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Global Navigation Satellite Systems and Space Weather: *Building upon the International Space Weather Initiative*

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Abstract Globally there is growing interest in better understanding solar-terrestrial interactions, particularly patterns and trends in space weather. This is not only for scientific reasons, but also because the reliable operation of ground-based and space-based assets and infrastructures is increasingly dependent on their robustness against the detrimental effects of space weather. Consequently, in 2009, the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) proposed the International Space Weather Initiative (ISWI), as a follow-up activity to the International Heliophysical Year 2007 (IHY2007), to be implemented under a three-year workplan from 2010 to 2012 (UNGA Document, A/64/20). All achievements of international cooperation and coordination for ISWI, including instrumentation, data analysis, modelling, education, training and public outreach, are made available through the ISWI Newsletter and the ISWI Website (http://www.iswi-secretariat.org/). Since the last solar maximum in 2000, societal dependence on global navigation satellite system (GNSS) has increased substantially. This situation has brought increasing attention to the subject of space weather and its effects on GNSS systems and users. Results concerning the impact of space weather on GNSS are made available at the Information Portal (www.unoosa.org) of the International Committee on Global Navigation Satellite Systems (ICG). This paper briefly reviews the current status of ISWI with regard to GNSS.

Keywords: Space Weather, United Nations, COPUOS, IHY2007, ISWI, international cooperation, data analysis, modelling, education, training, public outreach,

Introduction

The International Space Weather Initiative (ISWI) is a programme of international cooperation to advance space weather science by a combination of instrument deployment, analysis and interpretation of space weather data from the deployed instruments in conjunction with space data, and communicate the results to the public and students. ISWI is a follow-up activity to the International Heliophysical Year 2007 (IHY2007), focusing exclusively on space weather. The further goal of the ISWI is to develop the scientific insights necessary to understand the science, and to reconstruct and forecast near-Earth space weather. This includes instrumentation, data analysis, modelling, education, training, and public outreach. More than 1000 instruments, organized through 16 operating instrument arrays, consist of Global Positioning System (GPS) receivers, very low frequency receivers, magnetometers, solar spectrometers, and particle detectors. National coordinators for ISWI organizing international outreach, education, and research programmes have been designated in more than 100 nations. The status and results of the instrument arrays, data recording, and data analysis are being reported annually to the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) and its Scientific and Technical Subcommittee that mandated the organization of three workshops on ISWI hosted by Egypt in 2010 for Western Asia (UNGA Document, A/AC.105/994), Nigeria in 2011 for Africa (UNGA Document, A/AC.105/1018), and Ecuador in 2012 for Latin America and the Caribbean (UNGA Document, A/AC.105/1030). In ISWI, special emphasis is placed on the use of global navigation satellite systems (GNSS) receivers to better understand dynamical processes in the Earth' atmosphere due to the impact of solar-terrestrial interaction on navigation satellites.

GNSS refers collectively to all of the satellite navigation systems in operation or being developed around the world known as GPS of the United States, the Global Navigation Satellite System (GLONASS) of the Russian Federation, Galileo of the European Union and Compass/BeiDou of China. In addition, these systems are supplemented by space-based augmentation systems or ground-based augmentation systems. Examples of space-based augmentation systems are the United States Wide-area Augmentation System (WAAS), the Russian System for Differential Correction and Monitoring (SDCM), the European Geostationary Navigation Overlay Service (EGNOS), the Indian GPS-aided Geo-Augmented Navigation (GAGAN) and the Japanese Multi-functional Transport Satellite Satellite-based Augmentation System (MSAS) (UN Document, ST/SPACE/50). These systems augment the existing medium-Earth orbit satellite constellations with geostationary or geosynchronous satellites signals or other environmental factors, which may impact the signal received by the users. Using several or all of the GNSS satellites in orbit, productivity typically increases, as well as accuracy, compared with using only one of such systems.

The growing number of GNSS, their economic, social, and scientific benefits for humankind lead to the establishment of the International Committee on GNSS (ICG) in 2005 under the umbrella of the United Nations (S. Gadimova et al., 2010, and UNGA Document, A/AC.105/1035).

Soon after the establishment of ICG it was realized that the ICG also needs to address the adverse impact of space weather on navigation satellites (UN Documents, ST/SPACE/55 and ST/SPACE/59).

Space Weather Instrument Arrays of the International Space Weather Initiative

ISWI is implemented by the Office for Outer Space Affairs in the framework of its United Nations Basic Space Science Initiative (UNBSSI) and its series of annual workshops (http://www.iaucomm46.org/united-nations-basic-space-science-initiative-unbssi-1991-2012/). A first series of workshops dedicated to basic space science was held from 1991 to 2004 for Asia and the Pacific (India in 1991, Sri Lanka in 1995 and China in 2004), Latin America and the Caribbean (Costa Rica and Colombia in 1992, Honduras in 1997, Argentina in 2002), Africa (Nigeria in 1993, Egypt in 1994 and Mauritius in 2001), Western Asia (Jordan in 1999), and Europe (Germany in 1996 and France in 2000). From 2005 to 2009, the workshops were dedicated to the International Heliophysical Year 2007 (IHY2007) that also contributed to the deployment of space weather instruments to countries that were ready to host and operate them (H. Haubold et al., 2010). Currently, the following 16 space weather instrument arrays have become operational on a world-wide basis: African Meridian B-field Education and Research (AMBER); Atmospheric Weather Electromagnetic System for Observation Modeling and Education (AWESOME); Compound Astronomical Low-cost Low-frequency Instrument for Spectroscopy and Transportable Observatory (CALLISTO); Continuous H-alpha Imaging Network (CHAIN); Coherent Ionospheric Doppler Receiver (CIDR); Global Muon Detector Network (GMDN); African Dual Frequency GPS Network (GPS-Africa); Magnetic Data Acquisition System (MAGDAS); Magnetometers in Africa (MAG-Africa); Optical Mesosphere Thermosphere Imager (OMTI); Remote Equatorial Nighttime Observatory for Ionospheric Regions (RENOIR); South Atlantic Very Low Frequency Network (SAVNET); Scintillation Network Decision Aid (SCINDA); Space Environment Viewing and Analysis Network (SEVAN); Sudden Ionospheric Disturbance Monitor (SID); Ultra-low, extremely low and very low frequency network (ULF-ELF-VLF). Argentina and Germany are preparing two additional space weather instrument arrays to become operational shortly.

Figure 1 illustrates a worldwide current distribution of space weather instrument arrays in operation, and Table 1 summarizes the number of deployed space weather instruments belonging to 16 instrument arrays in 112 countries or areas.

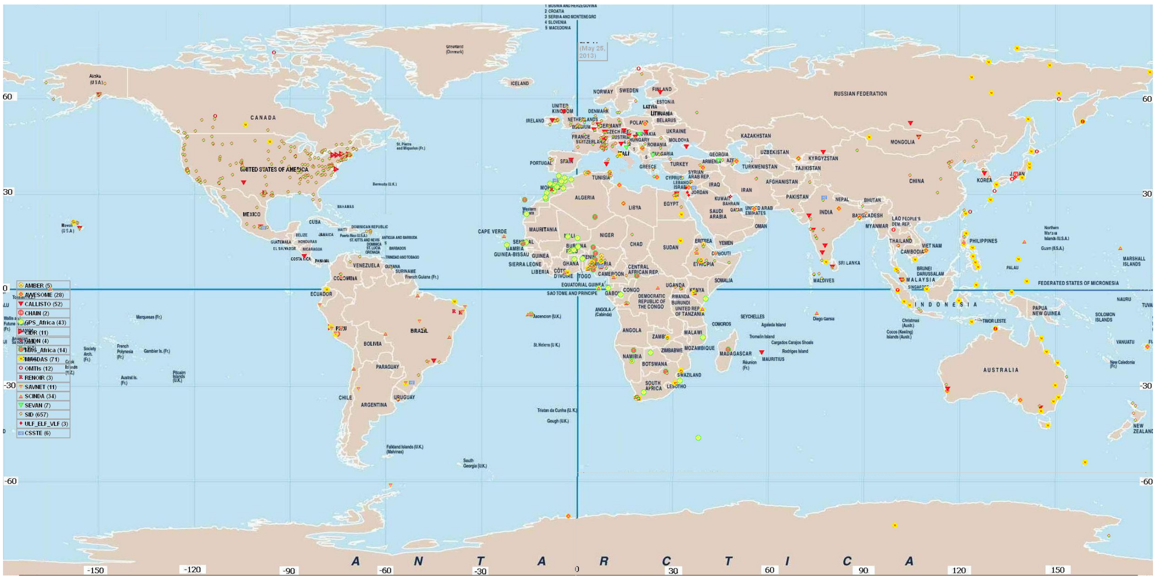

Figure 1: Worldwide current distribution of space weather instrument arrays in operation

Table 1. Current distribution of ISWI instrument arrays as operational data sources

Type of instruments	Number of instruments	Country or area
AMBER	5	Algeria(1), Cameroon(1), Ethiopia(1), Namibia(1), Nigeria(1)
AWESOME	25	Algeria(1), Antarctica(1), Azerbaijan(1), Ecuador(1), Egypt(1), Ethiopia(1), Fiji(1), Greece(1), India(2), Ireland(1), Israel(1), Libya(2), Malaysia(1), Morocco(1), Poland(1), Serbia(1), Tunisia(1), Turkey(1), United Arab Emirates(1), United States of America(2), Uzbekistan(1), Vietnam(1)
CALLISTO	51	Australia(2), Austria(1), Belgium(1), Brazil(2), Costa Rica(1), Czech Republic(1), Egypt(1), Finland(2), Germany(2), India(4), Ireland(4), Italy(2), Kazakhstan(1), Kenya(1), Malaysia(3), Mauritius(3), Mexico(1), Mongolia(2), Russia(1), Slovakia(1), South Korea(2), Spain(2), Sri Lanka(1), Switzerland(5), United Kingdom(1), United States of America(3), Ukraine(1)
CHAIN	3	Algeria(1), Japan(1), Peru(1)
CIDR	11	Egypt(1), Peru(1), United States of America(9)
GMDN	4	Australia(1), Brazil(1), Japan(1), Kuwait(1)
GPS_Africa	43	Algeria(1), Benin(1), Botswana(1), Burkina Faso(2), Cape Verde(1), Gabon(2), Ghana(1), Kenya(1), Mali(2), Morocco(19), Mozambic(1), Namibia(1), Niger(1), Sao Tome(1), Senegal(1), South Africa(7)
MAGDAS	71	Australia(11), Brazil(2), Canada(1), Cote d'Ivoire(1), Ecuador(1), Egypt(2), Ethiopia(1), India(1), Indonesia(8), Italy(1), Japan(7), Kenya(1), Malaysia(2), Micronesia(1), Mongolia(1), Mozambic(1), Nigeria(3), Peru(2), Philippines(6), Russia(9), South Africa(2), Sudan(1), Taiwan(1), Tanzania(1), United States of America(2), Vietnam(1), Zambia(1)
MAG_Africa	14	Algeria(1), Central African Republic(1), Cote d'Ivoire(2), Ethiopia(1), Madagascar(1), Mali(2), Namibia(1), Senegal(1), South Africa(2), Spain(1), United Kingdom(1)
OMTI	12	Australia(1), Canada(2), Japan(4), Malaysia(1), Norway(1), Russia(2), Thailand(1)
SAVNET	3	Brazil(2), Morocco(1)
SCINDA	34	Brazil(3), Cameroon(1), Cape Verde(1), Chile(1), Colombia(1), Congo(3), Cote d'Ivoire(1), Djibouti(1), Egypt(1), Ethiopia(2), Guyana(1), Kenya(2), Nigeria(4), Peru(1), Philippines(1), Republic of Marshal Islands(1), Sao Tome and Principe(1), South Africa(2), Tanzania(1), United Kingdom(2), United States of America(2), Uganda(1)
SEVAN	7	Armenia(3), Bulgaria(1), Croatia(1), India(1), Slovakia(1)
SID	657	Algeria(2), Antarctica(1), Australia(3), Austria(2), Azerbaijan(2), Bangladesh(1), Bosnia and Herzegovina(1), Brazil(7), British Virgin Islands(1), Bulgaria(1), Burkina Faso(1), Canada(17), China(29), Colombia(7), Congo(4), Croatia(5), Cypress(1), Czech Republic(1), Democratic Republic of Congo(2), Denmark(2), Egypt(3), England(1), Ethiopia(14), France(4), Germany(24), Greece(5), Guyana(1), India(16), Indonesia(2), Ireland(9), Italy(38), Kenya(3), Korea(2), Lebanon(11), Libya(1), Malaysia(16), Mexico(14), Mongolia(10), Mozambique(2), Namibia(1), Netherlands(2), New Zealand(4), Nigeria(38), Pakistan(3), Philippines(1), Portugal(3), Republic of Congo(1), Romania(3), Russia(1), Scotland(1), Senegal(1), Serbia(1), Slovakia(2), Slovenia(1), South Africa(13), Spain(1), Sri Lanka(1), Sweden(3), Switzerland(3), Taiwan(3), Thailand(5), Tunisia(9), Turkey(2), United Kingdom(16), Uruguay(7), United States of America(252), US Virgin Islands(2), Uganda(4), Uzbekistan(2), Venezuela(2), Vietnam(1), Zambia(2)
ULF_ELF_VLF	3	Israel(3)

IHY2007 and ISWI made significant progress in the installation of new ground-based instrumentation for the understanding of space weather impacts on Earth's upper atmosphere, generating new data streams useful for space weather in regions unobserved before. The data from those instrument arrays was a unique resource for the study of space weather influences on Earth's atmosphere. The IHY and ISWI schools trained several hundred graduate students and young scientists, many of whom are becoming mature scientists, as evidenced by their publications. The annual United Nations workshops on the ISWI facilitated information dissemination, instrument deployment and close international scientific collaboration. Consequently, many scientists in developing countries were able to develop and sustain research efforts in their own countries at the university level. Finally, pursuant to the observations and recommendations, adopted by the United Nations/Nigeria Workshop on the International Space Weather Initiative, hosted by Nigeria in 2011, the International Center for Space Weather Science and Education was established at Kyushu University, Fukuoka, Japan on 1 April 2012 (http://www.serc.kyushu-u.ac.jp/index_e.html).
Additionally to the 2012 workshop on ISWI, hosted by Ecuador, starting in 2012, a series of three annual Symposia on space weather related topics (UNGA Document, A/AC.105/1026), including data analysis and image processing, has been scheduled as a cooperation between the United Nations and the government of Austria and hosted by the Space Research Institute of the Austrian Academy of Sciences in Graz (http://www.iwf.oeaw.ac.at/?L=1).

In 2012, the Scientific and Technical Subcommittee of COPUOS, at its forty-ninth session (UNGA Document, A/AC.105/1001, para. 226), agreed that an agenda item entitled "Space Weather" should be introduced as a regular item on the agenda of the Subcommittee, in order to allow member States of COPUOS and international organizations having permanent observer status with COPUOS to exchange views on national, regional, and international activities related to space weather research with a view to promoting greater international cooperation in that area. The Subcommittee noted that it could, through that item, serve as an important advocate for efforts to close existing gaps in the space weather research field.

Space weather is inherently an international enterprise. Solar and magnetic storms can affect large regions of the Earth simultaneously, and equatorial ionospheric disturbances occur routinely around the globe. It is therefore appropriate for the United Nations to promote improvement in space weather modelling and forecasting for the benefit of all nations.

There has been significant scientific progress over the past decade in developing physics-based space weather models, and large-scale coupled (real-time) space plasma simulations. However, these models are limited by still being data starved in various spatial space weather domains and geographical locations. Thus, there is a crucial need for guaranteed continuous space weather data streams.

The overall ISWI objective is to develop the scientific insight necessary to understand the science, and reconstruct and forecast near-Earth space weather. Steps in this process include: (i) expanding and continuing the deployment of the existing ISWI instrument arrays and add new arrays as might be appropriate; (ii) expanding the data analysis effort for array data and using existing data bases (for the data being obtained by the arrays); (iii) coordinating the data products to provide inputs for physical modeling, input instrument array data into physical models of heliospheric processes, and developing data products that reconstruct past conditions in order to facilitate assessment of problems attributed to space weather effects; and (iv) coordinating the data products to permit predictive relationships to be developed, to develop data products yielding predictive relationships that enable the forecasting of space weather, and to develop data products that can easily be assimilated into real-time or near real-time predictive models.

Fundamental aspects of ISWI include education and training, and public outreach activities. The concept is to encourage and support space science courses, workshops and curricula in university and graduate schools that provide instrument support. There has been much success in these areas, but there is a strong need to continue the education and training, develop public outreach materials that are unique to ISWI, and coordinate their distribution. It is important to provide information on ISWI instruments and results to the media, especially to local media.

Space Weather Impacts on Global Navigation Satellite Systems

Space weather is important to humankind, which increasingly relies on space technology for education, business, transportation, and communications. Particle storms from space have disrupted GNSS reception and long-distance radio transmissions. Modern oil and gas drilling frequently involve directional drilling to tap reservoirs deep in the Earth, which depends on accurate positioning and timing using GNSS systems. Energetic particles at the magnetic poles have forced the rerouting of polar airline flights, resulting in delays and increased fuel consumption. Induced ground currents generated by magnetic storms have caused extended power blackouts and increased corrosion in critical energy pipelines. Atmospheric effects of solar activity have created drag on satellite orbits and altered the distribution of space debris.

Since the last solar maximum in 2000, special dependence on GNSS has increased substantially. Critical applications, such as railway control, highway traffic management, precision agriculture, emergency response, commercial aviation and marine navigation require GNSS services. Everyday activities such as banking, mobile phone operations and even the control of power grids are facilitated by the accurate timing provided by GNSS. As national, regional and international infrastructure, as well as global economy, is becoming increasingly dependent on positioning, navigation and timing services, society in general is vulnerable to disruptions that can be caused by space weather or variable conditions on the Sun and in the space environment that can influence space-borne and ground-based technological systems. Just as society takes for granted that electricity, heat and clean water will always be available, it also takes for granted that GNSS will be available, reliable and accurate. GNSS is so entrenched in the daily activities of individuals, businesses and government that any loss of satellite PNT services would be broadly disruptive.

Space-based observations showed unique equatorial ionospheric structures in the African region, although those had not been confirmed by ground-based observations, owing to a lack of ground-based instruments in the region. The AMBER magnetometer array, in partnership with GPS receiver arrays, would allow the understanding of the electrodynamics that governed equatorial ionospheric motions.

GPS consists of a minimum of 24 satellites orbiting the Earth at an altitude of approximately 20,000 km. Each satellite transmits a radio-wave signal to GPS receivers. By determining the time that the GPS signal reached a GPS receiver, one calculated the distance to the satellite in order to determine the exact position of the GPS receiver on Earth. Different errors in the determination of the distance between satellite and GPS receiver are introduced while the signal traversed the ionosphere and troposphere. The analysis of the satellite signal errors lead to the determination of geophysical parameters such as the total electron content (TEC) in the ionosphere or atmospheric water vapour distribution in the troposphere. The African Dual Frequency Global Positioning System Network (known as GPS-Africa) instrument array consists of a number of different networks of GPS receivers: International GNSS Services (IGS), the African Global Positioning System Receivers for Equatorial Electrodynamics Studies (AGREES), the Analyse Multidisciplinaire de la Mousson Africaine (AMMA), and SCINDA.

The African Global Positioning System Receivers for Equatorial Electrodynamics Studies (AGREES) instrument array was deployed to: (a) understand the unique structures of the equatorial ionosphere that had been reported from satellite observation data in the African region, which data had not been confirmed, validated or studied in detail by observations from the ground owing to a lack of suitable ground-based instrumentation in the region; (b) monitor and understand the processes governing electrodynamics and plasma production and loss in the lower and middle latitudes as a function of local time, season and magnetic activity; and (c) estimate the contribution of ionospheric and plasma spherical irregularities and their effect on GNSS and communications systems in the African region, where significant signal degradation (scintillation) had become a challenging problem.

GNSS signals, although vulnerable to ionospheric scintillation, provide an excellent mean to measure the same ionospheric effects on radio signals continuously.

SCINDA is a real-time, data-driven communication outage forecast and alert system. It aids in the specification and prediction of satellite communication degradation resulting from ionospheric scintillation in the equatorial region. Ionospheric disturbances caused rapid phase and amplitude fluctuations of satellite signals observed at or near the Earth's surface; those fluctuations are known as scintillation. The most intense natural scintillation events occur during night-time hours within 20 degrees of the Earth's magnetic equator, a region encompassing more than one third of the Earth's surface. Scintillation affects radio signals up to a few GHz frequencies and seriously degrades and disrupts satellite-based navigation and communication systems. SCINDA is designed to provide regional specification and short-term forecasts of scintillation activity to operational users in real time.

Multi-GNSS is gaining momentum and in the near future the expansion of the GPS instrument arrays to use signals from multi satellite-constellations will be available.

All the above issues are dealt with at annual workshops on ISWI (www.unoosa.org/oosa/en/SAP/gnss/icg/iswi.html) and the applications of GNSS (www.unoosa.org/oosa/SAP/gnss/index.html) (UNGA Documents, A/AC.105/1034 and A/AC.105/1022).

Conclusions

The paper reviews work performed in the frame of the United Nations workshops on IHY2007 (from 2005 to 2009) and ISWI (from 2010 to 2012) to build and to deploy new instrumentation for the understanding of space weather impacts on Earth's upper atmosphere, generating new data streams useful for space weather in regions unobserved before. Currently, more than 1,000 instruments are operational in 112 countries or areas as part of these instrument arrays. The data from these instrument arrays is a unique resource for the study of space weather influences on Earth's atmosphere.

To date, the vulnerabilities of GNSS are well categorized, and it is understood that space weather is largest contributor to single-frequency GNSS errors. Primary space efforts on GNSS include range errors and loss of signal reception. The GNSS industry faces several scientific and engineering challenges to keep pace with increasingly complex user needs: developing receivers that are resistant to scintillation; and improving the prediction of the state of the ionosphere. With GNSS modernization, the use of additional signals is expected to reduce errors caused by ionosphere.

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