United Nations A/AC.105/1302

General Assembly

Distr.: General
6 November 2023

Original: English

Committee on the Peaceful
Uses of Outer Space

Report on the United Nations workshop on the International Space Weather Initiative: the Way Forward

(Vienna, 26–30 June 2023)

I. Introduction

1. Space weather is a consequence of the behaviour of the Sun and the nature of the Earth's magnetic field and atmosphere. Globally, there is growing interest in better understanding solar-terrestrial interactions, in particular patterns and trends in space weather. This is not only for scientific reasons, but also because the reliable operation of ground- and space-based assets and infrastructures is increasingly dependent on their robustness in the face of the detrimental effects of space weather.

2. The International Space Weather Initiative, launched in 2009, is a programme of international cooperation to advance space weather science through the deployment of instruments such as magnetometers, solar telescopes, very low frequency monitors, global navigation satellite system receivers and particle detectors, the analysis of space weather data obtained from those instruments, in conjunction with other data, and the communication of the results of such analysis to the general public and to researchers and students.

3. The International Committee on Global Navigation Satellite Systems (ICG) has played an important role in the Initiative's work, as global navigation satellite system receivers are used to better comprehend the dynamic processes in the Earth's atmosphere caused by extreme space weather and solar-terrestrial interaction and the effects of those processes on satellites.

4. Information on all the achievements resulting from the international cooperation and coordination under the Initiative, including in relation to instrumentation, data analysis, modelling, education, training and public outreach, is made available through the Initiative's electronic newsletter and its website (www.iswi-secretariat.org). The newsletter is published once per month by ArkEdge Space, a space company based in Japan, while the website is maintained by Boston College in the United States of America. In addition, the Initiative hosts webinars on topics related to solar-terrestrial physics, which are recorded and posted on the YouTube channel of the Office for Outer Space Affairs (links to the recordings are available at www.unoosa.org/oosa/en/ourwork/psa/bssi/iswi_webinars.html).

5. The United Nations workshop on the International Space Weather Initiative: the Way Forward was organized and hosted by the Office for Outer Space Affairs. The workshop was co-sponsored by ICG, the European Space Agency and the National

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Aeronautics and Space Administration (NASA) of the United States. The workshop was held in a hybrid format in Vienna from 26 to 30 June 2023.

6. The present report sets out the background, objectives and programme of the workshop and provides a summary of the observations made and conclusions reached by the participants. It has been prepared for submission to the Committee on the Peaceful Uses of Outer Space at its sixty-seventh session and for consideration by the Scientific and Technical Subcommittee at its sixty-first session, both to be held in 2024.

A. Background and objectives

7. The Committee on the Peaceful Uses of Outer Space adopted the topic "Space weather" as a regular item on its agenda in 2013. The International Space Weather Initiative, as one of the elements of that topic, has continued to support the deployment of space weather instruments, data analysis, and training, education and public outreach programmes. Those activities have contributed to the expansion of existing instrument arrays, the deployment of new arrays and the inputting of instrument array data into physical models of heliospheric processes, thereby enabling space weather forecasting.

8. In line with the consideration by the Scientific and Technical Subcommittee of the agenda item entitled "Space weather" (see A/AC.105/1279, paras. 152–164), the purposes of the workshop were to (a) raise awareness among Member States of the impact of space weather; (b) focus on the deployment of new instruments, particularly in developing countries; (c) discuss methods for analysing data on space weather; (d) focus on new research results and findings; and (e) encourage greater cooperation in developing partnerships between instrument providers and instrument hosts. The discussions at the workshop were also linked to the Sustainable Development Goals.

B. Programme

9. At the opening of the workshop, welcoming remarks were made by the representatives of the Office for Outer Space Affairs and NASA. Keynote speeches were delivered by the representatives of NASA and the University of Graz, Austria.

10. The workshop programme consisted of eight technical sessions and discussions on observations and conclusions, followed by closing remarks by the co-organizers. A total of 61 presentations were given at the technical sessions, which covered topics in the areas of: (a) space weather instrumentation and data; (b) magnetosphere-ionosphere-thermosphere coupling; (c) space weather monitoring using low-cost receiver systems; (d) space weather modelling; (e) space weather effects on technology; (f) space weather research; (g) national and regional space weather programmes; and (h) space weather case studies. Two panel discussions enabled further deliberation on matters concerning space weather instruments and on issues concerning regional cooperative mechanisms and resources for implementing projects.

11. Each technical session included a discussion focusing on the key challenges and issues raised in the presentations. The results of the discussions were summarized and presented at the closing session, at which a final exchange of views was held and the conclusions were agreed.

12. An informative technical tour of GeoSphere Austria, a national geological, geophysical, climatological and meteorological service, was also organized for workshop participants.

13. A webinar on the theme "Solar flares and space weather", the twelfth in the Initiative's series of webinars, was held in conjunction with the workshop. The webinar provided a closer look at the origins of space weather and the current research on solar flares.

14. The programme was developed by the Office for Outer Space Affairs in cooperation with an international scientific organizing committee. The Chairs and

rapporteurs assigned to the technical sessions provided their comments and notes as input for the preparation of the present report.

15. The presentations given at the workshop, abstracts of the papers submitted, the workshop's programme and background materials are available on the website of the Office for Outer Space Affairs (www.unoosa.org).

C. Attendance

16. Scientists, engineers and educators from developing and industrialized countries in all economic regions were invited by the Office for Outer Space Affairs to participate in and contribute to the workshop. Participants were selected on the basis of their scientific, engineering and educational backgrounds and their experience in implementing programmes and projects in which the Initiative played a leading role. The preparations for the workshop were carried out by an international scientific organizing committee and the Office for Outer Space Affairs.

17. Funds provided by the United Nations, ICG and the European Space Agency were used to cover the travel, accommodation and other costs of 24 participants from 22 countries. A total of 228 experts were invited to attend the workshop.

18. The following 37 Member States were represented in person or online at the workshop: Argentina, Austria, Burkina Faso, Canada, Côte d'Ivoire, Croatia, Egypt, Ethiopia, France, Germany, Ghana, Greece, India, Indonesia, Italy, Japan, Kazakhstan, Kenya, Malaysia, Morocco, Myanmar, Nepal, Nigeria, Pakistan, Peru, Poland, Russian Federation, Rwanda, Serbia, Slovakia, Switzerland, Thailand, Türkiye, Uganda, United Kingdom of Great Britain and Northern Ireland, United States of America and Zambia. Representatives of the Office for Outer Space Affairs also attended the workshop.

II. Observations and conclusions

19. The keynote presentations delivered at the workshop provided an overview of the solar sources of space weather and their geospace consequences. It was noted that the solar disturbances affecting the Earth were flares, coronal mass ejections and co-rotating interaction regions. Flares on the side of the Sun facing the Earth would change the level of ionization in the ionosphere, having a significant effect on radio wave propagation and in turn affecting global navigation satellite systems. Both co-rotating interaction regions and coronal mass ejections could cause geomagnetic storms when they impinged on the magnetosphere with a southward field component. An overview of global collaboration efforts in the area of space weather was also provided.

20. The participants recalled that the Initiative continued to expand existing instrument arrays and deploy new ones, and there were currently 19 instrument arrays worldwide, with more than 1,000 instruments deployed that record data on solar-terrestrial interaction, from coronal mass ejections to variations in the total electron content of the ionosphere.

21. The participants noted that the Compound Astronomical Low-cost Low-frequency Instrument for Spectroscopy and Transportable Observatory (CALLISTO) spectrometer was a heterodyne receiver. It operated between 45 and 870 MHz, with a radiometricbandwidth of about 300 kHz. The data recorded by the CALLISTO instrument array were flexible image transport system files with up to 400 frequencies per sweep. The data were transferred via an R232 cable to a computer and saved locally. The integration time was 1 millisecond and the overall dynamic range was greater than 40 decibels. Many CALLISTO instruments had already been deployed worldwide through the Initiative's instrument deployment programme and all the spectrometers together formed the e-CALLISTO network. Information about

the network and related products is available at the website of the network (www.e-callisto.org).

22. The participants learned that the Low-Frequency Array (LOFAR) was a multi-functional, highly innovative low-frequency radio telescope that was distributed throughout Europe and that operated between 10 and 240 MHz. It was noted that a typical LOFAR observation of ionospheric structures was based on scintillation induced by radio waves. The amount of scintillation induced by ionospheric irregularities typically varied depending on the radio wave frequency, reaching higher values at lower frequencies. Preliminary results demonstrated that observations of very high frequency scintillation using LOFAR could be utilized to detect plasma structures forming in the mid-latitude ionosphere. The LOFAR project website is available at http:///www.astron.nl/telescopes/lofar.

23. The participants considered the challenges confronting users in accessing and using data obtained from the Initiative's instruments and how those challenges might be mitigated in the future. It was emphasized that coordination was needed to ensure that the Initiative's instrument networks operated continuously, and that, in order to broaden the use of the data, collaboration was needed to adopt a metadata standard such as that of the Space Physics Archive Search and Extract (SPASE) consortium for the purposes of data documentation. It was noted that two instruments, e-CALLISTO and the Atmospheric Weather Electromagnetic System for Observation, Modelling and Education, were now registered with the SPASE consortium.

24. The participants noted that the project team on space weather monitoring using low-cost global navigation satellite system receiver systems, established in 2021 under the ICG Working Group on Information Dissemination and Capacity-building, consisted of experts representing the Abdus Salam International Centre for Theoretical Physics in Italy, Boston College in the United States, the University of Tokyo and the Polytechnic Institute of Paris. The project team continued to explore the possibilities of using low-cost receiver systems for space weather monitoring and the implementation of a prototype system. It was noted that the results of a preliminary comparison between high-end and low-cost global navigation satellite system receivers showed that the two types of systems had a similar performance with respect to vertical total electron content, the rate of change of total electron content index and code-phase scintillation.

25. The participants observed that magnetosphere-ionosphere coupling encompassed many different subjects in the global study of near-Earth space physics, and there were many different complex phenomena to explore in that regard. In the context of space weather, magnetospheric processes were directly coupled to geomagnetic activity, as well as near-Earth high-energy particle environments that were of key importance. Three systems, the solar wind, the magnetosphere and the ionosphere, interact, transmitting solar wind energy and transforming it into energies of auroral phenomena, eventually depositing most of it as heat energy into the ionosphere.

26. With regard to the space weather modelling, it was noted that space weather had become a vital part of space physics, and there were several models in use for all kinds of space weather, including the solar wind and characteristics of the magnetosphere, the ionosphere and even the thermosphere. Those models were used in specific cases.

27. The participants learned about the main numerical approaches employed in the modelling of coronal mass ejections and their propagation through the inner heliosphere and discussed how the synergy between remote-sensing and in situ observations of coronal mass ejections made from multiple spacecraft enabled the achievement of more accurate and reliable predictions at various locations in the heliosphere. It was noted that, through the combination of data from ground and space-based sources and different techniques involving data assimilation and ingestion, it had been possible to adapt empirical models that represented the climate of the ionosphere to better match observations made under geomagnetically disturbed conditions.

28. The participants also learned about machine learning techniques to perform nowcasting and forecasting of different space weather subdomains. A global ionospheric prediction model based on machine learning to forecast total electron content 24 hours in advance under different space weather conditions was explained. It was noted that, among three different machine learning techniques, long short-term memory, gated recurrent units and convolutional neural networks, for the purpose of an operational service, the convolutional neural networks model had better predictive capabilities, even under geomagnetically disturbed conditions, and thus could be implemented in an operational manner for space weather applications and services.

29. The participants were informed that the Data Centre for Space Plasma Physics (CDPP) of France was available to any user for the retrieval of data from spacecraft and probes across the solar system, and also provided a set of ground-based instruments for observing the geospace. It was noted that the Data Centre was continuously improving its capabilities in order to facilitate the scientific exploitation of data and the distribution of data from future space missions. For those purposes, the Data Centre was developing tools and services to facilitate data extraction and analysis. The data were stored by the National Centre for Space Studies (CNES) of France at its information technology centre in Toulouse. Information on the Data Centre can be found at http://cdpp.eu.

30. The participants observed that space weather was among the natural threats that could result in global navigation satellite system errors and disruptions. The main impact was due to the Earth's ionosphere. The signals were slowing down owing to ionospheric effects that could cause global navigation satellite system positioning errors ranging from a few metres to several tens of metres. The effects could also cause cycle slips in phase measurements that degraded real-time kinematic performance. Space weather-related parameters such as total electron content and scintillation parameters (amplitude and phase) could be computed by measuring ionospheric effects on global navigation satellite system signals.

31. The participants took note of a method that outlined tasks for the assemblage of multi-source global navigation satellite system data and geomagnetic data into a single data set, which could be used for the development of global navigation satellite system ionospheric correction models using statistical and machine learning methods. The method was implemented using a combination of tailored software that was developed in the R environment for statistical computing and a freely available software application for global navigation satellite system-based estimation of total electron content. The assembled data, obtained in the demonstration of the presented method, was made available openly in support of the international scientific community.

32. With regard to the applications of space weather research, an overview of the space weather impact of solar energetic particles, their main acceleration processes and their transport through the interplanetary medium was presented. Two mechanisms that could energize solar energetic particles – solar flare-driven shocks and corona mass ejection-driven shocks – were explained. The Analysis of the MEsosphere and Lower Ionosphere fall Effect (AMELIE) project of the German Aerospace Centre, aimed at automatically detecting the so-called "fall effect" in very low frequency measurements, was also presented. The results analysed so far indicated that, independent of the solar zenith angle, mostly at high latitudes, a strong warming of the lower mesosphere during the fall could be observed, confirming dominating atmospheric inner dynamics.

33. The participants noted that the current peak of activity of solar cycle 25, known as the solar maximum, might be earlier and stronger than estimated. Therefore, increased disturbances from solar events were expected. Coronal mass ejections, high-speed streams, solar flares and solar energetic particle events were described as the primary transients relevant for space weather. For example, flares on the side of the Sun facing the Earth would change the level of ionization in the ionosphere, having a significant effect on radio wave propagation that could in turn affect global

navigation satellite system signals. Flare emissions in radio wavelengths could submerge the signals of radars and satellites and affect their operations.

34. The sessions on national space weather programmes and case studies provided participants with an additional opportunity to share their expertise with a view to increasing awareness of space weather events and their potential consequences. It was recognized that space weather research benefited from effective international coordination and collaboration with regard to the sharing and use of available observations; the assessment of space weather forecasting and analysis capabilities; the advancement of knowledge, theory and modelling; and the application of advances in research to space weather-related applications.

35. Two panel discussions, on the themes "The Initiative's instruments" and "The way forward", were held as part of the workshop. The objectives of the sessions were to discuss the current status of the Initiative's instrument networks and identify any significant gaps in instrument types and coverage; to identify problems in maintaining instruments and data flow in terms of the continuity, collection, analysis and modelling of data; and to discuss how to attract early-career scientists and support other ongoing international initiatives.

36. The key conclusions reached during the panel discussions were the following:

(a) Data from the Initiative's instrument arrays should be combined with space-based and other ground-based data to advance space weather science, thus leading to robust research output and the publication of scientific papers in international journals, and the space weather and global navigation satellite system communities should share data and collaborate on space weather research;

(b) The Initiative's space science schools and the annual United Nations workshops on the Initiative should be continued in the future, for the training of less experienced researchers in instrument operation and the science of heliophysics. The partnerships already established with international scientific organizations need to be strengthened to ensure that such capacity-building activities are accomplished efficiently and for the benefit of all Member States;

(c) New knowledge generated by the Initiative's activities should be effectively communicated to the public and the scientific community at large through the Initiative's newsletters, its website and other media.

37. The participants were informed that the journal *Sun and Geosphere* would publish a special issue on solar influences on the magnetosphere, ionosphere and atmosphere by the end of 2023. The participants were invited to submit their research results on space weather and solar terrestrial physics to the journal.

38. The participants expressed their appreciation to the United Nations and the co-sponsors for the substance, excellent organization and successful conclusion of the workshop.