STATEMENT OF GUIDANCE FOR SPACE WEATHER SERVICES

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1. Introduction

Space Weather is the physical and phenomenological state of the natural space environment including the Sun, the solar wind, the magnetosphere, the ionosphere and the thermosphere, and its interaction with the Earth. The associated scientific discipline aims, through observation, monitoring, analysis and modelling, at understanding the driving processes, predicting the state of the Sun, the interplanetary and planetary environments, including the Earth's magnetic field.

Originated from the Sun, the space weather disturbances evolve during their propagation through the interplanetary media before reaching the near-Earth space, disturbing the magnetosphere and ionosphere and impacting the Earth's magnetic field. Multiple types of modern technological infrastructure are affected by space weather. Among these vulnerable technologies are satellites, navigation and communication, electric power grid and pipeline operations, aviation and others.

Space Weather services are provided by Space Weather Centres located in different countries. An umbrella organization for them is the International Space Environment Service (ISES - http://www.spaceweather.org/). These services are essential for modern society due to increased dependence on the safe and secure operations of critical infrastructure vulnerable to the impacts of space weather.

In order to provide essential services, observations need to be done to monitor the space weather conditions all the way from the Sun to the Earth in timely manner and with high accuracy. This is not always possible due to the spatial extent of the domain, the wide variety of physical processes governing the space weather and limited observing capabilities.

Today, space weather services rely on both operational and research observing assets, ground-based and space-borne, which are not fully integrated into coordinated observing networks capable of provision of operational-quality data. Thus, the robustness and continuity of measurements are far from being sufficient for satisfaction of existing demand, which is identified in the following gap analysis. It should be noted, that the existing numerical Space Weather models are not a part of the following document.

The description of observational requirements and gap analysis have been divided in six categories, according to their physical domains, i.e. Solar, Solar Wind and Heliosphere, Energetic Particles in the near-Earth Environment, Ionosphere, Thermosphere and Geomagnetic Field.

The following terminology has been used for the evaluation of current state of observations:

-**Poor** (minimum observing requirements are not being met, no observations or limited quality observations are provided only by scientific instruments without plans for continuity)
-**Marginal** (minimum user requirements are being met, can be provided by research instruments with existing plans to convert them to operational)
-**Acceptable** (better than minimum user requirements but less than optimum, operational quality data, with identified risk of discontinuity in data flow)
-**Good** (the optimum requirements are satisfied, data are of operational quality, provided robustly and continuously).

2. Solar Observations

The Sun is the primary origin of space weather events, and thus, solar observations are an essential data source for the most space weather operational services. The field of solar physics has significantly advanced during the past several decades, resulting in the improvements of the understanding and forecasting of solar events. Yet the complexity of solar processes and difficulties in their observations left many questions not resolved, keeping the necessity to improve monitoring of the Sun as one of the most important and challenging tasks.

2.1 Introduction

The following solar phenomena are the most important sources of space weather variability and, therefore, their monitoring and forecasting are an essential part of the SW operational services.

Sunspots, dark spots (when observed in white light) of magnetic field concentration with a lower temperature than the surrounding photosphere, and a size of typically a few to up to 20Mm on the photosphere. The sunspot number has served as an index of solar activity for many centuries, exhibiting cyclic variations with a period of approximately 11-year. Groups of sunspots are associated with active regions best observed in the light emitted by the overlying chromosphere and corona. Active regions are the locations where the solar magnetic field typically has a complex structure creating a high probability for eruptive events (flares, coronal mass ejections) to occur.

Coronal holes, the dark areas in the corona of the size of up to the half of the solar radius, associated with the open magnetic field lines. Extending into the outer corona along magnetic field lines, coronal holes are the sources of the high speed streams in the solar wind, which, in turn, are producing associated space weather disturbances (geomagnetic substorms, accelerated particles). Coronal holes are co-rotating with the solar surface, often exhibiting ~ 27-day recurrence.

Solar filaments and prominences, extended from the chromosphere into the outer corona, are one of the possible sources of coronal mass ejections (CME), the solar phenomenon responsible for the most powerful geomagnetic and ionospheric storms, impacting multiple assets in space and on the ground.

Flares are the fastest eruptive solar phenomena, which release energy in many parts of the electromagnetic spectrum. The electromagnetic emissions from flares are the first signatures of these space-weather relevant disturbances. The X-ray and EUV emissions disturb the Earth ionosphere while sudden solar radio emission may also affect the radio technology directly. Quite often, the large flares are associated (co-located) with and accompanied by the CME and energetic particles.

Solar energetic particles (SEP) are charged particles (electrons, protons) of solar origin which often initiated after (and perhaps due to) the large flare and/or are accelerated by shocks produced during CME propagation through the solar corona and solar wind. SEP are affecting the ionosphere and can increase radiation dose at the near-Earth space and on multiple altitudes.

Solar magnetic field defines the dynamics of the solar phenomena and exhibits very complex behavior. The magnetically-complex solar active regions are the sources of the large eruptive events, such as flares, CMEs and SEPs. Data on the solar magnetic structures are used in real-time services for numerical modelling of the space weather and for the forecasting of CME propagation.

Generally, observations of the Sun comprise images and magnetograms of the solar disk, images of the corona and heliosphere, as well as the disk-integrated flux observed at specific wavelengths, integrated over broad wavelength bands or over the full solar spectrum.

Solar images are used to determine the sunspot number and sunspot groups; to identify the location and properties of active regions, flares, filaments, prominences and coronal holes in order to estimate their potential geo-effectiveness for forecasting and alerts purposes. They are used to characterize the magnetic field in the photosphere and chromosphere, which in turn is used as an input in different forecasting models.

Total X-ray and radio flux observations in different frequencies are used to monitor the time evolution and classifications of the most short-lived solar features, such as solar flares (X-ray flux) and solar radio bursts. Dynamic radio spectra are used to further characterize flares, CMEs and the associated shock waves -through the associated types II, III, IV radio emission signatures. Solar flux at 10.7 cm wavelength is also recorded daily and used for long-term climatological studies and as a proxy for other solar parameters used in models of the Earth's atmosphere. In addition, it should be noted that the Total Solar Irradiance (TSI) measurements, widely utilized in atmospheric applications, can also be used to track the short-term and long-term variations of the Sun as a part of Space Weather research.

2.2 Review and gap analysis:

- **Electromagnetic flux measurements: Solar EUV flux, X-ray flux, radio emissions**

These observations are chiefly used to drive alerts of hazardous conditions that can onset abruptly such as solar flares. A measurement cadence of 0.5 to 3 seconds with a delay of availability between 1 and 5 minutes is required for X-ray flux measurements as a means to drive the alerting for the associated influence on the ionosphere.

Space-based solar EUV flux, and X-ray flux measurements are available from the operational NOAA/GOES satellites. Alternative measurements in nearby frequency bands are also delivered by scientific missions such as Solar Dynamic Observatory (SDO) or PROBA2/LYRA although not meeting the same timeliness requirements.

For the solar electromagnetic radiation measurements, timely alerting is obviously not possible but measurements in the radio domain at selected frequencies (up to 3GHz as used by specific applications) can be useful to confirm the solar origin of failure or degradation of such specific applications. These data products are generally provided as by-products by ground based observatories providing dynamic radio spectra (see below).

For monitoring long-term solar variability and for feeding into numerical models of the space environment and atmosphere, measurements of the flux at 2800MHz frequency (10.7 cm) are used. These are currently only provided by the Penticton Radio Telescope. Long term continuity and consistency of these data series should be assured.
Alternatives at other frequencies (such as f30~1GHz) have been discussed but these represent no solution to the challenge of long-term consistency.

Radio emissions, indicating the occurrence of radio bursts, as well as the speed of shocks in the corona and solar wind, require the observation of dynamic radio spectra (color coded intensity diagrams as function of time and of wavelength/frequency) between 20MHz and 2GHz with a cadence of 1 to 60 seconds and a delay of availability of 1 and 5 minutes.

Such measurements obtained by ground-based infrastructure require the contributions of observatories around the globe in order to achieve 24h coverage. Networks that gather such data from around the globe exist but currently do not assure the public availability of the data meeting the above criteria. The Radio Solar Telescope Network (RSTN) operated by the U.S Air Force covers the globe in real time but not all real time spectra are publically available. The data from the eCallisto network are publically available but few of the stations contribute in real-time.

Provision of Solar EUV flux, X-ray flux, and Radio emission data should be evaluated as

marginal to acceptable.

- **Solar images: X-ray, EUV, H-Alpha, Calcium-K, White light, Magnetic field**

Solar images in various wavelengths are used to observe and characterize the different solar features that were summarized above: sunspots, active regions, coronal holes, filaments and prominences, and the orientation and strength of the photospheric magnetic field. Several types of image cadences and delivery delays can be acceptable, with their specific numbers depending on the features considered. For recurrent coronal holes, a cadence of even 12 hours could be acceptable, while assessing active region evolution requires at least sub-hour cadences.

The most stringent specifications, however, are required when the images are used to detect the onset, evolution, spatial extent and characteristics of solar eruptive phenomena, for example, in order to detect and analyze such their onset (location and time) and their evolution, the image cadences are required to be around 1 to 15 minutes, with a latency between 1 and 30 minutes.

On the very long time scales, to provide the long-term climatology (i.e. sunspot observations), consistency of data over long time is required, without strong requirements for the time resolution or delivery delay.

In optical wavelengths, the required images can be provided by ground-based observatories. Depending on the specific requirements on cadence, coverage and latency, the observations are used from individual observatories, collective contributions from around the globe (e.g. the contributions to the sunspot number computed at the Royal Observatory of Belgium or community-based Global Oscillation Network Group (GONG), which produces the solar magnetic maps. As well, data from the global networks managed by one organization (for example, the Solar Observing Optical Network (SOON) managed by U.S Air force, which collects H-alpha observations from its contributing stations, are used in the space weather services.

In other wavelengths, space-based solar observations include the measurements on board of SOlar and Heliospheric Observatory (SOHO), the Solar Dynamics Observatory (SDO), the Solar Terrestrial Relations Observatory (STEREO), PRoject for OnBoard Autonomy-2 (PROBA-2), and others.

Many of ground-based solar observations are semi-operationally supported, with some level of long-term continuity, although lacking the real-time services, while space-based observations, such as SOHO (most widely utilized in operational space weather services), SDO, and STEREO PROBA-2, are research missions. Being research missions they are generally not designed to meet the operational timeliness requirements, and most importantly it is not clear if and how their capabilities will be replaced.

Provision of Solar images: X-ray, EUV, H-Alpha, Calcium-K, White light, Magnetic field data should be estimated as **marginal.**

- **Solar Coronagraph images**

Coronagraphic images are used as input into models to evaluate the speed and expansion of a CME which requires an image cadence of at least 5 to 15 minutes. The delay of data availability must be within 15 to 60 minutes to allow sufficient time to initiate model runs and issue forecasts of the CME arrival time, which ranges from less than 1 day to several days from CME initiation.

Images of the solar corona are obtained mainly from measurements provided on-board of research missions, such as the Large Angle and Spectrometric COronagraph (LASCO) onboard the SOlar Heliosphere Orbiter (SOHO - located in the L1 Lagrange point on the Sun-

Earth line) and the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) instrument onboard the Solar TErrestrial RElations Observatory (STEREO - located off the Sun-Earth line). SOHO was launched in 1995 for a nominal lifetime of two years, but continues to be a primary resource for operational Space Weather forecast services.

With coronagraphic images and current numerical prediction models, the geoeffectiveness of CME and arrival time of CMEs can be forecast within a +/- 6-hour window. Without coronal images, with use of only solar radio burst data for speed estimates, the reliability of the forecasts of CME arrival will be significantly reduced which thus impacts virtually all customers of space weather services.

Provision of Solar Corona images should be estimated as **poor.**

2.3 General recommendations for provision of the essential solar data.

Overall, the robustness, availability, accuracy, spatial and temporal resolution of solar data can be defined as **marginal (coronograph data as poor)**.

The key ground-based systems designed for science <u>should develop a real-time mode for space weather applications and become coordinated at a world-wide level to ensure the continuity of observations and good inter-calibration.</u> Existing world wide networks include: GONG (community based initiative managed by the National Solar Observatory), and RSTN and SOON (run by the U.S. Air Force).

The continuity of long-term data series such as the sunspot number (provided by the Royal Observatory of Belgium based on a world-wide network of contributing stations) and the F10.7 radio flux measurements (provided by Dominion Solar Radio Astronomy, National Research Council Canada), must be assured through concrete continuity plans which are currently lacking.

<u>The key space-based observations onboard multiple research missions</u> such as: SOHO (NASA-ESA), SDO (NASA), secondary: STEREO and, in addition, PROBA, <u>should have clear plans for their continuity and include a real-time mode for space weather applications.</u> <u>The development of a dedicated Solar Weather operational mission to provide robust data on location and evolution of key solar features, such as coronal holes, active regions, flares, CMEs, filaments and prominences can be highly recommended.</u>

<u>A particular concern in that area is to assure the continuity of coronagraph data for the estimation of CME initiation parameters, which have a profound impact on Space Weather forecasting capabilities.</u> In addition, estimates of CME properties could be improved when coronal images are obtained simultaneously from multiple vantage points, both on the Earth-Sun line and significantly off the Earth-Sun line, such as at the L5 Lagrange point.

For a comprehensive radio diagnostic (e.g. about the magnetic field at the source and along the propagation path) the circular polarization information is a useful feature and should be provided by solar and interplanetary radio instruments. Polarization measurements are also essential to perform post-event analysis of space weather events such as GPS signal attenuation due to strong radio bursts. Real-time data are also necessary.

Further analysis should be conducted to identify strategies to maintain the highest priority capabilities on operationally supported future space missions and on expanding ground-based data capacity for solar observations.

Despite the long and successful history of solar research, the processes, governing the quasi-stationary and the eruptive solar activity still have many unresolved issues. Thus, the improvement of the solar monitoring is one of the most important and challenging tasks for space weather service providers and researchers.

3. Solar Wind and Heliosphere

The solar corona extends into the interplanetary space (heliosphere) and becomes a solar wind. The solar wind is the media where the original solar eruption propagate and evolve, therefore the continuous in-situ monitoring of real-time conditions in solar wind provides the space weather service operators with the information on the changes in solar wind and interplanetary space weather conditions which ultimately affect the Earth.

3.1 Introduction

The following solar wind observables were identified as the most important sources of the space weather variability and, therefore, their in-situ monitoring and forecasting are the essential part of the SW operational services and are required to drive a variety of operational services, such as numerical models for forecasting geomagnetic disturbances, radiation belt flux levels and ionospheric conditions.

Interplanetary magnetic field (IMF, vector) is measured at the Sun-Earth line shows the large fluctuations during the propagation of the disturbance originated on the Sun, such as Interplanetary CME, interplanetary shocks, and high speed streams/corotating interaction regions initiated by coronal holes features. It is currently accepted that when the amplitude of the IMF increases and has large southward component, the impact on the geomagnetic field is the most significant.

Bulk Solar wind parameters, such as density, velocity, temperature are derived from the measurements of the low-energy electron and ion fluxes. The variations in the solar wind balk parameters provide advance knowledge on the upcoming space weather disturbance, produced by CME, coronal holes high speed streams, etc.

Solar energetic particles fluxes, monitored by detectors located in the solar wind, give the information on the high energy particles which is used to confirm the direction of the propagation of the solar disturbance. Because the energetic particles are the fastest ones to arrive to the location of the solar wind monitor, their enhancements gives the earlier warnings on the possible disturbance arrival. Energetic electrons measured at L1 can give advance warning of solar energetic particle events; techniques have been developed to use energetic proton measurements at L1 as indicators of oncoming solar wind disturbances that can cause geomagnetic storms..

Heliospheric images from off- Sun-Earth line are a valuable asset that provides information on the motion of a CME as it advances toward Earth. Heliospheric images are complementary to coronal images in that coronal images are used to identify the initial properties of CMEs, and heliospheric images are used to monitor their motion toward Earth. This information could substantially improve forecasts of CME arrival time, although due to the luck of information on the IMF associated with the ICME, the forecast will have less confidence.

3.2. Review and gap analysis

- **Interplanetary Magnetic Field**

IMF data are required in 3 dimensions (GSE and/or GSM coordinate systems), with the availability 1-5 min and sampling rate of 1 sec. in order to identify the fast variations during the passage of the IP (interplanetary impulse) or CIR (co-rotating interaction regions) and sheath area of ICME.

- **Solar wind bulk velocity, density and temperature**

Solar wind data availability should be 1-5 min. with observing cycle of 60 sec. in order to identify the variations of bulk parameters during the passage of disturbances.

Solar wind parameters (including IMF) are provided by in-situ measurements at L1 point, which is located about 45 minutes ahead of Earth (on Sun-Earth line). Because the solar wind transit time from the L1 Lagrange point to Earth can be considerably less than 45 minutes during high-speed disturbances, high data timeliness is necessary to ensure as much warning lead time as possible. Currently the data are provided by ACE (Advanced Composition Explorer) research mission (NASA-ESA) together with recently launched operational mission DSCOVR (Deep Space Climate Observatory, NOAA). The ACE satellite was launched in 1997 and is well beyond its initial design lifetime. The most serious limitation with the ACE instrumentation is the inability to make reliable measurements of the solar wind velocity and density when the flux of energetic protons is enhanced. DSCOVR is placed in L1 Lagrange point and provides real-time measurements of the solar wind density, velocity, temperature and magnetic field. Its instruments are designed to function during solar proton events.

Unfortunately, due to the differences in instrumentation, the bulk solar wind parameters provided by these two satellites sometimes exhibit large differences.
The bulk solar wind parameters (except IMF) are also available (not in real time) from SOHO (located at L1 point), and from WIND research missions.
Current situation with data provision on solar wind bulk parameters and IMF can be estimated as **marginal.**

- **Solar energetic particles fluxes**

Should be available within 1-10 min. with observing cycle of 60 sec. in order to identify the energetic particle events and approximate propagation direction. At present time these data are obtained from several scientific missions at L1 point, ACE, SOHO (NASA/ESA), and WIND (NASA), although only data from ACE (including alpha-particles and ions) and DSCOVR are available in real time. Unfortunately, DSCOVR, does not have energetic particle instruments. Particle measurements for the planned NOAA DSCOVR follow-on mission (estimated 2020 launch) are currently being investigated. Off-L1 position the energetic particles are measured by one of STEREO satellites moving around the Sun (see details on orbit below). The availability of real-time solar energetic particles measurements from L1 location will cease when the ACE data stream is terminated and completely replaced by operational mission DSCOVR). High-energy electron measurements at L1 are not currently routinely available. Thus, current availability of data on solar energetic particles from measurements in solar wind should be defined as **poor**.

- **Heliospheric images**

These images are available from off the Sun-Earth line and their observing cycle should be 10-60 min with timeliness of 10-60 min. These images are currently produced by instruments on board of STEREO research mission. Launched in 2006, it consists of two satellites, one that leads Earth in its orbit around the Sun and one that lags with the separation between Earth and the two STEREO satellites changes by about 22.5 degrees per year. However, one of these satellites has recently ceased supplying observations.
Provision of data should be estimated as **poor.**

3.3 General recommendations for Solar Wind/ Heliosphere data.

Overall, the robustness, availability, accuracy, spatial and temporal resolution of in-situ solar wind/heliospheric data can be defined as **poor (with bulk solar wind information at marginal level)**.

Because of the unique capability of satellites upstream from Earth in the solar wind to provide advance warning of the most severe geomagnetic storms, maintaining these continuous, real-time measurements is essential. These data are the only reliable indicators of solar wind disturbances prior to their arrival at Earth. These disturbances impact our electric power infrastructure, our satellites, our communication capabilities, and our satellite-based navigation. Accurate, advance warning of large geomagnetic storms is central to our space weather service capabilities.

The information on the propagation of the solar disturbance evolution, its parameters in particular speed and magnetic field, while moving towards the Earth, is vital for space weather services and in particular for the forecasting. The development of the dedicated Solar Wind operational mission has undergo its first step with launch of the DISCOVR mission at L1 location, but, unfortunately, some types of data (particles) were not supported by instruments on DISCOVR. Thus, further development of continuous operational services from L1 position on the propagation, evolution and the most important parameters of solar features is highly recommended.

It is also valuable to have interplanetary measurements from satellites at different positions with regard to distance to the Earth, to increase the warning time from less than 45 minutes and the confidence on the disturbance parameters (i.e. IMF direction). One of possibilities is the L5 Lagrange point, off the Sun-Earth line and roughly 60 degrees lagging Earth, which will give a bit advance warning if the heliospheric image is taken from there.

Furthermore, the future multiple scientific missions with orbits closer to the Sun than 1 AU (for example, using “solar sail” technology) would be helpful in providing the simultaneous sampling of interplanetary ejecta from different positions in interplanetary space (possibly ahead of current L1 position) and unable to provide more accurate space weather forecasts.

4. Energetic Particles in the near-Earth environment.

4.1. Introduction

The energetic particles in the Sun-Earth environment are highly variable, both spatially and temporally. The dynamics of the Sun, interplanetary space and Earth’s magnetosphere all contribute to the variability of the energetic particles. Consequently, the particle populations vary over a wide range of time scales, from minutes to decades.

Operational measurements of energetic particles are needed to assess the causes of anomalous behavior in spacecraft systems and to protect space assets and human health. Real-time data are required to issue alerts of hazardous conditions at satellite and aircraft altitudes. A long, historical measurement baseline is required for spacecraft design, human radiation risk assessment (at ISS and aircraft altitudes), post-event analyses related to satellite and sub-system failures, and to characterize and enable predictions of the particle flux levels and their effects.

The following observables are identified as the most important for operational use:

- Electron and Proton differential directional flux (in-situ at GEO, MEO, LEO) and Heavy ion differential directional flux and mass spectrum (at GEO).

Measurements of the low-energy (eV) to high-energy (several MeV for electrons, hundreds of MeV for protons) electrons and protons, and energetic heavy ions (10s to 100s of MeV/nucleon), are required to provide operational information on the radiation environment. The electron, proton and heavy ion fluxes vary with location inside the magnetosphere by many orders of magnitude, and consequently observations at multiple satellite orbits, and multiple locations within each, are required.

- Cosmic ray neutron flux and radiation dose rate (different altitudes)

Cosmic ray flux measurements are required to provide information on the radiation environment that is hazardous to humans in space and at aircraft latitude, while dose rate measurements are required to determine the radiation levels at the airline cruising altitudes.

4.2. Review and gap analysis

Energetic particle measurements are being made by detectors on numerous satellites at LEO, MEO, GEO, and trans-magnetospheric orbits, on both operational (continuous) and science missions. Current missions include, for example, **LEO missions:** series of missions, such as NOAA-series (POES) and DMSP series, Meteor, MetOp, and Proba; **GEO** - the GOES satellite series Electro-L, U.S. Los Alamos National Laboratory missions; **MEO** - GPS satellites, trans-magnetosphere: CASSIOPE, THEMIS, Cluster and others. Satellites in Highly Elliptical Orbit (HEO) such as the research mission Van Allen Probe, are valuable for obtaining data from not well sampled regions.

Overall, the data provision cannot be uniformly characterized, spanning the whole range from **Acceptable** to **Poor.**

- Electron differential directional flux (GEO, MEO, LEO)

Flux levels can change dramatically in minutes, which requires high measurement cadence (1 – 10 min). Low data latency (1 – 100 min) is required to provide timely information when flux levels change abruptly. Coverage of low-energy electrons (< 100 keV) is poor, as is availability of data. Increasing the number of locations in GEO and LEO where these electrons are measured and making the data available in real time is required. Increased availability of high-energy electron measurements at both GEO and LEO is also needed, as is increased availability of high-energy electrons at LEO. Additional electron measurements in HEO orbits would improve the ability to specify the electron flux levels throughout the magnetosphere. **Marginal**

- Proton differential direction flux (GEO, MEO, LEO)

In comparison with electron measurements, fewer observation locations are required to characterize the intensity and distribution of energetic protons in the magnetosphere. Existing GEO and LEO measurements are generally adequate. However, increasing the real-time availability of currently existing GEO and LEO satellite measurements would improve the accuracy of flux levels and cutoff latitudes. **Acceptable.**

- Heavy ion differential directional flux and mass spectrum (GEO, heliosphere)

At GEO, alpha particle measurements are available from current NOAA GOES satellites, and energetic heavy ion measurements for elements up to iron will be available with the next generation of GOES (2016). Interplanetary (see solar wind and heliosphere part), the ACE CRIS data are available for services. **Acceptable**

- Cosmic ray neutron flux (surface based)

High measurement cadence (1 – 10 min) and low latency (1 – ~20-30 min) are required to identify rapid variability in the neutron flux levels and to enable rapid alerts when particle flux levels increase. Moderate horizontal resolution is required (1000 – 5000 km for neutron flux; 100-500 km for radiation dose rate), with higher resolution at high and mid latitudes, in order to characterize the steep flux gradients that occur due to the geomagnetic cutoff boundary. A vertical resolution of (0.1 – 2 km) in the radiation dose rate measurement is required to characterize the absorption with depth in the atmosphere.

Ground-based neutron monitors and muon detectors can observe fluxes of secondary cosmic rays, which are proxies for primary (space) cosmic rays. Neutron flux measurements are currently being made at a number of sites around the globe. Muon detectors on the ground are

complimentary to neutron monitors and help in the discrimination of different energies of primary cosmic rays.
However, only a limited number of sites provide high quality data in real time. Improving the real-time data quality and the incorporation of these data in global models could contribute to better estimates of radiation levels on aircraft. **Marginal**

- Radiation dose rate (aircraft based)

Radiation dose rate measurements are not routinely available on aircraft. A baseline should be established for these measurements that could be used to develop initial service capabilities (including verification of models) and later to refine measurement requirements. **Poor**

4.3 General recommendations for information on energetic particle in near-Earth environment:

The in-situ data on energetic particles are available from both operational and scientific satellites, although not all of them are available in real time. Thus, the deficiency of real time data makes the overall estimation of the data provision at the level: **marginal to acceptable**. Increased availability of high-energy electron measurements at both GEO and LEO is also needed, as is increased availability of high-energy electrons at LEO. Additional electron measurements in HEO orbits would improve the ability to specify the electron flux levels throughout the magnetosphere

At the same time, the data provision from ground and aircraft-based detectors (cosmic ray produced neutrons) is at the level **marginal to poor** due to their unavailability in “real” time and the lack of air-borne observations.

The energetic particle data are available from numerous space-borne sources, for which the intercalibration and interoperability have not been adequately addressed. In order to estimate the energetic particle flux at any location where satellites orbit, it will be necessary to aggregate the multiple data source, intercalibrate the data, and then incorporate the data into numerical models to estimate the flux levels throughout near-Earth space. Co-located measurements of the magnetic field would be helpful in understanding the variability of the particle fluxes.

The satellite mission on high latitude HEO (e.g. Molniya, TAP, MAP) orbits would be very useful to fill the currently existing gaps in and address important questions on particle dynamics.

5. Ionosphere

5.1 Introduction

The ionosphere is the electrically ionised part of the upper atmosphere (50 – 1000 km) embedded in the electrically neutral ‘thermosphere’ with its upper boundary coupled to magnetosphere and lower boundary coupled to atmosphere. The properties of ionosphere are controlled by fluctuations in high-energy solar radiation (EUV and X-rays), energetic particle flux by interaction of the solar wind with the Earth's magnetosphere and by dynamic processes in the thermosphere and the lower atmosphere. The ionosphere can therefore vary appreciably from day to day, hour to hour, and minute to minute and is characterised by phenomena having very different characteristics at high and low latitudes in comparison to mid-latitudes.

The most important ionospheric variable whose changes in time and space affect several types of infrastructure on Earth and in space is the electron density. Its altitude variations, together with some other parameters, define the traditional division of the ionosphere into D, E, and F layers, started from the lowest. However, in practice ionospheric electron density is rarely measured in-situ. Instead, ionospheric monitoring techniques commonly utilize radio waves whose propagation variables such as amplitude, phase, travel time and polarization are affected by the ionospheric plasma.

The variability of the ionosphere impacts the performance of Global Navigation Satellite system (GNSS), communication systems relying on HF (3-30 MHz) radio wave propagation, satellite systems using radio signals (SATCOM, SATNAV), and, to a lesser degree, remote sensing applications such as Synthetic Aperture Radar (SAR).

The ionospheric effect on GNSS signals both from the ground and space can manifest itself as

1) impacts on the multi-frequency differential signal delay on the GNSS signal. This is proportional to the **Total Electron Content (TEC),** which is the integral of the electron density along the radio link path. TEC may be geometrically specified as slant TEC (STEC) along the radio link or as vertically integrated electron density (VTEC). TEC observations are required by Positioning, Navigation and Timing (PNT) applications using single frequency GNSS receivers. Observations of STEC are required to drive alerts for spatio-temporal ionospheric gradients, which can impact PNT applications relying on network-based corrections, such as network Real Time Kinematic (nRTK).

2) the degree to which the ionosphere causes **scintillation** (rapid fluctuations in amplitude and/or phase) of the GNSS signal. The scintillation intensity indices (amplitude S4 and phase σ_ϕ,) are the effective indicators for describing the degree of ionospheric perturbation due to small scale irregularities and plasma bubbles which can cause fluctuations in the amplitude and phase of GNSS signals and lead to severe degradation in the quality of related applications. Scintillation observations for GNSS and SATCOM signals passing through the ionosphere at a particular location are used to provide warning on potential degradation of PNT accuracy and SATCOM conditions.

Active sounding of the ionosphere using HF radio waves with ionosondes conducted both in vertical incidence and oblique transmission modes. Ionosondes provide a set of ionospheric state variables, related to E-and F-regions of ionosphere, which are important for characterising GNSS and HF impacts such as:

foF2 / hmF2 / spread-F –The variable foF2 is the maximum radio frequency reflected vertically from the ionospheric F-region. hmF2 is the height of the density peak of the F2 layer. Spread-F is the amount of range spread of the HF radiowave reflected from the F region. foF2 observations are used to derive the Maximum Useable Frequency (MUF) for specific HF radio broadcast ranges or point to point connections. hmF2 observations are critical for HF Direction Finding (HFDF) and radar operations. The spread-F is used to classify conditions for HF radio communications and HFDF. In addition, the variable **foEs** represents the electron density of a thin but dense sporadic E layer near 110 km, and the increase of Es causes extraordinary propagation of both HF and VHF (30-300 MHz) radio waves.

Observations of **Ionospheric radio absorption** in the D-region are also important for characterising the impacts on communication. In polar areas, solar energetic particles may ionise the ionospheric D-region resulting in complete absorption of incident HF radio waves (polar cap absorption, PCA) for several days. Similarly, large X-ray flares can result in considerable D-region ionisation and consequent “HF blackout” on the sunlit side of the Earth for several hours. This absorption is observed using ground-based passive monitoring of the ionospheric effect on background Cosmic Radio Noise using riometers (Relative Ionospheric Opacity METERs).To certain extent, the observations done by use of ionosondes or VLF-measurements at 3-30 kHz can also help in evaluation of signal absorption in D-region.

5.2. Review and gap analysis

The requirements for timeliness, space resolution, and quality for the above listed variables vary from case to case and they are therefore summarized individually below.

TEC – Observations can be provided in the form of VTEC maps over a specific region or globally, or in the form of estimates of STEC from single sites or small regional CORS (Continuously Operating Reference Station) networks. For useful Near Real Time (NRT) services the goals for latency and observing cycle of VTEC are 1 min and 5 min, respectively. The goal in spatial resolution is <100 km. Current augmentation systems for aviation navigation such as WAAS and EGNOS need at least a 3-minute observational cycle, which is higher than proposed goal in OSCAR database and horizontal resolution of about 5^{o}. An uncertainty of less than 1 TECU is necessary to correct range errors in the order of 16 cm. Ground-based GNSS data provide accurate information about the horizontal electron density gradients, but limited information about the vertical gradients. On the other hand, RO (Radio Occultation) data obtained from low-Earth orbit (LEO) satellites equipped with GNSS receivers contain high-resolution information about the vertical gradients and smeared information about the horizontal gradients. In some regions the goal of TEC horizontal resolution of <100 km is already available by high resolution national or state CORS. The situation is worse with data availability above oceans, for which the space-based GNSS observations are a feasible way to bridge the gaps. The International GNSS Service (IGS) provides ground GNSS data from a network of globally distributed sites, including GPS and GLONASS, and in future could be extended to incorporate BeiDou (formerly named COMPASS), GALILEO and other GNSS. Overall for **ground GNSS** receivers data provision is **Acceptable** in some regions (e.g. in US, Japan, Europe) but **Poor** globally (problems particularly in the timeliness).

GNSS RO data acquired by meteorological satellites (e.g. Metop, Meteor-M, or FY-3 series) can be collected in near-real time through Direct Readout services, provided there have capability to provide the ionospheric observations. In favourable cases RO data from Direct Readout can be achieved even with timeliness of 20 min. The horizontal resolution and coverage of GNSS RO observations will be improved with the launch of COSMIC-II GNSS RO constellation (2017-2020), with estimated latency about 45 min. This is within the threshold, but is still **poor** compared to the goal. Thus, estimation of observations provided by **GNSS RO** is **Poor** (problems particularly in the timeliness).

Scintillation (S4 and σ_Φ) - The high spatio-temporal variability of ionospheric phenomena producing scintillation on GNSS and SATCOM signals sets high demands for the observational requirements: observation cycles between 10 minutes (threshold) and 1 minute (goal) and spatial resolutions between 200 km (threshold) and 50 km (goal). For scintillation measurements, there is a need in increasing the number of ground-based GNSS scintillation receivers, particularly in polar and equatorial regions where the phenomena most often occur, in order to achieve more homogeneous coverage and to satisfy the requirements. Innovative solutions should be searched to cover the ocean regions to support off-shore activities. Up to now, the data provision should be defined as **Poor.**

foF2 / hmF2 / spread-F -The horizontal resolution requirements are based on the characteristic spatial decorrelation scale for the ionosphere which, for HF, is roughly equivalent to the height of the ionospheric layer. Hence all observational variables related to the F2 region (foF2, hmF2, spread-F) have a goal horizontal resolution of 200km. This is different from goal resolution of 10 km for Spread F and goal resolution of 100 km for all other F-layer parameters currently stated in OSCAR. The observation cycle requirements are driven by characteristic temporal scales of the ionospheric F-region (~1-15 minutes) in order to adequately capture the full range of spatio-temporal ionospheric variability both at low and high latitudes. This is different from goal of 5 min currently stated in OSCAR database. Timeliness requirements of 1 min goal are driven by applications, which require NRT observations within delays comparable with the time scale of the dynamic ionosphere. Similarly, accuracy requirements on these variables are also driven by applications. HF communications applications perform adequately with the foF2 (and therefore MUF) accuracy of ~0.5 MHz, however, more sophisticated applications such as HFDF and radar operations define the goal requirement of 0.1 MHz. This is different from currently stated goal of 0.05 MHz, as listed in OSCAR.

foEs -The requirements on horizontal resolution, observation cycle and timeliness are similar as for the F-region parameters above, i.e. determined by the characteristic spatial and temporal scales of the ionosphere without over-sampling.

The spatial coverage of ionosondes' measurement sites varies considerably from region to region with extremely problematic coverage of ocean areas. It should be noted, that there are numerous ionosondes in isolated locations at high latitude, often deployed for scientific purposes rather than HF radio support and that some countries (e.g. northern and central Africa and parts of the former USSR) had better coverage several decades ago than they have now.

Data provision for monitoring the above characteristics of F and E-regions of ionosphere can be regarded as **Acceptable** in some regions (e.g. in Mid-Europe) but **Poor** globally (problems in the timeliness).

D-region absorption- Adequately mapping of the spatio-temporal distribution of D-region electron density enhancement across the polar cap drives requirements on riometric observations of between 10 min (threshold) and 1 min (goal) temporally and 500 km (threshold) and 100 km (goal) spatially.
A network of evenly distributed riometers at high latitudes would be useful for monitoring the appearance of PCA events. As riometers are currently used mainly in research, NRT availability of their data is sporadic in space and time. Utilization of riometer data in space weather applications would benefit from similar standardization of product(s) as is currently available for ionosondes.

Ionosondes are used to observe HF radio absorption occurring in the sunlit ionosphere as a result of solar X-ray flare activity. The necessary observations (lowest reflected frequency on the ionogram) are easily derived from standard ionospheric sounding, and thus the observational requirements for absorption events due to solar flares are less demanding than those related to HF sounding (such as those requiring observations of the critical frequency of the F2 layer).

Overall, the availability of D-region absorption observations is **Poor**. Additional availability and data timeliness, particularly from scientific riometer, would improve ionospheric specification in extreme conditions

5.3 General recommendations for ionospheric observations:

Overall, ionospheric data can be characterised as **Acceptable** in places where the network are dense, but **Poor** where the network of observations is difficult to implement (oceans, polar areas) or where data are provided by scientific instruments only.

Although the number of sources of ground-based **GNSS ionospheric data** is increasing, the data are not readily available in a coordinated network. Commercial companies, geodetic and seismic research communities, and meteorological services are maintaining dense GPS receiver networks whose data are not currently available for operational space weather services. The space weather community should establish a closer collaboration with these initiatives in order to improve the situation. A priority for the WMO Members should be to facilitate the inclusion of GNSS data in WIS (WMO Information System) and to share data among meteorological and space weather GNSS data networks with high timeliness.

Utilizing GNSS receivers mounted to aircraft or to buoys has been considered, but the technical challenges are still large. Space-based GNSS observations are most likely a more feasible way to bridge the gaps over oceans.

TEC data from the past can be used for quantifying the range of ionospheric variability in specific regions of the globe, through statistical analysis. Typically data from a full solar cycle over the region of interest are required to perform this kind of analysis.

In the framework of WMO the expertise of the Numerical Weather Prediction (NWP) community on data assimilation may be useful to integrate both ground based and RO GNSS data to ionospheric models and this way improve the benefit from these observations. It remains a challenge to merge GNSS RO data, of good global coverage but poor timeliness, with ground-based GNSS data, of poor coverage but short delay, in an ionospheric analysis system or data assimilative model.

nRTK applications are relying on high accuracy, high horizontal resolution observations of STEC in order to accurately model ionospheric delay over CORS networks. One example of this is PPP-RTK (or network PPP) algorithms, which require highly accurate ionospheric delay information in order to resolve phase ambiguities with short lead times. The requirements of these high precision systems drive the goal accuracy, horizontal resolution, observation cycle and timeliness requirements on STEC, which are currently not listed as observable described in OSCAR .Thus, updates are needed to the list of observables and requirements currently incorporated in OSCAR database of WMO.

High variability in the ionospheric conditions poses challenges for the ionosonde data analysis routines. Automated approaches providing typically good results at middle latitudes are not directly applicable to auroral or equatorial measurements.

Ionosphere monitoring by means of advanced sounding with space-borne techniques (RO) could radically increase global coverage of horizontal and vertical ionospheric characteristics. We estimate, however, that about 30 000 RO measurements/day would be needed to provide comparable data coverage as compared with ~80 globally distributed ionosondes.

Currently a number of observations by HF and VHF coherent backscatter radars are used in ionospheric modelling and they most likely would be a useful supporting asset also in near-real-time data-assimilation, but some additional research work is still needed to find out how these data can be harvested appropriately in operational systems.

Data on ionospheric D-region absorption, provided by Riometers, are especially important for high-latitude regions, but the special coverage of the existing networks are not dense enough and mostly provided by scientific instruments, thus level of data provision is **Poor**.

6 Thermosphere

6.1. Introduction.

Observations of temperature, atmospheric density and horizontal wind are required throughout the thermosphere to produce space weather alerts (e.g. of satellite drag). It is also increasingly recognized that the interaction between thermosphere and ionosphere is important, and that a well observed thermosphere can lead to improved ionosphere forecasts.

WMO observations requirements differ between the lower thermosphere (100-200 km altitude) and the upper thermosphere (200 to around 600 km altitude), because of the more rapid temporal variations and stronger vertical gradients in the former region The large changes with height structure in the lower thermosphere means that a goal vertical resolution of 5 km in this region has been selected, compared with 20 km in the upper thermosphere. However, the required horizontal resolution is the same throughout the thermosphere (ranging from 500 km threshold to 100 km goal).

The rapid response of the thermosphere to both solar and geomagnetic changes means that a goal observing cycle of 5 seconds is required, although, because this is practically challenging to achieve, threshold values of 5 minutes in the lower thermosphere (and 30 minutes in the upper thermosphere) are specified. Since the rapid variations in the thermosphere are largely externally driven by solar variability, ionospheric and geomagnetic storms, long-lead time forecasts of the thermosphere are challenging, and rapidly updated nowcasts are an effectively way of monitoring the changing state of the thermosphere. Such rapid updates imply timely reception of observations, hence a threshold requirement of 60 minutes and a goal requirement of 5-30 minutes.

6.2 Review and Gap analysis

The thermosphere is chiefly observed using satellites. They typically have global coverage but in many cases observe over a restricted vertical range or have coarse vertical resolution. Ground-based observations from Fabry-Perot Interferometers (FPIs) can produce high-quality, timely observations, but with limited horizontal resolution since they are based on observations from a selection of sites. There are also issues with limited vertical coverage since they are dependent on the heights of the airglow and auroral emission layers. Radars and lidars observe temperature and horizontal wind, but typically below 100-105 km. Rocket observations have better vertical resolution but are launched infrequently due to their high cost.

Temperature

Temperatures have been retrieved from the OSIRIS satellite instrument for the 90-110 km altitude range with accuracies of +/-2 to +/_6 K. Observations are made every 80-120 s, and the resolution is 1 km in the vertical and ~300 km in the horizontal. The OSIRIS measurements meet goal observation uncertainties and vertical resolution requirements for the lower thermosphere (other than the data not spanning the whole vertical range), and the horizontal resolution and observation cycle is better than the threshold requirements. It is assumed that these are research-level data only, with dissemination much less than the threshold requirement for timeliness.

FPI observations are limited to nighttime and clear sky conditions, and to a handful of locations. The FPI vertical view gives information on the thermosphere near 250 km, with 15-20K accuracy from 5 minutes exposure. For the upper thermosphere, the FPI observations fall short of threshold WMO observation requirements for horizontal and vertical resolution and timeliness, and they meet threshold requirements for observing cycle and exceed the goal requirements for observation error.

Gap Assessment: Lower Thermosphere Temperature: **Marginal** – OSIRIS data are available, but they do not cover whole vertical range and have poor timeliness

Gap Assessment: Upper Thermosphere Temperature: **Poor** – Only a few sparse FPI observations are available. Poor timeliness

Atmospheric Density

Recently, atmospheric densities in the upper thermosphere have been inferred from accelerometers that fly on LEO satellites (eg CHAMP, GOCE, GRACE), with a latency of a few months. The observations are made at an altitude of 250-450 km for CHAMP, 430-490 km for GRACE and 255 km for GOCE. These instruments have now ceased operations. Accelerometer data are now provided by the recently launched Swarm and DANDE missions. The observation error is 1-10%. The along-orbit horizontal resolution is 40 - 80 km. The longitude resolution is 25° at the equator (smaller at the poles). Observations are made every 5 s or 10 s. Mean atmospheric densities (averaged over a few days) can be inferred from orbit information in the form of TLEs or via very precise tracking systems of geodetic satellites. Densities are available in the 200-600 km height range. The TLE data are made available with a latency of less than one day.

The threshold requirements for observation uncertainty in the upper thermosphere are met, and the goal uncertainty (10%) is met in most cases. The vertical resolution of the accelerometer data from a constellation of satellites approximately meets the threshold vertical resolution requirement. The goal horizontal resolution requirements are met in the latitudinal direction, but in general not in the longitudinal direction. The observational cycle for the accelerometer data is about equal to the goal requirements, but the mean TLE-derived data, do not meet the threshold requirements. Data timeliness is insufficient for all data types, though there are no technical obstacles for retrieving sufficiently low latency density data from future accelerometer missions.

There are some observations of atmospheric density based on limb sounding satellite observations in the UV. GUVI atmospheric density profiles for the 110-300 km region were available from 2002 to 2007. Mean GUVI densities compare well with TLE densities. SSULI provides global upper atmosphere density profiles both day and night. Three SSULI instruments are in operation and two more are planned. SSUSI (like SSULI, flown on DMSP) uses UV spectrographic imaging, in a similar way to GUVI

Gap Assessment: Lower thermosphere Density - **Less than Marginal / Marginal** – SSUSI and SSULI may meet requirements, but no information is available on accuracy, observational cycle and timeliness

Gap Assessment: Upper thermosphere Density - **Margina**l – Swarm meets most of the requirement, apart from timeliness and vertical resolution. The latter could be addressed by the introduction of new missions like DANDE and the GRACE follow-on SSUSI and SSULI may meet requirements, but no information is available on accuracy, observational cycle and timeliness.

Horizontal Wind

Satellite observations can be used to infer lower and upper thermospheric wind, respectively, but most relevant missions are now defunct: WINDII and TIDI operated during the 1990s and 2002-2005, respectively. On NASA’s ICON mission (scheduled for launch in 2017), the MIGHTI instrument will measure winds between 90-300 km altitude (day) and between 90-105 km and 200-300 km (night) with a horizontal resolution of <500 km. FPI instruments have 5 m/s accuracy from 5 minutes of data. They fall short of threshold requirements for timeliness, and horizontal and vertical resolution. They meet threshold requirements for observing cycle and exceed the goal requirements for observation error. Accelerometers can also be used to infer wind, but maximum errors are around 1000 m/s for GRACE. These winds remain a research tool rather than something that can be used operationally

Gap Assessment: Lower thermosphere Wind - **Poor** – No current observations. Awaiting ICON mission in 2017

Gap Assessment: Upper thermosphere Wind – **Poor** – Only a few sparse FPI observations. Poor timeliness. Accelerometer winds have too large errors to be useful.

6.3 General Recommendations for Thermospheric Observations:

The thermosphere is very poorly observed, and efforts should be made using a range of observational techniques to improve observational coverage. This includes:

- Increase the number of observations of atmospheric density made by accelerometers flown on LEO satellites. Operation on a wider range of satellites would enable a greater range of altitudes to be observed and a greater range of local times. Future accelerometer-carrying satellites should deliver the required data with low latency.

- Maintain or increase the amount of limb satellite observations that provide density profiles (eg SSULI) for operational use. In addition, efforts should be made to supply OSIRIS measurements of the lower thermosphere temperature in near real time.

- Thermospheric winds are especially poorly observed. Techniques for accurately inferring winds from accelerometer data should be further developed and demonstrated. They will require cross-calibration with ground-based FPIs which make direct wind measurements. Doppler interferometry techniques (as used in TIDI) should be revisited in order to provide more for lower thermospheric wind profiles.

- Develop the operational aspects of FPIs to support the provision of space weather services, for example continuous operation, near real time dissemination of observations, or an expanded observation network. Routine daytime observations by triple etalon FPIs have yet to be achieved

- Exploit in-situ observations of temperature, density and constituents made on Cubesat missions (eg QB50) and use as the basis of a future, smallsat-based, operational observation system.

7 Geomagnetic field

The geomagnetic field at the surface of the Earth is a combination of the internal Earth magnetic field (main field) and perturbations caused by different external sources, i.e. related to the space weather. The geomagnetic variations associated with the space weather are: diurnal (24 hr) variations due to the impacts solar electromagnetic radiation on the ionosphere and currents driven by thermal-tidal motion (mostly E-region) and thermospheric winds; and short-term variations due to the disturbances of the solar and magnetosphere origin, such as geomagnetic storms and substorms, geomagnetic pulsations (effects of solar wind disturbances and waves in the magnetosphere), sudden impulses (due to the interaction of the shocks in the solar wind and magnetosphere) and others.

7.1. Introduction

The regular measurements of the spatio-temporal distribution of the magnetic field at the Earth surface are used in the development of the global International Geomagnetic Reference Field (IGRF) model of the Earth’s main magnetic field, upgraded every 5 years, which supports, for instance, long-term production of declination maps, or Earth interior studies. With the addition of satellite magnetic measurements, IGRF model is used in the development of the magnetospheric magnetic field model and coordinate systems for satellite environment assessments, among others. The results of the aeromagnetic surveys on variations of local internal geomagnetic field are used for mining and other geological applications.

Measurements of the short-term variations of the geomagnetic field are widely used in support of space weather services for monitoring and forecast of geomagnetic disturbances. One of the most traditional uses is production of several types of geomagnetic indices, such as Kp, Dst, AE (see The International Service of Geomagnetic Indices ISGI site http://isgi.latmos.ipsl.fr/observatory.html) developed in order to evaluate and forecast the spatial and temporal evolution of the geomagnetic disturbances on global and local scales. The requirement for high resolution real-time and historical data has increased in the last several years in order to support real-time monitoring numerical simulations and forecast as well as long-term assessments of the space weather impacts on critical ground-based infrastructures such as power lines, pipelines, and for monitoring pointing errors in directional drilling in oil or gas explorations and other services.

7.2 Review and Gap analysis

- **Ground-based observations of geomagnetic field**

The majority of operational-quality data are provided by permanent ground observatories and stations operated by governmental institutions (US Geological Survey, British Geological Survey, Natural Resources Canada, South African Space Agency etc.). The magnetometers used for geomagnetic field data collections at these observatories are of two types; one measures the variations of the three components of the magnetic field vector; and another measures the absolute value of the magnetic field, thus providing data on short-term variations and slow changes in the absolute value of internal field.

In order to increase the spatial coverage of geomagnetic monitoring in different areas on the globe, multiple collaborative groups were created. Among them the most recognizable for its dense global coverage and quality of data provision is INTERMAGNET (http://www.intermagnet.org/). Many other collaborative groups related to specific scientific projects, with different requirements on types of magnetometers or specific procedures for data evaluation, can also be listed, such as, for example: International Monitor for Auroral Geomagnetic Effects (IMAGE) http://www.geo.fmi.fi/image/, Canadian Array for Realtime Investigations of Magnetic Activity (CARISMA) http://www.carisma.ca/, the Step 210° Magnetic Meridian Network Project (http://denji102.geo.kyushu-u.ac.jp/denji/obs/210/210_obs_e.html), the Circum-pan Pacific Magnetometer Network http://denji102.geo.kyushu-u.ac.jp/denji/obs/cpmn/station/STAT95.htm), the Embrace Network in Brazil (http://www2.inpe.br/climaespacial/MainViewer/faces/mag_index.xhtml?lan=en), etc.

The ground geomagnetic data are traditionally divided into two classes depending on its quality, e.g. preliminary and definitive (released after the quality control has been done). The accuracy of definitive data recommended by INTERMAGNET to its participants is 5nT with resolution of 0.1 nT, sampling rate of 1 sec for vector measurements; for absolute measurements the resolution is 0.1 nT, accuracy is 1 nT, sampling rate is 30 sec. Thus, INTERMAGNET data satisfy the goal requirements of observing cycle (1 sec) and uncertainty (0.1 nT). At the same time, the INTERMAGNET data transmission is within 72 hours of acquisition, thus, threshold timeliness of 60 min is not met.

The **requirement of spatial distribution (100 km)** in several areas is not met based on current non-uniformity in the locations of the INTERMAGNET geomagnetic observations around the globe http://www.intermagnet.org/imos/imomap-eng.php . They are most dense in Europe and the least dense in Africa, South America and the Asian part of Russia. Other collaborative networks of the ground magnetometers do not satisfy the requirements on more parameters than INTERMAGNET.

In general, the data availability, sampling rate and quality of the ground-based geomagnetic data should be regarded as marginal to (in some places) **good**, while the timeliness is still **poor**.

- **Space-based observations (LEO, GEO) of geomagnetic field**

Space–based observations of the geomagnetic field are mostly carried by scientific LEO orbiting missions (MagSat, Champ, Oersted, Swarm constellation). The operational meteorological missions of GOES-series (NOAA) are providing continuous in-situ monitoring of the geomagnetic field at geostationary orbit for use in space weather monitoring. Expansion of these data collections are planned for future [Electro-L,M (Roshydromet) and FY-4 (CMA) series]. (See: http://www.wmo-sat.info/oscar/gapanalyses?view=171 for more complete list of satellites)

There are also multiple scientific space missions addressing the external sources of the geomagnetic (magnetospheric) field variability for studies of the space physics which have magnetometers on-board. Among them are the 5-satellite HEO orbiting THEMIS mission, 2 satellite Van Allen Probes HEO mission (NASA), and also non-scientific missions carrying on-board scientific instruments such as LEO orbiting Cassiope (MDA/CSA), DMSP (DoD) and Iridium constellation (~77 satellites, with some carrying magnetometers). These missions are all of different duration and orbits, with the magnetic data availability, sampling, resolution and quality defined by each specific institution, project and instrument PIs. See https://directory.eoportal.org/web/eoportal/satellite-missions/ for more details.

The temporal and spatial coverage of the space-based geomagnetic data to support the updating of the IGRF model (i.e. long-term variations of the magnetic field of interior origin) can be regarded as **good**, provided that missions will be regularly replaced to ensure continuity.

However, these measurements are not enough for real-time monitoring and forecasting of highly dynamical magnetospheric magnetic field (i.e. variations of the magnetic field inside the whole magnetosphere), whether to provide input to satellite environment models for long-term design considerations or in real-time space weather services. In order to properly follow the variations of the magnetospheric magnetic field and the associated variations of the trapped and transient particle population, measurements should be done to cover not only LEO and GEO orbits, but the whole magnetosphere extended from 15 Earth Radii on the day side to 100 earth radii on the night side and more than 30 Earth radii on each flank.

Thus, the requirements for observations of the geomagnetic field at GEO and LEO orbits can be regarded as met at level of **marginal** with the horizontal resolution goal on GEO and LEO are not met as well as timeliness for LEO.

But, as has being pointed out, these locations do not represent the overall status of the dynamical magnetosphere, especially at high latitudes of the magnetosphere, (which in the future might be filled by high inclination HEO mission).

Thus, the overall spatial coverage and the temporal resolution of the global-scale magnetospheric magnetic field data and needs to be improved and in its current state should be classified as **poor**.

7.3 General Recommendations for observations of the geomagnetic field:

Overall, the provision of the geomagnetic data can be characterized as **acceptable** for ground-based observations and **poor** for space-based observations.

An important development would be to increase the density of the geomagnetic observatories or stations in the areas where they are sparse or non-existent. Perhaps it could be done by consolidating the geomagnetic stations with the WMO meteorological stations.

The timely (real-time) availability of operational geomagnetic data is, perhaps, the most critical requirement in the space weather monitoring and forecasting services. Although it seems easy to mitigate this issue for ground-based observations, several problems need to be addressed first.

- Data policy- real time data are the source of revenue for many organizations, thus, their availability depends on a particular organization (Government). Efforts should be made for incorporating the requirement for real-time data provision at least in regard to INTERMAGNET participants as the most advanced group of data providers.

The requirement for fast sampled data (1 sec.), which is currently proposed for INTERMAGNET participants, is important for space weather services to provide better opportunity for monitoring and modelling of the impacts on power systems, where fast magnetic variations create more hazards to the system. Caution is needed, since faster sampling rate will require better real-time filtering of the spikes, which may be beyond the current capabilities of many observatories.

- Data quality- real-time data are preliminary and their quality is corrupt by interference, thus collaborative efforts should be made to consolidate the quality of real time data.

In addition, numerous geomagnetic measurements on Earth and in space are associated with long-term and short-lived scientific projects related to space physics and operated by university and/or government researchers funded by different organizations. Significant efforts would be required to consolidate these data into formats more useful for the space weather services.

The existing data sets have the low representation of the geomagnetically disturbed time periods, which makes it difficult to address the most important space environment conditions as well as to build dynamical models and space weather services to satellite operators.

The required temporal and spatial resolutions in terms of space-based in-situ observations are not well defined and the recommendation is to review them in OSCAR based on updating knowledge on the magnetospheric dynamics and on the required services for satellite operators.

Moreover, up to date there is no time-dependent self-consistent dynamical model of the magnetospheric magnetic field coupled with radiation environment model, which is capable to account for the temporal variability of trapped and transient radiation during space weather events, including geomagnetic storms.

8. Recommendations on how to address the identified gaps in provision of Space Weather data for operational SW services.

1. The level of provision of the space weather data can be in general summarized as poor,and especially continuous real-time streams, which is due to mostly the space which needs to be covered: from 1 AU in interplanetary space to kilometers. Thus, all Members should encourage improvements in the development of continuous, real-time data streams, in data acquisition and open dissemination of all ground-based and space-based space weather data.
2. Develop and regularly update the Guide on performing Space Weather observations (similar to see http://www.wmo.int/pages/prog/www/IMOP/CIMO-Guide.html) as a guidance to standardize instrumentation, to improve interoperability, cross-calibration and quality assurance. As a first step, tdevelop of a metadata standard compatible with WMO-WIS.
3. High-level coordination of space-based assets should be established to maintain continuity of solar flux measurements and solar imaging, solar wind and interplanetary magnetic field measurements, and heliospheric imaging. This coordination effort should include consideration of measurements at the L1 Lagrange point and at other locations in interplanetary space, such as the L5 Lagrange point and on the Sun-Earth line upstream from the L1 point, as well as the required global network of ground-based antennas for data reception and processing. This could be done under the auspices of WMO through the Coordination Group for Meteorological Satellites (CGMS) and in consultation with appropriate international committees such as the United Nations Committee on Peaceful Uses of Outer Space (UN-COPUOS).
4. Efforts should be made to coordinate and to standardize the existing ground-based solar data and to expand them where required for redundancy, including defining an approach for a common data portal or virtual observatory concept accessible via WIS and creating advanced, combined products and image-processing techniques. Currently, the continuation of the solar flux at 10.7 cm wavelength measurements is under question due to aging of the infrastructure.
5. Efforts should be made to encourage and improve modeling of the solar and interplanetary plasma, in particular with the purpose to develop operational software for numerical space weather prediction. This implies that the numerical modeling should be capable of ingesting as much as possible real-time data, and the models should be fast enough to yield sufficient lead times for their output to be translated into forecast variables.
6. The priorities for maintaining and improving space weather services for the plasma and energetic particle environment are as follows:
   (1) maintain long-term continuity, and if possible improve the spatial resolution, of measurements at all altitudes from LEO to GEO orbits;
   (2) improve the sharing of existing and planned plasma and energetic particle measurements;
   (3) routinely provide inter-calibration of particle detectors in order to provide consistency

and continuity of data;
(4) include energetic particle sensors on Highly Elliptical Orbit (HEO) satellites;
(5) conduct research to incorporate the plasma and energetic particle data into numerical models to give flux estimates at all locations where our satellites are in orbit.

7. Efforts should be made to increase the spatial resolution of ground-based Global Navigation Satellite System (GNSS) observations (Total Electron Content (TEC) and scintillation), either by deploying additional receivers in regions with sparse coverage, making the data from existing receivers accessible, or by utilizing different means of receiving GNSS data, such as aircraft-mounted receivers, to reduce gaps over the oceans.
8. Efforts should be made to increase the use of space-based GNSS measurements onboard Low Earth Orbit (LEO) satellites to get information about the vertical electron density distribution of the ionosphere/plasmasphere system. In parallel, the timeliness of space-based GNSS measurements should be improved (e.g. by use of a network of satellite ground stations for rapid transmission).
9. Actions should be taken to enable sharing of ground-based GNSS data and GNSS radio occultation (RO) data among the meteorological and space weather communities, and to facilitate the timely access to these data through WIS. The International Radio-Occultation Working Group (IROWG) established in 2011 by CGMS and WMO can be an appropriate forum to address these issues.
10. Data assimilation and related techniques should be developed to produce a more accurate, higher resolution representation of the 3D electron density distribution in the ionosphere and plasmasphere. These techniques effectively reduce propagation errors in GNSS applications. The combination of ground- and space-based GNSS measurements is required in order to avoid problems related to lack of global coverage and poor data timeliness, respectively.
11. The coordinated use of dual-frequency radar altimeter observations should be ensured to improve or validate ionospheric models and for operational TEC monitoring in combination with ground-based GNSS measurements in order to fill data gaps, e.g. over the oceans.
12. Efforts should be made to increase the availability of ground-based magnetometer data with high timeliness. This can be accomplished by: (i) considering the deployment of magnetometers in regions with limited coverage; (ii) utilizing the WMO data infrastructure to disseminate data from existing magnetometers; and (iii) working with providers of proprietary data to allow their data to be used in space weather products.
13. An effort is recommended by WMO members to facilitate the real-time transmission of high quality data.
14. With respect to the global distribution of magnetic sites, it is recommended to promote the implementation of new magnetic sites in the least covered areas with the help of capacity building programs involving local experts from those areas, including recurrent technical and financial support to ensure full incorporation of the knowledge and sustainability of the activity.
    (1) Actions should be taken to enhance the magnetic site infrastructures through co-location with weather stations.
    (2) Action shall be conducted to increase WMO Members' awareness of the benefit of linking the main universities, centers, observatories and associated entities through high speed large bandwidth internet connections.
15. The thermosphere is very poorly observed. Recommended actions to address this include:
    1) Increase the number of atmospheric neutral density observations by deploying more accelerometers to be flown on LEO satellites. Operation on a wider range of satellites would enable a greater range of altitudes to be observed and a greater range of local times. Future accelerometer-carrying satellites should deliver the required data with low latency. In addition, limb satellite observations that provide density profiles (eg SSULI) for operational use should also be maintained or increased. l
    2) Regarding temperature, efforts should be made to supply OSIRIS measurements of the lower thermosphere temperature in near real time.
    3) Further develop and demonstrate techniques for accurately inferring winds from accelerometers. interferometry techniques (as used in TIDI) should be revisited in order to provide more lower thermospheric wind profiles.

4) Develop other observations for space weather operational use. In particular, FPIs should be developed to support the provision of space weather services, for example via continuous operation, near real time dissemination of observations, or an expanded observation network. In addition, mass spectrometers, which provide in situ measurements of temperature and neutral density (as well as constituent mixing ratio) are deployed on CubeSat missions for research purposes and efforts should be made to design future such missions with an operational focus.

ACRONYMS

ACE	Advanced Composition Explorer
AMPERE	Active Magnetosphere and Planetary Electrodynamics Response Experiment
CGMS	Coordination Group for Meteorological Satellites
CHAMP	CHAllenging Mini-Satellite Payload
CME	Coronal Mass Ejection
COSMIC	Constellation Observing System for Meteorology, Ionosphere & Climate
DEMETER	Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions
DMSP	Defense Meteorological Satellite Program
DSCOVR	Deep Space Climate Observatory
ERG	Energization and Radiation in Geospace
ETS	Environmental Test Satellites
foEs	The highest ordinary-wave frequency reflected back from a sporadic E layer and observed by an ionosonde.
foF2	Critical frequency of the F2 layer of the ionosphere.
GEO	Geostationary Earth Orbit
GNSS	Global Navigation Satellite System
GNSS-RO	Global Navigation Satellite System Radio-occultation
GOES	Geostationary Operational Environmental Satellites
GONG	Global Oscillation Network Group
HEO	Highly Elliptical Orbit
h'F	Virtual height of the bottom of the ionospheric F-layer.
hmF2	Altitude of the peak density in the ionospheric F2 layer.
h'P (Spread F)	Vertical thickness of highly structured ion density in the F-region of the ionosphere.
ICAO	International Civil Aviation Organization
ICTSW	Inter-Programme Coordination Team on Space Weather
IGS	International GNSS Service
INTEGRAL	International Gamma Ray Astrophysics Laboratory
IROWG	International Radio-Occultation Working Group
ISR	Incoherent Scatter Radar
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
PCW	Polar Communication and Weather
POES	Polar Orbiting Environmental Satellites
PROBA	PRoject for OnBoard Autonomy
RBSP	Radiation Belt Storm Probes
SDO	Solar Dynamics Observatory
SEON	Solar Electro-optical Observing Network
SRAL	Synthetic Aperture Radar Altimeter
SOHO	Solar and Heliospheric Observatory
STEREO	Solar Terrestrial Relations Observatory
SWOT	Surface Water and Ocean Topography
TEC	Total electron content
TSI	Total Solar Irradiance
UN-COPUOS	United Nations Committee for the Peaceful Uses of Outer Space
WIGOS	WMO Integrated Global Observing System
WIS	WMO Information System
