Report of Working Group D: Reference Frames, Timing and Applications

1. Introduction

The key Working Group D (WG-D) activities throughout the week of ICG-5 were:

- Sunday, 17 October: WG-D Co-Chairs met with Co-Chairs of the other Working Groups and ICG-5 organizers to prepare for the week of meetings for ICG-5;
- Monday, 18 October: two of WG-D Co-Chairs (Matt Higgins for FIG, and John Dow for IGS) made presentations in the first plenary session of the ICG;
- Tuesday, 19 October: the WG-D Co-Chairs met with the Chairs of Task Force D1 on Geodetic References and Task Force D2 on Timing References to prepare for the main WG-D meetings;
- Wednesday, 20 October: Main meeting of WG-D followed by a special technical session of the ICG on Timing Issues;
- Thursday, 21 October: Second meeting of WG-D to finalize recommendations and other matters prior to the presentation of the WG-D report and recommendation to the second plenary session of the ICG;
- Friday, 21 October: participation in the third plenary session of the ICG, where WG-D recommendations were accepted.

The remainder of this report concentrates on the two WG-D meetings on 20 and 21 October and the major outcomes for the week being:

- Continued progress on the templates for Geodetic and Timing References;
- An updated work plan and name for the Working Group, and;
- Five new Recommendations to the ICG.

2. WG-D First Meeting

2.1. Introduction of Attendees

The Co-Chairs welcomed everyone and attendees were asked to briefly introduce themselves. There were 44 attendees at this first meeting. Attendees at both WG-D meetings are listed in an Attachment to this report.

2.2. Review of Minutes from Newcastle Meeting

Minutes were noted.

2.3. Task Force on Geodetic References

2.3.1. Presentations on Geodetic References[1]

- "Latest Developments with ITRF 2008" (by Zuheir Altamimi, IERS, France);
- "Recent Development of CGCS2000" (by Prof. YANG Yuanxi from CNAGA, China);
- "Realization of Terrestrial Reference Frame for GNSS" (by Hongping ZHANG, Wuhan University, China);
- "The WGS84 Instance of the Template for Global and Regional Reference System Description" (by Barbara Wiley, NGA, USA).

2.3.2 Discussion on Geodetic References

The presentations were followed by question and answer sessions about specific issues raised during the presentations. This was followed by discussion of the Global and Regional Reference System Description Template and progress by other System Providers in providing instances for their systems.

[1] *Presentations are available on the ICG web site along with all other presentations from ICG-5 at www.icgsecretariat.org*

Templates on the following Geodetic References are included as attachments to this report:

- World Geodetic System 1984 (WGS84);
- Galileo Terrestrial Reference Frame (GTRF);
- International Terrestrial Reference Frame (ITRF);
- International Terrestrial Reference System (ITRS).

2.4. Task Force on Timing References

2.4.1. Presentations on Timing References[2]

- "COMPASS/BEIDOU Time System" (by Prof. HAN Chunhao, BGIC, China);
- "The GPS Instance of the Template for GNSS GNSS Timescale Description" (by Ed Powers, USNO, USA).

2.4.2. Discussion on Timing References

The presentations were followed by questions and answer session about specific issues raised during the presentations. This was followed by discussion of the GNSS Timescale Description Template and progress by other System Providers in providing instances for their systems.

The USNO's template describing the Timing Reference for GPS is also included as an attachment to this report.

2.5. Working Group D General Business

2.5.1. WG D Participation in the Multi-GNSS Project in the Asia Oceania Region

The Working Group re-iterated its support for the Multi-GNSS Asia Oceania demonstration campaign and associated activities and agreed on the need to draft a recommendation to the ICG along those lines.

2.5.2. Retro-reflectors on GNSS Satellites

The Working Group discussed how it was good to see that Japan had deployed retro-reflectors on its recently launched QZSS satellite. WG-D agreed on the value of a recommendation to the ICG noting progress by several system providers with plans for deploying retro-reflectors on future GNSS satellites.

2.5.3. Sustainability of the International Organizations that support Geodetic and Timing References

The Working Group discussed the need for ICG Members to help ensure the long term sustainability of the International Organizations that support the establishment of the Standards and Conventions for Geodetic and Timing References to which GNSS systems are being aligned. It was noted, for example, that system providers and many GNSS users were becoming increasing reliant on services offered by organizations such as the BIPM for UTC and related timing services, the International Earth Rotation Service for the International Terrestrial Reference Frame and the International GNSS Service for improved satellite orbits and clocks and yet all of these organizations tend to offer such services on a best effort basis and rely on data from reference stations that are also operated on a best effort basis. The Working Group agreed to develop a proposal for a discussion session between those relevant ICG Associate Members and the System Providers at the next ICG meeting in Japan in 2011.

2.6. Action Items from First Meeting of Working Group D

[2] *Presentations are available on the ICG web site along with all other presentations from ICG-5 at www.icgsecretariat.org*

The first key outcome from the meeting was that all System Providers that have not already submitted templates on their Geodetic and/or Timing References agreed to do so by the end of November 2010.

Task Force Chairs and Working Group Chairs will then harmonize and summarize the templates with a view to submitting them for consideration at the first System Providers Forum in 2011. It is planned that these templates will eventually be included in the ICG's standardized description of the various GNSS Systems. The Working Group also discussed the next steps in its work following publication of the Templates on References, e.g. issues such as extending to best practices for system providers and whether the WG's role extends further to issues like user education on Geodetic and Timing Reference topics.

The second key outcome from the meeting was agreement on a number of recommendations to the ICG. These were drafted formally by the Co-Chairs and Task Force Chairs following the Working Group meeting and were discussed at the second meeting of the entire Working Group and are therefore covered in the following section of this report.

The third point to note was a very useful discussion about the future work of the Task Forces, which centred on the idea that ensuring interoperability is about more than simply documenting the existing Geodetic and Timing References used in each of the systems. An example that was discussed was that when the templates were completed the Task Forces should perhaps identify best practices among the current approaches and work towards some recommended practices to further improve interoperability in the future.

Jim Ray (USA) extended that discussion about the future work of the Task Forces by pointing out that the reference frames as actually realized in an end user's position are influenced by much more than just the nominal terrestrial reference frame of the respective GNSS monitor stations. Subsequently to the meeting Jim sent an email outlining this issue in more detail, the content of which is an Attachment to this report. The underlying point is that possible inconsistencies in position and time results obtained from different GNSSs result from three main sources:

- The GNSS Terrestrial Reference Frames (TRFs);
- The Earth orientation parameters (EOPs) used for predicted orbits broadcast in the nav message of a given GNSS, and;
- The Orbit modeling used for the predicted orbits.

All three categories of error above contain both systematic and random contributions. The random errors can be reduced by averaging over time while systematic errors do not average down over time or do so slowly.

Jim believes that the scope of information that must be shared among systems and users for improved GNSS interoperability must be much broader than just the respective Geodetic and Timing references adopted. Collection of that information will require closer coordination between WG-A and WG-D. From this discussion it is clear that the draft templates prepared so far in WG-D are only a first step towards improved GNSS interoperability.

The Co-Chairs of WG-D propose that the issues raised by Jim Ray will be further discussed by working group members via email during the coming months with a view to potential extension to the work plan and/or workshops in the lead up to ICG-6.

3. WG-D Second Meeting

3.1. Introduction of Attendees

There were 25 attendees at this second meeting. Attendees at both WG-D meetings are listed in an attachment to this report.

3.2. Proposal to Change the Name of WG-D

The Working Group discussed and agreed to propose to ICG that it changes its name to the *ICG Working Group D on Reference Frames, Timing and Applications* (RFTA). A Recommendation was drafted accordingly (see below).

3.3. Updated Work Plan

The Working Group discussed and agreed to changes to its Work plan. Key activities identified in the updated work plan include:

- Coordinate Geodetic and Timing References for GNSS systems through its two task forces;
- Recommend the adoption of operational performance standards for GNSS monitoring networks;
- Recommend approaches for the use of civil user networks for independent calibration and validation of site quality and system integrity;
- Develop an ICG strategy, in cooperation with ICG Secretariat, to promote National support for regional reference frame realizations, especially in developing countries;
- The updated work plan also spells out links to the other three Working Groups.

This was followed by a wide ranging discussion on the Work Plan and key issues affecting the work of WG-D. Key issues raised were:

- There was general discussion of the second and third dot points above and the interplay between monitoring stations (core parts of each GNSS) and civil user networks such as the Continuously Operating Reference Stations operated by the IGS;
- Both the Russian and Chinese representatives highlighted their desire to see future co-location of monitor stations from the various GNSS. This stimulated discussion with various views expressed (both in favor and against) on the technical benefits of such co-location. It was also noted that as well as technical issues, there are also logistical and security issues associated with co-locating monitor stations for multiple GNSS at the same site. It was agreed that this issue of co-location of monitor stations should be discussed further within WG-D and that liaison with WG-A on this issue may also be required.
- It was also recognized that there is a need to continue to discuss and clarify the respective roles of GNSS monitor stations compared to those operated by organizations such as the IGS.
- China also raised the issue of needing regular updates to the ITRF and to ensure a clear relationship between ITRF and any periodic changes to the national reference frame. The IERS representative indicated that current practice was to update ITRF when day-to-day analysis of data contributing to ITRF indicated sufficient improvement to warrant such an update.
- China also expressed interest in closer cooperation between Beidou and IGS/IERS to ensure changes over time are properly managed for both the international use of Beidou and for any effect on national activities within China.

The overall outcome from discussion of the work plan was Recommendation #6 to the ICG seeking endorsement of the updated work plan (see below). The new Work Plan as ratified by ICG-5 is also included as an attachment to this report.

3.4. Recommendations from WG-D to the Plenary Meeting of the ICG

The meeting then reviewed (and in some cases amended) the wording of the draft recommendations from WG-D to the ICG on the following topics:

- WG-D Recommendation #06 - New Name and Updated Work Plan

- WG-D Recommendation #07 - Multi-GNSS Demonstration
- WG-D Recommendation #08 - Adoption of the International Terrestrial Reference System by the General Conference on Weights and Measures in October 2011
- WG-D Recommendation #09 - Liaison with Radio Technical Commission for Maritime Services (RTCM)
- WG-D Recommendation #10 - Retro-reflectors for Laser Ranging to GNSS Satellites

As the full wording of the recommendations give the background and rationale for each recommendation that detail will not be repeated here.

The only recommendation that was further amended following the WG-D meeting and based on discussions at the second plenary session of ICG-5 was Recommendation #10 in relation to retro-reflectors on GNSS satellites.

- The first amendment was requested by Japan because, while retro-reflectors are included in plans for future QZSS satellites, the next phase of QZSS does not yet have funding fully committed and it therefore cannot be guaranteed that retro-reflectors will be deployed on <u>all</u> future QZSS satellites, even though that is Japan's current intention. The amended recommendation therefore referred to inclusion in the design of future satellites;
- The second amendment was requested by the Indian delegation who were not represented at the second meeting of WG-D but who indicated during the second plenary session of ICG-5 that retro-reflectors are also included in the design of IRNSS satellites. India was therefore added to the list of system providers named in the recommendation. It should also be noted and welcomed that two new Laser Ranging stations are planned to be built in India to take advantage of retro-reflectors on IRNSS and other GNSS satellites.

Each recommendation as agreed by the Providers Forum and then accepted at the third plenary meeting of the ICG 5 is included as attachment to this report.

An additional recommendation on convening a Workshop on Scientific Applications of Multi-GNSS was briefly discussed in the WG, but only brought orally to the attention of the Plenary, due to lack of time. Noting that GNSS has clearly demonstrated its potential as a powerful tool for applications in the geosciences, metrology and fundamental physics; that two International Colloquia on “Scientific and Fundamental Aspects of the Galileo Programme” already took place in Europe, with a third planned for August 2011; and further that the Global Geodetic Observing System (GGOS), the focal project of IAG, is coordinating applications of the space geodetic techniques for the resolution of a wide range of scientific and societal issues: it was recommended that ICG convenes in 2012 a Workshop involving GNSS System Providers and GGOS to consider the advantages of multi-GNSS for scientific applications. This recommendation will be reconsidered at the next WG-D meeting, for possible adoption at ICG-6.

4. WG-D Contribution to the Joint Statement for ICG-4

At each ICG meeting a Joint Statement is released to summarize the outcomes of the meeting suitable for use in press releases etc. The following is the wording from Working Group D:

> *Working Group D on Reference Frames, Timing and Applications noted excellent progress in the work of its two Task Forces focussed on standard descriptions of geodetic and timing references for existing and planned systems. The WG agreed on an updated work plan. Recommendations were proposed and adopted by the ICG on several matters of relevance to the coordination of Geodetic and Time References. The Working Group reiterated its support for Multi-GNSS campaigns. An important new development was the agreement of the System Providers to liaise with relevant international bodies to ensure that receiver output formats for future GNSS signals are unambiguously defined.*

ATTACHMENT 1

Draft
Work Plan of the International Committee on Global Navigation Satellite Systems (ICG) Working Group D on Reference Frames, Timing and Applications (RFTA)

Revised, October 2010

ICG Working Group-D on Reference Frames, Timing and Applications (RFTA) will coordinate and organize activities in order to fulfill its objectives by bringing together all interested ICG participants (experts from the system and service providers, key user communities, etc) and by reviewing the present situation (existing documents, resolutions or practices). The WG-D can accomplish this by liaising with national and regional authorities and relevant international organizations, particularly in developing countries.

ICG Working Group D on Reference Frames, Timing and Applications (RFTA) will :

1. Coordinate Geodetic and Timing References for GNSS systems through its two task forces:
   a. The Task Force on Geodetic References plans to:
      i. Discuss and agree upon a consistent terminology for geodetic references and related understanding;
      ii. Prepare recommended practices for the realization of each GNSS Geodetic Reference and its alignment to ITRF;
      iii. Outline and encourage implementation plans in each relevant provider and user community;
      iv. Propose mechanisms for informing users of the current realization of a particular Geodetic Reference and any changes that may occur from time to time.

   b. The Task Force on Time References plans to:
      i. Discuss and agree upon a consistent terminology for timing references and related understanding;
      ii. Prepare recommended practices for the realization of each GNSS Time Reference and its alignment to UTC;
      iii. Outline and encourage implementation plans in each relevant user community;
      iv. Propose mechanisms for informing users of the current realization of a particular Time Reference and any changes that may occur from time to time.

2. Recommend the adoption of operational performance standards for GNSS monitoring networks; e.g., the IGS standards and conventions for continuous GNSS stations. The WG-D will engage in the evolution of these standards for multi-GNSS stations. WG-C will assist to disseminate this information;

3. Recommend approaches for the use of civil user networks (global IGS or denser regional networks, e.g. EUREF, SIRGAS, AFREF, EUPOS, etc) for independent calibration and validation of site quality and system integrity;

4. Develop an ICG strategy, in cooperation with ICG Secretariat, to promote National support for regional reference frame realizations, especially in developing countries (e.g., AFREF, SIRGAS, AP-REF).

In addition, Working Group –D has a number of overlapping activities that could be joint with other WG's, as highlighted in the previous workplan:

(a) WG-A Compatibility and Interoperability

Fundamental to compatibility and interoperability is the relationship of various GNSS' geodetic reference and timing systems. These are being addressed in WG-D within two task forces, the Task Force on Geodetic References and Task Force on Timing References, established in Dec 2008 at ICG-3 Pasadena.

(b) WG-B Enhancement of performance of GNSS services

Actions within WG-B can be facilitated by the extensive activities within the Associate and Observer members organizations (FIG, IAG, IGS, IERS, BIPM and their contributing national and regional organizations) participating in WG-D with regards to documentation and applications related to ionospheric and tropospheric models and algorithms, multipath analysis and mitigation, and timing aspects, primarily for fixed continuous GNSS stations.

(c) WG-C User Information Dissemination

Many of the activities within WG-C can and should be coordinated with WG-D's Associate and Observer members in order to broadly disseminate information and promote outreach for GNSS applications.

ATTACHMENT 2

Galileo Terrestrial Reference Frame

Responsible Organization: European Space Agency (ESA)

Abbreviated Frame Name: GTRF

Associated TRS: ITRS

Coverage of Frame: Global

Type of Frame: 3-Dimensional

Last Version: GTRF09v01

Brief Description

The GTRF09v01 is the current GTRF prototype solution obtained by accumulating time series of station positions of 133 stations, including 13 Galileo Experimental Sensor Stations (GESS), using GPS observations. The GTRF09v01 was computed by the GGSP (Galileo Geodetic Service Provider) consortium.

Definition of Frame

- **Origin**: Zero translation and translation rate with respect to ITRF2005
- **Scale**: Zero scale and scale rate with respect to ITRF2005
- **Orientation**: Zero rotation and rotation rate with respect to ITRF2005.
- **Time Evolution**: Zero rotation rate with respect to ITRF2005.

Coordinate System: Cartesian coordinates (X, Y, Z)

References:

- http://www.ggsp.eu/ggsp_home.html

Transformation Parameters

Transformation parameters from GTRF09v01 to other frames. "ppb" refers to parts per billion (or 10^{-9}). The units for rate are understood to be "per year."

ITRF Solution Epoch (mas)	Tx (mm)	Ty (mm)	Tz (mm)	D (ppb)	Rx (mas)	Ry (mas)	Rz
ITRF2005	(ZEROS BY CONSTRUCTION)						
ITRF2008 2000.0	2.0	0.9	4.7	-0.94	0.00	0.00	0.00
rates	-0.3	0.0	0.0	0.00	0.00	0.00	0.00

ATTACHMENT 3

International Terrestrial Reference Frame

Responsible Organization: International Earth Rotation and Reference Systems Service (IERS)

Abbreviated Frame Name: ITRF

Associated TRS: ITRS

Coverage of Frame: Global

Type of Frame: 3-Dimensional

Last Version: ITRF2008

Brief Description

The ITRF2008 is the current realization of the ITRS obtained by combination of VLBI, SLR, GPS and DORIS time series of station positions and Earth Orientation Parameters provided by the IAG Services (IVS, ILRS, IGS, IDS), together with local ties in co-location sites. The ITRF2008 is published by the ITRS product center of the IERS

Definition of Frame

- **Origin**: Zero translation and translation rate with respect to SLR long-term solution used in the ITRF2008 combination
- **Scale**: Zero scale and scale rate with respect to the mean scale of VLBI and SLR long-term solutions used in the ITRF2008 combination.
- **Orientation**: Zero rotation and rotation rate with respect to ITRF2005.
- **Time Evolution**: Zero rotation rate with respect to ITRF2005.

Coordinate System: Cartesian coordinates (X, Y, Z)

References:

- http://itrf.ensg.ign.fr/ITRF_solutions/2008/ITRF2008.php

Transformation Parameters

Transformation parameters from ITRF2008 to past ITRFs. “ppb” refers to parts per billion (or 10^{-9}). The units for rate are understood to be “per year.”

ITRF Solution	Epoch	Tx (mm)	Ty (mm)	Tz (mm)	D (ppb)	Rx (mas)	Ry (mas)	Rz (mas)
ITRF2005	2000.0	-2.0	-0.9	-4.7	0.94	0.00	0.00	0.00
rates		0.3	0.0	0.0	0.00	0.00	0.00	0.00
ITRF2000	2000.0	-1.9	-1.7	-10.5	1.34	0.00	0.00	0.00
rates		0.1	0.1	-1.8	0.08	0.00	0.00	0.00
ITRF97	2000.0	4.8	2.6	-33.2	2.92	0.00	0.00	0.06
rates		0.1	-0.5	-3.2	0.09	0.00	0.00	0.02
ITRF96	2000.0	4.8	2.6	-33.2	2.92	0.00	0.00	0.06
rates		0.1	-0.5	-3.2	0.09	0.00	0.00	0.02
ITRF94	2000.0	4.8	2.6	-33.2	2.92	0.00	0.00	0.06
rates		0.1	-0.5	-3.2	0.09	0.00	0.00	0.02
ITRF93	2000.0	-24.0	2.4	-38.6	3.41	-1.71	-1.48	-0.30
rates		-2.8	-0.1	-2.4	0.09	-0.11	-0.19	0.07
ITRF92	2000.0	12.8	4.6	-41.2	2.21	0.00	0.00	0.06
rates		0.1	-0.5	-3.2	0.09	0.00	0.00	0.02
ITRF91	2000.0	24.8	18.6	-47.2	3.61	0.00	0.00	0.06
rates		0.1	-0.5	-3.2	0.09	0.00	0.00	0.02
ITRF90	2000.0	22.8	14.6	-63.2	3.91	0.00	0.00	0.06
rates		0.1	-0.5	-3.2	0.09	0.00	0.00	0.02
ITRF89	2000.0	27.8	38.6	-101.2	7.31	0.00	0.00	0.06
rates		0.1	-0.5	-3.2	0.09	0.00	0.00	0.02
ITRF88	2000.0	22.8	2.6	-125.2	10.41	0.10	0.00	0.06
rates		0.1	-0.5	-3.2	0.09	0.00	0.00	0.02

ATTACHMENT 4

International Terrestrial Reference System

Responsible Organization: International Earth Rotation and Reference Systems Service (IERS)

Abbreviated System Name: ITRS

Coverage of System: Global

Type of System: 3-Dimensional

Brief Description

A spatial reference system co-rotating with the Earth in its diurnal motion in space. In such a system, positions of points attached to the solid surface of the Earth have coordinates which undergo only small variations with time, due to geophysical effects (tectonic or tidal deformations).

Definition of System

- **Origin**: It is geocentric, its origin being the center of mass for the whole Earth, including oceans and atmosphere
- **Scale**: The unit of length is the meter (SI). The scale is consistent with the TCG time coordinate for a geocentric local frame, in agreement with IAU and IUGG (1991) resolutions. This is obtained by appropriate relativistic modelling
- **Orientation**: Its orientation was initially given by the BIH orientation at 1984.0
- **Time Evolution**: The time evolution of the orientation is ensured by using a no-net-rotation condition with regards to horizontal tectonic motions over the whole Earth.

Coordinate System: Cartesian coordinates (X, Y, Z)

References:

- IERS Conventions (2010): http://tai.bipm.org/iers/convupdt/convupdt.html

ATTACHMENT 5

Global and Regional Reference System Description

System Name: World Geodetic System 1984 (WGS 84)

Coverage of System (e.g. Global, Regional, Local): Global

Type of System (e.g. Horizontal, Vertical, 3-Dimensional): 3-Dimensional

Definition of System

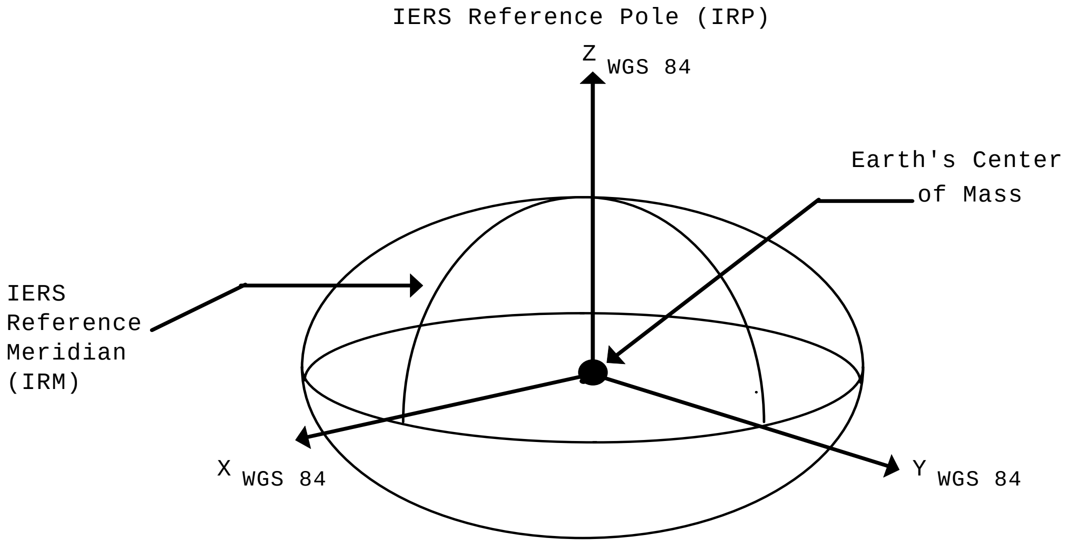
1. **Description**: e.g. Conventional Terrestrial Reference System conforming to IERS Technical Note 21.

The WGS 84 Coordinate System is a Conventional Terrestrial Reference System (CTRS). The definition of this coordinate system follows the criteria outlined in the International Earth Rotation Service (IERS) Technical Note 21. These criteria are repeated below:

- It is geocentric, the center of mass being defined for the whole Earth including oceans and atmosphere;
- Its scale is that of the local Earth frame, in the meaning of a relativistic theory of gravitation;
- Its orientation was initially given by the Bureau International de l'Heure (BIH) orientation of 1984.0;
- Its time evolution in orientation will create no residual global rotation with regards to the crust.

2. **Describe Coordinate System** (e.g. Right-handed, orthogonal, origin, axes)

The WGS 84 Coordinate System is a right-handed, Earth-fixed orthogonal coordinate system and is graphically depicted below.



The WGS 84 Coordinate System Definition

The origin and axes are defined as follows:

- Origin = Earth's center of mass

- Z-Axis = The direction of the IERS Reference Pole (IRP). This direction corresponds to the direction of the BIH Conventional Terrestrial Pole (CTP) (epoch 1984.0) with an uncertainty of 0.005″
- X-Axis = Intersection of the IERS Reference Meridian (IRM) and the plane passing through the origin and normal to the Z-axis. The IRM is coincident with the BIH Zero Meridian (epoch 1984.0) with an uncertainty of 0.005″
- Y-Axis = Completes a right-handed, Earth-Centered Earth-Fixed (ECEF) orthogonal coordinate system

The WGS 84 Coordinate System origin also serves as the geometric center of the WGS 84 Ellipsoid and the Z-axis serves as the rotational axis of this ellipsoid of revolution.

3. Reference Ellipsoid

a. Name: WGS 84 Ellipsoid
b. Parameters (e.g. flattening, semi-major axis)

Parameter	Notation	Value
Semi-major Axis	a	6378137.0 meters
Reciprocal of Flattening	1/f	298.257223563

4. Reference Epoch: 2001.0

5. Physical Constants

a. Earth's gravitational constant (with and without Earth's atmosphere included)
b. Angular velocity of the Earth

Parameter	Notation	Value
Angular Velocity of the Earth	ω	7292115.0 x 10^{-11} rad/s
Earth's Gravitational Constant (Mass of Earth's Atmosphere Included)	GM	3986004.418 x $10^8 m^3/s^2$

WGS 84 Parameter Values for Special Applications

Parameter	Notation	Value	Accuracy (1σ)
Gravitational Constant (Mass of Earth's Atmosphere Not Included)	GM′	3986000.9 x 10^8 m^3/s^2	±0.1 x 10^8 m^3/s^2
GM of the Earth's Atmosphere	GM_A	3.5 x 10^8 m^3/s^2	±0.1 x 10^8 m^3/s^2
Angular Velocity of the Earth (In a Precessing Reference frame)	ω*	(7292115.8553 x 10^{-11} + 4.3 x 10^{-15} T_U) rad/s	±0.15 x 10^{-11} rad/s

6. **List additional physical and geometric constants** such as

a. Second Degree Zonal Harmonic
b. Semi-minor axis
c. First Eccentricity
d. Theoretical Gravity potential of the ellipsoid
e. Theoretical gravity formula constant
f. Mass of the earth (including Earth's atmosphere)

g. Speed of light in a vacuum
h. Universal Constant of gravitation

Physical and geometric constants for WGS 84

Constant	Notation	Value
Second degree Zonal Harmonic	$\overline{C}_{2,0}$	-0.484166774985 x 10^{-3}
Semi-minor Axis	B	6356752.3142 m
First Eccentricity	E	8.1819190842622 x 10^{-2}
Theoretical (Normal) Gravity Potential of the Ellipsoid	U_0	62636851.7146 m^2/s^2
Theoretical (Normal) Gravity Formula Constant	K	0.00193185265241
Mass of the Earth (Includes Atmosphere)	M	5.9733328 x 10^{24} kg
Velocity of Light (in a Vacuum)	C	299792458 m/s
Universal Constant of Gravitation	G	6.673 x 10^{-11} $m^3/kg\ s^2$

Describe how the system was developed or formulated. (General description of how the physical and geometric constants were determined or derived. Include such items as types and accuracy of sources and models used to develop system. Include mathematical formulas where appropriate. Identify core sites used to determine the origin of the system including location and velocity or velocity model.)

The original WGS 84 reference frame was established in 1987 using the Navy Navigation Satellite System (NNSS) or TRANSIT system. The main objective in the original effort was to align, as closely as possible, the origin, scale and orientation of the WGS 84 frame with the BIH Terrestrial System (BTS) frame at an epoch of 1984.0. This development is given in DMA TR 8350.2, First Edition and Second Edition). Initial uncertainties, in 1987, were 1-2 meters with respect to the BTS.

G1150 is the third update to the realization of the WGS 84 Reference Frame. The previous realizations were designated WGS 84 (G730) and WGS 84 (G873) and WGS 84. The “G” indicates that GPS measurements were used to obtain the coordinates. The number following the “G” indicates the GPS week number of the week during which the coordinates were implemented in the NGA GPS precise ephemeris estimation process. The GPS OCS implemented WGS 84 (G730) and WGS (G873) on 29 June 1994 and 29 January 1997, respectively. The original WGS 84 has no such designation. Note that the original WGS 84 was generated using the TRANSIT system while all others use GPS. Detailed documentation of the previous iterations is in NIMA TR 8350.2, (2004). The following table shows the name, implementation date, epoch and accuracy of each realization.

Name	Implementation	Epoch	Accuracy
WGS 84	1987		1-2 meters
WGS 84 (G730)	29 Jun 1994	1994.0	10 cm/component rms
WGS 84 (G873)	29 Jan 1997	1997.0	5 cm/component rms
WGS 84 (G1150)	20 Jan 2002	2001.0	1cm/component rms

WGS 84 is the reference system used by GPS. Users directly receive WGS 84 coordinates from a GPS receiver if no changes to the reference frame are selected or made. There is a step-wise adjustment of WGS 84 delivered through GPS broadcast orbits. Annually, NGA provides the WGS 84 coordinates of its sites adjusted for plate tectonic motion at the mid-year epoch (2010.5 for example) and this is incorporated into the GPS broadcast orbits.

WGS 84 (G1150) Methodology

The Naval Surface Warfare Center Dahlgren Division (NSWCDD) and NGA personnel used GPS observations from the USAF and NGA permanent GPS monitor stations and selected International GNSS Service (IGS) (previously named International GPS Service for Geodynamics) stations to estimate refined coordinates for the USAF and NGA stations. The NGA sites included NGA GPS Monitor Station Network (MSN) stations and Differential GPS Reference Stations (DGRS) located at remote NGA geodetic survey offices.

● Data was collected from all sites for the period 14-28 February 2001.

● A set of 49 IGS stations was selected to serve as control in the Reference Frame solution. The International Terrestrial Reference Frame (ITRF) 2000 coordinates of these stations were held fixed during the estimation. The ITRF2000 coordinates are referenced to epoch 1997.0. The two IGS station positions were propagated forward in time to the data collection period using the station velocities provided with the ITRF2000 coordinates.

● Meteorological data were utilized for all stations. Data from nearby sites or default values were used when meteorological data was not collected at the GPS station.

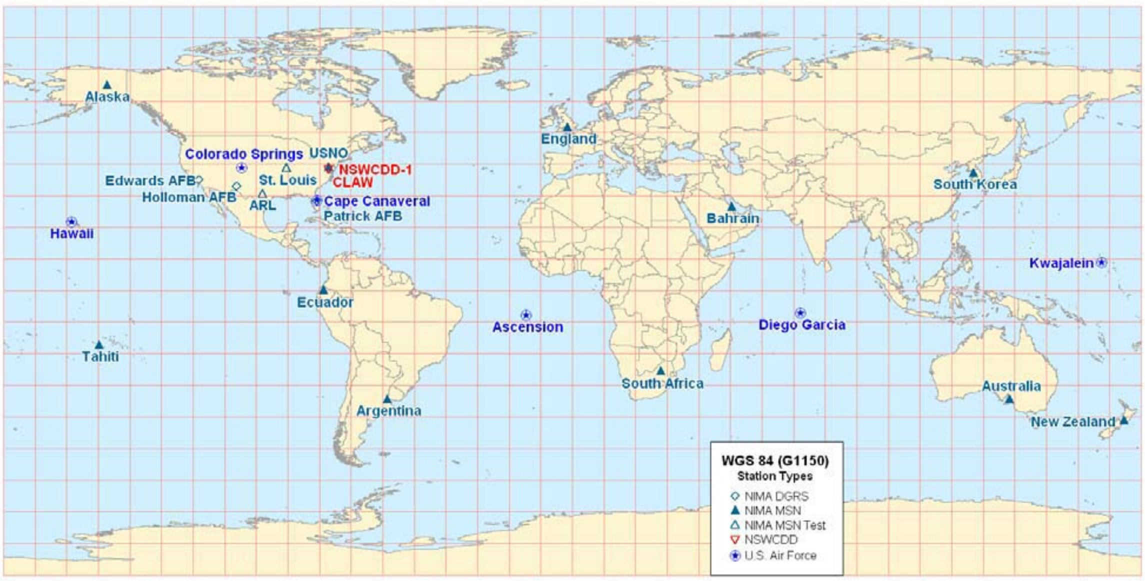


Figure 1: WGS 84 (G1150) Reference Frame Stations

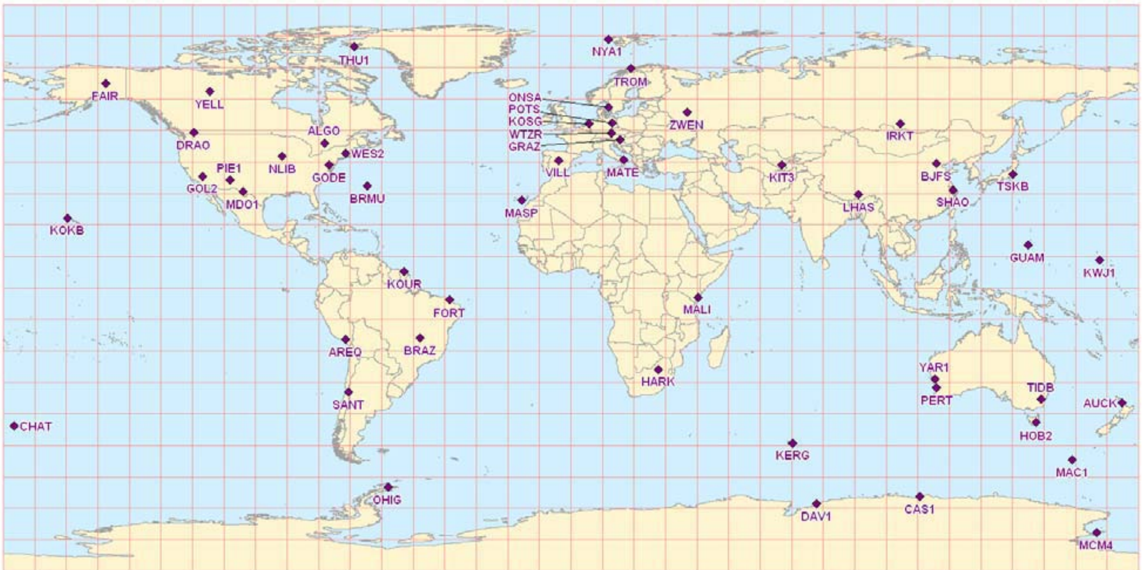


Figure 2: International GNSS Service (IGS) fiducial stations

The WGS 84 (G1150) realization included a much larger set of IGS stations and the best-known velocities of the stations, rather than relying solely on the NNR-NUVEL1A plate motion model. In particular, the station velocities of Ecuador and New Zealand, which are located on plate boundaries, were not derived from the NNR-NUVEL1A model. The velocities of the USAF and NGA stations used in this realization are given in a table. Site information for IGS stations may be obtained through the IGS website currently at http://igscb.jpl.nasa.gov.

NSWCDD and NGA have also made improvements to the geophysical modeling used in the estimation process. Examples include:

- integration of the IERS tide model,
- inclusion of pole tide effects,
- integration of a tropospheric refraction model that estimates the horizontal gradient.

The WGS 84 core sites with their Cartesian Coordinates and velocities are:

WGS 84 (G1150) Cartesian coordinates* and velocities for epoch 2001.0

Station Location	NGA Station Number	X (km)	Y (km)	Z (km)	X* (cm/yr)	Y* (cm/yr)	Z* (cm/yr)
Air Force Stations							
Colorado Springs	85128	-1248.597295	-4819.433239	3976.500175	-1.8	0.1	-0.4
Ascension	85129	6118.524122	-1572.350853	-876.463990	-0.3	-0.5	1.0
Diego Garcia	85130	1916.197142	6029.999007	-801.737366	-4.2	2.0	3.1
Kwajalein	85131	-6160.884370	1339.851965	960.843071	2.1	6.7	2.7
Hawaii	85132	-5511.980484	-2200.247093	2329.480952	-1.0	6.3	3.0
Cape Canaveral	85143	918.988120	-5534.552966	3023.721377	-1.0	-0.2	0.2
NGA Stations							

Australia	85402	-3939.182131	3467.075376	-3613.220824	-4.08	0.36	4.73
Argentina	85403	2745.499065	-4483.636591	-3599.054582	0.21	-1.00	0.70
England	85404	3981.776642	-89.239095	4965.284650	-1.38	1.65	0.77
Bahrain	85405	3633.910757	4425.277729	2799.862795	-2.97	0.91	2.53
Ecuador	85406	1272.867310	-6252.772219	-23.801818	0.30	0.04	0.99
US Naval Observatory	85407	1112.168358	-4842.861664	3985.487174	-1.48	-0.01	0.10
Alaska	85410	-2296.298410	-1484.804985	5743.080107	-2.22	-0.36	-0.92
Alaska**	85410	-2296.298460	-1484.805050	5743.080090	-2.22	-0.36	-0.92
New Zealand	85411	-4780.787068	436.877203	-4185.258942	-2.35	1.92	2.20
South Africa	85412	5066.232133	2719.226969	-2754.392735	0.01	2.09	1.40
South Korea	85413	-3067.861732	4067.639179	3824.294063	-2.90	-0.76	-1.02
Tahiti	85414	-5246.403866	-3077.285554	-1913.839459	-4.25	4.68	2.91

* Coordinates are for the electrical phase centers of the antennas.
** Post 3 Nov 2002 earthquake. Steady-state velocity is assumed to be unchanged.

Describe associated models used for applications such as gravitational model and geoid model.

Describe this reference systems relationship with other global and/or regional reference systems. Give transformation parameters and accuracy if determined.

Historically, NGA and its predecessor organizations have ensured that WGS 84 is consistent with ITRF which is generated by the IGS. The purpose of this alignment is to ensure scientific integrity and follow best practices. The ITRF incorporates multiple methods to realize the reference system such as satellite laser ranging and very-long-baseline interferometry that NGA does not include. Adjusting WGS 84 to ITRF allows the reference system to take advantage of those methods without directly incorporating them into the coordinate determination software.

How the alignment is accomplished is described under "Methodology". The estimated accuracy of WGS 84 (G1150) is on the order of one centimeter (one standard deviation) in each coordinate component for each of the USAF and NGA stations. At its implementation, WGS 84 (G1150) with epoch 2001.0 had an alignment of the same magnitude in relation to ITRF2000 (1997.0) when adjusted for the different epochs of the two systems. Current comparisons between WGS 84 (G1150) and ITRF2008 show larger differences.

NGA contributes data from its 11 operational GPS Monitor Station sites to the IGS for inclusion in their network. NGA routinely incorporates data from a few IGS sites into its GPS orbit determination process. Those sites currently include Kerguelen and Maspalomas. In the past, that list has also included Yakutsk.

Future Plans

NGA is planning to recompute its monitor station coordinates in 2011. During 2009 and 2010, NGA is deploying new GPS receivers and antennas at all of its sites. To establish a tie between the new and old antennas, a reference mark is occupied simultaneously with each antenna to yield a relative position between them. When completed, the latest realization of WGS 84 will be published.

ATTACHMENT 6

GNSS Timescale Description

GPS

Definition of System

1. **System timescale: GPS Time**

2. **Generation of system timescale:**

Clock ensemble of monitor station frequency standards and GPS satellite clocks.

3. **Is system timescale steered to a reference UTC timescale?** Yes

   a. **To which reference timescale:** UTC(USNO)

   b. **Whole second offset from reference timescale?** Yes, 15 seconds ahead of UTC as of 07/2010, with changes corresponding to the addition/subtraction of leap seconds

   c. **Maximum offset (modulo 1s) from reference timescale?** 1 microsecond, typically within 10 nanoseconds

4. **Corrections to convert from satellite to system timescale?** Yes. **If yes:**

   a. **Type of corrections given; include statement on relativistic corrections**
   Quadratic coefficients broadcast as part of the GPS navigation message. The expression for relativistic correction is given in IS-GPS-200. This expression accounts for 1^{st} order deviations in eccentricity of individual GPS orbits from the mean orbital elements.

   b. **Specified accuracy of corrections to system timescale**
   part of the overall GPS system specification of user range error which is expressed as a combination of satellite position error and satellite clock error: 6 meter for legacy GPS. Typical errors are much better than this specification.

   c. **Location of corrections in broadcast messages**
   Subframe 1 of the legacy GPS navigation message.

   d. **Equations to correct satellite timescale to system timescale**

a_f0 + a_f1(t-t_oc) + a_f2(t-t_oc)^2 + delta_t_r
With: a_f0, a_f1, a_f2 = Quadratic coefficients
t = GPS system time
t_oc = Time of clock data
delta_t_r = Delta time due to relativistic correction

delta_t_r = F e sqrt(A) sin(E_k)
With: F = -2 sqrt(mu) / c^2 = constant
mu = value of Earth's Universal gravitational parameters
c = Speed of Light
e = Eccentricity
A = Semi-major axis
E_k = Eccentric anomaly

5. Corrections to convert from system to reference UTC timescale? If yes:

a. Type of corrections given
Linear coefficients and leap second terms

b. Specified accuracy of corrections to reference timescale
40 nanoseconds (95 %), but typically within 10 nanoseconds. This is the accuracy of the UTC(USNO) offset data in the broadcast navigation message portion of the SPS SIS which relates GPS time (as maintained by the Control Segment) to UTC (as maintained by the U.S. Naval Observatory).

c. Location of corrections in broadcast messages
Subframe 4, page 18

d. Equations to correct system timescale to reference timescale
delta_t_utc = delta_t_LS + A_0 + A_1 (t_E - t_ot + 604800(WN-WN_t))
With: delta_t_LS = delta time due to leap seconds
A_0, A_1 = linear coefficients
t_E = GPS time as estimated by the user
t_ot = Reference time for UTC data
WN = current week number
WN_t = UTC reference week number

6. Specified stability of system timescale

Not specified

7. Specified stability of reference timescale

UTC(USNO) stability of $3x10^{-15}$ per day

8. Specified stability of satellite clocks

Not published, stability depends on block of satellite

9. Availability of System to GNSS Time Offset (GGTO)

GPS plans to broadcast a GGTO correction as part of the modernized navigation messages.

a. Systems for which corrections are given?
Up to 7 GNSS systems

b. Type of GGTO corrections given
Quadratic coefficients

c. Stated accuracy of GGTO correction, if available
GPS has a stated goal of 5 ns (95 %) for a GPS to Galileo Time Offset. Accuracy of GGTO corrections to other systems will be highly dependent on each system’s time scales predictability.

d. Location of corrections in broadcast messages
As specified in IS-GPS-200D, IS-GPS-705 and IS-GPS-800

e. Equations used for GGTO message
Similar to 4d without relativistic correction

Describe the details of the system, i.e. locations of system and reference timescale clocks, generation of timescales, and other details.

The GPS Master Control Station is located in Schriever AFB, Colorado, USA and GPS Time is computed as part of the overall clock and orbit estimation process. GPS operates 6 monitor stations regional distributed around the world in addition to using 6 monitoring stations operated by NGA. Each reference station receiver is referenced to a Cesium atomic clock. At two reference stations Hydrogen MASER clocks are used. These clocks and the satellite clocks are ensembled to make GPS Time.

The oscillator frequencies onboard the GPS satellites have been offset from their nominal values in order to account for special and general relativistic effects with respect to ground-based observers so that the received frequencies at the Earth's surface are consistent with terrestrial time (e.g., UTC), assuming mean nominal GPS orbital elements.

Describe how the timescale transfers from the reference timescale to the system timescale and finally to the satellites. Include the nominal rate of SV updates.

USNO monitors the offset of GPS time from UTC(USNO) and reports this data to GPS Operations for use in timescale steering and UTC broadcast corrections. Satellites are nominally updated at least once per day.

If any other pertinent details exist concerning the generation and realization of system and/or reference time, include them as well.

GPS Time is realized by simultaneous L1 P(Y) and L2 P(Y) pseudorange observations used in a linear combination to remove the 1st order ionospheric propagation delay, according to IS-GPS-200. Users of other GPS signals must account for inter-signal biases to obtain the broadcast GPS Time consistently.

ATTACHMENT 7

Recommendation for Committee Decision (WG-D Recommendation #06)

Prepared by ICG Working Group D

Date of Submission 22 October 2010

Issue Title: Working Group D: **New Name and Updated Work Plan**

Background/Brief Description of the Issue:

Working Group D proposes a name change and outlines its revised workplan in the Attached document.

Discussion/Analyses:

The original name of Working Group D is "Interaction with National and Regional Authorities and Relevant International Organizations", in order to better reflect the activities of the WG, and to facilitate remembering the name, we propose to rename the WG to:

ICG Working Group D on Reference Frames, Timing and Applications (RFTA)

After lengthy discussion, the workplan for WG-D is similarly revised and attached.

Recommendation of Committee Action:

It is therefore recommended that the ICG

a. Approve and accept the new name, and

b. Approve and accept the updated workplan.

ATTACHMENT 8

Recommendation for Committee Decision (WG-D Recommendation #07)

Prepared by ICG Working Group D

Date of Submission 22 October 2010

Issue Title: Working Group D: **Multi-GNSS Demonstration**

Background/Brief Description of the Issue:

The IGS, IAG and FIG are already committed to supporting the Multi-GNSS Demonstration Project in the Asia Oceania region in line with the relevant recommendations at ICG-4. The IGS is now extending that support through a wider Call for Participation in a global Multi-GNSS Demonstration Campaign, which will bring in other relevant international activities.

Discussion/Analyses:

The working group notes that the IGS Governing Board decided in June 2010 to prepare a Call for Participation (CfP) in a Multi-GNSS Demonstration Campaign to initiate longer-term preparation to incorporate and utilize other GNSS and regional systems.

This is a similar approach taken by the IGS in 1998 when a CfP was developed for an International GLONASS Experiment (IGEX) that resulted in a phased approach to observing, analyzing and ultimately incorporating GLONASS into the IGS processing streams. This contributed to the decision to change the name of IGS from International GPS Service into the International GNSS Service in 2005. GLONASS and GPS are both routinely handled on a continuous basis with the IGS network and processing streams.

Recommendation of Committee Action:

It is therefore recommended that the ICG

a. Note the IGS support for ICG WG-D Recommendation 5 on Multi-GNSS in support of Japan’s proposal, and,

b. Note that the CfP will extend this to a global Multi-GNSS Demonstration Campaign and that the CfP will be broadly distributed within ICG.

ATTACHMENT 9

Recommendation for Committee Decision (WG-D Recommendation #08)

Prepared by ICG Working Group D

Date of Submission 22/10/2010

Issue Title: **Adoption of the International Terrestrial Reference System (ITRS) by the General Conference on Weights and Measures (CGPM) in October 2011**

Background/Brief Description of the Issue:

The International Terrestrial Reference System (ITRS) has been recommended by the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG) for application in space and Earth sciences. Access to ITRS is primarily through the International Terrestrial Reference Frame (ITRF), and with an approximation ranging between 3 and 40 cm by WGS84, PZ-90, the Galileo Terrestrial Reference Frame (GTRF), the China Geodetic System 2000 (CGS'2000), and the regional densifications.

Discussion/Analyses:

As previously noted, interoperability of the various GNSS benefit greatly by aligning to a common geodetic and time references.

The ICG is a unique mechanism to recommend that GNSS Service Providers align their Geodetic and Time References to the internationally recognised standards and conventions represented by the ITRS and UTC for the operation of their systems. A key issue for ICG to note is that while UTC has been endorsed by the CGPM in 1975, the ITRS has never been officially recommended for use by any intergovernmental organization.

Recommendation of Committee Action:

Considering

- that international geodetic reference is ITRS as realized by ITRF;
- that the International Committee for Weights and Measures (CIPM) agreed in October 2009 on the need to support the adoption of the ITRS as the reference for geodetic metrological applications;
- that the General Conference on Weights and Measures (CGPM) will vote in October 2011 on a resolution recommending the adoption of the ITRS as the international standard for terrestrial reference frames used for all metrological applications;
- that the endorsement by the CGPM will bring the ITRS under the umbrella of the Metre Convention: an international treaty to which all current System Providers and many GNSS user countries are signatories.

WG D recommends to the ICG

a. Note the above and its implications for the work of the Working Group D Task Forces and the System Providers.

ATTACHMENT 10

Recommendation for Committee Decision (WG-D Recommendation #09)

Prepared by ICG Working Group D

Date of Submission 22/10/2010

Issue Title: **Radio Technical Commission for Maritime Services**

Background/Brief Description of the Issue:

RTCM is considering the establishment of a sub-committee devoted to the definition and extension of the RINEX (Receiver Independent Exchange) format. IGS is a full member of RTCM and is working in the RTCM on GNSS format issues, including real-time formats, and seeking a common, open (non-proprietary) format to be agreed upon by receiver manufacturers as a common interface to users.

Discussion/Analyses:

The IGS has been in discussion with JAXA, as the lead organization for the Asian Pacific Multi-GNSS campaign, to extend the RINEX format to handle data from QZSS.

Data and exchange formats for multi-GNSS are increasingly complicated and a more unified approach seems prudent.

Recommendation of Committee Action:

C*onsidering*

WG D recommends to the ICG

That all System Providers be aware of these issues and recognize the importance of open descriptions of GNSS signals to ensure proper implementation, into new multi-GNSS receivers, the output of well-defined measurement data, and

They are also encouraged to liaise with IGS and RTCM to ensure that future signals from next generation GNSS are supported through unambiguously defined exchange formats (e.g., extensions to RINEX, or common receiver output) and output data streams.

ATTACHMENT 11

Recommendation for Committee Decision (WG-D Recommendation #10)

Prepared by **Working Group D**

Date of Submission **21 October 2010**

Issue Title: **Retroreflectors for Laser Ranging to GNSS Satellites**

Background/Brief Description of the Issue:

Satellite Laser Ranging (SLR) involves precise range measurement between an SLR ground station and a retroreflector- equipped satellite using laser pulses corrected for refraction, satellite center of mass, and the internal delay of the ranging machine.

Several aspects of SLR are of particular interest to the ICG:

- SLR can perform a completely independent Quality Assurance on the computation of the orbits of GNSS satellites;
- SLR is fundamental to the definition and realization of the International Terrestrial Reference System through its ability to measure the position of the center of mass of the earth and to define and constrain the scale of and realization of the ITRS;
- SLR can help to ensure that the realization of each Geodetic Reference used in a GNSS in order to improve accuracy, reliability and consistency with respect to the International Terrestrial Reference Frame (ITRF).

There are also many important scientific applications for SLR, including:

- Precision Orbits and Calibration of Altimetry missions (Oceans, Ice) and other Low Earth Orbiting (LEO) missions;
- Plate Tectonics and Crustal Deformation;
- Static and Time-varying Gravity Field;
- Earth Orientation and Rotation (Polar Motion, length of day);
- Total Earth Mass Distribution.

Discussion/Analyses:

During discussions at ICG5, WG-D reiterated its commitment to the Recommendation to ICG3 in Pasadena to encourage all GNSS System Providers to ensure that all future GNSS satellites carry a suitable retroreflector array.

Recommendation of Committee Action:

It is therefore recommended to the ICG and its Providers Forum that:

a. It commends Japan for its deployment of retroreflectors on their recently launched QZSS satellite, and;

b. Notes that Japan therefore joins China, Europe, India and Russia among the System Providers now including retroreflectors in their current designs for GNSS satellites.

ATTACHMENT 12

From: Jim.Ray
Subject: comments on frame & time interoperability

To WG-A, WG-D, and Task Force chairs,

In an effort to maintain the new momentum that began last week in Turin, below are some comments dealing with the technical issues related to interoperability. As noted during the meeting, it would be invaluable to establish a forum where such exchanges could be facilitated.
Regards,
--Jim Ray

Comments on GNSS Reference Frame & Time Scale Alignment for Interoperability

As I mentioned in a WG-D meeting in Turin, the effective reference frames realized in the results of GNSS users are influenced by more than just the nominal terrestrial reference frame of the respective GNSS tracking stations.

Users have available to them their receiver data (code and phase observations) as well as the geocentric coordinates and clocks of the transmitting GNSS satellites via the broadcast nav messages. Together these allow the expression of user position and time results in the instantaneous frames corresponding to the nav messages. Possible inconsistencies in position and time results obtained from different GNSSs result from these sources:

* GNSS Terrestrial Reference Frames (TRFs) -- Any differences between the TRFs of the GNSS systems enter directly into different results for users for each GNSS. However, generally all the system providers use frames closely aligned to ITRF (within several cm), except for GLONASS. The GLONASS frame seems empirically to be rotated about the Earth's polar axis by roughly 20 milliarcseconds (mas) based on IGS results, or an east-west (longitude) shift of the equator of the about 60 cm. Other TRF differences for GLONASS are below about 10 cm.

* Earth orientation parameters (EOPs) -- The broadcast nav orbits are the product of projections of past observed orbits into the future. This step requires predictions of the future orientation of the Earth, which does not rotate perfectly uniformly. The IERS estimates that over the first day after the latest measured EOP values that their predictions have RMS errors of about 0.5 mas for each component of polar motion and about 0.15 ms (2.25 mas) for UT1. UT1 (axial rotation) variations are larger than for polar motion and more difficult to predict. This error corresponds to about 7 cm of RMS east-west (longitude) scatter over the first day of EOP predictions. The nav orbit errors due to polar motion predictions should be smaller by a factor of at least four or so.

* Orbit modeling -- Projecting GNSS satellite orbits into the future incurs additional errors due to inaccuracies in the dynamical models used. Normally, for well-aligned TRFs, the common-mode components of these errors on all the satellites of a given GNSS dominate the overall quality of the derived user reference frames. The effects can be mitigated operationally by reducing the orbit prediction interval by increasing the satellite upload rate. The RMS orbit prediction errors normally should grow approximately as the square-root of the projection time, so 24-hr uploads will lead to satellite orbit errors about double those for 6-hr uploads. From IGS experience the most difficult components to control in satellite orbit predictions are net reference frame rotations. These are the limiting orbit errors even for post-processed results where no predictions are involved. In recent years, typical errors for GPS can be summarized as follows:

X & Y origin translations -- mostly random, RMS ~5 cm for each component
Z origin translation -- annual systematic oscillation with amp <10 cm + random, RMS ~few cm
X & Y rotations -- systematic & random, RMS ~few cm each component
Z rotation -- systematic longitude drift over range of +- ~15 cm + random, RMS ~few cm
daily residuals (1D after removing translations & rotations) -- random, RMS ~90 cm

All three categories of error above contain both systematic and random contributions. The systematic errors are correlated in time so they do not average down over time or do so slowly. The random errors are temporally uncorrelated and can be reduced by averaging over an interval T by the factor 1/sqrt(T).

In the case of GPS, orbit modeling errors most severely limit user access to the underlying reference frame, followed by EOP prediction errors, then the GPS TRF itself. It is very likely that the same will apply to other GNSSs except for specific TRF discrepancies, as the GLONASS longitude rotation.

For timing interoperability between GNSSs, there are similar considerations that affect user-realized clock estimates besides just the different system time scales that are maintained. In particular, prediction of future satellite clock values from past observations for the broadcast nav messages generally introduces the largest error component. As with orbits, the operational upload cycle can be used to strongly mitigate these errors by shortening the prediction intervals.

Therefore, for improved GNSS interoperability the scope of information that must be shared among systems and users must be much broader than just the respective TRFs and time scales adopted. Collection of that information will require closer coordination between WG-A and WG-D. The draft templates prepared so far are only a very limited step towards accomplishing this task.

Respectfully,
--Jim Ray