracy over baselines extending several hundred kilometres. The WCDA has been densified during the last decade and now consists of over 14 permanent sites [*Henton et al*. this issue].

The core national network was further expanded and upgraded to include a real-time capability in the mid-1990's with the intention of providing real-time access to the reference frame through wide-area GPS corrections, applicable Canada-wide. This additional component would allow users to overcome the GPS signal degradation imposed by Selective Availability (SA), which since 1993 had limited stand-alone GPS positioning to a precision of about 100m, insufficient for many geomatics applications (SA was eventually removed on May 1, 2000). The CACS network was at that time expanded to 12 tracking sites giving it the spatial density required to provide simultaneous observations of all satellites visible over Canada from at least two locations, creating observation redundancy to increase correction robustness and reliability.

Additional continuously operating tracking stations were deployed in response to regional studies and are operated through joint funding agreements. They include six stations distributed along a broad line running from the Atlantic coast to Hudson Bay that covers the portion of the Canadian Shield most affected by post-glacial rebound, with uplift rates in excess of 1 cm/year in north-western Quebec. Uplift of this magnitude over such a large area is unique and of interest to operators of space gravimeters who can infer the corresponding gravity change to calibrate the long wavelengths of the Earth's gravity field. This particular geophysical effect, most pronounced in Canada, offers an ideal natural "laboratory" for Earth science, helping to link together time-limited space missions intended to observe a continuous field. Another eight GPS stations co-located with tide gauges have been installed in the Arctic to monitor crustal motion and sea level rise in support of climate change studies. Finally, five GPS stations equipped with surface meteorological sensors are contributing to a cooperative network of ground-based GPS receivers co-located with water level gauges around the shores of the Great Lakes. This network is being used primarily to monitor the effects of post-glacial rebound on the Great Lakes water levels and provide access to a consistent vertical datum. In addition, meteorological services in both Canada and the US use this GPS data to recover integrated precipitable water for assimilation into weather forecasting models.

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4. Products, Tools and Services for Satellite Geodesy

Although the basic equipment required for positioning is a satellite receiver (currently GPS), ancillary products and services are needed to ensure that coordinates obtained from GPS are connected to reference frames that support geodetic applications. This section describes products and services, including GPS orbits and clocks, currently available to Canadian users to facilitate access to the reference frame.

4.1 GPS Orbits and Clocks

As already mentioned, the IGS has computed GPS products in support of precise positioning applications for more than a decade. NRCan's GSD was one of the original IGS collaborating agencies and has since participated as an Analysis Centre (AC) and provided AC Coordination during its initial years of operation [*Donahue et al.* 2004].

The collaborative global tracking network of some 300 permanent, continuously-operating GPS stations provides a rich data set that enables the AC to generate precise products such as GPS satellite orbit and clock solutions. The IGS GPS orbit and clock products combined from the ACs individual contributions [*Kouba* 2003] come in various flavours that differ mainly by their latency and the extent of the tracking network used for their computations (see Table 1). The IGS "Final" orbit and clock product is usually available the thirteenth day after the last observation. The "Rapid" orbit and clock product is combined 17 hours after the end of day. The latency is mainly due to the varying availability of tracking data from stations of the IGS global tracking network, which use a variety of data acquisition and communication schemes. The evolution of the IGS over the past 12 years from a daily to hourly data availability model, followed by the development of a sub-daily orbit product, has resulted in reliable GPS orbit predictions with high precision available for real-time applications, in particular GPS meteorology. The sub-daily orbit product, and more specifically its predicted portion, continuously updated every three hours, is a direct input to the NRCan real-time correction system and key to its optimal performance. The estimated portion of the IGS "Ultra-Rapid" orbit is equally important for Precise Point Positioning (PPP) applications [*Kouba and Héroux* 2001].

4.2 Connecting to the NAD83(CSRS) Reference Frame

4.2.1 CACS Network Observational Data

As seen earlier, users may choose to occupy a geodetic control station with coordinates preferably known in NAD83(CSRS), collect their own GPS data and use differential processing techniques to obtain accurate coordinates within this reference frame. An alternative to the occupation of control stations directly by the user is to download files and acquire observations available from continuously tracking stations of CACS. This simplifies fieldwork logistics and provides reliable and accurate coordinates for the selected control points. The CACS GPS stations all collect dual frequency pseudo-range and carrier phase observations at sampling intervals varying from 1 to 30 seconds by continuously tracking all GPS satellites in view. Data are retrieved from the sites, translated to RINEX format and stored on a public archive with latencies varying from 15 minutes to 24 hours. Details about data availability and how to access it

Table 1: IGS Orbits and Clocks Product Table.

Solution Type	Products	Precision	Latency	Updates
Broadcast (1)	Clocks	< 7 ns	real-time	4 times daily
	Orbits	< 160 cm		
Ultra-Rapid Predicted Part	Clocks	< 5 ns	real-time	4 times daily
	Orbits	< 10 cm		
Ultra-Rapid Estimated Part	Clocks	< 0.2 ns	3 hours	
	Orbits	< 5 cm		
Rapid	Clocks	< 0.1 ns	17 hours	daily
	Orbits	< 5 cm		
Final	Clocks	< 0.1 ns	13 days	weekly
	Orbits	< 5 cm		

Notes (1): Broadcast orbits and clocks are included for comparison only and are not official IGS products.
(2): IGS products increase in precision, reliability and robustness as you move down the Table.
(3): A more detailed version of that Table is available at the following address:
(*http://igscb.jpl.nasa.gov/components/prods.html*)

is available at: *http://www.geod.nrcan.gc.ca/network_a/obs_e.php*.

Because of the sparse distribution of CACS stations, long baselines may be formed but errors in the broadcast orbits may cause decimetre errors in position. This is overcome with the use of precise GPS satellite orbits available by Internet, although tropospheric effects must be properly estimated in software for utmost accuracy.

4.2.2 On-Line Precise Point Positioning (CSRS-PPP)

Alternatively, PPP processing can be applied for single station solutions without the need to occupy control stations. This technique fixes the precise orbit and clocks obtained from an external source, such as IGS, to improve the parameter estimates, including user position. Typically, with IGS orbits/clocks, positioning is provided directly in ITRF at the centimetre precision level. The ITRF positions can then be easily transformed into the NAD83(CSRS) using adopted transformations [*Craymer et al.* 2000]. Precise station clock and zenith tropospheric delay solutions as well as instantaneous (kinematic) positioning at a level of a few centimetres are also possible.

Since the Fall of 2003, a web service, CSRS-PPP [*Tétreault et al*. 2005], provides a convenient mean to process GPS RINEX observations from a single GPS receiver in order to obtain NAD83(CSRS) or ITRF coordinates. Table 2 lists the various PPP modes and accuracies attained after ambiguity convergence. Convergence is achieved once the estimated carrier-phase ambiguities have reached a constant value that is within the carrier phase noise

When using combined code and carrier observations, ambiguity convergence is critical to the PPP solution reaching its utmost accuracy, whether GPS is used in static or kinematic mode. Typically, ambiguities converge within 30 minutes in static mode and one hour in kinematic. Once the ambiguities have converged, all parameters can be re-evaluated by back substituting their final estimates into the solution to effectively recover optimal estimates for all parameters over the entire observing session. This functionality is particularly useful to recover optimal user trajectories in kinematic mode. Otherwise, the PPP solution remains sub-optimal and does not fully benefit from the full precision of the carrier phases, although it still provides the performance of corrected code observations.

For PPP solutions using code-only observations, no ambiguity parameters are involved, although the accumulation of observations over time may improve the parameter estimates in static mode processing, notwithstanding the observation noise and multipath and the uncertainty in the modeled atmospheric delays. In summary, the accuracy of

Table 2: PPP Performance after Convergence – Single and Dual Frequency – Static and Kinematic Modes.

Receiver	**Observation Processed**	**PPP Mode**	**Precision (cm)**		
			Latitude	**Longitude**	**Height**
Dual Frequency	Code & Carrier	Static	1	1	2
		Kinematic	4	4	10
Single Frequency	Code Only (1)	Static	10	10	100
		Kinematic	50	50	150
Single Frequency	Code & Carrier (2)	Static	2	3	4
		Kinematic	25	25	50

Notes (1): Quoted PPP code-only performance is for surveying grade receiver.
(2): May not yet be available in CRSR-PPP at time of publishing.

parameters estimated with CSRS-PPP remains a function of the quality, quantity and type of GPS observations used. Consequently, it is important to carefully select the user equipment and procedures and consider the operating environment to ensure that the collected GPS data will satisfy the project accuracy specifications.

4.3 Orthometric Height Determination from Space-Based Technique

In practical terms this means that water can only flow in the direction of decreasing orthometric height although it could possibly flow towards a point of higher ellipsoidal height.

Traditional geodetic techniques separately provided the horizontal and vertical components of positions using different surfaces or datums, either an ellipsoid or geoid. The traditional separation between horizontal and vertical networks originated from the different measuring techniques used for levelling, either geometric (spirit-level) or trigonometric (vertical angle/distance measurement). Spirit levelling was used to establish the national primary vertical control network while trigonometric levelling served mainly to determine ellipsoidal heights of horizontal control points for data reduction. Space-based technologies such as GPS, on the other hand, provide three-dimensional Cartesian coordinates with respect to the geocentre. Once a reference ellipsoid is selected (a uniform mathematical surface that approximates the shape of the Earth), Cartesian coordinates can be readily transformed into ellipsoidal latitude, longitude and height. In contrast, heights above sea level or so-called orthometric heights, are with respect to a surface of constant gravity potential (equipotential surface), a physical surface called geoid. In practical terms this means that water can only flow in the direction of decreasing orthometric height although it could possibly flow towards a point of higher ellipsoidal height.

Ellipsoidal heights (h) can be transformed to more practical and physically meaningful orthometric heights (H) by applying the geoid undulation (N) for the location of interest. The Canadian Gravimetric Geoid model, once based on observations made exclusively with land or airborne gravity surveys, has recently been updated to include data from the latest satellite gravimetry missions (CHAMP and GRACE). It has a local relative precision that is comparable to what can be achieved with spirit-levelling and a nation-wide accuracy that is compatible with the quality of GPS determined ellipsoidal heights [*Véronneau et al.* this issue]. This state-of-the-art geoid model is at the core of the modernization of the height reference system in Canada, with the objective to reduce our dependency on a monumented vertical network. Combining GPS and geoid to recover orthometric heights is gaining popularity as users move to space geodetic techniques for greater operational efficiency. A tool known as GPS-H, available as a software package or on-line application at *http://www.geod.nrcan.gc.ca/software/gpsht_e.php* is available for height transformation.

5. Towards Real-Time Geodesy

The increasing availability of wireless communication devices has brought along the possibility of making GPS corrections accessible ‘in the field.’ Building on this capacity, a real-time component to the CACS was developed to further facilitate end-user access to the reference frame by streamlining users operations and eliminating the requirement for post-mission processing.

5.1 Real-Time GPS Data acquisition

During the mid-1990’s, a wide-area model to deliver real-time GPS corrections (GPS·C) Canada-wide and provide access to the NAD83(CSRS) frame at the few decimetre accuracy level was envisioned. In 1996, four ACPs of the CACS network were upgraded with real-time communication and the GPS tracking data began streaming to a central processing facility at 1Hz data rate [*Caissy et al.* 1996]. Over the next few years, this number grew to a total of 12 real-time ACPs covering the Canadian territory.

5.2 Expanding Real-Time Capabilities

Mindful of Internet expansion and interest in real-time GPS applications, the IGS has recently formed a working group to demonstrate real-time global GPS data exchange over the Internet [*Muellerschoen and Caissy* 2004]. This capability could eventually lead to the production of global combined real-time GPS products. Such products could support a number of correction distribution services and various scientific objectives, namely Low-Earth-Orbiters (LEO) orbit determination and atmospheric sounding from satellite occultation. Only a global network can support the production of orbit products with centimetre accuracy that fully exploit the high-resolution of the GPS carrier-phase measurements.

As evidenced in Table 3, positioning performance is limited when a GPS tracking network extends over only a national or continental scale. In order to achieve the optimal level of positioning performance, a global tracking network is essential to continuously track all the GPS satellites in the constellation. NRCan has been working with IGS partners for the last three years to develop a world wide real-time GPS tracking network. To date, a global network consisting of 40 stations exchanging data in real-time is being demonstrated by the IGS real-time working group and a pilot project expected to start sometime this year will further advance this initiative. Long-time IGS contributing agencies including the Jet Propulsion Laboratory, the European Space Agency, the German GeoForschungsZentrum, and Geoscience Australia are actively upgrading a subset of their respective IGS tracking stations to support real-time data streaming. GSD is keeping abreast of these developments, sharing expertise developed during GPS·C implementation and accessing the global network to improve the quality of its wide-area corrections.

5.3 Real-Time GPS Corrections (GPS·C)

Software development for the production of GPS corrections started in parallel with the availability of real-time data streams from CACS stations. A state-space domain scheme, known as Wide Area Differential GPS (WADGPS), was preferred over a local differential model since it considerably reduced the number of real-time ACPs to be installed and operated. In WADGPS, separate corrections for specific error sources are computed and transmitted to the users: GPS satellite orbital errors, GPS satellite clock errors and ionospheric delay errors. Tropospheric delay errors are handled locally by users. This development formed the GPS·C correction service [*Lahaye et al*. 1997].

Within GPS-C the orbit corrections are determined from predictions based on the processing of hourly tracking data from the global IGS network. The satellite clock corrections are computed in real-time from dual frequency tracking data streamed from the real-time ACPs to a central computing facility. Ionosphere-free, carrier-phase smoothed pseudorange data at two second intervals are combined with the latest satellite orbit predictions and tracking station coordinates in a least-squares adjustment to determine satellite and station clock offsets with respect to a virtual reference clock kept aligned with GPS time. Observed ionospheric delays between the tracking station receivers and observed satellites are used to update a single layer grid, in latitude versus local solar time. These correction values are encoded in messages that provide high-resolution clock and orbit corrections (0.004m) to support decimetre level real-time positioning.

As previously mentioned, with more timely access to tracking data from a global network and advances in satellite orbit prediction, the possibility to provide users with corrections that support positioning at the sub-decimetre accuracy level is on the horizon. While this capability has been demonstrated, improvements to the current service still depend on the availability of real-time GPS data from a global tracking network on a continuous basis.

5.4 The Canada-Wide Differential GPS Service (CDGPS)

In early 2000, Federal, Provincial, and Territorial geomatics agencies coordinated through the Canadian Council of Geomatics (CCOG) formed

Table 3: GPS Corrections - The Network Difference.

Input - GPS Corrections Computation			Positioning RMS* (cm)		
Orbit	Tracking Network	Observation	Lat	Lon	Hgt
Predicted (IGU)	Wide Area	Code-Filtered	29	26	38
Predicted (IGU)	Wide Area	Code-Carrier	11	12	22
Predicted (IGU)	Global	Code-Carrier	5	6	10
*After ambiguity convergence					

the Canada-wide DGPS Service (CDGPS) to fund the distribution of the GPS·C over a geostationary satellite channel (MSAT). Despite the high-cost of satellite bandwidth, this approach was selected to seamlessly offer coverage over the Canadian landmass and territorial waters using a single broadcast. This project included improvements to the GPS·C computation infrastructure and its management to ensure high availability (99.97 per cent) of the corrections. A robust broadcast protocol with open/public documentation and software to facilitate decoding of the over-the-air corrections by GPS equipment manufacturers were developed. Finally, 1000 proof-of-concept radios were manufactured and distributed to demonstrate the CDGPS capability. The correction distribution elements were designed for optimized reception for ground users, even under forest canopy. In late 2003, CDGPS declared the Initial Operation Capability status for the service [*CDGPS* 2003]. Several GPS receiver manufacturers now offer "CDGPS ready" receivers that take advantage of this real-time service.

5.5 The Network Transport of RTCM via Internet Protocol (NTRIP)

As interest in wireless Internet increases and communication networks expand, alternate means of distributing GPS·C corrections are emerging. A recently adopted standard known as Network Transport of RTCM via Internet Protocol (NTRIP) now facilitates the transfer of GPS data and products using the Internet [*Weber* 2004]. This application level protocol takes advantage of existing communication services for mobile Internet users mainly in populated areas. It also enables providers of GPS correction services to serve their users over the Internet instead of having to deploy and support expensive dedicated channels for the dissemination of their product. At this time, NTRIP is being adopted mainly by GPS users of Real-Time Kinematic (RTK) applications. With NTRIP, providers of correction services have the means to control user access and monitor connection time to support a pay-per-use model for cost-recovery. In areas of cellular coverage, GPS users accessing RTK correction streams created by reference stations within a few tens of kilometres from where they operate can position with centimetre relative precision. This meets the requirements of many georeferencing applications at the municipal level. Nevertheless, the limited area of applicability of RTK corrections and patchy Internet coverage does not provide a solution that can be easily expanded to cover the large expanses of the sparsely populated Canadian territory.

Nevertheless, the limited area of applicability of RTK corrections and patchy Internet coverage does not provide a solution that can be easily expanded to cover the large expanses of the sparsely populated Canadian territory.

A possible alternative for areas with Internet coverage that are without RTK correction streams is GPS·C distribution using NTRIP [*Collins et al.* 2005]. Access to the GPS·C correction stream can complement and also extend the CDGPS service, especially in urban areas and at northern latitudes where MSAT signal penetration or its low elevation visibility is problematic.

6. Summary

Space geodetic techniques, in particular the advent of global navigation satellites and space gravimetry missions, have revolutionized the field of positioning and navigation. By improving the quality of, and access to, a geodetic reference frame which sustains our ability to work in a 'coordinated' world, the CSRS has also significantly evolved to remain compatible with new technologies and the possibilities they bring. Today, a stable global reference frame with centimetre accuracy can be readily accessed. Continuously available precise satellite orbits are simplifying the maintenance of national references frames such as NAD83(CSRS), facilitating the direct integration of user positioning and enabling the interchange of geospatial information at an unprecedented level of precision on a global scale. The impact of satellite gravimetry missions on geoid model improvement is also enabling the recovery of orthometric heights without relying on time consuming and costly spirit-levelling. These developments are leading to the unification of the geometric and gravimetric reference frames on a global scale, further enhancing the usefulness of geodetic techniques for multi-disciplinary applications, in earth and atmospheric sciences.

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8. References

Altamimi, Z., P. Sillard, and C. Boucher, ITRF2000: A new release of the International Terrestrial Reference Frame for earth science applications, J. Geophys. Res., 107(B10), 2214, doi:10.1029/2001JB000561.

Beutler, G., M. Rothacher, S. Schaer, T.A. Springer, J. Kouba, R.E. Neilan. 1999. The International GPS Service (IGS): An Interdisciplinary Service in Support of Earth Sciences, Adv. Space Res. 23(4), pp. 631-635.

Caissy M., P. Héroux, F. Lahaye, K. MacLeod, J. Popelar, J. Blore, D. Decker, R. Fong. 1996. Real-Time GPS Correction Service of the Canadian Active Control System, Proceedings of the 9th International Technical Meeting of The Satellite Division of the Institute of Navigation, ION GPS-96, September 17-20, 1996, pp 1787-1791.

CDGPS. 2003. Press Release, http://cdgps.com/e/cdgps_documents/PressRelease_2003-10-14_CDGPSServiceLaunch.pdf, October 14, 2003.

Collins, P., Y. Gao, F. Lahaye, P. Héroux, K. MacLeod, K. Chen. 2005. Accessing and Processing Real-Time GPS Corrections for Precise Point Positioning - Some User Considerations", *Proceedings of the 18th International Technical Meeting of the Satellite Division of the Institute of Navigation*, Long Beach, California, September 13-16.

Craymer, M., R. Ferland, S. Snay. 2000. Realization and Unification of NAD83 in Canada and the U.S. via the ITRF. In R. Rummel, H. Drewes, W. Bosch, H. Hornik (eds.), Towards an Integrated Global Geodetic Observing System (IGGOS), IAG Section II Symposium, Munich, October 5-9, 1998, International Association of Geodesy Symposia Volume 120, Springer-Verlag, Berlin, pp. 118-121.

Craymer, M. 2006. The Evolution of NAD83 in Canada, *Geomatica*, this issue.

Donahue, B., Y. Mireault, C. Huot, P. Tétreault and J. Kouba. 2004. NRCan Analysis Centre Contributions to the IGS: 1994 – 2004, 10 Years IGS, Workshop and Symposium, March 1-5, 2004, Berne, Switzerland.

Dragert, H, X. Chen, J.Kouba. 1995. GPS monitoring of crustal strain in southwest British Columbia with the western Canada Deformation Array; J. *Geomatica* 49(3), 1995; pages 301-313.

Goad, C.C. (ed.).1985. Positioning with GPS, Proceedings of the 1st International Symposium on Precision Positioning with the Global Positioning System, published by the National Ocean Service, Vol. 1-508pp, Vol. 2-438pp.

Henton, J.A., M.R. Craymer, H. Dragert, S. Mazzotti, R. Ferland and D.L. Forbes. 2006. Crustal Motion and Deformation Monitoring of the Canadian Landmass, *Geomatica*, this issue.

Junkins, D. and G. Garrard. 1998. Demystifying Reference Systems: A Chronicle of Spatial Reference Systems in Canada. *Geomatica*, 52(4), pp. 468-473.

Kouba, J., P. Héroux. 2001. Precise Point Positioning Using IGS Orbit and Clock Porducts, *GPS Solutions*, 5(2), pp.12-28.

Kouba, J. 2003. Guide to using International GPS Service (IGS) Products, On-Line Publication (*http://igscb.jpl.nasa.gov/igscb/resource/pubs/GuidetoUsingIGSProducts.pdf*)

Lahaye, F., M. Caissy, P. Héroux, K. MacLeod, J. Popelar. 1997. Canadian Active Control System Real-Time GPS Correction Service Performance Review, *Proceedings of the National Technical Meeting of the Institute of Navigation*, Santa-Monica, USA, January 14-16, 1997, pp. 695-698.

Muellerschoen R. and M. Caissy. 2004. Real-Time Data Flow and Product Generation for GNSS, Celebrating a Decade of the International GPS Service, Workshop and Symposium, March 1-5, 2004, Berne, Switzerland, p 69-75.

NASA. 2002. National Aeronautics and Space Administration, Living on a Restless Planet, Solid Earth Science Working Group Report, Pasadena, California, USA, p.8.

Pearlman, M., Z. Altamimi, N. Beck, R. Forsberg, W. Gurtner, S. Kenyon, D. Behrend, F.G. Lemoine, C. Ma, C.E. Noll, E.C. Pavlis, Z. Malkin, A.W. Moore, F.H. Webb, R.E. Neilan, J.C. Ries, M. Rothacher, P. Willis. 2006. Global Geodetic Observing System–Considerations for the Geodetic Network Infrastructure[1], *Geomatica*, this issue.

Smith, D.E. and M. Baltuck. 1993. Introduction. In Smith, D.E. and Turcotte, D.L., eds., Contributions of Space Geodesy to Geodynamics: Crustal Dynamics, Geodynamics Series, American Geophysical Union, v. 23, p. 1-3.

Tétreault, P., J. Kouba, P. Héroux and P. Legree. 2005. CSRS-PPP: An Internet Service for GPS User Access to the Canadian Spatial Reference Frame, *Geomatica*, 59(1), pp. 17 to 28.

Véronneau M., R. Duval, J. Huang. 2006. A Gravimetric Geoid Model as a Vertical Datum in Canada, *Geomatica*, this issue.

Weber, G., M. Honkala. 2004. The future is talking NTRIP, article Trimble Newsletter, published by Trimble GmbH Raunheim.

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A GRAVIMETRIC GEOID MODEL AS A VERTICAL DATUM IN CANADA

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The need for a new vertical datum in Canada dates back to 1976 when a study group at the Geodetic Survey Division (GSD) of Natural Resources Canada investigated problems related to the existing vertical reference system (CGVD28) and recommended a redefinition of the vertical datum. The US National Geodetic Survey and GSD cooperated in the development of a new North American Vertical Datum (NAVD88). Although the USA adopted NAVD88 as its datum in the early 90s, Canada did not follow suit because unexplained discrepancies of about 1.5 m were still present between east and west coasts. GSD continued to maintain and expand the vertical datum using the spirit levelling technique; however related cost and inherent deficiencies to this technique has forced GSD to rethink its approach for the delivery of the height reference system in Canada. Meanwhile, advances in space-based technologies and new developments in geoid modelling have emerged and now offer an alternative to spirit levelling. A new project to modernize the vertical datum is currently in progress in Canada. GSD is planning the adoption of a geoid model as the new vertical datum, which will allow users of space-based positioning technologies access to an accurate and uniform vertical datum everywhere across the Canadian landmass and surrounding oceans. Furthermore, this new vertical datum will be less sensitive to geodynamic activity, local crustal uplift and subsidence, and deterioration of benchmarks.

Le Canada a senti le besoin de se doter d'un nouveau système de référence altimétrique en 1976 alors qu'un groupe d'étude à la Division des levés géodésiques (DLG) de Ressources naturelles Canada étudiait des problèmes liés au système de référence altimétrique existant (CGVD28) et avait recommandé une nouvelle définition du système de référence altimétrique. Le National Geodetic Survey des États-Unis et la DLG ont travaillé ensemble à l'élaboration d'un nouveau système de référence altimétrique nord-américain (NAVD88). Bien que les États-Unis aient adopté le NAVD88 et comme système de référence altimétrique vers le début des années 1990, le Canada ne l'a pas adopté à cause de lacunes inexpliquées d'environ 1,5 mètre entre les côtes Est et Ouest. La DLG a continué à maintenir et à améliorer le système de référence altimétrique en utilisant le nivellement de précision (à bulle). Cependant, à cause des défauts et des coûts associés à cette technique, la DLG a dû trouver une autre façon d'établir le système de référence altimétrique au Canada. Entre temps, les technologies spatiales et la modélisation du géoïde ont connu des percées importantes et offrent maintenant une alternative intéressante au nivellement de précision (à bulle). Ce projet est d'ailleurs déjà lancé au Canada. La DLG planifie l'adoption d'un modèle de géoïde en tant que système de référence altimétrique, ce qui permettra aux usagers des technologies de positionnement spatiales d'y accéder pour partout sur le continent canadien et les océans qui nous entourent. De plus, ce nouveau systtème de référence altimétrique sera moins sensible à l'activité géodynamique, au soulèvement ou à l'affaissement local de la croûte terrestre et à la détérioration des repères de nivellement.

1. Introduction

Height determination within a consistent reference system is at the basis of a large number of economic activities. These activities range from mapping, engineering, and dredging to environmental studies and natural hazards; from precision agriculture and forestry, to transportation, commerce and navigation; and from mineral exploration and management of natural resources to emergency and disaster preparedness. All of these depend on the compatibility of height information enabled by a common coordinate reference system through which all types of geo-referenced information can be interrelated and exploited reliably. While the height reference system supports numerous technical applications, it is also referred to in many legal documents related to land and water management and safety such as easement, flood control, and boundary demarcation.

Until recently, Geodetic Survey Division (GSD) of Natural Resources Canada (NRCan) has relied on conventional levelling methods to provide a physical framework of vertical reference points. The benchmarks established by this method were accessible to users across the country and used as the basis for their surveys. Conventional levelling methods use line-of-sight survey measurements and require that crews of surveyors literally walk from coast to coast, taking measurements every 100 metres or so along major roadways. The height reference system established in this fashion over the last 100 years consists in a network of more than 80,000 benchmarks spread over approximately 150,000 kilometres of levelling lines (Figure 1).

In recent years, limitations of the current height reference system (instability, distortion, limited coverage, etc.) and its high maintenance costs, combined with opportunities and pressures of new technology, forced GSD to re-think the methods it uses to provide height reference in Canada.

Today, new technologies in absolute and airborne gravimetry and the launch of satellite gravity missions have greatly enhanced geoid modelling capabilities, providing an alternative for the definition of the height reference surface. More importantly, the Global Navigation Satellite Systems (GNSS) continue to expand and improve in accuracy and ease of use, gaining further acceptance as tools of choice for geo-referencing in the geomatics and scientific communities. Nowadays, the Global Positioning System (GPS) offers a relatively inexpensive means for users to obtain consistent 3D positioning (latitude, longitude, and height) connected to geocentric terrestrial reference systems such as NAD83 or ITRF as well as providing the means for geomatics agencies to maintain these reference systems at a lower cost. Unfortunately, the current height reference system is not compatible with GPS at the precision level required by users. A modernization program has therefore been initiated to fully support and realize the substantial benefits of GPS and related modern technologies for accurate height measurement.

The current plan to realize a new vertical datum and replace the Canadian Geodetic Vertical Datum of 1928 (CGVD28) is not a first attempt for NRCan. In 1976-1977, a GSD study group investigated problems related to the existing vertical reference system (CGVD28) and recommended a redefinition of the vertical datum. The US National Geodetic Survey (NGS) and GSD agreed to cooperate on the realization of a new vertical datum for North America, to be completed by 1988. This project was

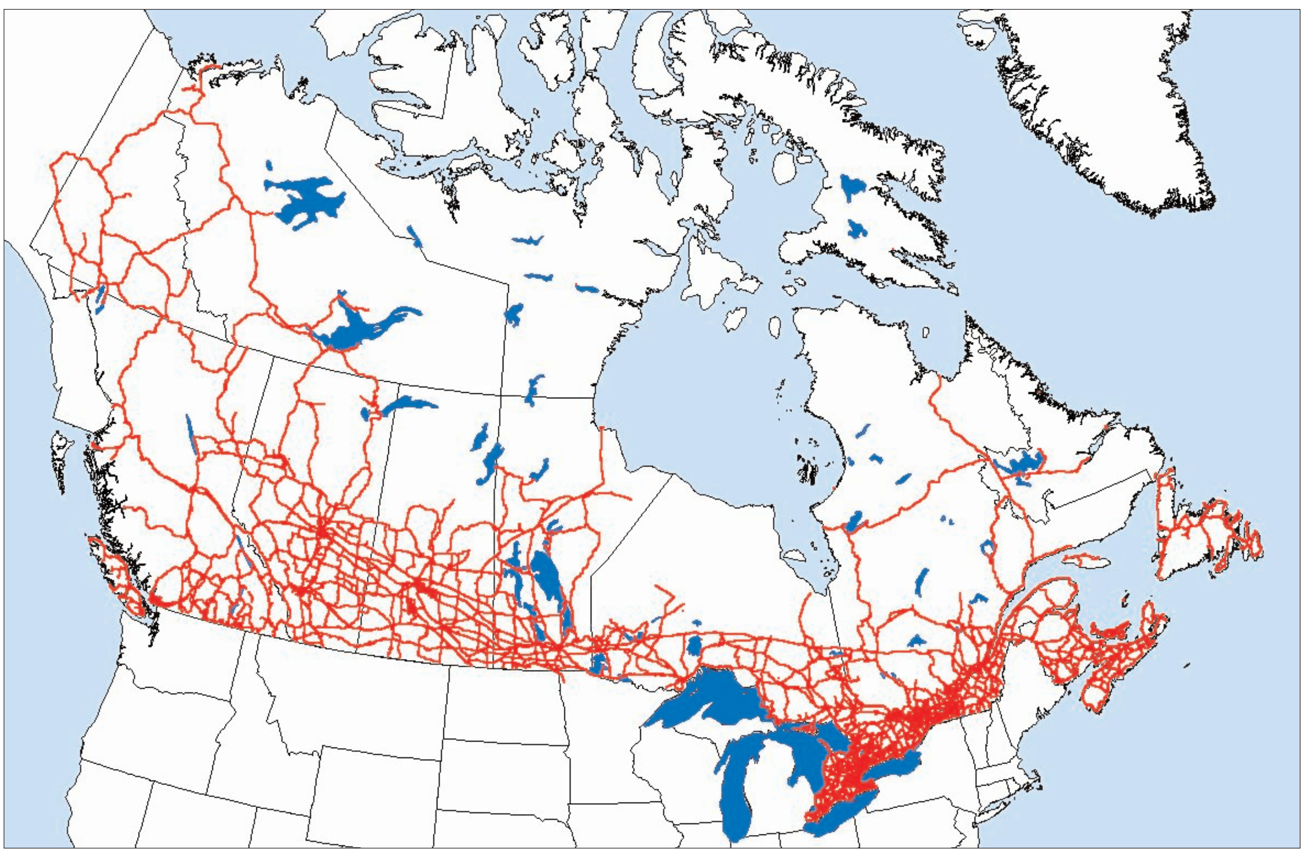

Figure 1: Physical extent of the first-order levelling network in Canada.

known as the North American Vertical Datum of 1988 (NAVD88). During that period, significant effort was devoted to improving the precise levelling procedures and a large portion of the primary vertical network was re-observed. Although the US NGS adopted NAVD88 as their new vertical datum in the early 90s, GSD did not follow suit because of unexplained discrepancies of the order of 1.5 m from east to west coasts (likely due to accumulation of systematic errors) and the overall slight improvement this new datum would have brought. Since then, GSD has reduced physical maintenance of the primary levelling network while concentrating on its mathematical analysis and the development of a gravimetric geoid model as a more advanced potential solution for height modernization.

The recently computed geoid models CGG2000 [*Véronneau* 2002] and CGG05 [*Huang and Véronneau* 2006], although not yet meeting the accuracy requirement for a new datum, confirm the potential of implementing a gravity-based system as a seamless vertical datum covering the whole Canadian landmass and surrounding oceans. Such a datum would also be compatible with modern positioning techniques for more accessible height determination. Current and upcoming international satellite gravity missions, combined with theoretical progress in geoid modelling, will contribute greatly to improve the accuracy of the Canadian geoid model for its adoption as a new datum. Computation of a new geoid model is currently planned for 2008 at the earliest, in order to take advantage of data from the most recent satellite gravity missions. An additional one to two years of work will be required prior to the formal implementation of a new system to validate this geoid model as the basis for the new datum, to finalize the development of related user applications, and to carry out the mathematical adjustment to propagate the new heights through the existing vertical networks.

Similar to the transition from the North American Datum of 1927 (NAD27) to NAD83, which was initiated several years ago and is still ongoing, it is expected that the transition from CGVD28 to a new datum will span several years or even decades during which time the two systems will co-exist. Our experience with the transition to NAD83 is exemplified by the fact that several organizations throughout the country are still using NAD27 today.

Although GSD and the Canadian Geodetic Reference System Committee (CGRSC) are well aware of the technical issues related to the modernization of the vertical reference system, there are a number of practical issues that need to be taken into consideration in the development of an implementation plan. A key concern is that the envisioned modernization and related transition are conducted in a manner that minimizes negative impacts and maximizes benefits for users of the reference system. Therefore, a stakeholder consultation is currently underway which should identify users concerns and needs as well as developing recommendations to facilitate the transitions to the new datum. This consultation will be a critical input to the height modernization implementation plan.

2. Levelling-Based Vertical Datum

The spirit levelling technique is a well-known approach that has been used for more than 200 years [*Gareau* 1986] and still provides the most accurate method for determining height differences over short distances. It involves making differential height measurements between two vertical graduated rods, approximately 100 metres apart, using a tripod mounted telescope whose horizontal line of sight is controlled to better than one second of arc by a spirit level vial or a suspended prism. This process is repeated in a leap-frog fashion to produce elevation differences between established benchmarks that constitute the vertical control network. Despite upgrades to the instrumentation with new technologies, the methodology remains costly, time consuming, and laborious.

From 1972 to 2000, the Canadian vertical network was almost entirely re-surveyed with about 124,000 kilometres of levelling lines observed. Until 1993, GSD carried out an average of 4000 to 5000 kilometres of levelling annually. Approximately 65 per cent (~3000 kilometres) was for maintenance purposes, the other 35 per cent (~1500 kilometres) related to network expansion. From 1994 to 2000 (following federal government Program Review and associated budget reductions), GSD performed an average of 1200 kilometres of levelling annually, with a steady decline over the years. GSD has performed only minimal targeted levelling since 2001.

To maintain the vertical network on a 25-year cycle, the observation of approximately 5,600 kilometres of levelling would be required annually. At a rate of $250 to $350 per kilometre, the cost of re-survey alone would range between $1.4M and $2.0M annually. Furthermore, this cost would not include repair or replacement of damaged benchmarks ($1000 to $2500 per benchmark depending on the type), nor the salary costs related to the surveys coordination, mathematical adjustment, and

Current and upcoming international satellite gravity missions, combined with theoretical progress in geoid modelling, will contribute greatly to improve the accuracy of the Canadian geoid model for its adoption as a new datum.

related data management. Even a skeletal network of about 30,000 kilometres, once proposed as the minimum vertical framework for Canada, would cost about $400,000 per year to maintain and potentially pre-empt or delay the work essential to establishing a modernized solution.

The heights currently published are a construct that results from annual survey observations dating back to 1904. Despite the great care administered to minimize potential error sources, the network was established in a piece-meal fashion by combining observations made over successive years and adjusted locally. This resulted in significant regional distortions in the current published heights. Further degradation of the accuracy of the published height is attributable to the vertical crustal motion over time. Comparisons of the heights currently published against more recent scientific network re-adjustments and the most recent geoid models indicate regional distortions of up to one metre. Although, the consistency of relative heights is probably still at the sub-centimetre precision level locally, the regional distortion impede on the application of new technology such as GPS to obtain accurate point heights consistent with the current datum.

As an extension of the latter difficulty, the current published heights were based on the assumption that the Pacific and Atlantic oceans were at the same height. In fact, according to oceanographic evidence, the water level at Vancouver could be higher than the water level at Halifax by 40 to 70 cm. This discrepancy causes a national-scale tilt in the published heights that has significant impact on a number of applications. It also has implications for existing discrepancies in heights along the Canada/US border, where the US Government adopted NAVD88.

The alternative approach to spirit levelling for the realization of a vertical datum is geoid modelling.

Due to the extent of the network and the related time required to carry out a full inspection, it is difficult to assess the exact physical state of the network at this time. We can only extrapolate based on statistics available in our databases or derived from the most recent inspections of small sections of the network.

Although only five per cent of the 80,000 benchmarks in the GSD database are identified as being in dubious condition (damaged, destroyed, not found, displaced or inaccessible), it is expected that the current state of the vertical network is in much worse shape. Until 1996, GSD inspected 3000 to 4000 kilometres of levelling lines annually as part of its vertical network maintenance program. These inspections found that 11 to 22 per cent of the benchmarks inspected became unusable or were destroyed over an approximate 20-year cycle, for an average rate of degradation of about 16 per cent over that period. In urban or near-urban settings the rate can be much higher. A recent systematic inspection of some 400 primary benchmarks established 25 years ago in the Greater Vancouver Regional District reported 32 per cent of the benchmarks were either not found, inaccessible, or destroyed. Consistent with these statistics, a student summer project recently carried out by the Ontario Ministry of Natural Resources (MNR) yielded a level of destruction of 22 per cent based on the inspection of 110 benchmarks selected randomly in and around six cities. On the other hand, the Alberta provincial geodetic agency indicated that between 1988 and 2003 they inspected 12 per cent of the federal benchmarks on their database since 1988 and only 2.5 per cent were reported as destroyed or having an “anomalous” condition. At the other end of the spectrum, the Newfoundland provincial survey agency estimates the destruction rate at about 2.5 per cent per year (yielding a rate of about 40 per cent over 20 years) based on the destruction rate of their own control monuments in the province.

Thus, we can probably estimate the degradation rate of the network across Canada to be in the range of 15 to 20 per cent per 20 years. In urban or near-urban areas the degradation rate could reach 35 per cent for the same period. In the context of datum modernization, this implies that a significant portion of the existing monumented networks should remain intact and enable a transition period of a few decades. However, additional network maintenance may be necessary in certain areas where damage to the physical network occurs at a rate unacceptable for a successful transition.

Subsidence or uplift of individual benchmarks due to frost or other local instability is another weakness of the network, significantly affecting its accuracy (or equivalently, confidence in that accuracy) at a local level. Occasional reports of such inconsistencies in the levelling network are expected to increase as the length of time since the last maintenance increases. Further details about limitations of the CGVD28 can be found in [*Véronneau et al*. 2002].

3. The Geoid as a Vertical Datum

The alternative approach to spirit levelling for the realization of a vertical datum is geoid modelling. If the two approaches were errorless, they would define the same datum. For the levelling technique, the datum is realized by monuments in the Earth’s crust, which is an unstable surface due to geodynamic effects and local uplift and subsidence. A datum realized with spirit levelling only provides known heights at the benchmark locations. On the other hand, the geoid is realized in relation to an ellipsoid (e.g., GRS80) and represents a continuous surface known everywhere across the Canadian territory. Height modernization using a geoid model is a novel approach that is also being considered in New Zealand [*Hannah* 2001].

The geoid is an equipotential surface, i.e., a level surface where gravity (plumb line) is perpendicular at all points on the surface and water stays at rest. There are an infinite number of equipotential surfaces. The geoid, by definition, corresponds to the surface that best approximates mean sea level globally (Gauss-Listing geoid). The difference between the geoid and actual mean sea level is the permanent sea surface topography (SST), which ranges globally from –1.8 m to +1.2 m [*LeGrand et al.* 2003]. This SST is due to factors such as water temperature, salinity, and surface ocean currents.

The separation between the ellipsoid and geoid is the geoid height or geoid undulation (N) and is determined from measurements of the Earth's gravity field. The geoid height allows the relation between the ellipsoidal height (h), which can be obtained by GPS, and the orthometric height (H):

$$H = h - N. \tag{1}$$

Thus, the application of the geoid model for height determination is simply a subtraction, but one has to make sure that the ellipsoidal heights and geoid heights are in the same reference frame (e.g., NAD83 (CSRS)). On the other hand, the realization of a geoid model is complex. It requires a global set of gravity measurements, which are corrected for a series of topographical effects before solving for Stokes's integral [*Heiskanen and Moritz* 1967]. The accuracy of the geoid model is as good as the input data.

The development of an accurate geoid model for a country as vast as Canada is always a challenge. The rough relief of the Western Cordillera, the large water surfaces such as the surrounding oceans, Hudson Bay and Great Lakes, the harsh Arctic conditions, and the natural motion of the topography due to earthquake and postglacial rebound render the collection of land and marine gravity measurements difficult with the required accuracy, density, and homogeneity. Furthermore, detailed digital elevations models are also required to refine the geoid model especially in the mountainous regions. However, the recently launched satellite missions of CHAMP and GRACE [*Reigber et al.* 2002; *Reigber et al.* 2005; *Tapley et al.* 2004], dedicated to the measurements of the Earth gravity field, contribute significantly in improving the long wavelength components of the geoid model for Canada.

The vertical datum for Canada does not necessarily have to be defined by the "global" geoid i.e. global mean sea level. Any equipotential surface that best serves Canada's requirement can be selected as a datum. Therefore, in addition to the equipotential surface (W_0), which represents global mean sea level for which values can be obtained from scientific papers (e.g., *Burša et al.* 2002; *Burša et al.* 2004; *Mäkinen* 2004), GSD is currently investigating an equipotential surface that would correspond to the mean water level at the tide gauge on the Saint-Lawrence River in Rimouski (Pointe-au-Père), Quebec. This gauge is one of the six used to define mean sea level for CGVD28 [*Cannon* 1929], but also the only gauge defining mean sea level for both NAVD88 [*Zilkoski* 1986; *Zilkoski et al.* 1992] and the International Great Lakes Datum of 1985 (IGLD85). This could be accomplished by selecting the equipotential surface such that the geoid height (N) in Rimouski is equal to the difference between the NAVD88 height (H) and ellipsoidal height (h) at that location:

$$N_{NAD83} = h_{NAD83} - H_{NAVD88.} \tag{2}$$

This definition would represent a difference of approximately 35 cm from the equipotential surface representing global mean sea level.

The advantage of using the geoid defining the global mean sea level is the direct compatibility with a global standard, facilitating the integration of geoid undulations with ellipsoidal heights obtained from space-based technology (e.g., GPS). It allows also the determination of the absolute sea surface topography from satellite radar altimetry. The advantage of using the mean water level at Rimouski is the closeness with the datums currently used in Canada and the USA (CGVD28, NAVD88 and IGLD85) meaning that, at least, the heights in eastern Canada would remain approximately the same as before. At this time, the selection of the equipotential surface defining the vertical datum is still a subject of discussion.

Figure 2 shows the difference between the levelling-based datum CGVD28 and a preliminary geoid-based datum aligned with mean water level at Rimouski. Table 1 gives the change in heights between CGVD28 and the two considered datum options for selected localities along an east-west corridor in southern Canada. The values in Figure 2 and Table 1 should not be considered as final because they are based on the latest developmental geoid model CGG05 determined from early datasets processed from the CHAMP and GRACE

The development of an accurate geoid model for a country as vast as Canada is always a challenge.

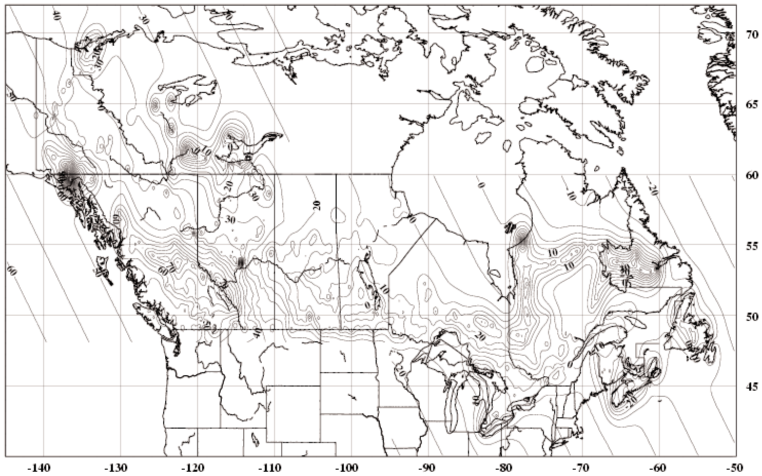

Figure 2: Change between the levelling-based datum CGVD28 and a preliminary geoid-based datum when using mean water level at Rimouski. (C.I.: 5 cm)

Table 1: Change of heights in centimetres in new proposed datums in relation to CGVD28 (preliminary results).

Locality	Datum [a] (Global)	Datum [b] (Rimouski)	Locality	Datum [a] (Global)	Datum [b] (Rimouski)
Halifax	-64	-36	Regina	-26	1
Montréal	-37	-10	Edmonton	-3	25
Toronto	-34	-6	Banff	54	81
Winnipeg	-32	-5	Vancouver	22	50

[a]: Datum is the equipotential surface representing global mean sea level
[b]: Datum is the equipotential surface at mean water level at the tide gauge in Rimouski.

satellite gravity missions. Unfortunately, the new datum would not coincide with NAVD88. There is an increasing systematic difference between the preliminary geoid-based datum and NAVD88 that reaches approximately 85 cm in Vancouver when both datums are defined at Rimouski. Early investigations indicate that this discrepancy is related to systematic errors in NAVD88.

This paper will not discuss the use of the ellipsoid as a vertical datum [*Burkholder* 2002]. Although this proposition eliminates the use of a geoid model, it significantly impacts the absolute heights. For example, using an ellipsoidal reference, the western coastline of Hudson Bay would have an elevation of approximately –50 m. Selecting this option would therefore require that topographical maps in Canada be updated which would introduce additional complexity in monitoring water flow since ellipsoidal heights have no physical meaning (water can flow uphill). This alternative would only add confusion to the process of moving to a modernized height system that is already difficult for many users.

With the adoption of a new vertical datum compatible with space-based positioning techniques, a drastic reduction in reliance on the dense monumented ground network is expected. This reduction would go hand-in-hand with the increasing adoption by the geomatics community of new technologies with their related improvements in accuracy and efficiency.

4. Monumented Height Network in the New Datum

Contingent on the recommendations of stakeholder consultations, it is likely that the future national monumented network for heights, at the highest-level, will consist of the federal Active Control Points (ACP) and Canadian Base Network (CBN) points. It is anticipated that NRCan will continue the physical maintenance and monitoring at these sites to ensure datum stability and observe the data required to derive the mathematical transformations required by users. Densification could be provided by the Provincial High Precision Network (HPN) points, as required. NRCan will also continue the mathematical maintenance of the existing primary vertical network with respect to the new datum through links to the CBN and ACPs. This will require an overall readjustment of the network, not only to generate heights with respect to the new datum, but also to remove much of the distortion resulting from the piece-meal construction of the network. It should be noted however that the historic levelling observations have their limitations and a new adjustment will not account for or correct for monuments that have moved over the years, nor for changes in the Earth's crust (uplift/subsidence) that affect the accuracy of individual benchmarks.

The availability of heights referenced to this new datum for the existing network should greatly facilitate the transition to the new datum. To help ease the potential burden associated with moving information to a new datum, and as further incentive, NRCan will also provide and maintain transformation and corresponding software tools to support the conversion of existing data sets from CGVD28 to the new datum.

5. Summary

In terms of accuracy and accessibility, the Canadian Geodetic Vertical Datum of 1928 (CGVD28) does not satisfy today's users needs for precise height determination. Furthermore, it preempts the use of modern and efficient space-based technologies for both precise height determination and maintenance of the vertical reference frame. A readjustment of the levelling network similar to the NAVD88 project, albeit more accurate than CGVD28, would only be a temporary solution. It would not solve the problem of limited coverage and cost of maintenance. More importantly, it would not account for the effect of crustal motion and localized benchmark movements. The most viable alternative for the realization of a long-term vertical datum for Canada is a geoid model. It would define the datum in relation to an ellipsoid, making it compatible with space-based positioning technologies (e.g., GPS and satellite radar altimetry). It would allow easy access to orthometric heights everywhere across the Canadian territory. The existing monumented first-order levelling network would be readjusted by constraining it to orthometric heights derived from ellipsoidal and geoid heights at selected CBN stations across Canada. The new datum would change the heights assigned to benchmarks within a range of one metre across Canada. However, the height differences locally would maintain the same relative precision of a few millimetres. CGVD28 will continue to co-exist with the new datum for quite some time, but its use will progressively diminish as geomatics communities across the country acknowledge the benefits and efficiency that should come with a modernized datum.

References

Burkholder E.F. 2002. Elevation and the global spatial data model (GSDM). Institute of Navigation 58th annual meeting, June 24-26, Albuquerque, New Mexico.

Burša M., E. Groten, S. Kenyon, J. Kouba, K. Rad?j, V. Vatrt, and M. Vojtišková. 2002. Earth's dimension specified by geopotential. Studia geophysica et geodaetica, 46, 1-8.

Burša M., S. Kenyon, J. Kouba, Z. Šima, V. Vatrt, M. Vojtišková. 2004. A Global vertical reference frame based on four regional vertical datums. Studia geophysica et geodaetica, 48, 493-502.

Cannon J.B. 1929. Adjustments of the precise level net of Canada 1928. Publication No. 28, Geodetic Survey Division, Earth Sciences Sector, Natural Resources Canada, Ottawa, Canada.

Gareau R. 1986. History of precise levelling in Canada and the North American vertical datum readjustment. Graduate thesis, University of Calgary, Calgary, Alberta.

Hannah J. 2001. An assessment of New Zealand's height systems and options for the future height datum. Report for the Surveyor General, Land Information New Zealand, PO Box 5501, Wellington.

Heiskanen W.A. and H. Moritz. 1967. Physical Geodesy, Freeman.

Huang J., M. Véronneau. 2006. In preparation.

LeGrand P., E.J.O. Schrama and J. Tournadre. 2003. An inverse estimate of the dynamic topography of the ocean. Geophys. Res. Lett., 30(2), 1062, doi:10.1029/2002GL014917.

Mäkinen J. 2004. Some remarks and proposals on the redefinition of the EVRS and EVRF. Presented at the meeting of the IAG Subcommission for the European Reference Frame (EUREF), Bratislava, June 1, 2004.

Reigber, Ch., G. Balmino, P. Schwintzer, R. Biancale, A. Bode, J.-M. Lemoine, R. Koenig, S. Loyer, H. Neumayer, J.-C. Marty, F. Barthelmes, F. Perosanz and S.Y. Zhu. 2002. A high quality global gravity field model from CHAMP GPS tracking data and accelerometry (EIGEN-1S) Geophysical Research Letters, 29(14), 10.1029/2002GL015064.

Reigber Ch., R. Schmidt, F. Flechtner, R. König, U. Meyer, K.-H. Neumayer, P. Schwintzer, S.Y. Zhu. 2005. An Earth gravity field model complete to degree and order 150 from GRACE: EIGEN-GRACE02S, *Journal of Geodynamics* 39(1), pp. 1-10.

Tapley B.D., S. Bettadpur, M. Watkins and C. Reigber. 2004. The gravity recovery and climate experiment: Mission overview and early results. Geophys. Res. Lett., Vol. 31, L09607, doi:10.1029/2004GL019920.

Véronneau M., A. Mainville and M.R. Craymer. 2002. The GPS height transformation (v2.0): An ellipsoidal-CGVD28 height transformation for use with GPS in Canada. Report, Geodetic Survey Division, Earth Sciences Sector, Natural Resources Canada, Ottawa, Canada.

Véronneau M. 2002. The Canadian gravimetric geoid model of 2000 (CGG2000). Report, Geodetic Survey Division, Earth Sciences Sector, Natural Resources Canada, Ottawa, Canada.

Zilkoski D.B. 1986. The new adjustment of the North American datum. *ACSM Bulletin*, April, pp. 35-36.

Zilkoski D.B., J.H. Richards and G.M. Young. 1992. Results of the general adjustment of the North American vertical datum of 1988. *American Congress on Surveying and Mapping, Surveying and Land Information Systems*, 52(3), pp. 133-149.

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CRUSTAL MOTION AND DEFORMATION MONITORING OF THE CANADIAN LANDMASS

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The science of geodesy and the corresponding reference systems it develops have increasingly been applied to measuring motions and slow deformations of the Earth's crust driven by plate tectonics. Improvements to geodetic methodologies have therefore enabled better understanding of the Earth's systems, including improved modelling and forecasting of changes that may affect society. These geophysical processes also systematically affect the reference frames used as standards for geodetic surveys. Reference frames therefore must not only define the system of coordinate axes (including orientation, origin, and scale), but also characterize the time-evolution of spatial coordinates on the Earth's surface. When evaluating the effect on reference standards within a given area, it is also important to realize that geodynamic processes operate on various spatial scales. In this paper we summarize some of NRCan's efforts to monitor contemporary crustal dynamics across Canada. Progressing from continental to smaller regional scales, we outline the rationale, techniques, and results. The observational data and interpretations presented are fundamentally dependent on the Canadian Spatial Reference System yet in turn also contribute to the incremental improvement of its definition and maintenance.

La science de la géodésie et les systèmes de référence correspondants ont été de plus en plus utilisés pour mesurer les mouvements et les lentes déformations de la croûte terrestre causés par les plaques tectoniques. L'amélioration des méthodes géodésiques nous a donc permis de mieux comprendre les systèmes de la Terre en nous permettant, entres autres, de mieux modéliser et prévoir les changements qui risquent de nous toucher. Ces processus géophysiques modifient aussi systématiquement les cadres de référence qui servent de normes aux levés géodésiques. Les cadres de référence doivent alors non seulement définir le système des axes des coordonnées (incluant l'orientation, l'origine et l'échelle), mais doivent aussi définir l'évolution temporelle des coordonnées spatiales sur la surface terrestre. Lorsqu'on évalue leur effet sur les normes de référence dans une zone donnée, il est aussi important de réaliser que les processus géodynamiques se produisent à plusieurs échelles spatiales. Dans cet article, nous résumerons certains des efforts de surveillance de la dynamique contemporaine de la croûte terrestre canadienne par Ressources naturelles Canada. De l'échelle continentale à l'échelle régionale, nous présenterons un survol du besoin, des techniques et des résultats. Les données et les interprétations observationnelles présentées dépendent fondamentalement du Système canadien de référence spatiale tout en contribuant à l'amélioration de sa définition et à sa maintenance.

1. Introduction

Today the Earth Sciences Sector (ESS) continues to respond to the Order in Council that created the Geodetic Survey of Canada in 1909 tasking the then Minister of Interior "to determine… the positions of points throughout the country… which may form the basis of surveys for all purposes, topographical, engineering or cadastral, and thereby assist in the survey work carried on by other departments of the Dominion Government, by Provincial Governments, and by municipalities, private persons or corporations."

[passage from Canadian Spatial Reference System (CSRS) service logic model].

Geodynamic monitoring is demanding in terms of observational accuracy and stability over a wide range of spatial- and temporal-scales. An appropriate reference frame is a requisite tool that enables better understanding of geodynamic systems that in turn provides better constraints to predicted impacts on society. However, the effects of geodynamic and geophysical crustal deformation processes can systematically bias the reference frames used for geodetic surveys. Kinematic processes affecting the Earth's surface can systematically affect geodetic measurements and ultimately lead to inconsistencies between observations at different epochs. As measurement and processing accuracies and requirements have increased, the Canadian Spatial Reference System (CSRS) is now in an era in which the time-variability of its outputs must be evaluated.

For Canada the largest observed deformation rates are at the level of 1-2 cm/yr. Millimetre-per-year resolution, and better, is required to investigate many processes of the dynamic Earth and consequently to better quantify their potential impacts on society (*e.g.* natural hazard and climate change effects). Measuring these rates requires very high-precision geodetic techniques coupled with suitably long observation windows. The frequency of observations is largely dependent on the magnitude of the deformation process and the precision of the measurement technique. Survey design and data processing must also consider any quasi-periodic signals (*e.g.* the annual signals resolved by GPS) that could bias estimates of geodynamic motions.

…a unified and consistent global spatial reference system has long been necessary.

Within ESS of Natural Resources Canada (NRCan), regions of geophysical interest (particularly hazards) have warranted densified geodetic infrastructure. For ESS, long-term topics of interest for geodetic investigations include studies of post-glacial isostatic adjustment across the Canadian landmass, the Saint Lawrence seismic zone in eastern Canada, the active plate boundary above the Cascadia subduction zone along Canada's west coast, and the active fault margin of the Queen Charlotte Islands. Additionally, investigations of the vulnerability of Canada's coasts to climate change processes have increasingly relied on precise geodetic observations.

Targeted regional studies within ESS augment the CSRS and thus contribute to aiding and strengthening international services to the geophysical and geomatics communities. The international- and national-scale geodynamic monitoring efforts, in turn, support regional deformation studies. Within a specific region there are often different kinematic processes operating on various spatial scales. At the largest scale, rigid tectonic plate motions may need to be considered. Then, measuring long-wavelength signals at a broader (*e.g.* national) scale provides the regional deformation "background signal" which is useful when assessing more localized deformation signals during regionally-targeted kinematic studies.

This paper outlines a number of efforts within ESS that contribute to monitoring crustal motion and deformation at differing scales across the Canadian landmass. It is not a complete review, but rather intends to provide a well-rounded cross-section of Sector studies. Progressing from larger to smaller spatial scales, the rationale, methodology, and results (for established studies) are summarized for the geodynamic investigations. Although this article emphasizes the work of ESS, a considerable amount of data, analyses, and interpretations have been dependent on the work and productive collaborations of numerous other groups and agencies. Further information and details may be found in the publications referenced in each section.

2. Global-Scale Plate Kinematics and the ITRF

With the wide-spread use of space-based techniques for positioning in the scientific and engineering communities, a unified and consistent global spatial reference system has long been necessary. The International Terrestrial Reference System (ITRS) was proposed and implemented over two decades ago. Its physical realization, the International Terrestrial Reference Frame (ITRF), provides a high accuracy and easily accessible global coordinate system for the study of Earth dynamics at all scales [*Altamimi et al.* 2001]. Several updates of the ITRF have been made available with each one improving on its predecessor. Although originally developed for and by the scientific community, this system eventually became the most widely used reference system for positioning. For example, some countries have adopted versions of the ITRF as the national standard and even WGS84, the native reference system for GPS, is now based on ITRF. Additionally these frames provide velocity information and use kinematic constraints in their realizations.

Any ITRF is composed of a set of station coordinates at a given epoch and their velocities in three dimensions with appropriate covariance information. The frame is currently defined via four techniques: (1) Very Long Baseline Interferometry (VLBI), (2) Satellite Laser Ranging (SLR), (3) Global Positioning System (GPS), and (4) Détermination d'Orbite et Radiopositionement Intégré par Satellite (DORIS) [*Boucher et al.* 2004]. A combination of the techniques is necessary because none alone is sensitive to all the parameters necessary to define a reference frame. The combination takes advantage of the strength of each technique; *e.g.* the SLR contribution is essential for the determination of the origin while VLBI and SLR contribute to determine the scale. The combination of the networks from each technique also requires that they be connected at as many collocated sites as possible. Repeated local surveys are required to precisely measure the three-dimensional offsets between the markers for each collocated technique and detect any potential change. All of the techniques contribute to the velocity field, which is used to solve for the time evolution and the no-net rotation condition of the system. For the general user community, it is the GPS products (coordinates and satellite orbits) that enable easy access to the ITRF.

Earth scientists rely on ITRF products for many investigations related to large-scale mass redistribution, including characterization of the Earth's interior and climate change studies. In particular, space-geodetic techniques have revolutionized the study of plate tectonics. At one time, plate motion models were primarily constrained by sea-floor magnetic anomalies and other geological information with rates averaged over millions of years. With GPS it is possible to directly measure contemporary tectonic plate movement on a time scale of years. The motion of any rigid body on the surface of a sphere can then be represented by a rate of rotation about an axis (*i.e.* Euler pole) and expressed as a rotation vector. The North American Plate, for example, undergoes a counter-clockwise rigid body rotation around an Euler pole located near equatorial, northwestern South America (*refer to* Figure 1). The associated tectonic plate motions for Canadian sites are on the order of 2 cm/yr.

When accurately defining the rotation vector of a plate, it is important to ignore stations biased by local site effects and those in known deforming zones unless reliable models of such deformations are available. Ideally, only the sites that best represent the rigid parts of the tectonic plate should be used. High-precision GPS has allowed scientists to discriminate subtle differences in velocities within what had been considered individual tectonic units, and in the process identify new plates or sub-plates and quantify their individual rotation vectors. The improved resolution of plate rotation vectors is also very useful for investigations that utilize kinematic information (*e.g.* fault and other crustal deformation studies). However, the comparison of precise GPS-determined results is often complicated by investigators using different techniques to produce a plate-fixed reference frame in which to express their results. For North America the SNARF initiative (discussed in the next section) will provide a consistent reference system in which scientific and geomatics results (*e.g.* positions in tectonically active areas) can be produced and inter-compared.

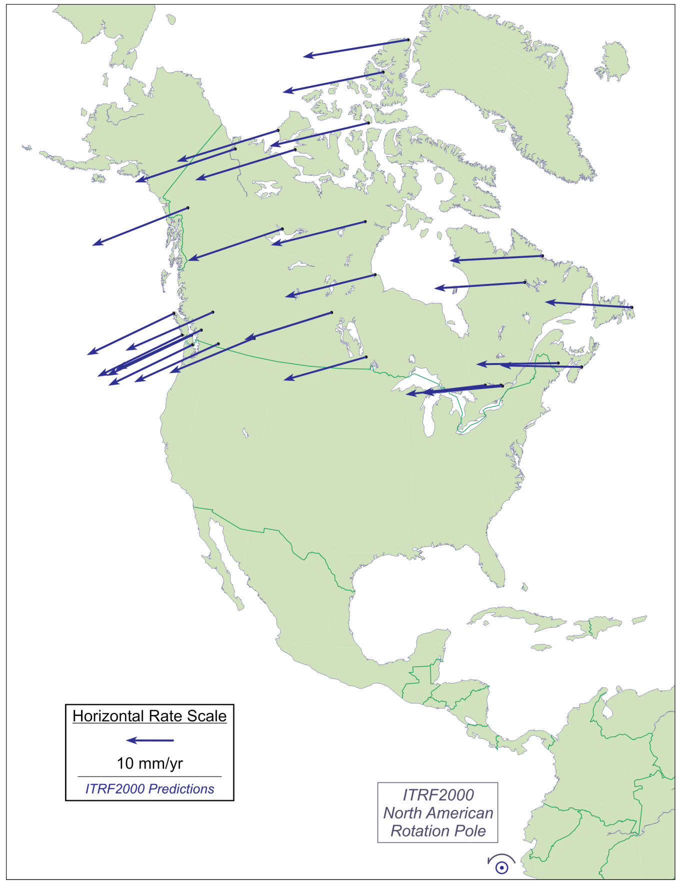

Figure 1: North American plate rotation pole and predicted velocities. The blue vectors represent the motion for those sites predicted from North American rotation about its pole. The arrow lengths are proportional to the rates at their origin point and are given for Canadian continuous GPS sites present in the IGS cumulative solution (GPS week 1345). The North American rotation pole is from ITRF2000 [*Altamimi et al.* 2002].

3. Continental & National Scale Monitoring Efforts

3.1 NAREF Densification of ITRF in North America

Since the beginning of 2000, ESS has been playing a leading role in the North American Reference Frame (NAREF) Working Group of the IAG Sub-Commission 1.3c (Regional Reference Frames for North America) [*Craymer and Piraszewski* 2001]. One of the primary objectives of this working group is the densification of the ITRF in North America using continuously operating GPS (CGPS) stations. Following the distributed processing approach advocated by the International GNSS Service (IGS) [*Blewitt* 1997], the NAREF working group members have been independently computing weekly regional coordinate solutions for CGPS sites throughout North America.

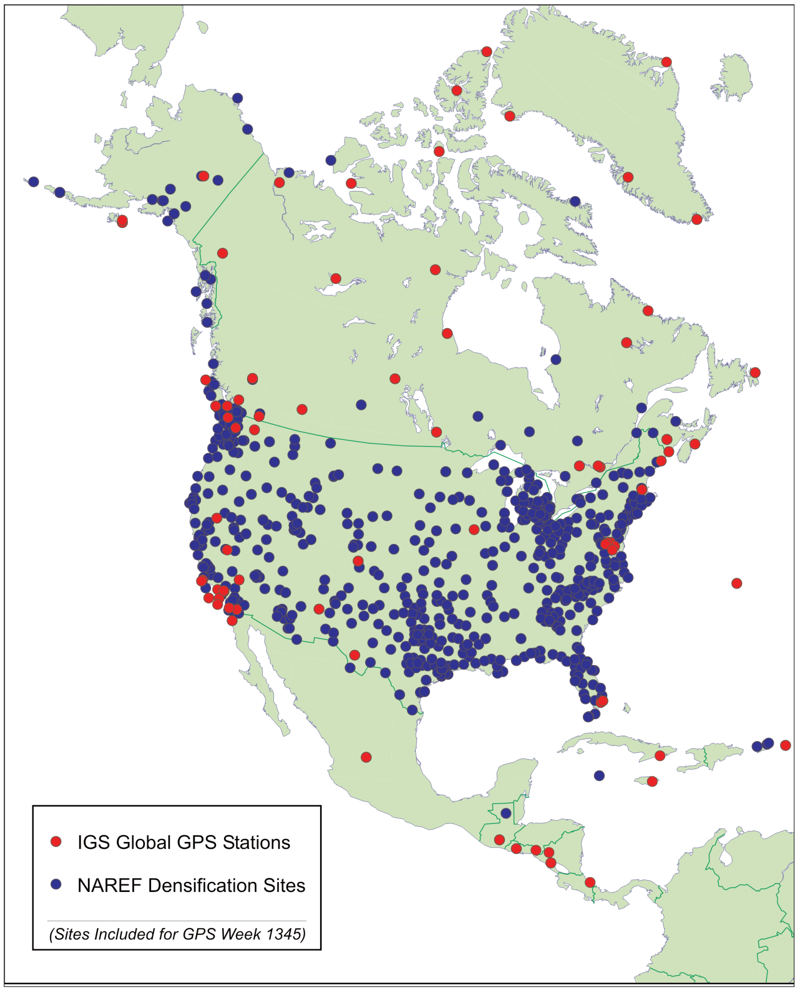

Figure 2: NAREF network of continuous operating GPS receivers. The red circles represent stations in the IGS global network while the blue circles represent densification stations.

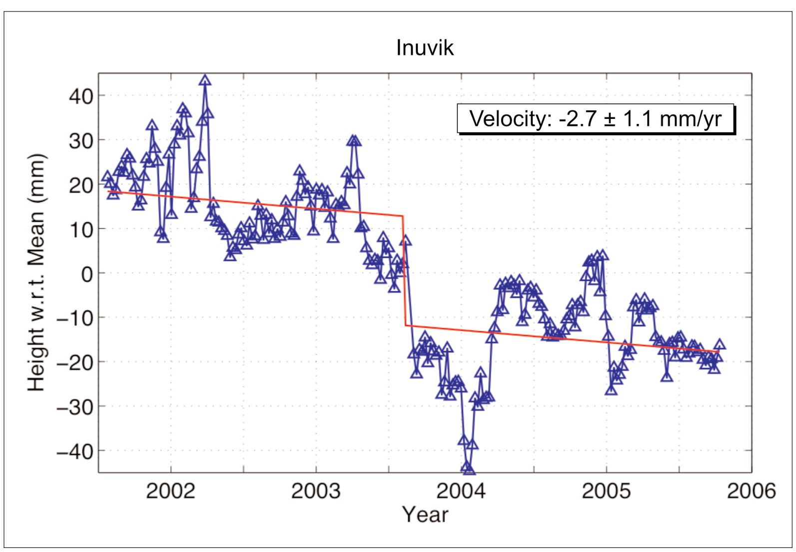

Figure 3: Time series for station INVK in Inuvik, NWT illustrating relatively large seasonal fluctuations primarily due the effects of snow on the antenna phase centre. Note also the step (discontinuity) in the time series just after 2003.5 due to the addition of an antenna dome.

NRCan has been producing three such weekly regional solutions for Canada. Two are being generated by NRCan's Geodetic Survey Division (GSD) on a regular basis for redundancy and quality control. One of these solutions incorporates additional stations just outside Canadian borders for further redundancy and continuity with American solutions. In addition, NRCan's Geological Survey of Canada—Pacific Division has also been contributing weekly solutions for their Western Canada Deformation Array (see later section) on the west coast. Other solutions include a preliminary version of the Plate Boundary Observatory from the Scripps Institution of Oceanography, and the entire US CORS (Continuously Operating Reference Stations) network from the US National Geodetic Survey that includes nearly 700 stations. More recently, efforts are underway to include stations from provincial GPS networks, including those of British Columbia, Quebec and, soon, New Brunswick.

Following internationally accepted densification methodologies [*Ferland et al.* 2003], these different regional solutions are being combined into a single NAREF weekly solution. NAREF combination solutions beginning the first week of 2001 have been submitted to the IGS data archives and are usually available with about a four-week latency. There are presently over 800 stations in the combined NAREF network (*refer to* Figure 2). Many stations are included in more than one solution to provide redundancy checks and to allow for the correct weighting of the different solutions relative to each other and to the global solutions. The goal is to have all stations included in at least two different solutions. All regional solutions agree with each other and with the global ITRF and IGS solutions at the level of a few millimetres.

The weekly NAREF solutions have recently been combined into a single so-called cumulative (multi-epoch) solution to provide estimates of both station coordinates and their velocities with respect to a consistent reference frame throughout North America. Velocity estimates with accuracies of less than 1 mm/yr are expected to be achievable in the near future with the accumulation of several years of data. This relatively long time series is required in order to estimate and remove systematic annual and semi-annual signals due to seasonal effects and discontinuities caused by changes in equipment or software (*refer to* Figure 3). Nevertheless, even today, these solutions can be used to support geodynamics studies of both large and small scale crustal motions, including the direct measurement of the motion of the North American tectonic plate and intra-plate deformations such as post-glacial rebound as discussed later in this paper. A preliminary version of this NAREF velocity solution has also been used to help define a North American plate-fixed reference frame for studies of intra-plate crustal motions (see next section).

3.2 A Stable North American Reference Frame (SNARF)

As discussed earlier, regional reference frames fixed to the stable part of a tectonic plate are often required to facilitate geophysical interpretation and inter-comparison of geodetic solutions of crustal motions. In 2003, the Stable North American Reference Frame (SNARF) Working Group was established under the auspices of UNAVCO, Inc. and IAG Regional Sub-Commission 1.3c for North America especially to address needs for the US-led EarthScope project. The goal is to define a regional reference frame that is consistent and stable at the sub-mm/yr level throughout North America.

The SNARF Working Group identified and addressed several issues that must be dealt with to properly define such regional frames, including (1) the selection of "frame sites" based on geologic and engineering criteria for stability, (2) the selection of a subset of "datum sites" which represent the stable part of the plate and will be used to define a no-net rotation condition, (3) the modelling of any significant intra-plate motions using a relatively dense GPS velocity field, and (4) the generation and distribution of reference and deformation products for general use [*Blewitt et al.* 2005]. The SNARF vertical datum is consistent with ITRF2000 in that the centre of mass of the whole Earth system is taken to be the origin while the horizontal datum differs by a rotation rate that brings the rotation of the stable part of North America to rest.

The first release of SNARF provides a rotation rate vector that transforms ITRF2000 velocities into the SNARF frame, and an initial reference frame is defined via a list of selected sites, epoch coordinates and velocities in a Cartesian system. This rotation effectively defines the SNARF reference frame in relation to the ITRF. It was computed using only stable sites from a combination of velocity solutions from GSD for the NAREF network and the Canadian Base Network (see next section), and a velocity solution from Purdue University for a selection of US CORS stations. Horizontal intra-plate velocities in the SNARF frame exhibit a pattern that is more consistent with expected deformations from post-glacial rebound than velocities obtained from other estimates; *e.g.*, ITRF2000 (*refer to* Figures 4a & 4b). In addition, these velocity solutions were also used to determine a semi-empirical model of post-glacial rebound based upon a novel assimilation technique that combines GPS velocities with a geophysical model [*Blewitt et al.* 2005] (*see* Figure 5). Over the next few years SNARF will be incrementally improved through further research and as more accurate velocity solutions become available.

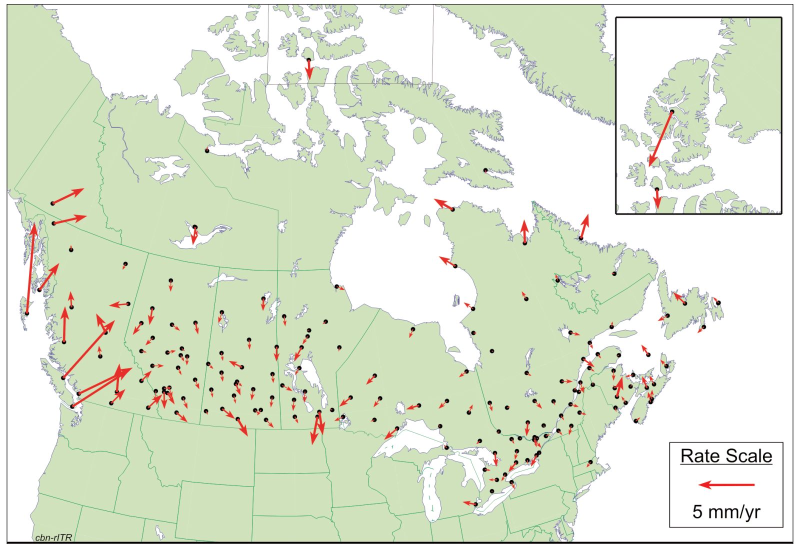

Figure 4a: Residual horizontal intra-plate velocities of CBN network using North American plate motion estimates (rotations) from ITRF2000. The plate motion estimate absorbs much of the horizontal motion from post-glacial rebound that is expected to radiate outward from the areas of maximum uplift. Little outward horizontal motion is seen in the intra-plate velocities.

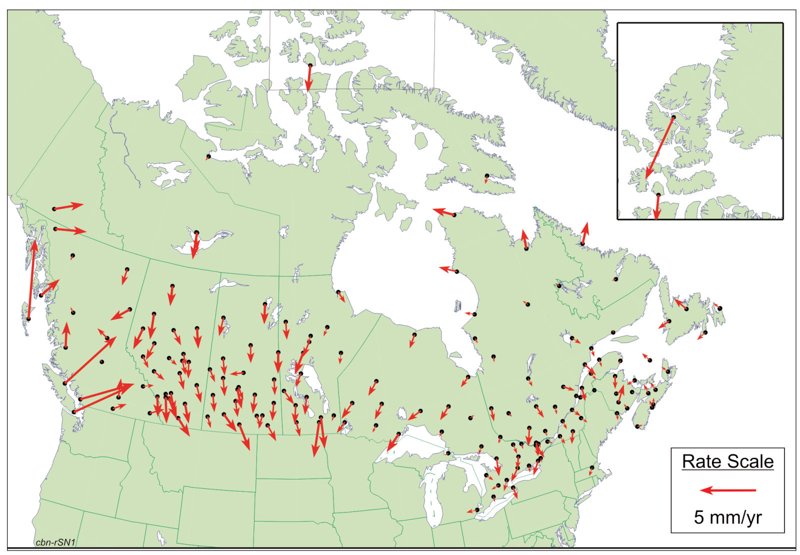

Figure 4b: Residual horizontal intra-plate velocities of CBN network using North American plate motion estimates (rotations) from SNARF 1.0. In this reference frame defined by the SNARF plate motion estimate, the outward pattern of intra-plate velocities is more clearly visible. The SNARF plate motion estimate is affected less by post-glacial rebound.

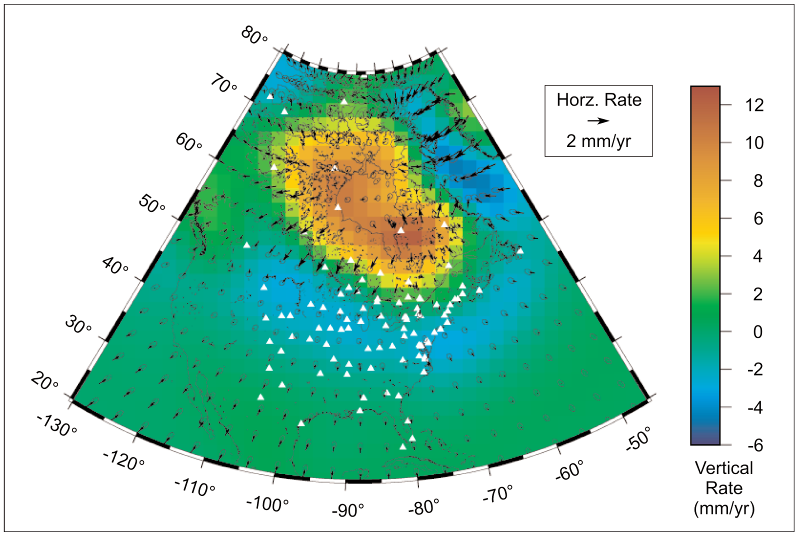

Figure 5: Post-glacial rebound rates from the SNARF model (courtesy of Jim Davis, Harvard-Smithsonian Center for Astrophysics [after *Blewitt et al.* 2005]). This empirical model of post-glacial rebound employs a novel technique that combines observed GPS velocities with a geophysical model.

3.3 Geodynamic Observations from the CBN

Initiated in 1994, the Canadian Base Network (CBN) is a national network of high-stability pillar monuments with forced-centering mounts for Global Positioning System (GPS) receiver antennas. The initial role of the CBN was to complement the Active Control System (ACS) of the CSRS by providing easily accessible 3D reference coordinate sites, with a reasonable distribution across Canada. In order to maintain the accuracy of the CSRS reference frame realization, CBN sites have been reoccupied to confirm initial positions and to detect crustal movements. By combining nearly 10 years of repeated multi-epoch (episodic) GPS measurements, GSD has begun to estimate velocities at the CBN sites in order to provide an increased spatial sampling of crustal deformation throughout Canada. To determine individual station velocities, regional CBN solutions for each measurement epoch are systematically combined into a single Canada-wide, multi-epoch cumulative solution (*i.e.* similar to the previous discussions for NAREF and SNARF). In order to generate time series of consistent, high-accuracy coordinates for velocity estimation, it is necessary to ensure consistency of the integration into the reference frame. This is accomplished by aligning each of the individual CBN solutions to a subset of stations from a recent cumulative solution for the IGS global network in ITRF. Fortunately, there are many IGS stations in Canada and most were included in each regional CBN solution to strengthen the connection to reference frame and ensure consistency between epochs. Consistent and realistic weighting of the individual CBN solutions is improved through the estimation of separate variance components relative to the IGS global solution. After the individual CBN solutions are aligned and weighted, they are combined together in a simultaneous cumulative solution to produce velocities at each site [*Henton et al.* 2004].

On the national scale, glacial isostatic adjustment is the most significant geodynamic process driving vertical deformation [*e.g., Tushingham and Peltier* 1991; *Peltier* 1994]. Preliminary results from the combination of CBN regional solutions in Canada exhibit a spatially coherent pattern of uplift consistent with the expected post-glacial rebound (PGR) signal (*refer to* Figure 6). Regions of highest uplift rates are generally consistent with areas of greatest ice accumulation during the last period of continental glaciation [*e.g., Dyke* 2004; *Peltier* 1994]. Horizontal velocities associated with PGR are also spatially coherent (typically directed radially outward from regions of highest uplift) but have smaller rates. These modest horizontal velocities can provide an important additional constraint to PGR models. However, the horizontal vectors may be significantly biased by differing reference system rotation-rate vectors (*e.g.*, Figures 4a & 4b). The definition of SNARF should minimize this issue. Eventually the deformation maps, coupled with PGR model predictions, may allow NRCan to interpolate or estimate coordinates at different epochs for regions that display spatial coherence in the velocity field.

3.4 Using Absolute Gravity to Monitor Uplift at CBN Sites

The integration of geodetic techniques is desirable when monitoring geodynamic processes (and simplifies any connections between corresponding reference standards). Absolute gravimetry (AG), which is independent of GPS, has demonstrated that it plays a complimentary role to GPS especially while measuring vertical crustal motions [*e.g., Lambert et al.* 2001]. In addition, repeated GPS and AG observations at common sites provide insight into the geophysical processes that drive the observed deformation since AG is sensitive to internal mass changes and not just deformation alone. Therefore, issues such as mass redistribution or changes in density contrasts within the Earth may be addressed by monitoring positional changes (*i.e.*, primarily height changes) and integrating these observations with gravitational variations. However, the observed rates of gravity change resulting from

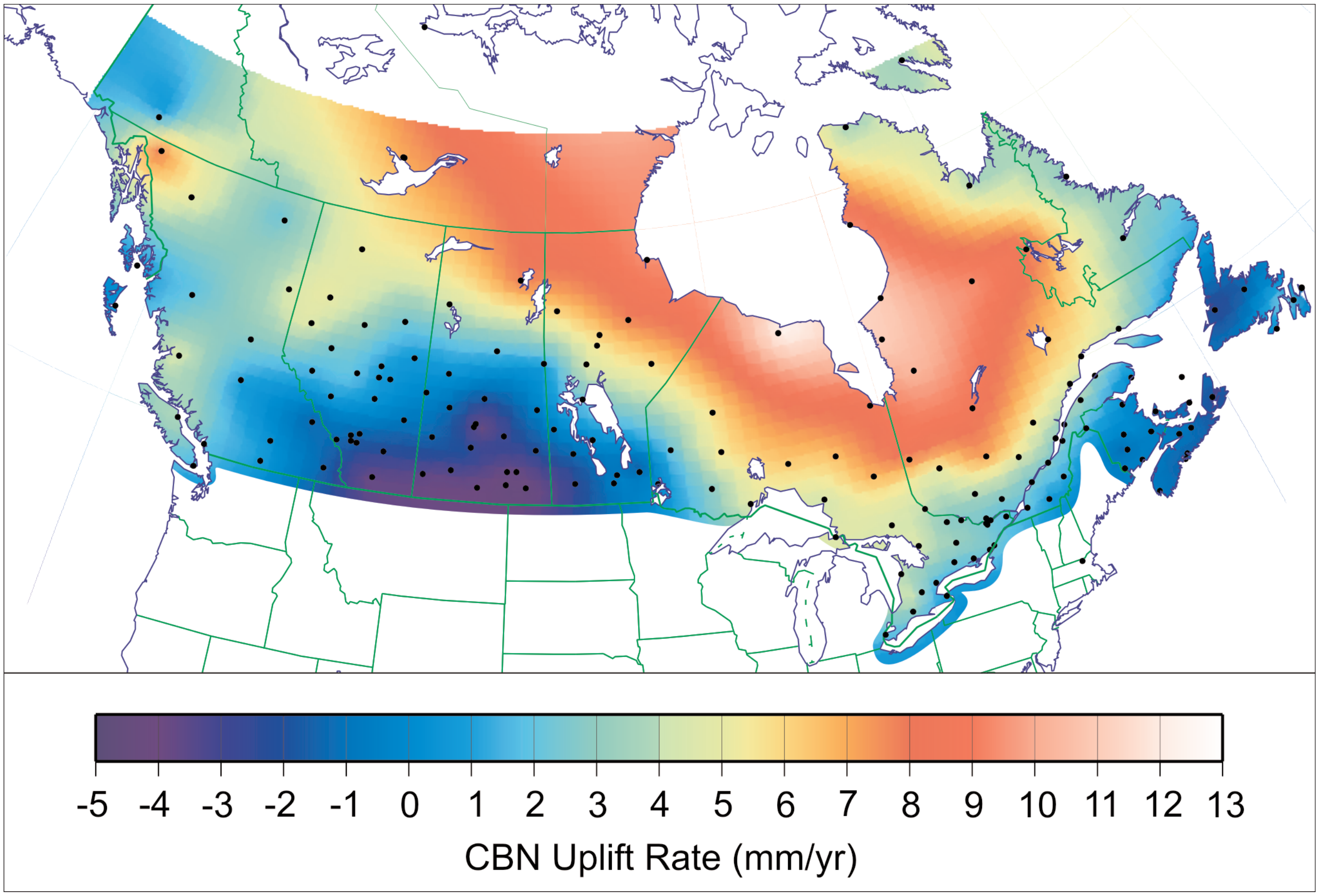

Figure 6: Contour map of observed CBN vertical rates. Preliminary results from the combination of CBN regional solutions in Canada exhibit a spatially coherent pattern of uplift consistent with the expected post-glacial rebound (PGR) signal. Black dots represent the locations of CBN sites.

post-glacial rebound in Canada are no greater than approximately -2 μGal/yr (one μGal is approximately one part-per-billion of the Earth's surface gravity). Observing such a small signal requires a suitable combination of high-precision and observation length. The principle of most modern absolute gravimeters is to observe (using laser interferometry) the acceleration of a free-falling test mass in a vacuum. This technique therefore requires very precise measurements of length and time over repeated "drops." Despite the simple fundamental principles, high-accuracy absolute gravimeters involve a great deal of instrumental and electronic sophistication. Properly operated and after careful processing, AG can provide the value of the Earth's gravity at a point with an accuracy of one part-per-billion, and the instruments can be maintained nearly drift-free. Also the AG instruments of the CSRS are tied to international standards through comparisons at the Bureau International des Poids et Mesures (BIPM). Continued improvements in absolute gravimetry have made these instruments more compact, robust, and efficient.

In order to monitor the temporal variations in gravity resulting from regional glacial isostatic adjustment, a set of absolute gravity measurement sites has been established in northern Quebec, collocated near pillars of the CBN. The Nouveau Quebec-Labrador region of eastern Canada was the site of one of the major ice domes of the Laurentide Ice Sheet [*e.g., Dyke* 2004; *Peltier* 1994] and is currently experiencing post-glacial rebound. For eastern Canada the highest uplift rates are in the vicinity of James Bay through to southwestern Labrador. Rates decrease to the south and become negative towards the coastal Atlantic margins. For post glacial rebound, surface gravity measurements sense the effect of increasing distance from the centre of mass of the earth (*i.e.* gravity decreases) coupled with the redistribution of mass due to viscous flow at great depth (increases gravity). The resulting regional gravity decrease associated with uplift due to post-glacial uplift is approximately -0.15 μGal/mm [*Lambert et al.* 2001]. Preliminary absolute-gravity trends for this region show decreasing gravity with time. Values range from about -2 μGal/yr (*i.e.* ~13 mm/yr for regional PGR) near Kuujjuarapik and Radisson and decrease southward to approximately -0.5 μGal/yr (~3 mm/yr) near Val d'Or. These preliminary results exhibit general agreement between the rates for GPS uplift velocities and gravity trends. Additionally, the observed (GPS & AG) rates are generally consistent with predictions of vertical crustal motion from post-glacial rebound models. To better contribute to the definition of the vertical component of a highly accurate, multi-purpose, active and integrated CSRS, efforts are now underway to create a sparse array of absolute gravity observation sites collocated with geometric reference (*i.e.* VLBI, continuous and episodic GPS) stations across Canada.

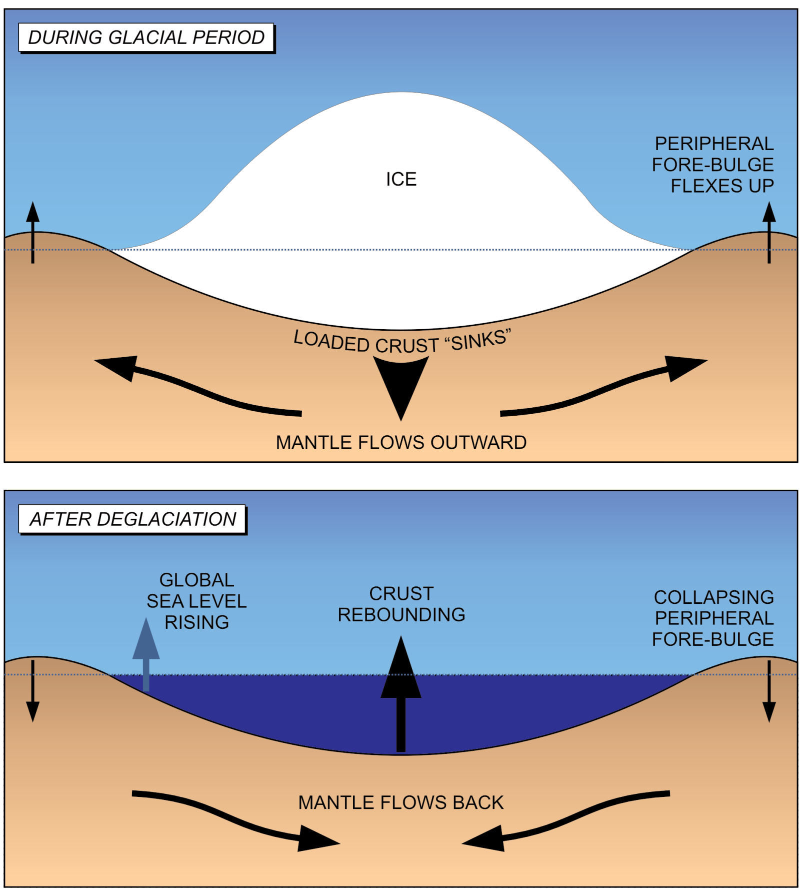

Figure 7: Generalized process of post-glacial rebound. The mantle acts like an extremely viscous fluid; it continues to flow back to regions where heavy ice sheets had forced out portions of the mantle 18,000 years ago. These regions, like northern Quebec, experience "post-glacial rebound." Around the edges of the ice sheet the crust flexes upward creating a peripheral fore-bulge. After deglaciation, the fore-bulge slowly collapses resulting in subsidence for regions such as the Maritimes.

4. Monitoring Relative Sea Level for Coastal Impact Studies

4.1 Introduction

As potential impacts of climate change and sea-level rise on coastlines depend in large measure on the localized rates of relative sea-level height change, it is important to quantify vertical deformation velocities in vulnerable coastal regions. The magnitude of the rate of relative sea-level change can be used to better understand future impacts (*e.g.* flooding, storm-surge levels). Sea level heights have traditionally been determined by tide gauges which measure the relative sea level height with respect to land. The long-term changes in relative sea level observed at tide gauges reflect both the vertical component of regional crustal kinematics and the change in the regional (and/or global) sea level surface. Through this linkage with relative sea level observations, understanding the kinematics of post-glacial rebound in vulnerable coastal areas is an important adjunct to relative sea level studies.

4.2 Eastern Canada

While most of the Canadian landmass is currently experiencing uplift associated with post-glacial isostatic adjustment, the Maritimes are experiencing subsidence. This is primarily due to collapse of the peripheral bulge following the deglaciation of the Laurentide Ice Sheet (*refer to* Figure 7), in addition to the effects of rising post-glacial sea level loading the continental shelf. The subsidence rates are not particularly large, typically on the order of -1 to -2 mm/yr. However they are of the opposite sign to sea level height change (on the order of +2 mm/yr) and consequently relative sea-level rise (with respect to land) is regionally more rapid. Sea-level rise can produce significant impacts in the coastal zone, particularly for low-lying parts of the Maritime Provinces [*e.g., Forbes et al.* 2004b]. These include storm impacts on the coast (waves, surges, and flooding), sediment movement and erosion hazards, impacts on ecological systems (*e.g.* coastal wetlands and fisheries), and damage to private or commercial property and public infrastructure [*e.g., O'Reilly et al.* 2005]. Work is underway within ESS to better quantify these hazards through the installation of additional geodetic infrastructure (*e.g.* new continuous GPS sites at select regional tide gauges).

4.3 Great Lakes

The Great Lakes is an important economic corridor where lower water levels can have significant impacts such as the need for expensive dredging of ports and harbours, and reduction in hydro-electric power generation. Additionally, elevated erosion rates have been evident in regions of the Great Lakes during previous higher water levels. These potential impacts ultimately depend in large measure on the rate of change of relative water-level heights with respect to land. Again, although the rate of crustal tilting driven by PGR is not particularly large, it steadily accumulates over time and can be clearly observed in water-level gauge records [*e.g., Mainville and Craymer* 2005]. This regional vertical deformation must be considered when evaluating long-term impacts on datums, water management, infrastructure, and basin ecology.

The regions north of the Great Lakes are rising faster than the regions to the south. In fact, much of the southern areas are part of the collapsing glacial "forebulge" and are experiencing subsidence. This on-going process of crustal "tilting" (*see* Figure 8) results in a pattern of slowly declining lake levels on northern shores with a commensurate rise in lake levels on southern shores. These relative changes of water level for a single lake can be resolved quite precisely from a long history of water gauge observations [*e.g., Mainville and Craymer* 2005]. However, it is difficult to accurately relate levels on one lake with those of another.

GPS stations have recently been established at Great Lakes water gauge sites in Canada by GSD in collaboration with the Ohio State University, and in the US by the US National Geodetic Survey. Combining these with other GPS measurements (*e.g.* the CBN) is enabling the determination of an accurate and spatially coherent pattern of absolute crustal velocities that is consistent with the expected rates of glacial isostatic adjustment. These results will enable lakes to be linked to each other as well as to sea level in support of bathymetry, hydraulic operations, and hydrological studies in the Great Lakes Basin.

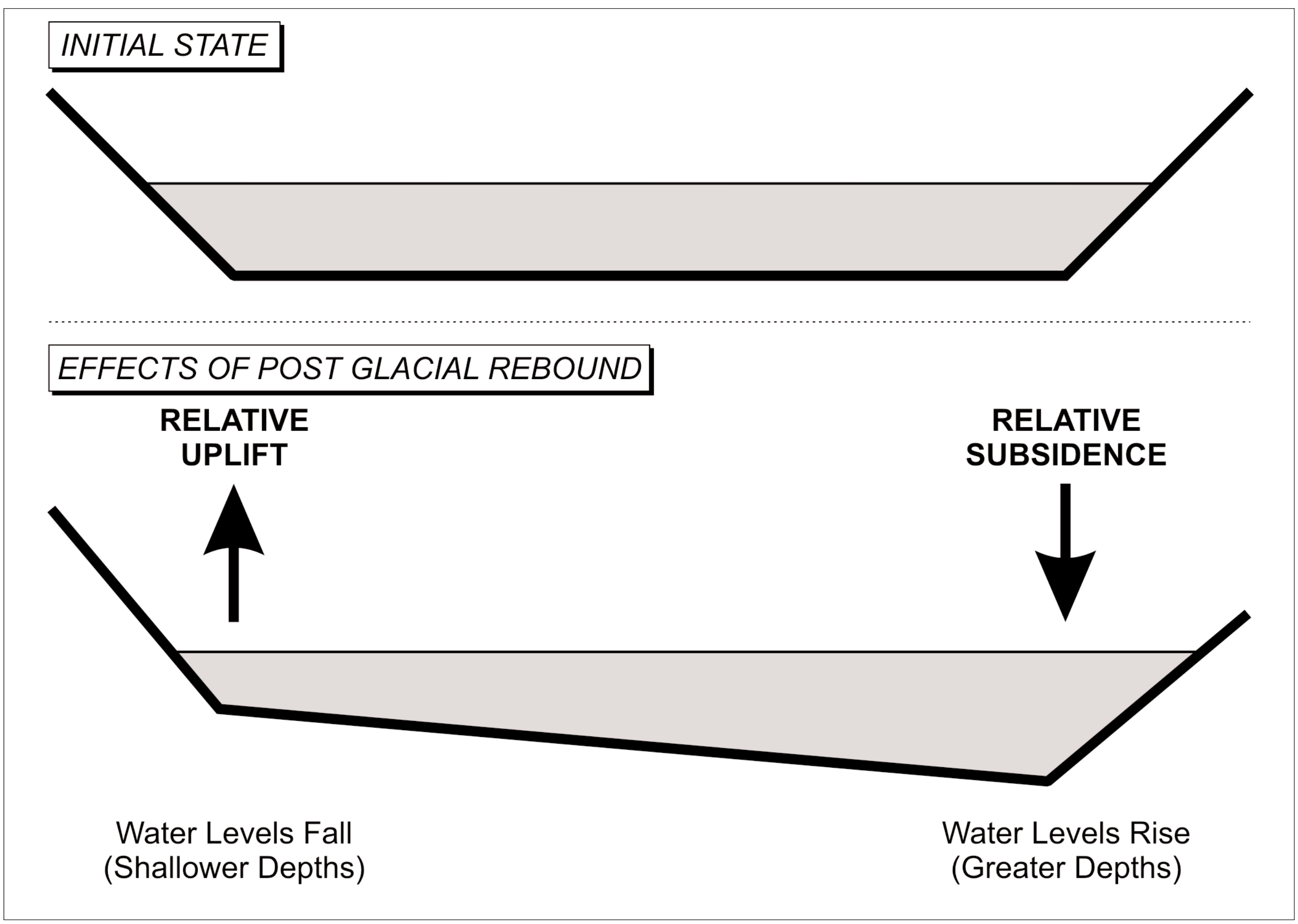

Figure 8: Glacial isostatic effects along lake shorelines. In addition to the effect of "tilting" generalized in this illustration, on-going changes in average water level may also contribute to the impact on vulnerable coastal regions.

4.4 Arctic Canada

Observed climate warming in the Arctic may lead to increases in Arctic Ocean sea level [*Proshutinsky et al.* 2001]. Sea-level rise increases the flooding risk and is a clear concern for coastal communities such as Tuktoyaktuk [*Manson et al.* 2005]. Furthermore the coastal area subject to rising relative sea level is expected to expand [*Forbes et al.*, 2004a]. With recent infrastructure development associated with hydrocarbon production in the Mackenzie River delta region, this work has become more timely. As the impacts on coastlines ultimately depend in large measure on the localized rate of relative sea level height change, it is important to better quantify crustal deformation velocities throughout coastal northern Canada. Inherent to this study is the need to better map the observed pattern of PGR throughout northern Canada in order to more tightly constrain post-glacial isostatic adjustment models.

To provide a framework in which to monitor these changes, a consistent velocity field will be determined from GPS observations throughout North America, including the Canadian Arctic Archipelago and the Mackenzie Delta region. To determine the contribution of vertical motion to sea-level rise under climate warming in the Canadian Arctic, ESS in collaboration with the Canadian Hydrographic Service has established collocated tide gauges and continuous GPS at a number of sites across the Canadian Arctic, from Alert and Qikiktarjuaq in the east to Ulukhaktok (Holman) and Tuktoyaktuk in the west. The continuous GPS sites have been augmented with multi-epoch (episodic) sites in places such as Kugluktuk (Coppermine) and Mercy Bay (northern Banks Island). This expanded network will further enhance regional geophysical studies including the discrimination of crustal motion, other components of coastal subsidence, and sea-level rise.

5. Campaign GPS Constraints on Regional Tectonics and Seismicity

5.1 Introduction

GPS and other geodetic measurements of crustal deformation provide an important new tool for estimating earthquake hazard. In addition to the standard method of earthquake hazard based on past earthquake statistics, it is now possible to relate current deformation rates to the frequency of large earthquakes. Both continuous and campaign GPS stations have been established for earthquake hazard in four areas, the western Canada subduction zone, the Queen Charlotte transform fault zone, the Yukon crustal deformation region, and the eastern Canada region of high seismicity.

As a complement to a network of continuous GPS stations, campaign GPS surveys provide an economical way to obtain a denser map of crustal deformation. Major limitations associated with campaign GPS measurements are: (1) lack of resolution of short-term (less than one year) deformation episodes, and (2) less accurate estimates of long-term velocities. Relative velocities across tectonically active regions are typically of the order of 5 - 50 mm/yr, which can generally be resolved with campaign GPS data acquired every year over a three to five year period. In the following sub-sections, two examples of campaign surveys in western Canada (Queen Charlotte Margin and Northwestern Canada, investigated in collaboration with University of Victoria) are described, where the relative motions are associated with plate boundary interactions and strain transfer within the Canadian Cordillera.

In contrast, relative velocities across intraplate (tectonically stable) regions are typically less than 1 mm/yr. Such relative motions are at the current limit of resolution of GPS measurements. An example of a GPS survey (in collaboration with Université Laval) of intraplate deformation at the eastern edge of the Canadian Shield along the lower Saint Lawrence Valley is presented. In all of the examples within this section, typical surveys consisted of measurements of two to three full days at each site. The data, along with data from nearby continuous stations, were processed at the Pacific Geoscience Centre (Geological Survey of Canada—Pacific Division, Sidney, BC) with the Bernese GPS Software package. Processing details can be found in the publications referenced in each section.

5.2 The Queen Charlotte Margin

Since mid Eocene (*ca.* 42 Ma), the Queen Charlotte (Q.C.) margin has been primarily under a strike-slip tectonic regime associated with the Pacific-North America relative motion [*Hyndman and Hamilton* 1993]. At about 5 Ma, a small change in the Pacific-America relative motion resulted in the current oblique convergence along Q.C. margin. A wide range of geophysical data indicates a component of convergence and possibly under-thrusting along the southern Q.C. margin (*e.g.* high offshore heat flow, seismic structure studies) [*Smith et al.* 2003]. The seismicity shows primarily strike-slip faulting (*e.g*. the great M=8.1 earthquake of 1949), although there are some thrust mechanisms near the southern end of the islands.

In 1998, NRCan established a small local network of five campaign GPS sites in the central and north-eastern Q.C. Islands. These sites were re-surveyed in 1998 and 2001 [*Mazzotti et al.* 2003a]. In 2002, three new sites along the west coast of the islands and one on the mainland at Prince Rupert were then added [*Bustin et al.* 2004]. The full network (nine sites) has been surveyed every year from 2002 to 2005. These campaign GPS network sites were augmented by the continuous station at Williams Lake, to provide a stable tie to the North America plate, and campaign measurements from the Canadian Base Network sites in northern British Columbia, to provide some constraints for the kinematics of the central Cordillera. The GPS velocity field, with respect to North America, indicates oblique convergence along the Q.C. margin, with relative motion of 5 - 10 mm/yr directed mostly northward (*refer to* Figure 9). The landward gradient in left lateral shear (*i.e.* decrease in margin-parallel motion) shows that the Q.C. fault is currently locked and is building up strain until the next large earthquake rupture [*Mazzotti et al.* 2003a]. The results also show that a small component of the Pacific-North America oblique convergence (~10 per cent) is probably accommodated by distributed shear across the Q.C. margin and possibly in mainland [*Mazzotti et al.*, 2003b]. A possible interpretation is that this oblique convergence is accommodated mainly by partitioning into strike-slip earthquakes on the Q.C. fault and infrequent large under-thrusting earthquakes beneath the margin [*Bustin et al.*, 2004]. Thus, the earthquake hazard along the Q.C. margin may be higher than current estimates based solely on an active transcurrent Q.C. fault.

5.3 The Yukon & Northwestern Canada

Northwestern Canada is known for the intense tectonism during the Mesozoic (*ca.* 250 to 65 Ma) associated with the accretion and deformation of the different terranes that form the Canadian Cordillera. No sign of significant tectonic activity has been recorded along the major faults and deformation zones in most of northwestern Canada for the last ~50 Myr. In contrast, the southwestern Yukon Territory and adjacent Alaska Panhandle region is the locus of intense deformation due to the collision of the Yakutat block, a composite oceanic-continental terrane that is currently being accreted in the corner of the Gulf of Alaska. This collision produces the highest mountain ranges in Canada (*e.g.* St. Elias range and Mount Logan). Earthquake activity is very high in this collision zone including several M~8 events, but surprisingly substantial seismicity also occurs in the far-field Mackenzie and Richardson Mountains, around 800 kilometres northeast of the collision zone [*Mazzotti and Hyndman* 2002; *Hyndman et al.* 2005]. The Mackenzie Mountains appear to be undergoing NE-SW shortening, while N-S right-lateral strike-slip deformation is occurring in the Richardson Mountains.

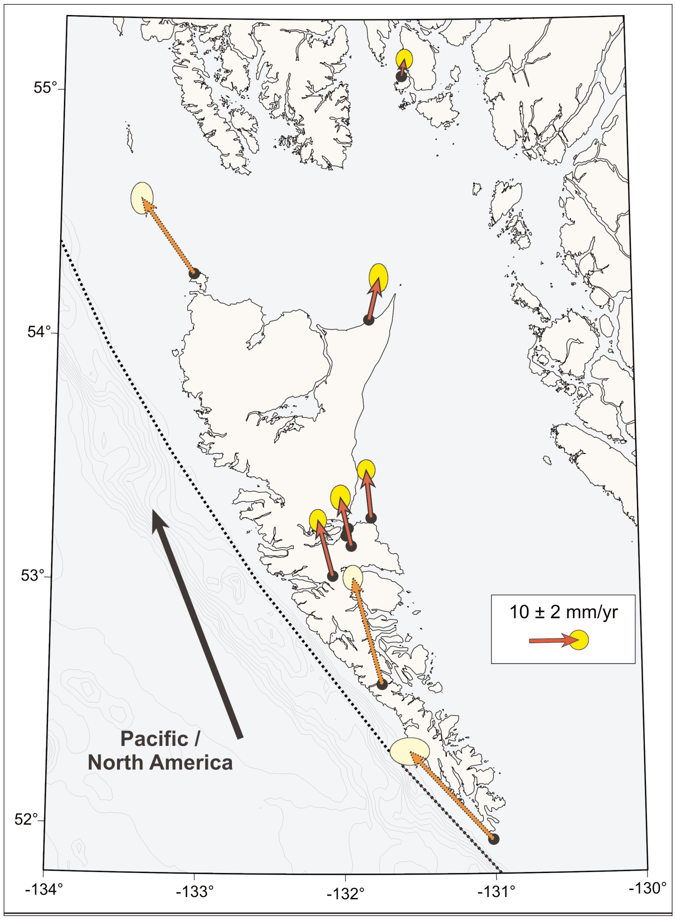

Figure 9: GPS velocities along the Queen Charlotte margin. Red and orange vectors show velocities with respect to stable North America for campaign sites with five years of data or more and three years of data, respectively. Uncertainty ellipses show the 95 per cent confidence region. The large black vector shows the motion (from the rotation vector of *DeMets and Dixon* [1999]) of the Pacific plate relative to North America.

In order to understand the details of the whole northwestern Canada tectonics and seismicity, NRCan started a campaign GPS survey in 1999 across the Yukon and Northwest Territories. The current network comprises 20 campaign GPS sites, supplemented by a larger network of 28 continuous GPS stations from British Columbia to Alaska [*Leonard et al.* 2005]. The campaign sites were surveyed at four or five epochs since 1999. The interpretation of these results have been complicated by the occurrence of the very large (magnitude M~8) Denali earthquake in December 2002. Coseismic and post-seismic displacements related to this earthquake at our GPS sites reach a few centimetres and create an offset that needs to be removed in order to estimate the long-term velocities of our sites. Overall, the continuous and campaign GPS velocities are consistent with the transfer of compressive strain (~5 mm/yr) across the northern Canadian Cordillera to the foreland fold-and-thrust belt with little intervening deformation [*Mazzotti and Hyndman* 2002; *Leonard et al.* 2005] (*see* Figure 10). These results indicate that the whole northern Cordillera is currently part of the large-scale Pacific-North America plate boundary zone and accommodates about 10 per cent of the full relative plate motion.

5.4 The Lower Saint Lawrence Valley

The Saint Lawrence Valley, Quebec, presents one of the largest concentrations of earthquakes in eastern North America. Background seismicity extends over 900 kilometres from the Gulf of Saint Lawrence to Montreal following the Paleozoic Iapetan Rift system [*e.g., Adams and Basham* 1991; *Lamontage et al.* 2003]. Two main seismic zones occur along this trend: Charlevoix, the most active in eastern Canada and the locus of at least five M6+ earthquakes in the last 350 years; and lower Saint Lawrence, where the largest known earthquakes are about M5. Integration of earthquake moment statistics in both zones indicates that the equivalent seismic deformation rates are 1.0 ± 0.5 mm/yr and 0.2 ± 0.3 mm/yr, respectively [*Mazzotti and Adams* 2005; *Mazzotti et al.* 2005].

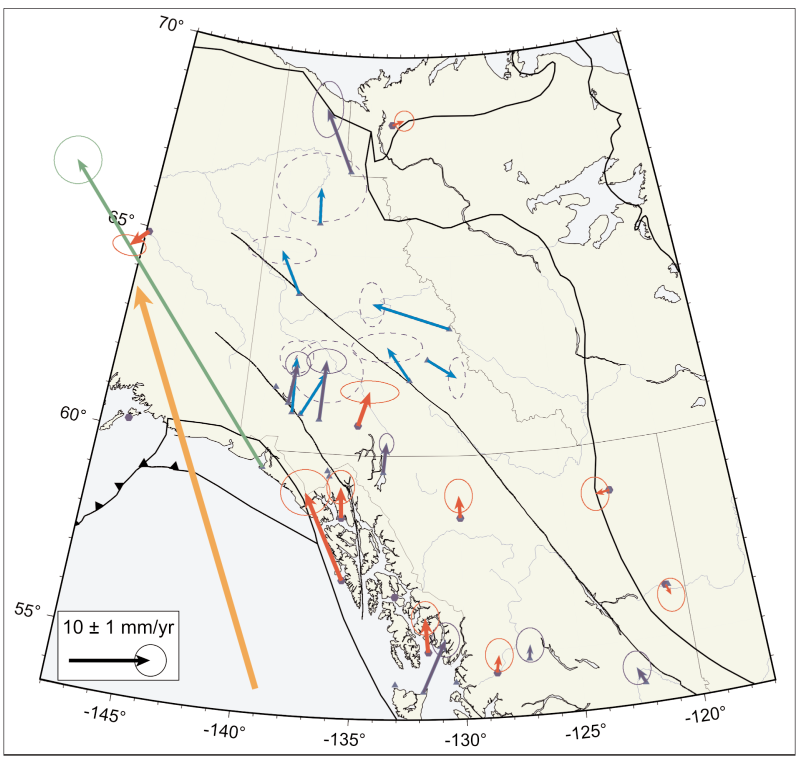

Figure 10: GPS velocities in northwestern Canada. Red and blue vectors show velocities with respect to stable North America for continuous and campaign GPS sites, respectively. The green vector shows the Yakutat site GPS velocity. Uncertainty ellipses show the 95 per cent confidence region. The large orange vector shows the Pacific/North America relative motion from *DeMets and Dixon* [1999].

Unlike plate margins where the seismic activity is directly correlated with plate interactions, eastern Canada earthquakes lie in the "stable" interior of the North American Plate. The driving mechanisms behind of these earthquakes are thus more difficult to determine. Additionally, the hazard posed by potentially devastating earthquakes for this region is not well constrained due to limitations with the probabilistic seismic hazard estimation method (*e.g.* the inexact nature of extrapolating the rate of occurrence of frequent small events to the occurrence of infrequent larger events, relatively short instrumental and historical records, and limited paleoseismic evidence for past large events).

In 2003, NRCan started a new program to study the geodynamic aspects of earthquake hazard in eastern Canada. The study [*Mazzotti et al.* 2005] used the existing network and data for the Canadian Base Network and added an additional survey to a network of 16 stations surrounding the Saint Lawrence Valley. These high-precision campaign data provide relative velocities and strain rates across both the Charlevoix and lower Saint Lawrence seismic zones based on three to four campaigns over the last seven to nine years. On a regional scale, horizontal strain rates are 0.5-2 nanostrain per year of roughly NNW-SSE shortening (*refer to* Figure 11). This strain pattern agrees well with earthquake focal mechanisms. Horizontal velocity vectors on both sides of the Saint Lawrence River suggest that this shortening corresponds to a maximum convergence of 0.5 ± 0.5 mm/yr between the north and south shores, in general agreement with the rate from earthquake statistics. Assuming that seismicity in Charlevoix follows typical Gutenberg-Richter statistics, the GPS results constrain the return of a potentially very damaging magnitude M~7 earthquake to ~170 years.

6. Monitoring Crustal Motions at an Active Plate Boundary with Continuous GPS

6.1 Introduction

The coastal region of southwestern British Columbia comprises the northern portion of the

Cascadia Subduction Zone (CSZ) that forms the convergent plate boundary between the Juan de Fuca and North America plates. This boundary is marked by extensive earthquake activity as well as a belt of active arc volcanoes stretching from northern California to southwest British Columbia. Special aspects of this subduction zone are the relative youth of the subducting oceanic crust, which ranges from six to 10 Ma at the oceanic trench, and a modest convergence rate of under 40 mm/yr. Seismic, thermal, and geodetic studies have determined that the shallower interface of the CSZ is locked, and that stress is accumulating for the next great subduction thrust earthquake. From paleoseismic evidence, such great events occur every 500 to 600 years, the last having occurred in 1700.

The monitoring of crustal motions along the coastal margin of southwestern BC using continuous GPS stations was initiated on Vancouver Island in 1992 with sites established in Victoria (ALBH) and Holberg (HOLB) [*Dragert and Hyndman* 1995]. These sites, along with a reference site near Penticton (DRAO), form the basis of the Western Canada Deformation Array (WCDA) which now consists of 16 stations in southwestern BC. Using low-multipath antennas mounted on stable geodetic monuments, the relative position of these stations hundreds of kilometres apart can be monitored on a daily basis to an accuracy of a few millimetres. This level of accuracy allows the resolution of long-term crustal movement associated with major plate motions as well as the relative squeezing and buckling of the plate margins. More recently, GPS data from a number of WCDA stations have also revealed transient crustal motions that are related to repeated slow slip on the deeper subducting plate interface.

6.2 Long-term Deformation

Analyses of GPS data from WCDA sites have confirmed that long-term elastic deformation occurs along the northern Cascadia Margin due to the locking of converging plates across a portion of the subduction interface between the Juan de Fuca (JDF) plate and the overlying North America (NA) plate [*cf. Flueck et al.* 1997; *Mazzotti et al.* 2003c]. The motion vectors shown in Figure 12, the largest exceeding 1 cm/yr, are based on the linear trends in the time series of changes in horizontal positions of GPS sites with respect to the reference site DRAO, located south of Penticton, British Columbia, and assumed fixed on the NA plate. The pattern of the regional crustal velocity field is a key constraint in determining the location and extent of the locked fault zone - *i.e.* that portion of the fault that will ultimately rupture in a great subduction-thrust earthquake [*cf. Wang et al.* 2003]. For the northern Cascadia margin, the fully locked portion of the subducting plate interface lies offshore beneath the continental slope and the "transition zone," marked by a transition from fully-locked to free-slipping plates, terminates directly beneath the coastline of Vancouver Island and the western edge of the Olympic Peninsula. The landward extent of the incipient rupture zone for the next megathrust earthquake is a key parameter for estimating strong motions that can be expected in the densely populated areas of Vancouver and Seattle from such an earthquake.

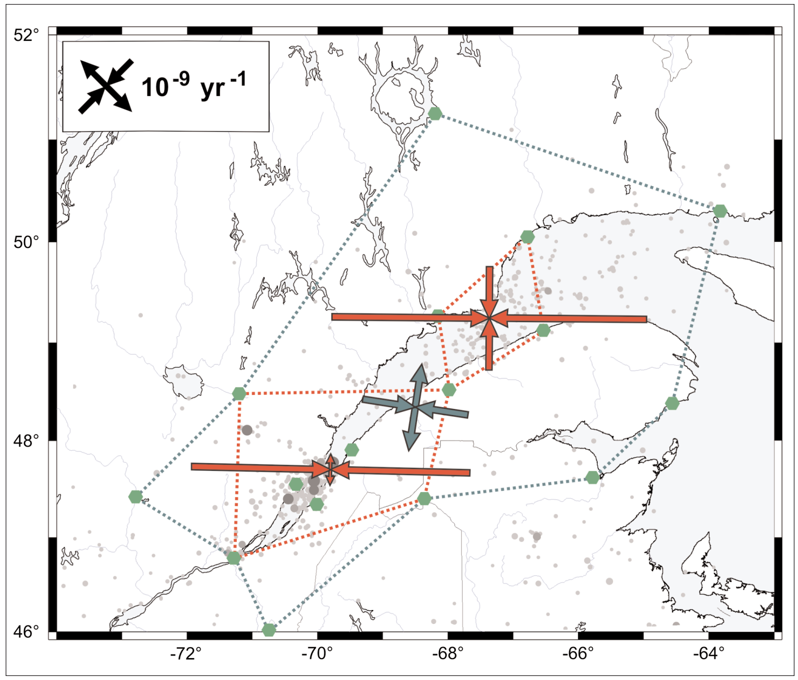

Figure 11: GPS horizontal strain-rates for the Saint Lawrence seismic zones. Dark cyan arrows show the average horizontal principal strain rates for the network (spatial extent given by dotted grey polygon). Red arrows show the horizontal principal strain rates for sub-networks around the Charlevoix and lower Saint Lawrence seismic zones (spatial extent given by dotted red polygons). Light grey circles indicate the pattern of regional seismicity [after *Mazzotti et al.* 2005].

6.3 Episodic Tremor and Slip

Improvements in the accuracy of IGS precise orbits and the regional densification of continuous GPS coverage were two key factors leading to the discovery of a "silent" slip event that occurred along the Cascadia Subduction Zone in August 1999 [*Dragert et al.* 2001]. Analysis of GPS data from 1994 to 2005 has revealed that the motions of continuous GPS sites in northern Washington State and southern Vancouver Island are marked by numerous, brief, episodic reversals. This is best illustrated by the east-component time series at the

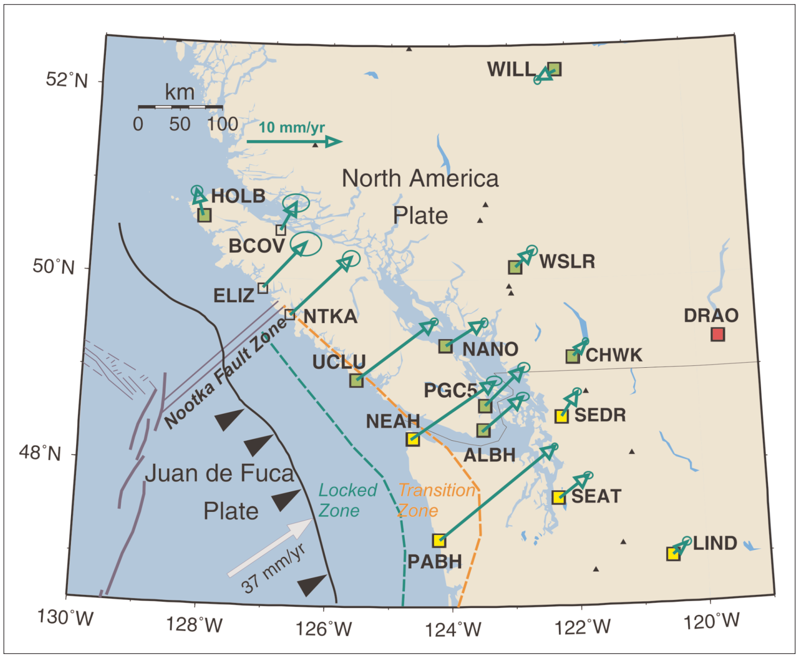

Figure 12: Long-term velocities of regional continuous GPS sites. Three to 10-year linear trends in the horizontal position with respect to Penticton (DRAO) for some of the sites of the Western Canada Deformation Array (WCDA: green squares) and the Pacific Northwest Geodetic Array (PANGA: yellow squares) are plotted by green arrows with 95 per cent error ellipses. The position of the strongly coupled zone determined from slip-dislocation models is indicated by the locked and transition zones. The convergence vector of the Juan de Fuca plate is with respect to the North America (NA) plate, and the GPS reference station DRAO is assumed fixed on the NA plate [from *Dragert et al.* 2004].

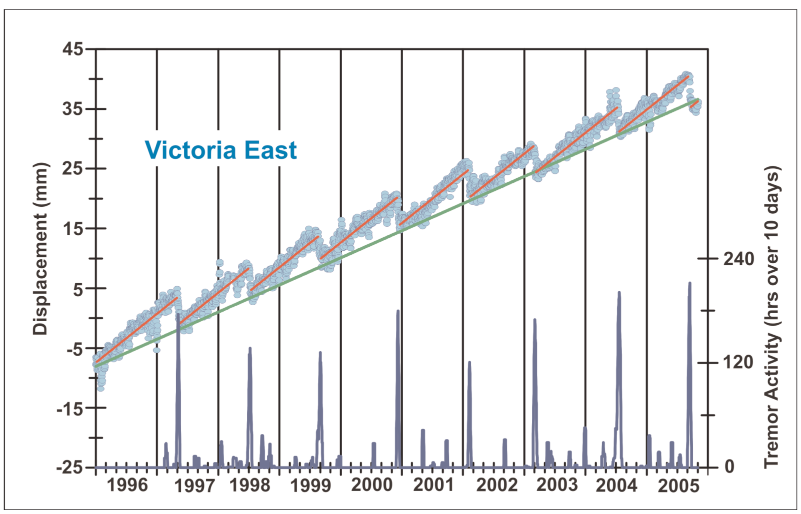

Figure 13: Record of slip and tremor activity observed for the Victoria area. Blue circles show day-by-day change in the east component of the GPS site ALBH (Victoria) with respect to DRAO (Penticton) which is assumed fixed on the North America plate. Continuous green line shows the long-term (interseismic) eastward motion of the site. Red line segments show the mean elevated eastward trends between the slip events which are marked by the reversals of motion every 13 to 16 months. Bottom graph shows the total number of hours of tremor activity observed for southern Vancouver Island within a sliding 10-day period. Ten days corresponds to the nominal duration of a slip event. Pronounced tremor activity coincides precisely with slip events.

Victoria GPS site (ALBH) where the motion relative to DRAO is clearly characterized by a sloped saw-tooth function: For periods of 13 to 16 months, there is eastward motion that is more rapid than the long-term rate, followed by a one to three week period of reversed motion (*refer to* Figure 13). These transient reversals of motion are surprisingly regular events, having a recurrence interval of 445 ± 35 days. The cumulative displacements over the two-week periods of these transient events is generally less than six millimetres, in a direction opposite to the longer-term deformation motion. For the longer-lasting events, station displacements were not simultaneous at all coastal margin sites but appear to migrate along strike of the subduction zone at speeds ranging from 5 to 15 km/day. These transient events are accompanied by distinct, low-frequency tremors [*e.g., Rogers and Dragert* 2003], similar to those reported in the forearc region of southern Japan [*Obara*, 2002]. The one-to-one correspondence of slip events with pronounced tremor activity prompted the naming of this phenomenon as "Episodic Tremor and Slip" (ETS) [*Rogers and Dragert* 2003].

The transient surface displacements can be replicated by simple slip-dislocation models if one adopts the subduction interface geometry from *Flueck et al.* [1997] and assumes that slip occurs at the plate interface and consists of updip motion of the overlying crustal block. Figure 14 shows modelling results for four of these events. The good agreement between observed and modeled displacements shows that the transient motions can be represented by simple slip on the subducting plate interface between depths of 25 and 45 km, with the slip region parallel to the strike of the subducting plate. The downdip boundary appears to be sharper whereas the updip boundary is more diffuse, requiring a gradual tapering of the slip amplitude. Although the maximum slip is only a few centimetres per event, the large area of slip generates an equivalent moment magnitude for these "slow earthquakes" ranging from 6.5 to 6.8.

Although the physical processes involved are not well understood, Figure 15 outlines the conceptual kinematic model for ETS on the northern CSZ. Both offshore and at greater depths (>50 km), the two plates converge steadily at ~4 cm/yr, the geological average rate. Across the shallower interface, the plates are locked for centuries, moving catastrophically past each other only at times of great thrust earthquakes. At depths of 25 to 45 km, plates resist motion temporarily for ~14 months accumulating some stress, and then slip the equivalent of a few centimetres over periods of one to two weeks releasing that small stress accumulation. This release is accompanied by unique seismic tremors on and above the region of slip. In the context of seismic hazard, the recognition of this ETS slip zone has two significant implications. First, since the repeated slip events define a region where little or no shear stress accumulates over longer periods of time, the updip edge of the slip zone can serve as a proxy for the maximum downdip (*i.e.* landward) extent for subduction thrust rupture. This can be used to improve estimates of strong motion in the densely populated regions of southwest BC. Secondly, it can be shown that the occurrence of slip on this deeper part of the plate interface adds stress to the shallower portion of the locked plate interface, driving it closer to rupture in discrete increments. Consequently, during the time of slip, the weekly cumulative probability of a megathrust earthquake is significantly greater than at times between slip events [*Mazzotti and Adams* 2004]. This provides, for the first time, a potential basis for time-dependent seismic hazard estimates.

7. Summary

Geophysical processes systematically affect the spatial reference frames used for geodetic surveys. Geodynamic rates in most of Canada (*i.e.* away from active plate margins) are generally rather modest (typically 1-2 cm/yr). However, when highest accuracy is required, the measurable effects of geodynamic processes must be considered. When evaluating the effect on reference frames within a given

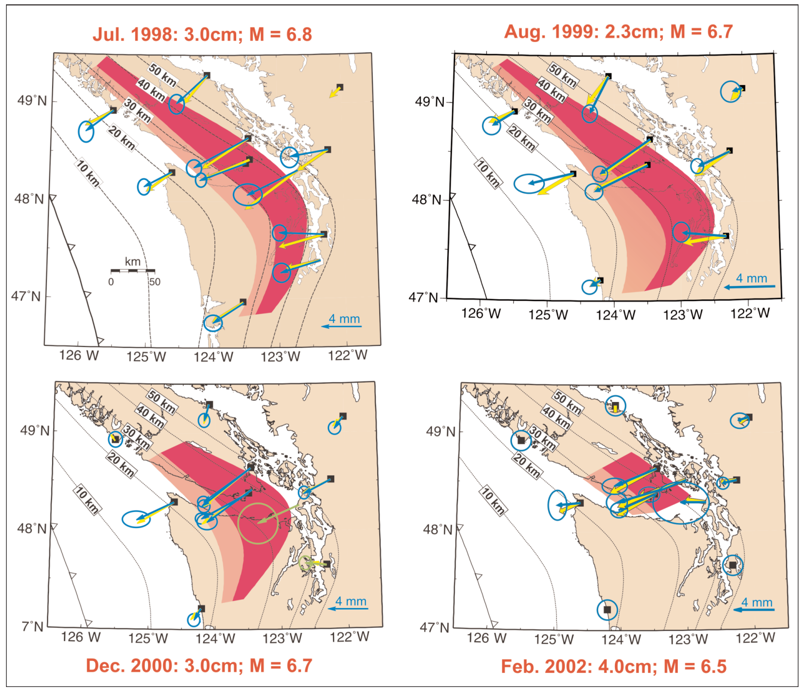

Figure 14: Models for slow slip events. The geometry of the subducting plate interface established from structural studies [*Flueck et al.*, 1997] is adopted, and simple linear slip distribution directed up-dip is assumed. The four panels illustrate the results of elastic dislocation modelling [*Okada*, 1985] of four recent slip events. Blue arrows show observed horizontal surface displacements with 95 per cent error ellipses that were used to constrain the models; green arrows show surface displacements obtained from separate analyses and not used in model constraint; yellow vectors show model displacements. Dark shading indicates fault areas with full slip whose magnitudes are shown in panel headers; light shading indicates fault areas where slip is tapered linearly from full to zero at the up-dip end. Also shown are equivalent moment-magnitudes assuming a rigidity of 40 Gpa [from *Dragert et al.* 2004].

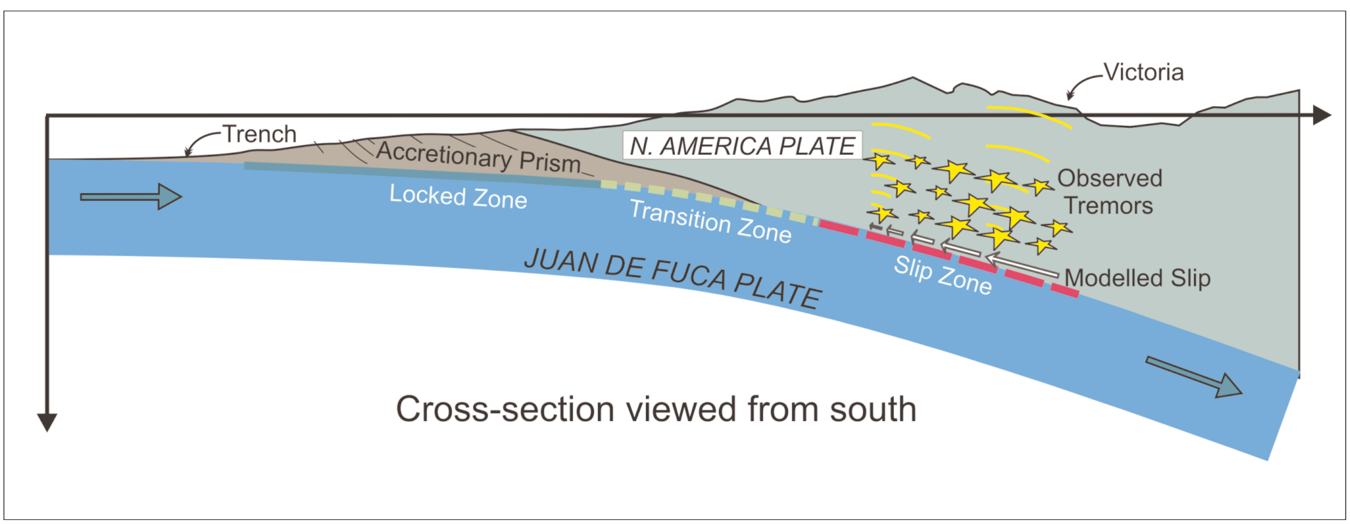

Figure 15: Cross-section of a conceptual model for CSZ plate-interface kinematics. The blue region represents the subducting Juan de Fuca plate and the green and brown regions, the overlying margin of the North America plate. Seaward of the trench (to the left of the diagram) and landward of Victoria (to the right), the plates converge continuously. Beneath the continental slope, mostly comprised of the accretionary prism, the plates are fully locked thereby causing an accumulation of stress that will be released in the next megathrust earthquake. At depths of 25 to 45 km, plates resist motion temporarily for ~14 months and then slip a few centimetres over periods of one to two weeks, accompanied by distinct seismic tremors (yellow stars). The transition zone marks the region on the plate interface where a transition from "locked" to "stick-slip" behaviour occurs.

area it is important to note how kinematic processes operate on various spatial scales.

Within regions of particular interest (*e.g.* earthquake hazards), NRCan has complemented the CSRS and installed additional geodetic infrastructure to monitor specific geodynamic processes. An observation strategy for geodynamics based mainly on GPS should optimize both the accuracy of results and the use of complementary data sets from independent techniques where tenable (*e.g.* absolute gravity, tide gauges). All geodynamic investigations require a long-term commitment to systematic monitoring in order to determine the relatively small kinematic rates and to subsequently develop useful quantitative models. Many years of observations are therefore invaluable and often required to better understand the particular regional geodynamic processes. Furthermore, the data and results can be used to improve the realization and maintenance of national NAD83(CSRS) reference frame for the general georeferencing community.

For much of the Canadian landmass the most significant crustal movement is vertical motion, as demonstrated by current models and analyses of post-glacial rebound. Post-glacial isostatic adjustment, whose maximum uplift rates occur generally near Hudson Bay, is a process that is evident throughout much of Canada. Crustal tilt associated with post-glacial rebound can, albeit slowly, affect water resources and alter risks associated with flooding. Of specific practical importance are changes in relative sea level for coastal areas including regions that may be particularly vulnerable to climate change such as arctic regions. It is therefore highly useful to monitor and confirm coastal height variations at geodetic reference stations over time.

Seismic activity in intraplate zones tends to be related to the regional stress fields, with earthquakes concentrated in regions of crustal weakness. Horizontal strain rates can be directly related to the frequency of large earthquakes. Vertical motions may provide additional insight into the regional seismic process. Thus the occurrence of large earthquakes in active seismic regions of eastern Canada (e.g. lower Saint Lawrence Valley, Charlevoix, and Ottawa Valley) can be better characterized through long-term precise geodetic monitoring.

Detailed regional surveys continue to map the crustal deformation field associated with the geophysical processes in Canada noted above. For regions with active seismicity and/or faults, measurements of crustal deformation supply direct information on crustal-strain accumulation which is essential for studies of tectonic and seismogenic processes and is increasingly used in seismic hazard assessments. Particularly exciting was discovery of the “silent-slip” phenomenon along the Cascadia subduction-zone interface. This was first observed within the time-series of precise, continuous GPS measurements on Canada’s west coast and its implications continue to be explored.

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References and Bibliographies

Adams, J. and P.W. Basham. 1991. The seismicity and seismotectonics of eastern Canada, in Neotectonics of North America, Slemmons, D.B., E.R. Engdhal, M.D. Zoback and D.D. Blackwell (eds.), *Geol. Soc. Amer. Decade Map* Vol. 1, Boulder CO, pp. 261-276.

Altamimi, Z., D. Angermann, D. Argus, G. Blewitt, C. Boucher, B. Chao, H. Drewes, R. Eanes, M. Feissel, R. Ferland, T. Herring, B. Holt, J. Johannson, K. Larson, C. Ma, J. Manning, C. Meertens, A. Nothnagel, E. Pavlis, G. Petit, J. Ray, J. Ries, H-G. Scherneck, P. Sillard and M. Watkins. 2001. The terrestrial Reference Frame and the dynamic Earth, *Eos Trans AGU*, 82(25), pp. 273, 278-279.

Altamimi, Z., P. Sillard and C. Boucher. 2002. ITRF2000: A new release of the International Terrestrial Reference Frame for earth science applications, *J. Geophys. Res.*, vol. 107, 2214, doi:10.1029/2001JB000561.

Blewitt, G., D. Argus, R. Bennett, Y. Bock, E. Calais, M. Craymer, J. Davis, T. Dixon, J. Freymueller, T. Herring, D. Johnson, K. Larson, M. Miller, G. Sella, R. Snay and M. Tamisiea. 2005. A Stable North American Reference Frame (SNARF): First Release, *Joint UNAVCO/IRIS Workshop (Proceedings)*, Stevenson, WA, USA, June 9-11.

Blewitt, G. 1997. IGS Densification Program, *IGS 1996 Annual Report, International GPS Service*, pp. 24-25.

Boucher, C., Z. Altamimi, P. Sillard and M. Feissel-Vernier. 2004. The ITRF2000, (IERS Technical Note; 31) Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 2004. 289 pp., paperback, ISBN 3-89888-881-9.

Bustin, A.M., R.D. Hyndman, J. Cassidy and S. Mazzotti. 2004. Strain Partitioning of Oblique Convergence: Initiation of Subduction on the Queen Charlotte Margin?, *Eos Trans. AGU*, 85(17), Jt. Assem. Suppl., Abstract T31C-02.

Craymer, M.R. and M. Piraszewski. 2001. The North American Reference Frame (NAREF): An Initiative to Densify the ITRF in North America, *Proceedings of KIS 2001: International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation*, Banff, Canada, June 5-8.

DeMets, C. and T.H. Dixon. 1999. New kinematic models for Pacific-North America motion from 3 Ma to present, I: Evidence for steady motion and biases in the NUVEL-1A model, *Geophys. Res. Lett.*, vol. 26, pp. 1921–1924.

Dragert, H. and R.D. Hyndman. 1995. Continuous GPS monitoring of elastic strain in the northern Cascadia subduction zone, *Geophys. Res. Lett.*, vol. 22, pp. 755-758.

Dragert, H., K. Wang and G. Rogers. 2004. Geodetic and Seismic Signatures of Episodic Tremor and Slip in the Northern Cascadia Subduction Zone, *Earth Planets Space*, vol. 56, 1143-1150.

Dragert, H., K. Wang and T.S. James. 2001. A Silent Slip Event on the Deeper Cascadia Subduction Interface, *Science*, vol. 292, pp. 1525-1528.

Dyke, A.S. 2004. An outline of North American deglaciation with emphasis on central and northern Canada, *Quaternary Glaciations - Extent and Chronology, Part 2, North America*, ed. J.Ehlers and P.L. Gibbard, Elsevier.

Ferland, R., Z. Altamimi, C. Bruyninx, M. Craymer, H. Habrich and J. Kouba. 2003. IGS Position Paper: Regional Networks Densification, *Proceedings of the IGS Network, Data and Analysis Center Workshop, Ottawa, April 8-11,* IGS Central Bureau, Jet Propulsion Laboratory, Pasadena CA, pp. 123-132.

Flueck, P., R.D. Hyndman and K. Wang. 1997. Three-dimensional dislocation model for great earthquakes of the Cascadia Subduction zone, *J. Geophys. Res.*, vol. 102, pp. 20539-20550.

Forbes, D.L., M. Craymer, S.M. Solomon and G.K. Manson. 2004a. Defining limits of submergence and potential for rapid coastal change in the Canadian Arctic, *Rep. Polar and Marine Res (Alfred Wegener Institute)*, vol. 482, pp. 196-202.

Forbes, D.L., G.S. Parkes, G.K. Manson and L.A. Ketch. 2004b. Storms and shoreline retreat in the southern Gulf of St. Lawrence. *Mar. Geol.*, vol. 210, pp. 169-204.

Henton, J.A., M.R. Craymer, M. Piraszewski and E. Lapelle. 2004. Crustal Deformation Velocities From Episodic Regional Measurements at Canadian Base Network Sites, *Eos Trans. AGU*, 85(47), Fall Meet. Suppl., Abstract G31B-0797.

Hyndman, R.D. and T.S. Hamilton. 1993. Queen Charlotte area Cenozoic tectonics and volcanism and their association with relative plate motion along the northeastern Pacific margin, *J. Geophys. Res.*, vol. 98, pp. 14,257-14,277.

Hyndman, R.D., P. Flück, S. Mazzotti, T. Lewis, J. Ristau and L. Leonard. 2005. Current tectonics of the Northern Canadian Cordillera, *Can. J. Earth Sci.*, vol. 42, doi:10.1139/E05-023, pp. 1117-1136.

Lambert, A. N. Courtier, G.S. Sasagawa, F. Klopping, D. Winester, T.S. James and J.O. Liard. 2001. New constraints on Laurentide postglacial rebound from absolute gravity measurements, *Geophys. Res. Lett.*, vol. 28, pp. 2109-2112.

Lamontagne, M., P. Keating and S. Perreault. 2003. Seismotectonic of the Lower St. Lawrence seismic zone, Québec: Insights from geology, magnetics, gravity, and seismics, *Can. J. Earth Sci.*, vol. 40, pp. 317-336.

Leonard, L. J., R.D. Hyndman, S. Mazzotti, J.F. Cassidy, G.C. Rogers and J. Adams. 2005. GPS measurements, seismicity, and current tectonics in the northern Canadian Cordillera: Northward stress transfer from the Yakutat collision, *Proceedings, IASPEI Conference,* Santiago, Chile, October 2-7.

Mainville, A. and M.R. Craymer. 2005. Present-day tilting of the Great Lakes region based on water level gauges, *GSA Bulletin*, vol. 117 (7/8), doi:10.1130/B25392.1, pp. 1070-1080.

Manson, G.K., S.M. Solomon, D.L. Forbes, D.E. Atkinson and M. Craymer. 2005. Spatial variability of factors influencing coastal change in the western Canadian Arctic, *Geo-Mar. Lett.*, vol. 25, doi:10.1007/s00367-004-0195-9, pp. 138-145.

Mazzotti, S. and J. Adams. 2005. Rates and uncertainties on seismic moment and deformation in eastern

Canada, *J. Geophys. Res.*, vol. 110, B09301, doi:10.1029/2004JB003510.

Mazzotti S. and J. Adams. 2004. Variability of near-term probability for the next great earthquake on the Cascadia subduction zone, *Bull. Seism. Soc. Am.*, vol. 94, pp. 1954-1959.

Mazzotti, S. and R.D. Hyndman. 2002. Yakutat collision and strain transfer across the northern Canadian Cordillera, *Geology,* vol. 30, pp. 495-498.

Mazzotti, S., R.D. Hyndman, P. Flück, A. J. Smith and M. Schmidt. 2003a. Distribution of the Pacific/North America motion in the Queen Charlotte Islands-S. Alaska plate boundary zone, *Geophys. Res. Lett.*, vol. 30, 1762, doi:10.1029/2003GL017586.

Mazzotti, S., R.D. Hyndman and A. Bustin. 2003b. Strain and stress partitioning of the Pacific/North America interaction along the Queen Charlotte Islands-Alaska Panhandle, *Eos Trans. AGU*, 84(46), Fall Meet. Suppl., Abstract T52A-0229.

Mazzotti S., H. Dragert, J. Henton, M. Schmidt, R.D. Hyndman, T.S. James, Y. Lu and M. Craymer. 2003c. Current tectonics of northern Cascadia from a decade of GPS measurements, *J. Geoph. Res.*, vol. 108, 2554, doi:10.1029/2003JB002653.

Mazzotti, S., T.S. James, J. Henton and J. Adams. 2005. GPS crustal strain, postglacial rebound, and seismic hazard in eastern North America: The Saint Lawrence valley example, *J. Geophys. Res.*, vol. 110, B11301, doi:10.1029/2004JB003590.

Obara, K. 2002. Non-volcanic deep tremor associated with subduction in southwest Japan, *Science*, vol. 292, pp. 1679-1681.

Okada, Y. 1985. Surface deformation due to shear and tensile faults in a half space, Bull. *Seismol. Soc. Am.*, vol. 75, pp. 1135-1154.

O'Reilly, C.T., D.L. Forbes and G.S. Parkes. 2005. Defining and adapting to coastal hazards in Atlantic Canada: facing the challenge of rising sea levels, storm surges, and shoreline erosion in a changing climate, *Ocean Yearbook*, vol. 19, pp. 189-207.

Peltier, W.R. 1994. Ice age paleotopography, *Science*, vol. 265, pp. 195-201.

Proshutinsky, A.Y., V. Pavlov and R.H. Bourke. 2001. Sea level rise in the Arctic Ocean, *Geophys. Res. Lett.*, vol. 28, pp. 2237-2240.

Rogers, G.C. and H. Dragert. 2003. Episodic tremor and slip on the Cascadia Subduction Zone: The chatter of silent slip, *Science*, vol. 300, pp. 1942-1943.

Smith, A. J., R.D. Hyndman, J.F. Cassidy and K. Wang. 2003. Structure, seismicity, and thermal regime of the Queen Charlotte Transform Margin, *J. Geophys. Res.*, vol.108, 2539, doi:10.1029/2002JB002247.

Tushingham, A.M. and W.R. Peltier. 1991. ICE-3G: A new global model of late Pleistocene deglaciation based upon geophysical predictions of post-glacial relative sea-level change, *J. Geophys. Res.*, vol. 96, 4497-4523.

Wang, K., R. Wells, S. Mazzotti, R.D. Hyndman and T. Sagiya. 2003. A revised dislocation model of interseismic deformation on the Cascadia subduction zone, *J. Geophys. Res.*, vol. 108, pp. 2009-2022.

Wessel, P. and W.H.F. Smith. 1998. New, improved version of the Generic Mapping Tools released, *Eos Trans. Amer. Geophys. U.*, 79(47), pp. 329.

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GLOBAL GEODETIC OBSERVING SYSTEM—CONSIDERATIONS FOR THE GEODETIC NETWORK INFRASTRUCTURE

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Properly designed and structured ground-based geodetic networks materialize the reference systems to support sub-millimetre global change measurements over space, time, and evolving technologies. The Ground Networks and Communications Working Group (GN&C WG) of the International Association of Geodesy's Global Geodetic Observing System (GGOS) has been working with the IAG measurement services (the IGS, ILRS, IVS, IDS and IGFS) to develop a strategy for building, integrating, and maintaining the fundamental network of instruments and supporting infrastructure in a sustainable way to satisfy the long-term (10 to 20 years) requirements identified by the GGOS Science Council.

Activities of this Working Group include the investigation of the status quo and the development of a plan for full network integration to support improvements in terrestrial reference frame establishment and maintenance, Earth orientation and gravity field monitoring, precision orbit determination, and other geodetic and gravimetric applications required for the long-term observation of global change. This integration process includes the development of a network of fundamental stations with as many co-located techniques as possible, with precisely determined intersystem vectors. This network would exploit the strengths of each technique and minimize the weaknesses where possible. This paper discusses the organization of the working group, the work done to date, and future tasks.

Des réseaux géodésiques terrestres bien conçus et structurés permettent de matérialiser les systèmes de référence afin de prendre en compte les changements mondiaux dans l'espace, le temps et les nouvelles technologies à un niveau inframillimétrique. Le groupe de travail sur les communications et les réseaux terrestres (Ground Networks and Communications Working Group (GN&C WG)) du Système global d'observation géodésique (GGOS) de l'Association internationale de géodésie (AIG) a travaillé avec les services de prises de mesures de l'AIG (l'IGS, l'ILRS, le SIR, l'IDS et l'IGFS) afin d'élaborer une stratégie pour édifier, intégrer et maintenir le réseau essentiel d'instruments et d'infrastructures de façon durable afin de répondre aux besoins à long terme (10 à 20 ans) cernés par le Conseil des sciences du GGOS.

Le Groupe de travail se prête notamment à l'évaluation du statu quo et à l'élaboration d'un plan pour l'intégration complète du réseau afin de comprendre les améliorations à l'élaboration et au maintien du cadre de référence terrestre, la surveillance de l'orientation et du champ gravitationnel terrestres, la détermination précise de l'orbite et d'autres applications géodésiques et gravimétrique nécessaires à l'observation des changements mondiaux à long terme. Ce processus d'intégration comprend l'élaboration d'un réseau de stations principales intégrant autant de techniques conjointes que possible et de vecteurs, déterminés avec précision, entre les systèmes. Ce réseau exploiterait les forces de chacune des techniques et minimiserait leurs faiblesses. Cet article présente l'organisation du groupe de travail, le travail accompli à ce jour ainsi que ses prochaines tâches.

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1. Introduction

The Ground Networks and Communications Working Group (GN&C WG) of the Global Geodetic Observing System (GGOS) is charged with developing a strategy to design, integrate, and maintain the fundamental space geodetic network. In this report, we review the significance of geodetic networks and the GGOS project. We also summarize the present state of, as well as future improvements to, and requirements on space geodetic networks, services, and products. The approach of the GN&C WG and preliminary conclusions follow.

1.1 Significance of the Terrestrial Reference Frame

Space geodesy provides precise position, velocity, and gravity on Earth, with resolution from local to global scales. The terrestrial reference system defines the terrestrial reference frame (TRF) in which positions, velocities, and gravity are reported. The reference surface for height reckoning, the geoid, is defined through the adopted gravity model, which is referenced to the TRF. The TRF is therefore a space geodesy product that links each of these observable quantities to other geophysical parameters on Earth. Its position, orientation, and evolution in space and time are the basis through which we connect and compare such measurements over space, time, and evolving technologies. It is the means by which we verify that observed temporal changes are geophysical signals rather than artefacts of the measurement system. It provides the foundation for much of the space-based and ground-based observations in Earth science and global change, including remote monitoring of sea level, sea surface, and ice surface topography, crustal deformation, temporal gravity variations, atmospheric circulation, and direct measurement of solid Earth dynamics. A precise TRF is also essential for interplanetary navigation, astronomy, and astrodynamics.

A fundamental aspect of GGOS is the establishment of a global network of stations with co-located techniques, to provide the strongest reference frames.

The realization of the TRF for its most demanding applications requires a mix of technologies, strategies and models. Different observational methods have different sensitivities, strengths, and sources of error. The task is complicated by the dynamic character of Earth's surface, which deforms on time scales of seconds to millennia and on spatial scales from local to global.

1.2 The Role of GGOS

In early 2004 under its new organization, the International Association of Geodesy (IAG) established the GGOS project (*www.ggos.org*) to coordinate geodetic research in support of scientific applications and disciplines [*Rummel* et al. 2002]. GGOS is intended to integrate different geodetic techniques, models, and approaches to provide better consistency, long-term reliability, and understanding of geodetic, geodynamic, and global change processes. Through the IAG's measurement services (International GNSS Service, formerly the International GPS Service (IGS), International Laser Ranging Service (ILRS), International VLBI Service for Geodesy and Astrometry (IVS), International DORIS Service (IDS), International Gravity Field Service (IGFS), and future International Altimeter Service (IAS)), GGOS will ensure the robustness of the three aspects of geodesy: geometry and kinematics, Earth orientation, and static and time-varying gravity field. It will identify geodetic products and establish requirements on accuracy, time resolution, and consistency. The project will work to coordinate an integrated global geodetic network and implement compatible standards, models, and parameters.

A fundamental aspect of GGOS is the establishment of a global network of stations with co-located techniques, to provide the strongest reference frames. GGOS will provide the scientific and infrastructural basis for all global change research and provide an interface to geodesy for the scientific community and to society in general. GGOS will strive to ensure the stability and ready access to the geometric and gravimetric reference frames by establishing uninterrupted time series of state-of-the-art global observations.

As shown in Figure 1, GGOS is organized into working groups headed by a Project Board and guided by a Science Council that helps define the scientific requirements to which GGOS will respond.

1.3 Role of the Ground Networks and Communications Working Group

The ground network of GGOS is fundamental since all GGOS data and products emanate from this infrastructure.

The Charter of the Ground Networks and Communications Working Group (GN&C) within GGOS is to develop a strategy to design, integrate, and maintain the fundamental geodetic network of instruments and supporting infrastructure in a sustainable way to satisfy the long-term (10 to 20 years) requirements identified by the GGOS Science Council. At the base of GGOS are the sensors and observatories situated around the world providing the timely, precise, and fundamental data essential for creating the GGOS products. Primary emphasis must be on sustaining the infrastructure needed to maintain evolving global reference frames while at the same time ensuring support to the scientific applications' requirements. Opportunities to better integrate or co-locate with the infrastructure and communications networks of the many other Earth Observation disciplines now organizing under the Global Earth Observation System of Systems (GEOSS) should be sought and taken into account [*Group on Earth Observations* 2005].

Recognizing that the infrastructure and operations collectively contributing to the Services of the IAG are possible solely due to the voluntary contributions of the globally distributed collaborating agencies and their interest in maximized system performance and sustainable long-term efficient operations, the Working Group is made up of representatives of the measurement services plus other entities that are critical to guiding the activities of the Working Group:

- IGS: Angelyn Moore, Norman Beck
- ILRS: Mike Pearlman, Werner Gurtner
- IVS: Chopo Ma, Zinovy Malkin
- IDS: Pascal Willis
- IGFS: Rene Forsberg, Steve Kenyon
- ITRF and Local Survey: Zuheir Altamimi, Jinling Li
- IERS Technique Combination Research Centers: Marcus Rothacher
- IAS (future): Wolfgang Bosch
- Data Centers: Carey Noll
- Data Analysis: Erricos Pavlis, Frank Lemoine, Frank Webb, John Ries, Dirk Behrend

2. Global Geodetic Network Infrastructure

All infrastructure, and resulting analysis and products of GGOS and its constituent services are made possible through the goodwill voluntary contributions of national agencies and institutions and are coordinated by the IAG governance mechanisms.

The ground network of GGOS includes all the sites that have instruments of the IAG measurement services either permanently in place or regularly occupied by portable instruments. Some sites have more than one space geodesy technique co-located, and knowledge of the precise vectors between such co-located instruments (known as "local ties") is essential to full and accurate use of these co-locations.

Analysis centres use the ground networks' data for various purposes including positioning, Earth orientation parameters (EOP), the TRF, and the gravity field. The ground stations of the satellite techniques provide data for precise orbit determination (POD). The individual sites' reference points

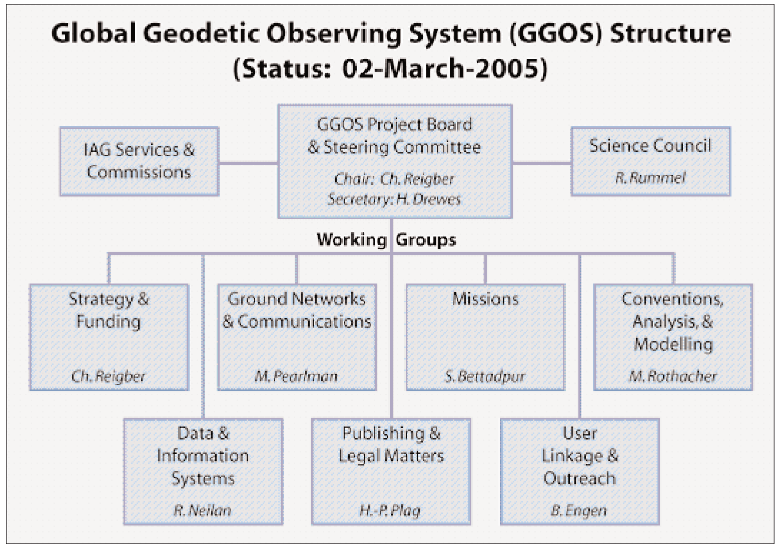

Figure 1. GGOS Organization.

of the contributing space geodesy networks are the fiducial points of the TRF.

2.1 IAG Measurement Services

Each service coordinates its own network, including field stations and supporting infrastructure. Here we will review the current status of each measurement service.

2.1.1 IGS

The foundation of the International GNSS Service (IGS, formerly the International GPS Service) is a global network of more than 350 permanent, continuously operating, geodetic-quality GPS and GPS/GLONASS sites. The station data are archived at four global data centres and six regional data centres. Ten analysis centres regularly process the data and contribute products to the analysis centre coordinator, who produces the official IGS combined orbit and clock products. Timescale, ionospheric, tropospheric, and reference frame products are analogously formed by specialized coordinators for each. More than 200 institutes and organizations in more than 80 countries contribute voluntarily to the IGS, a service formally begun in 1994. The IGS intends to integrate future GNSS signals (such as Galileo) into its activities, as demonstrated by the successful integration of GLONASS. [*Kouba et al.* 1998; *Beutler et al.* 1999; *Dow* 2003].

2.1.2 ILRS

The International Laser Ranging Service (ILRS), created in 1998, currently tracks 28 retroreflector-equipped satellites for geodynamics, remote sensing (altimeter, SAR, etc.), gravity field determination, general relativity, verification of GNSS orbits, and engineering tests [*Pearlman et al*. 2002]. Satellite altitudes range from a few hundreds of kilometres to GPS altitude (20,000 kilometres) and the Moon. The network includes forty laser ranging stations, two of which routinely range to four targets on the Moon. Satellites are added and deleted from the ILRS tracking roster as new programs are initiated and old programs are completed. The collected data are archived and disseminated via two centres, and several analysis centres voluntarily and routinely deliver products for TRF, EOP, POD, and gravity modelling and development.

2.1.3 IVS

The International VLBI Service for Geodesy and Astrometry (IVS) was established in 1999 and currently consists of 74 permanent components: coordinating centre, operation centres, network stations, correlators, analysis centres, and technology development centres. The IVS observing network includes about 30 regularly-observing IVS stations and 20 to 30 collaborating stations participating in selected IVS programs on an irregular basis [*Behrend and Baver* 2005]. Twenty-four-hour sessions twice per week as well as other less frequent sessions are used to determine the complete set of EOP (polar motion, celestial pole coordinates, UT1-UTC), station coordinates and velocities, and the positions of the radio sources. VLBI is the only space technique capable of Universal Time (UT1) monitoring. IVS uses daily one-hour single baseline sessions with low latency for this purpose [*Schlueter et al*. 2002].

2.1.4 IDS

The International DORIS Service (IDS) was created in 2003 [*Tavernier et al*. 2005]. The current ground tracking network is composed of 55 stations allowing an almost continuous tracking of the current five satellites (SPOT-2, -3 and -4 used for remote sensing applications, Jason-1, and Envisat used for satellite altimetry). The main applications of the DORIS system are precise orbit determination, geodesy and geophysics [*Willis et al*. 2005]. Using improved gravity Earth models derived from the GRACE mission [*Tapley et al*. 2004], DORIS weekly station positions can now be regularly obtained at the 10mm level [*Willis et al*. 2004]. DORIS data are available at the two IDS Data Centers since 1990 (SPOT-2). In 1999 a DORIS Pilot Experiment was created by the IAG [*Tavernier et al*. 2002] leading gradually to the IDS. The French space agency (CNES) has the leading role in the IDS.

2.1.5 IGFS

The International Gravity Field Service (IGFS) was created in 2003 to provide coordination and standardization for gravity field modelling. It supports the IAG scientific and outreach goals and therefore GGOS, through activities such as collecting data for fundamental gravity field observation networks (e.g., a global absolute reference network, co-located with satellite stations and other geodetic observation techniques), data collection and release of marine, surface, and airborne gravity data for improved global model development (e.g., EGM96 [*Lemoine et al*. 1998]), and advocating consistent standards for gravity field models across the IAG services. Establishing new methodology and science applications, particularly in the integration and validation of data from a variety of sources, is another focus of the service. The IGFS is composed of a variety of primary service entities: Bureau Gravimétrique International (BGI), International Geoid Service (IGeS), International Center for Earth Tides (ICET), and International Center for Global Earth Models (ICGEM), with the National Geospatial-Intelligence Agency (NGA) participating as an IGFS Technical Center.

2.2 Communications

Transmission of data from the network instruments to data centres and processing or analysis centres is a function critical to all the techniques. For the satellite services, data transmission is normally via primarily the Internet through terrestrial or satellite communications networks. Due to the volume of data (terabytes per station per 24 hours), VLBI data are currently shipped on recorded media, but transmission of data via high-speed fibre is a future goal. Gravity data are currently exchanged via Internet or massive storage media on an “as needed” basis. Control and coordination information is also routinely and primarily sent via the Internet. Sites are often situated where suitable access to communications networks, and ideally Internet, exists. In some cases, however, connectivity must be installed at existing sites. Communications costs are borne by the operating agencies, which in remote areas is often at considerable expense. The GN&C WG will improve efficiency through coordinated implementation of modern methods and additional sharing of communications facilities and infrastructure.

3. Synergy of the Observing Techniques

At the dawn of space age about half a century ago, the individual national classical systems that were then dominating geodesy started slowly to be replaced by initially crude global equivalents (e.g., the SAO Standard Earth models), and later on, when the first satellite navigation constellations like TRANSIT became available, by more sophisticated "World Geodetic Systems" (e.g., the US DoD-developed WGS60, 66, 72, and WGS84). As space techniques proliferated throughout the world, it soon became apparent that the optimal approach would be to make use of all available systems, and to share the burden of the development through international coordination and cooperation. This section reviews the synergistic contributions of space geodetic techniques to various products.

3.1 The Terrestrial Reference Frame

The dramatic improvement of space geodesy techniques in the eighties, thanks to NASA's Crustal Dynamics Project and Europe's WEGENER Project, has dramatically increased the accuracy of TRF determination [*Smith and Turcotte* 1993]. However, none of the space geodesy techniques alone are able to provide all the necessary parameters for the TRF datum definition (origin, scale, and orientation). While satellite techniques are sensitive to Earth's centre of mass, VLBI is not. The scale is dependent on the modelling of some physical parameters, and the absolute TRF orientation (unobservable by any technique) is arbitrary or conventionally defined through specific constraints. Once the conventions are established, VLBI, unlike the other space techniques, can observe the progression of ITRF orientation in space. The utility of multi-technique combinations is therefore recognized for the TRF implementation, and in particular for accurate datum realization.

Since the creation of the International Earth Rotation and Reference Systems Service (IERS), the current implementation of the International Terrestrial Reference Frame (ITRF) has been based on suitably weighted multi-technique combination, incorporating individual TRF solutions derived from space geodesy techniques as well as local ties of co-location sites. The IERS has recently initiated a new effort to improve the quality of ties at existing co-location sites, crucial for ITRF development [*Richter et al.* 2005].

The particular strengths of each observing method can compensate for weaknesses in others. SLR defines the ITRF2000 geocentric origin, which is stable to a few mm/decade, and SLR and VLBI define the absolute scale stability to around 0.5 ppb/decade (equivalent to a shift of approximately 3mm in station heights) [*Altamimi et al.* 2002]. Measurement of geocentre motion is under refinement by the analysis centres of all satellite techniques. The density of the IGS network provides easy and rigorous TRF access world-wide, using precise IGS products and facilitates the implementation of the rotational time evolution of the TRF in order to satisfy the No-Net-Rotation condition over tectonic motions of Earth's crust. DORIS contributes a geographically well-distributed network, the long-term permanency of its stations, and its early decision to co-locate with other tracking systems. We recognize that we will need to consider non-linear motions in future reference frame solutions. A first step towards this goal is the use of time series analysis rather than just position and velocity products.

The TRF is heavily dependent on the quality of each network and suffers with any network degradation over time. The current distribution and quantity of co-location sites as depicted in Figure 2 (in particular sites with three and four techniques) is sub-optimal.

3.2 Earth Orientation Parameters

Earth orientation parameters measure the orientation of Earth with respect to inertial space (which is required for satellite orbit determination and spacecraft navigation) and to the TRF, which is a precondition for long-term monitoring. Polar motion and UT1 track changes in angular momentum in the fluid and solid components of the Earth system driven by phenomena like weather patterns,

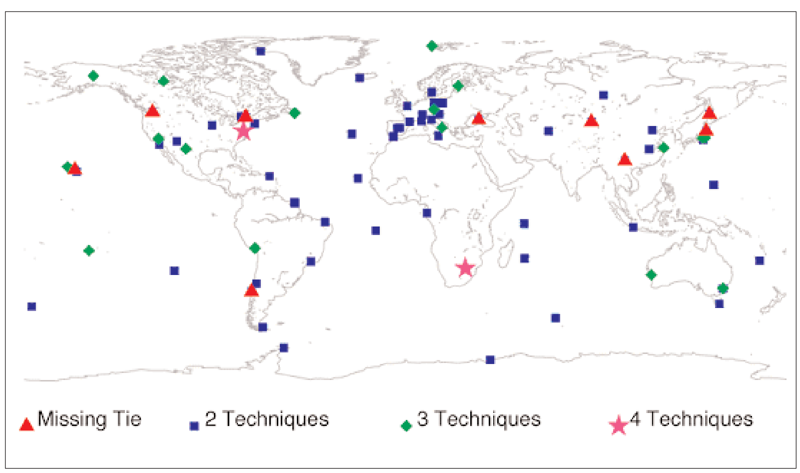

Figure 2. Distribution of space geodesy co-location sites since 1999.

ocean tides and circulation, post-glacial rebound, and great earthquakes. The celestial pole position, on the other hand, is dependent on the deep structure of Earth. Only VLBI measures celestial pole position and UT1, and VLBI also defines the ICRF (International Celestial Reference Frame) [*Ma et al*. 1998], whose fiducial objects (mostly quasars) have no detectable physical motion across the sky because of their great distance. The two-decade VLBI data set contributes a long-time series of polar motion, UT1 and celestial pole position. Satellite techniques (GPS, SLR, and DORIS) measure polar motion and length of day relative to the orbital planes of the satellites tracked. In practice, recent polar motion time series are derived from GPS with a high degree of automation, and predictions of UT1 rely on GPS length of day and atmospheric excitation functions.

3.3 Gravity, Geoid, and Vertical Datum

Gravity is important to many scientific and engineering disciplines, as well as to society in general. It describes how the "vertical" direction changes from one location to another, and similarly, it defines at each point the equipotential surface; therefore, it describes the direction that "water flows." Global scale models of terrestrial gravity and geoid [*Lemoine et al*. 1998] are now routinely delivered on a monthly basis by missions like GRACE, with a resolution of 200 kilometres or so, and high accuracy [*Tapley et al*. 2004]. The addition of surface gravity observations can extend the resolution of these models down to tens of kilometres in areas of dense networks. Worldwide databases of absolute and relative gravity, airborne and marine gravity are collected and maintained by IGFS. Astronomically-driven temporal variations of gravity (Earth, ocean, and atmospheric tides) are also a product of this and other IAG services. The combination of all this information is crucial in precisely determining instantaneous position on Earth or in orbit, the direction of the vertical and the height of any point on or around Earth, and the computation of precise orbits for near-Earth as well as interplanetary spacecraft. Similarly, the vertical datum is the common reference for science, engineering, mapping, and navigation problems. Achieving a globally consistent vertical datum of very high accuracy has been a prime geodetic problem for decades, and only recently (thanks to satellite altimetry and the latest gravity missions like CHAMP and GRACE) is a successful result in reach. Strengthening and maintaining a close link between the "geometric" and "gravimetric" reference frames is of paramount importance to the goals of GGOS.

3.4 Precise Orbit Determination

Precise orbit determination is one of the principal applications of the satellite techniques (GPS, SLR, DORIS), and has direct application to many different scientific disciplines such as ocean topography mapping, measurement of sea level change, determination of ice sheet height change, precise geo-referencing of imaging and remote sensing data, and measurement of site deformation using synthetic aperture radar (SAR) or GPS. The techniques have evolved from metre-level orbit determination of satellites such as LAGEOS in the early 1980's to cm-level today. The computation of precise orbits allows these satellite tracking data to be used for gravity field determination (both static and time-variable) and the estimation of other geophysical parameters such as post glacial rebound, ocean tidal parameters, precise coordinates of tracking sites, or the measurement of geocentre motion.

Precise orbit determination, which requires precise UT1 and gravity models, underpins the analysis that in parallel has resulted in improved station coordinate estimation, and thereby improved realizations of the TRF (e.g., ITRF2000). There is close synergy between POD and TRF realization. The density of data available from GPS (and in the future from other GNSS including Galileo) allows the estimation of reduced-dynamic or kinematic orbits with radial accuracy of a few centimetres even on low-altitude satellites such as CHAMP and GRACE. Only a few satellites carry multiple tracking systems, but space-based co-location is invaluable. The detailed inter-comparison of orbits computed independently from SLR, DORIS, and GPS data confirms that Jason-1 orbits have a one-centimetre radial accuracy [*Luthcke et al*. 2003]. These techniques are complementary; the precise but intermittent SLR tracking of altimeter satellites, such as Envisat or TOPEX/Poseidon, is complemented by the dense tracking available from the DORIS network. SLR tracking of the GPS, GLONASS or future Galileo satellites is and will be vital to calibrating GNSS satellite biases and assuring the realization of a high quality TRF.

4. Future Requirements

The measurement requirements for GGOS will be set by the GGOS Project Board with guidance from the Science Council [*Rummel* et al. 2002]. Until these requirements are formally specified, we judge the practical useful target for the TRF and space geodetic measurement accuracy to be roughly a factor of five to 15 below today's levels. Given that the TRF and global geodesy are now accurate to the order of 1cm (or five to 15 millimetres for different quantities) and 2mm/yr, we foresee near-term utility in global measurements with absolute accuracies at or below 1mm and 0.2mm/yr. Corresponding levels of improvement are required for Earth orientation and gravity.

5. Evolution of the Techniques

Each of the GGOS Services techniques envisions technological and operational advances that will enhance measurement capability. Some advances are currently being implemented while others are in the process of design or development. In addition, each technique-related service is seeking to improve not only data quality and precision, but also reliability of data and product delivery, performance, continuity, station stability, data latency (which in the case of GNSS includes real-time) and data handling techniques and modelling. While making these improvements, contributors seek operational efficiencies in order to minimize costs.

5.1 GNSS

Geodetic GNSS has already evolved from GPS-only operations to inclusion of GLONASS, and upgrades to next-generation receivers will allow full benefit from modernized GPS signal structures, Galileo signals, and GLONASS signals. Studies leading to improved handling of calibration issues such as local signal effects (e.g., multipath) and antenna phase patterns are underway, as are initiatives to fill remaining network gaps, particularly in the southern hemisphere. Elsewhere, station density is less problematic and the focus has shifted to consolidation of supplementary instrumentation such as strain metres and meteorological sensors.

5.2 Laser Ranging

Newly designed and implemented laser ranging systems operate semi-autonomously and autonomously at kilohertz frequencies, providing faster satellite acquisition, improved data yield, and extended range capability, at substantially reduced cost. Improved control systems permit much more efficient pass interleaving and new higher resolution event-timers deliver picosecond timing. The higher resolution will make two-wavelength operation for atmospheric refraction delay recovery more practical and applicable for model validation. The current laser ranging network suffers from weak geographic distribution, particularly in Africa and the southern hemisphere. The comprehensive fundamental network should include additional co-located sites to fill in this gap.

Improved satellite retroreflector array designs will reduce uncertainties in centre-of-mass corrections, and optical transponders currently under development offer opportunities for extraterrestrial measurements.

5.3 VLBI

The VLBI component of the future fundamental network will be the next-generation system now undergoing conceptual development. Critical elements include fast slewing; high efficiency 10-12m diameter antennas; ultra wide bandwidth front ends with continuous radio frequency (RF) coverage; digitized back ends with selectable frequency segments covering a substantial portion of the RF bandwidth; data rate improvements by a factor of two to16; a mixture of disk-based recording and high speed network data transfer, near real-time correlation among networks of processors, and rapid automated generation of products. Better geographic distribution, especially in the southern hemisphere, is required.

5.4 DORIS

The DORIS tracking network is being modernized using third-generation antennae and improvements to beacon monumentation [*Tavernier et al.* 2005]. Efforts are underway to expand the network to fill in gaps in existing coverage. DORIS beacons are also being deployed to support altimeter calibration, co-location with other geodetic techniques, or specific short-term experiments. A specific IDS working group is selecting sites and occupations for such campaigns, using additional DORIS beacons provided by CNES to the IDS.

5.5 Gravity

Gravity observations are most sensitive to height changes; they therefore provide an obvious way to define and control the vertical datum. A uniformly-distributed network of regularly cross-calibrated absolute gravimeters supported by a well-designed relative measurement network that will be repeatedly observed at regular intervals, and a sub-network of continuously operating superconducting tidal gravimeters are expected in a fundamental network of co-located techniques. These permanent networks should be augmented with targeted airborne and ship campaigns to collect data over large areas that are devoid of gravimetric observations. A well-distributed global data set of surface data is necessary to calibrate and validate products of the recent (CHAMP and GRACE) and upcoming (GOCE) high-accuracy and -resolution missions. Eventually, gravimetry will need to devise a method analogous to InSAR, to continuously "map" changes in the field with resolution many orders of magnitude higher than currently achievable from any geopotential mapping mission. The organization of a gravity field service is underway and the integration of its activities should emerge shortly.

6. Approaches to Network Design

The final design of the GGOS network must take into consideration all of the applications including the geometric and gravimetric reference frames, EOP, POD, geophysics, oceanography, etc. We will first consider the TRF, since its accuracy influences all other GGOS products. Early steps in the process are:

1. Define the critical contributions that each technique provides to the TRF, POD, EOP, etc.
2. Characterize the improvements that could be anticipated over the next 10 years with each technique.
3. Examine the effect in the TRF and Earth orientation resulting from the loss of a significant part of the current network or observation program.
4. Using simulation techniques, quantify the improvement in the TRF, Earth orientation, and other key products as stations are added and station capability (co-location, data quantity, and quality) is improved. We will also explore the benefit of adding new SLR targets.

6.1 Impact of Network Degradation on the TRF

Preliminary results [*Govind* 2005] indicate the origin drift caused by removal of one station, Yarragadee (Australia), from SLR analysis. The drift is about 0.6, 1, and 1mm/yr over the origin components around the three axes X, Y, Z, respectively. This drift is at least three times larger than requirements for high-precision Earth science applications such as sea level change and other geophysical processes.

6.2 Effect of System and Network Degradation on Other GGOS Products

The TRF is a primary space geodesy product, but it is also the basis on which every other product is referenced. As such, degradation in its definition and maintenance influences the quality of these other products and services, such as EOP, geocentre motion, temporal global gravity variations, and POD.

The degradation can originate in two ways: geometric changes (as those shown by the example of section 6.1) and changes in the type, amount and spatiotemporal distribution of the observations. In practice what happens is a combination of both. To quantify the resultant errors is not an easy task because there are infinitely many possible variations in the network of TRF stations, supporting techniques, and selection of data. Examination of particular station deletions that either happened in practice or had been proposed indicates [*Pavlis and Kuzmicz-Cieslak* 2005] that even moderate degradations impact results significantly more than their quoted accuracies. This confirms the present ILRS network is not robust to any contraction; the smallest perturbation of the system yields large uncontrolled changes in the products.

The closing of the Arequipa Peru and Haleakala Hawaii SLR sites for example, degraded origin, orientation and scale by 3 to 4 times the standard deviation of the relevant parameters. Impact on geocentre motion was almost two times worse. Temporal variations of the gravity field coefficients are less sensitive due to their nature as proxies of global scale changes, but were still degraded by several standard deviations. On the positive side, for a modest improvement from an old TRF (ca. 1995) to the current one (ITRF2000), POD-based products (such as altimeter derived Mean Sea Level) improved by 30 per cent.

Much more work is required to assess the effects of such changes in the tracking networks of all space geodesy techniques, and their combined effect on the final products. The sizes of these separate networks and the infinite possible variations in their design, overlap and operation, and the quality of their data and the targets used for collecting their observations complicate this task, but a few well-thought-through scenarios will be tested with future simulations.

6.3 Improvements in the TRF and Other Key Products

Expected advances in instrumentation, as described in section 5, will cause improvements in the TRF and the various products, but the accuracy needed for future science applications will require optimization of the ground network. Simulation capabilities will be developed that will allow for evaluation and optimization of the locations of potential sites.

In addition, the benefit of introducing a few new SLR targets needs to be evaluated. Target interaction with the current large LAGEOS satellites is one of the principal limitations in mm-level SLR, and smaller targets would support the necessary accuracy. New lower-altitude targets would allow more observation opportunities per day, increased probability of tracking from lower-power systems (particularly during daylight) and a more accurate determination of the Earth's mass centre, critical for both controlling the drift in the origin of the TRF as well as observing the seasonal geocenter motions associated with large-scale mass transport within the Earth system.

Simultaneously, enhanced performance of each of the individual techniques should result as each technique's data and analysis outputs are further combined and compared and eventually integrated.

7. Sustaining the Ground Network Over the Long Term

The measurement techniques services have each maintained their own networks and supporting infrastructure, routinely producing data, but suffer from severe budget constraints of the voluntarily contributing agencies that prevent appropriate maintenance and development of physical and computational assets. This degradation of the observing network capability coincides with the deployment of high-value science investigations and missions, such as sea level studies from ocean and ice-sheet altimetry missions, eroding their scientific return and limiting their ability to meet the mission goals.

Many of the elements of the current networks are funded from year to year and depend on specific activities. Stations are often financed for capital and maintenance and operations costs through research budgets, which may not constitute a long-term commitment. Sudden changes in funding as priorities and organizations change have resulted in devastating impacts on station and network performance. On the other hand, missions and long-term projects have assumed that the networks will be in place at no cost to them, fully functioning when their requirements need fulfillment. GGOS will be proactive in helping to persuade funding sources that the networks are interdependent infrastructure that needs long-term, stable support. The GGOS community must secure long-term commitments from sponsoring and contributing agencies for its evolution and operations in order to support its users with high-quality products. Since the present networks must support current as well as future requirements, the GGOS network must evolve without interruption of data and data products. In view of the difficulties in securing long-lasting and stable financial support by the interested parties, new financial models for the networks must be developed. This Working Group will work with the Strategy and Funding Working Group to develop an approach.

Since the present networks must support current as well as future requirements, the GGOS network must evolve without interruption of data and data products. In particular, the TRF relies on a long continuous history of data for its stability and robustness. New and upgraded systems, changes in stations locations, and changes in the way products are formed must be planned and phased so that the impacts are well documented and well understood.

The analysis and simulation procedures being undertaken by the Working Group will identify network voids and shortcomings. The Ground Networks and Communications Working Group, in concert with the other GGOS entities, will work with agencies and international organizations toward filling in these gaps.

8. Summary

A permanent geodetic network of complementary yet interdependent space geodetic techniques is critical for geodetic and geophysical applications and underpins the Global Earth Observation System of Systems. Thanks to the generous and voluntary contributions of many national agencies and institutions around the world, the IAG has been able to coordinate global collaborations for geodetic technique-based services from which all benefit. There is a strong need for coordination of the planning, funding and operation of future integrated geodetic networks to maximize performance in meeting evolving requirements while taking into account the need for sustainable infrastructure and efficient operations. The GGOS Ground Networks & Communications Working Group has initiated studies, which will guide the services in infrastructure planning for optimal benefit to Earth science and associated engineering and societal concerns.

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References

Altamimi, Z., P. Sillard and C. Boucher. 2002. ITRF2000, A new release of the International Terrestrial Reference Frame for earth science applications. *Journal of Geophysical Research*, Solid Earth, 107(B10), 2214.

Behrend, D. and K.D. Baver (Eds). 2005. International VLBI Service for Geodesy and Astrometry 2004 Annual Report, NASA/TP-2005-212772, 2005.

Beutler, G., M. Rothacher, S. Schaer, T.A. Springer, J. Kouba and R.E. Neilan. 1999. The International GPS Service (IGS), An interdisciplinary service in support of Earth Sciences, *Advances in Space Research*, 23(4), pp. 631-653.

Dow, J.M. 2003. IGS, The International GPS Service for leading-edge space missions, *ESA Bulletin*, 116, pp. 64-69.

Govind, R. 2005. Private communication.

Group on Earth Observations. 2005. Global Earth Observation System of Systems GEOSS 10-Year Implementation Plan Reference Document - GEO 1000R, 209 pages.

Kouba, J., Y. Mireault, G. Beutler, T. Springer and G. Gendt, 1998. A Discussion of IGS Solutions and Their Impact on Geodetic and Geophysical Applications *GPS Solutions*, 2(2), pp. 3-15.

Lemoine, F.G., S.C. Kenyon, J.K. Factor, R.G. Trimmer, N.K. Pavlis, D.S. Chinn, C.M. Cox, S.M. Klosko, S.B. Luthcke, M.H. Torrence, Y.M. Wang, R.G. Williamson, E.C. Pavlis, R.H. Rapp, and T.R. Olson. 1998. The Development of the Joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) Geopotential Model EGM96, NASA/TP-1998-206861, Goddard Space Flight Center, Greenbelt, Maryland, 575 pages.

Luthcke, S.B., N.P. Zelensky, D.D. Rowlands, F.G. Lemoine and T.A. Williams. 2003. The 1-centimeter orbit, Jason-1 precision orbit determination using GPS, SLR, DORIS, and altimeter data, *Marine Geodesy*, 26(3-4), pp. 399-421.

Ma, C., F. Arias, T.M. Eubanks, A.L. Fey, A.M. Gontier, C.S. Jacobs, O.J. Sovers, B.A. Archinal and P. Charlot. 1998. The International Celestial Reference Frame as realized by Very Long Baseline Interferometry, *Astronomical Journal*, 116(1), pp. 516-546.

Pavlis, E.C. and M. Kuzmicz-Cieslak. 2005. Impact of SLR Tracking Network Variations on the Definition of the TRF, IAG/IAPS∅IABO Joint Assembly, Cairns Australia. August 22-26. Series: IAG Symposia, Vol. 130, in press.

Pearlman, M.R., J.J. Degnan and J.M. Bosworth. 2002. The International Laser Ranging Service, *Advances in Space Research*, 30(2), pp. 135-143.

Richter, B., W. Schwegmann and W. Dick (eds.). 2005. Proceedings of the IERS Workshop on site co-location. Matera, Italy, 23 - 24 October 2003 (IERS Technical Note ; 33).

Rummel, R., H. Drewes and G. Beutler. 2002. Integrated Global Observing System IGGOS, A candidate IAG Project, In Proc. *International Association of Geodesy*, Vol. 125, pp. 135-143.

Schlueter, W., E. Himwich, A. Nothnagel, N. Vandenberg and A. Whitney. 2002. IVS and its important role in the maintenance of the global reference systems, *Advances in Space Research*, 30(2), pp. 145-150.

Smith, D. and D. Turcotte (eds.). 1993. Contributions of Space Geodesy to Geodynamics: Crustal Dynamics (23), Earth Dynamics (24) and Technology (25), AGU Geodynamics Series.

Tapley, B.D., S. Bettadpur, M. Watkins and C. Reigber. 2004. the Gravity Recovery and Climate Experiment, Mission overview and early results, *Geophysical Research Letters*, 31(9), L09607.

Tavernier, G., H. Fagard, M. Feissel-Vernier, F. Lemoine, C. Noll, J.C. Ries, L. Soudarin and P. Willis. 2005. The International DORIS Service, IDS. *Advances in Space Research*. 36(3), pp. 333-341, DOI: 10.1016/j.asr.2005.03.102.

Tavernier, G., L. Soudarin, K. Larson, C. Noll, J. Ries and P. Willis. 2002. Current status of the DORIS Pilot Experiment and the future International DORIS Service, *Advances in Space Research*, 30(2), pp. 151-156.

Willis, P. and M. Heflin. 2004. External validation of the GRACE GGM01C Gravity Field using GPS and DORIS positioning results, *Geophysical Research Letters*, 31(13), L13616.

Willis, P., C. Boucher, H. Fagard and Z. Altamimi. 2005. Geodetic applications of the DORIS system at the French Institut Geographique National. *Comptes Rendus Geoscience*, 337(7), pp. 653-662.

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