Radiocommunication Study Groups

INTERNATIONAL TELECOMMUNICATION UNION

Source: Document 7C/TEMP/38

Subject: Question ITU-R 256/7, WRC-23 Preliminary agenda item 2.3, Resolution **657 (WRC-15)**

Annex 7 to
Document 7C/91-E
2 November 2016
English only

Annex 7 to Working Party 7C Chairman's Report

PRELIMINARY DRAFT NEW RECOMMENDATION
ITU-R RS.[SPACE_WEATHER_SENSORS]

Technical and operational characteristics of RF-based Space Weather sensors

Scope

This recommendation documents the technical and operational characteristics of RF-based sensors used for detection of solar activity and the impact of solar activity on the Earth, its atmosphere and its geospace.

Keywords

Space Weather, Earth exploration-satellite service (passive) systems, radio astronomy

Abbreviations/Glossary

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

Related ITU Recommendations/Reports

The ITU Radiocommunication Assembly,

considering

a) that space weather observations are becoming increasingly important in detecting solar activity events that could impact services critical to the economy, safety and security of administrations;

b) that these observations are made from platforms that may be ground-based, airborne or space-based;

c) that some of the sensors operate by receiving low-level natural emissions of the Sun or the Earth’s atmosphere, and therefore may suffer harmful interference at levels which could be tolerated by other radio systems;

d) that in order to perform studies, the technical and operational characteristics of these sensors and systems must be known,

recommends

that the information in the Annex to this Recommendation be used in ITU-R studies related to the operations of RF-based Space Weather Sensors.

ANNEX

1 Introduction

Space Weather refers to the physical processes occurring in the space environment, driven by the Sun and Earth’s upper atmosphere, and ultimately affecting human activities on Earth and in space. In addition to the continuous ultra-violet (UV), visible and infra-red (IR) radiation, which provides radiative forcing to our weather and climate at the top of the atmosphere and maintains the ionosphere, the Sun emits a continuous flow of solar wind plasma, which carries the Sun's embedded magnetic field. The Sun also releases energy in an eruptive mode, as flares of electromagnetic radiation (radio waves, IR, visible, UV, X-rays), energetic particles (electron, protons and heavy ions), and high speed plasma through coronal mass ejections. The solar wind and the eruptive disturbances propagate out into interplanetary space and impact interplanetary space and Earth’s near-space environment.

The electromagnetic radiation, traveling at the speed of light, takes about 8 minutes to move from Sun to Earth, whereas the energetic charged particles travel more slowly, taking from tens of minutes to hours to move from Sun to Earth. At typical speeds, the background solar wind plasma reaches Earth in about four days, while the fastest coronal mass ejections can arrive in less than one day. The solar wind and solar disturbances interact with the Earth's magnetic field and outer atmosphere in complex ways, causing strongly variable energetic particles and electric currents in the Earth’s magnetosphere, ionosphere and surface. These can result in a hazardous environment for satellites and humans at high altitudes, ionospheric disturbances, geomagnetic field variations, and the aurora, which can affect a number of services and infrastructure at the Earth’s surface, or airborne, or space-borne in Earth orbit. Disturbances in the ionosphere and atmosphere have important impacts on radio communication, satellite navigation systems and atmospheric drag experienced by LEO satellites, including the International Space Station. Radionavigation satellite service (RNSS) signals, which are used for a growing number of precision positioning, navigation, and timing applications, as well as for atmospheric radio-occultation, are affected by the ionosphere. Strong spatial irregularities in the ionosphere (ionospheric scintillations) can cause loss of lock between a receiver and the satellites and result in a total disruption of service. Variability in the total electron content (TEC) between the receiver and the satellite degrades the positioning accuracy. As our society is increasingly reliant on advanced – and interdependent - technology, its vulnerability to space weather hazards is correspondingly increasing. While space weather typically impacts infrastructure and services, the degradation or denial of critical services in times of emergencies could also directly affect the health and welfare of the average citizen.

Space weather observations are critical, therefore, to monitor and forecast the occurrence probability of space weather disturbances; to drive hazard alerts when disturbance thresholds are crossed; to maintain awareness of current environmental conditions; to determine climatological conditions for the design of both space-based systems (i.e., satellites and astronaut safety procedures) and ground-based systems (i.e., electric power grid protection and airline traffic management); to develop and validate numerical models of space weather drivers; and to conduct research that will enhance our understanding of the Sun and Earth’s extended atmosphere. The vastness of space and the wide range of physical scales that control the dynamics of space weather demand that numerical models be employed to characterize the conditions in space and to predict the occurrence and consequence of disturbances, from the Sun to the soil. Data assimilation techniques must be utilized to obtain the maximum benefit from our sparse measurements. Space weather observations of both the radiative and particulate signals – with disparate characteristics, including spatial and temporal resolution - are therefore used through data assimilation into empirical or physics-based models.

Forecasting the space environment conditions is enabled by monitoring the background magnetic configuration and precursor phenomenon that take place on the Sun and propagate in the interplanetary medium before reaching Earth. This should be based, first of all, on the measurement of the solar electromagnetic output in order to detect eruptive or pre-eruptive structures on the solar disc, which requires measurements in radio, visible, UV and X-ray wavelengths. Ideally, such observations should be available from different vantage points in the solar system.

When coronal mass ejections are released from the Sun, their initial velocity and size must be measured to initiate models that predict their trajectories and arrival times at Earth. In addition, measurements must be made of the plasma density, speed and magnetic field in the solar wind upstream from Earth to provide warnings of hazardous conditions. Fast propagating coronal mass ejections can cause enhancements of energetic particle radiation that reach levels several orders of magnitude above background and can persist for hours to days.

When the disturbances hit the outer boundary of Earth's magnetic field, the Earth's magnetic field is strongly distorted; it drives electrical currents through the magnetosphere, ionosphere and atmosphere; and it modifies the plasma and energetic particle distributions within the magnetosphere, including those that comprise the inner and outer radiation belts. Consequently, observations on the ground and within the ionosphere/magnetosphere system are necessary to determine the current state of the near-Earth environment and to forecast the consequences of disturbances.

Synergistically, the processing of RNSS signals produces an estimate of the TEC between the satellite and receiving station. The effects of the electron density field must be removed before using radio occultation data for deriving the temperature profile of the stratosphere and upper troposphere and the humidity profile of the lower troposphere, and these ionospheric corrections can then be used to estimate the electron density itself.

A comprehensive space weather observation network must therefore include ground-based and space-borne observatories. Both the ground-based and the space-based segments should contain a combination of remote sensing and in-situ measurements of electromagnetic radiation, magnetic fields, and charged particles. The measurements can be obtained by both active and passive sensing techniques.

2 Space Weather observational domains

The information contained in Sections 2 and 3 of this Recommendation is paraphrased from the Statement of Guidance created by the WMO Inter-Programme Coordination Team on Space Weather.

Operational space weather products and services are delivered by a network of about 20 organizations around the globe. The products and services to support space weather needs are organized in four broad categories: Ionospheric, Geomagnetic, Energetic Particles, and Solar and Interplanetary (solar wind). Currently, space weather observational products are being made available under these categories at the recently established WMO Space Weather Product Portal (http://www.wmo.int/pages/prog/sat/spaceweather-productportal_en.php). A larger number of products are being distributed by the international space environment centres that have not been included in the Portal.

Although there can be considerable overlap in the use of observations in one domain for the products in a different domain (e.g., solar wind data needed for ionospheric, geomagnetic, and energetic-particle products), the assessment of space weather observations has been conducted with respect to the main product categories. For the purposes of this document, the Solar and Interplanetary category has been presented in two separate sections: Solar and Solar Wind.

Ionospheric observations are performed by the following active or passive techniques:

2.1 Ionospheric observations

There are six techniques used in monitoring the ionosphere:

2.1.1 GNSS receiver: Total electron content (TEC) along a given propagation path can be measured by tracking the time delay and phase shift of radio signals of a Global Navigation Satellite System by a ground receiver (so called ground based GNSS). As the satellite (or satellites) moves over the observer, the TEC along many propagation paths can be used to reconstruct the distribution of ionospheric electron density along the satellite path. Space-based measurements of the ionosphere via GNSS radio-occultation enhance the ground-based GNSS measurement coverage to a planetary scale and, being based on limb measurements, provide vertical distribution information. The satellite data therefore complement ground-based GNSS receiver observations in that they provide an orthogonal look direction enabling more accurate “tomographic” reconstruction of the three-dimensional ionospheric structure. The space-based constellation also provides good global coverage, particularly important over ocean areas where a sufficiently dense ground-based GNSS network is lacking. The data also provide one of the only ways of getting vertical profiles of electron density on a global scale.

2.1.2 Radio absorption: Ground-based measurements of radio signals from known sources above the atmosphere (usually cosmic radio sources) can be used to map the absorption by the lower ionosphere (e.g. using relative ionospheric opacity meters, or riometers). As the Earth turns, each radio source moves across the observer, and this information can be used to map the distribution of absorbing ionisation in the lower ionosphere. Ionosondes can also detect absorption through the minimum frequency (fmin) observed on an ionogram, although lower values of fmin are limited by terrestrial radio noise and instrument sensitivity. The density of ground-based observations is very low. There are approximately 50 riometer sites around the world, and most are at high latitudes.

2.1.3 Ionosonde: An ionosonde transmits a sweep of radio signals into the ionosphere. Echoes are returned where the local plasma frequency equals the radio frequency. The peak frequency returned from each ionospheric layer is therefore a direct measure of the electron concentration. In contrast, the height of each layer is estimated from the time of flight of the radio signal assuming propagation through free space. Heights derived from ionosonde data are denoted by the prefix h’, and are referred to as virtual heights. Models such as POLAN or ARTIST attempt to correct for underlying ionisation to generate true-heights, but such models invariably involve assumptions about the distribution of the underlying ionisation. Modern research ionosondes can also be used to measure additional variables, most notably plasma velocities and the spectrum of gravity waves. There are only approximately 38 near real time ionosonde reports globally.

2.1.4 Incoherent Scatter Radar: Incoherent Scatter Radars (ISRs) transmit powerful VHF or UHF (typically hundreds of MHz) radio pulses into the ionosphere and use the backscatter from electrons whose motion is controlled by the dynamics of the much slower and heavier ion population to determine the distribution of ionisation. While the height of ionospheric layers can be determined very accurately with ISRs, cross-calibration with ionosondes or the use of specific features in the ISR spectra are required to calibrate the electron concentration since the electron concentration is inferred from the total returned power. Careful fitting of the ISR spectrum can generate a host of parameters including line-of-sight velocities, electron and ion temperatures, and ion composition. Estimates of the horizontal distribution of ionisation can be obtained by moving the radar dish or by altering the phase of an antenna array. Vector velocities can be calculated by combining data from different antennas or from different beam directions. These valuable research data are not yet available continuously in real time.

2.1.5 Coherent radar: Coherent radars broadcast ~MHz radio pulses and receive coherent echoes from local plasma instabilities in the ionosphere. In this way, the returned power and line-of-sight velocity can be determined. Vector velocities can be calculated by combining data from two or more radar stations.

2.1.6 Ionospheric scintillation receivers: In addition to the above, ionospheric monitoring is also achieved by ionospheric scintillation receivers, which measure the fluctuation of radio waves, and dual-frequency radar altimeters. Auroral imaging by all-sky cameras and photometers provides information on the location and strength of energy coupling between the ionosphere and the magnetosphere. Space-borne auroral observations include sensors for auroral imaging (visible and UV) and auroral kilometric radiation.

2.2 Geomagnetic Observations

Magnetic field observations are required globally on the surface of Earth using ground-based magnetometers. Magnetic observatory data, and scalar magnetic indices derived from the data, are widely used to track the geographic evolution of magnetic disturbances during storms, to measure the absolute size of magnetic storms, to provide statistics on past storm occurrences, to assess physics-based models of the magnetosphere and ionosphere, and to estimate the induction of ground electric currents that represent hazards for the operation of electric power grids. Magnetic observatories provide monitoring data that are used for directional drilling for oil and gas, especially at high latitudes where the magnetic field can be active during storms. Magnetic observatory data are also used in conjunction with satellite and air-borne magnetometers to make global and regional maps of the magnetic field that are used for geologic studies, mineral exploration and compass-based navigation.

Space-borne sensors are required for in-situ observations of the local magnetic field in space, at altitude ranges from LEO to GEO. Magnetic field measurements at geostationary orbit are used to indicate extreme compressions of the magnetosphere that cause the magnetopause boundary to move inside geostationary orbit. Measurements at GEO and LEO indicate the level of geomagnetic activity, the occurrence of strong electrical currents and abrupt releases of energy within the magnetosphere-ionosphere system, and the occurrence of low-frequency magnetospheric waves. Magnetic field measurements also are used to interpret plasma and energetic particle measurements.

2.2.1 Vector Magnetic Field – Earth's Surface: Ideally, ground magnetometer measurements would come from a dense distribution of stations having long and reliable operational histories, that are supported by agencies dedicated to maintaining operations into the future, and that report their data to the operational community in near-real-time. Traditional magnetic observatories are reasonably well positioned to fulfill these requirements with some existing gaps, such as over the African continent, South America, and the Russian Federation.

On an international scale, magnetic observatory operation is supported by a variety of national government and academic institutions, sometimes in collaboration with private companies. One of the main organizations that coordinate the work of these institutes is INTERMAGNET, a voluntary federation that promotes the operation of magnetic observatories according to modern standards and which promotes the dissemination of observatory data. Presently, 120 INTERMAGNET observatories are supported by 56 institutes from 41 countries. Definitive data that have been processed and fully-calibrated are available for all member observatories. Presently about 38 INTERMAGNET observatories report preliminary data with an average delay of only a few minutes. Data from an additional 11 sites are available within an hour of the measurement. The number of these observatories is expected to increase slowly in the future, and the average delay is expected to decrease.

2.2.2 Vector Magnetic Field – LEO and GEO: Real-time magnetometer data are available from a number of geostationary satellites, including the NOAA Geostationary Operational Environmental Satellites (GOES) and the JAXA Environmental Test Satellites (ETS). Although these measurements are only available at a limited number of locations in geostationary orbit, they provide valuable information on the level of geomagnetic activity. The magnetic field information is also important for interpreting the energetic particle measures made simultaneously on the satellite.

Magnetometer measurements have been obtained from a number of LEO satellites, including the CHAllenging Mini-*Satellite* Payload (CHAMP), Oersted, and the *Defense Meteorological Satellite Program* (DMSP). New satellite missions, like SWARM (launch in July, 2012) will further support this approach. However the data delay from LEO satellites is typically 90 minutes or greater, resulting in low value for operational space weather services. These data are important for historical event studies and for creating statistical models of auroral-region currents which can support space weather services. An innovative approach has been taken by the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) project to utilize engineering magnetometers on the Iridium satellite constellation to map the current systems connecting the ionosphere and magnetosphere in near-real time. This effort will have important future applications, both in establishing a relationship between private satellite programs and research/operational space weather efforts and in testing the ability to map accurately the current systems and their utility for space weather services.

2.3 Energetic particles

The energetic particles in the Earth-space environment can be broadly classified into three categories, each with important effects on spacecraft systems, humans, and other regions of the environment such as the ionosphere and atmosphere. These three categories are: 1. geomagnetically trapped particles; 2. energetic particles of direct solar origin; and 3. galactic cosmic rays. The dynamics of the Sun, interplanetary space and Earth's magnetosphere/ionosphere system 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. Real-time data are required to issue alerts of hazardous conditions, and long-term monitoring is necessary to characterize, and enable predictions of, the particle flux levels and their effects. Because the energetic particle environment can vary strongly from location to location within the magnetosphere, local measurements need to be assimilated in numerical models to yield estimates of the 3D flux levels.

Measurements of the high-energy (hundreds of keV to several MeV) electrons and protons are required to provide operational information on the radiation environment that is hazardous to humans in space and that causes interior charging and radiation dose in spacecraft. These measurements are the basis for operational alerts and warnings (high-energy electrons). The real-time measurements are used to determine the cause of anomalous behaviour in spacecraft systems, and for spacecraft design, human radiation risk assessment, and post-event analyses relating to satellite and sub-system failures.

Energetic particle measurements are being made by numerous satellites in LEO, MEO, GEO, and in interplanetary space. Current missions obtaining energetic particle measurements from LEO orbit include: the European Space Agency (ESA) PRoject for OnBoard Autonomy-1 (PROBA-1) mission, the Russian Federation Meteor-M, China's FengYun-3 (FY-3), the European MetOp, and the United States (U.S.) Polar Orbiting Environmental Satellites (POES) and Defense Meteorological Satellite Program (DMSP) satellite series. Satellites with energetic particle sensors in GEO orbit include: the Russian Federation Electro-L, China's FY-2, the U.S. GOES satellite series. Energetic particle measurements are also made at GEO orbit by U.S. Los Alamos National Laboratory instruments. Measurements of protons and electrons in MEO orbit are currently acquired by the GPS satellites and some scientific missions; however, real-time access to the data is not available.

Satellites in Highly Elliptical Orbit (HEO) are also valuable for obtaining measurements in regions not well sampled by satellites in other orbits. The planned Canadian Polar Communication and Weather (PCW) satellites and the Russian Federation Arctica satellites are expected to obtain energetic particle measurements in HEO. Upcoming research missions, such as the U.S. Radiation Belt Storm Probes (RBSP) and Japan’s Energization and Radiation in Geospace (ERG) satellite, will obtain energetic particle measurements throughout the inner magnetosphere and address important questions on particle dynamics. ESA’s International Gamma Ray Astrophysics Laboratory (INTEGRAL) spacecraft is currently making energetic electron and proton measurements. At the L1 Lagrange point, there are three spacecraft equipped with instruments that provide valuable energetic particle information: NASA ACE, ESA/NASA Solar and Heliospheric Observatory (SOHO), and NASA WIND.

2.4 Solar observations

The determination of solar active region characteristics, flare properties, radio emissions, coronal structure and photospheric magnetic field are made today with a combination of ground-based and space-based instruments.

Solar observations are obtained from a combination of ground-based and space-based instruments. The basic ground-based observations for solar activity include images in the Hydrogen-alpha, white light and Calcium-K wavelengths. In addition, solar-surface magnetic field measurements are obtained with line-of-sight and vector magnetographs, and solar radio emissions are observed with radio frequency spectrographs. The main limitation for ground-based observations is, however, the absorption and scattering of the electromagnetic signals by the ionosphere and atmosphere, including the disruption due to weather, which is a particular concern for visual observations, leading to data gaps and reduced accuracy and resolution.

Space-based observations include solar images at multiple wavelengths, images of the solar corona and heliosphere, images of the solar-surface magnetic field, and full-disk integrated measurements of total solar irradiance (TSI), radio emissions, EUV flux and X-ray flux. Substantial advantages of space-based observations are the continuity and quality of the observations since they are not perturbed or rendered impossible by atmospheric effects, and also the full spectral coverage, including wavelength ranges that are inaccessible from ground-based observations (e.g. EUV and X-ray). Substantial disadvantages of space-based data are the high cost to obtain them, the limited lifetime of space missions and the vulnerability of space instruments to space weather events, i.e. precisely the events they are intended to monitor.

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

Solar images are required to analyze sunspot groups; identify the location of flares, filaments and prominences; and to characterize the magnetic field in the photosphere and corona. Image cadences of 1 to 15 minutes are necessary to detect the rapid evolution of solar structures, particularly prior to solar eruptions. Data availability between 1 and 60 minutes of the time of measurement is necessary to determine the source location of an eruption and to enable the immediate warning of hazardous conditions.

Quite separate from this is the recent development of reliably determining sub-surface solar magnetic fields through helioseismology, leading to advances in the forecasting capacity for solar events. Still in its infancy, further development of this technique may lead to substantial breakthroughs in the near future.

2.4.2 Solar EUV flux, X-ray flux, and Radio emissions

Disk-integrated solar X-ray flux is the most immediate indicator of a solar flare. These measurements drive the alerts of hazardous conditions that can onset abruptly. These data are required with a measurement cadence of 0.5 to 3 seconds and with a delay of availability between 1 and 5 minutes. Scientific advances in flare precursor determination may soon lead to more stringent requirements. Radio emissions, indicating the occurrence of radio bursts and the speed of shocks in the solar wind, are required with a cadence of 1 to 60 seconds and a delay of availability of 1 and 5 minutes.

2.4.3 Solar Corona images and heliospheric images

Images of the solar corona are critical for determining the initial properties (e.g., speed, location, and size) of coronal mass ejections (CMEs) that erupt from the sun. CMEs are the drivers of severe space weather storms at Earth. They are the source of the largest geomagnetic disturbances, ionospheric disturbances and solar energetic particle enhancements. In order to image the evolution of a CME as it rapidly expands away from the sun, image cadence must be at least 5 to 15 minutes. With the information of the CME properties, numerical prediction models are initiated to calculate the trajectories of the disturbance in interplanetary space and to determine the arrival time at Earth. The delay of availability must be within 15 to 60 minutes to allow sufficient time to initiate models runs and issue forecasts of arrival time, which ranges from less than 1 day to several days.

Estimates of CME properties are most accurate 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 (roughly 60 degrees from the Earth-sun line along Earth’s orbital path).

Heliospheric imagers are used to observe the CME-related disturbance as they propagate from the sun to Earth. These images are preferred to be made off the Earth-sun line to determine accurately the trajectory of a disturbance moving 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.

3 Summary of frequencies used for Space Weather activities

The tables in Annex 1 summarize the outcome of a preliminary survey of frequencies used in support of space weather sensor operations. The table entries are a representative indication of the main frequencies used for space weather but cannot be considered to be exhaustive.

Regarding the bands listed in Table IV of Annex 1, that are used for passive observation of the Sun, the status of frequency allocations is highly dependent on the region and the countries concerned. However, the following allocations can be noted, from the International Radio Regulations Table of Frequency allocations:

- 322-328.6 MHz – Fixed service, mobile service and radio astronomy.
- 608-614 MHz – is allocated to radio astronomy on a primary or secondary basis depending on the Regions and countries.
- 1 400-1 427 MHz – Earth exploration-satellite (passive), radio astronomy, space research (passive).
- 1 660-1 660.5 MHz – Mobile satellite service (Earth-to-space), radio astronomy.
- 1 660.5-1 668 MHz – Radio astronomy, space research (passive), fixed (secondary), mobile except aeronautical mobile (secondary).

- 1 668-1 668.4 MHz – Mobile satellite (Earth–to-space), radio astronomy, space research (passive), fixed (secondary), mobile except aeronautical mobile (secondary).
- 1 668.4-1 670 MHz – Fixed service, meteorological aids, mobile except aeronautical mobile, mobile satellite (Earth-to-space), radio astronomy.
- 2 700-2 800 MHz – Aeronautical radionavigation (ground-based radars and associated airborne transponders, meteorological aids (ground-based radars), radiolocation (secondary).
- 4 990-5 000 MHz – Fixed, mobile except aeronautical mobile, radio astronomy, space research (passive) (secondary).
- 8 215-8 400 MHz – Aeronautical mobile (ground-to-air), Earth exploration-satellite (space-to-Earth), fixed, fixed satellite (Earth-to-space), mobile except aeronautical mobile.
- 10.6-10.68 GHz – Earth exploration-satellite (passive), fixed, mobile except aeronautical mobile, radio astronomy, space research (passive), radiolocation (secondary).
- 10.68-10.7 GHz – Earth exploration-satellite (passive), radio astronomy, space research (passive).
- 15.35-15.4 GHz – Earth exploration-satellite (passive), radio astronomy, space research (passive).

It should be noted that many frequency bands listed above are allocated to the radio astronomy service. However, some of the space weather sensor applications may not fit within the definition of the radio astronomy service.

4 Technical and operational parameters of Space Weather sensors

Space weather sensors include a wide variety of systems, which may transmit and receive or be receive only, and may be located on the ground, in the air or in satellites in Earth orbit and beyond. In order to understand how RF-based space weather observing systems fit into the radiocommunication ecology, it is necessary to document the technical and operational characteristics of the observing systems. Table 1 lists the parameters typically needed to characterize space weather sensors.

TABLE 1

Technical and operational parameters of space weather sensors

Characteristics	Value	Instructions
Function		What is system used for?
Platform type		Where is it installed?
Frequency (MHz)		Center Frequency(ies) of Operation
Modulation Type		If system includes a transmitter.
Power into antenna		If system includes a transmitter, indicate whether Peak or Average
Pulse width (µs) and Pulse repetition rate (pps)		Needed for pulsed systems only.
Maximum duty cycle		Needed for pulsed systems only.
Pulse rise/fall time (µs)		Needed for pulsed systems only.
Antenna pattern type		
Antenna type		
Antenna polarization		
Antenna main beam gain (dBi)		
Characteristics	**Value**	**Instructions**
Antenna elevation beamwidth (degrees)		
Antenna azimuthal beamwidth (degrees)		
Antenna side-lobe (SL) levels (1st SLs and remote SLs)		
Antenna height		Required if ground based only
Receiver IF 3 dB bandwidth (MHz)		
Receiver noise floor (dBm)		
Minimum Required S/N		
Receive loss, dB		Loss between Antenna and Receiver
RF emission bandwidth (MHz) 3 dB –20 dB		Required only if system includes a transmitter

ANNEX 1

Preliminary tabulation of main radio-frequencies used for space weather observations

Note: The tables below summarize the response of several WMO members to a preliminary survey. The table entries are a representative indication of the main frequencies used for space weather but cannot be considered to be exhaustive.

I. Active ionospheric observations					
Frequency range	**Application**	**T/R**	**Country**	**Location**	**Comments**
1-20 MHz	Digital Ionospheric Sounder	T/R	Belgium	Bourbes	http://ionosphere.meteo.be
0.5-30 MHz	Ionosphere sounder (Ionosonde)	T/R	China	Xinjiang Atushi Fujian Xiamen Shanxi Changan Guangxi Hengxian Qinghai Dulan Hubei Wuhan	Protection: - no radio emission within 1 km in these frequencies - no high voltage power line within 100 m
1-30 MHz	Ionosphere sounder (Ionosonde)	T/R	Japan	Wakkanai, Japan Kokubunji, Japan Yamagawa, Japan Okinawa, Japan Chiang Mai, Thailand Chumphon, Thailand, Kototabang, Indonesia Bac Lieu, Vietnam Cebu, Philippines Syowa, Antarctic	We have operated ionosondes at four sites in Japan, five sites in the Southeast Asia, and one site in the Antarctic. http://wdc.nict.go.jp/IONO/
1-30 MHz	Ionosonde	T/R	Rep. of Korea	Jeju, Icheon	http://spaceweather.rra.go.kr/observation/ground/ionosphere/jeju http://spaceweather.rra.go.kr/observation/ground/ionosphere/icheon
2 ± 0.02 MHz	Middle frequency radar	T/R	China	Shanxi Wuzai Heilongjiang Mohe	Protection - no radio emission within 1 km in these frequencies - no high voltage power line within 100 m
3-30 MHz	Vertical ionosondes (VIS)	T/R	Australia		TX licence and quiet Rx Risk of interference with remote sources http://www.ips.gov.au/HF_Systems/1/3

3 to 100 MHz (?)	Oblique ionosphere sounding (OIS)	T/R	Australia		Extends to “Lower VHF”.
8-20 MHz	Ionospheric irregularities observation	T/R	China	Xinjiang Wulumuqi Gansu Jiuquan (41.1ºN,100.31ºE)	
9-16 MHz (TBC)	Ionospheric research radars	T/R	SUPERDARN consortium of 10 countries	Canada, USA, Iceland, Finland, Japan, Australia, New Zealand, Antarctica	Super Dual Auroral Radar Network (SUPERDARN) including 20 radars in the Northern Hemisphere and 11 in the Southern Hemisphere. (http://vt.superdarn.org/)
9-16 MHz	HF Coherent radar for measuring Doppler velocity in the ionosphere	T/R	Japan	King Salmon, AK, USA	Our HF radar belongs to SuperDARN consortium. Detailed information can be seen in http://vt.superdarn.org/
38.9 MHz	Meteor Radar for upper atmospheric wind field and meteor measurements	T/R	China	Hainan Fuke,	http://www.stern.ac.cn/RadarMonitor.asp
40.8 MHz	Daejeon VHF Coherent Scatter Radar	T/R	Rep. Korea	Daejeon	
47 MHz	VHF radar for ionospheric irregularities observation	T/R	China	Hainan Fuke,	Chinese Meridian Project
200-240 MHs	European Incoherent Scatter Radar (EISCAT)	T/R	Norway	Tromso	
500 MHz	European Incoherent Scatter Radar (EISCAT)	T/R	Norway	Svalbard	
449-450 MHz	Advanced Modular Incoherent Scatter Radar (AMISR)	T/R	Canada	Poker Flat	http://amisr.com/amisr/about/amisr-overview/
430-450 MHz	Advanced Modular Incoherent Scatter Radar (AMISR)	T/R	Canada	Resolute Bay	http://amisr.com/amisr/about/amisr-overview/

II. Passive and GNSS ionospheric observations					
Frequency range	**Application**	**T/R**	**Country**	**Location**	**Comments**
38.2 MHz	Ionosphere D-Region absorber	R	China	Heilongjiang Mohe Heilongjiang Jia Musi Beijing Lingsan Hainan Tunchan	Protection: - no radio emission within 1 km in these frequencies - no high voltage power line within 100 m
1 100-1 600 MHz	GNSS receivers	R	Australia		See the GNSS frequencies: http://www.positim.com/gnss_freqs.jpg
1 100 to 1 600 MHz mainly 1.22-1.57 GHz	GNSS ionospheric monitoring	R	Belgium	ROB, Brussels for an European network	http://gnss.be
1 100 to 16 00 MHz mainly 1.22-1.57 GHz	GNSS ionospheric monitoring	R	Japan	More than 1 200 stations in Japan	GNSS-TEC maps have been produced using a dense GNSS receiver network, GEONET, operated by GSI, Japan. http://seg-web.nict.go.jp/GPS/GEONET/
1 227 MHz 1 575 MHz	Ionospheric scintillation receiver	R	Rep. Korea	Daejon, Gangneung, Gwangju, Icheon, Jeju	http://spaceweather.rra.go.kr/observation/ground/sciserial
1 575.42±1.023 MHz 1 227.6±10.23 MHz 1 598-1 610 MHz 1 242-1 252 MHz	Ionospheric scintillation receiver	R	China	Guangdong Maoming Guangdong Guangzhou Fujian Xiamen Guangdong Shaoguan Hubei Wuhan	Protection: - no mobile phone base station within 1 km - no high voltage power line within 100 m
1 227 MHz 1 575 MHz	Ionospheric scintillation receiver	R	Rep. Korea	Antarctic Jangbogo station	

III. Solar Observations (Spectrographs)					
Frequency range	**Application**	**T/R**	**Country**	**Location**	**Comments**
10-80 MHz	Decameter Array (including HF spectrograph)	R	France	Nançay (47°N, 2°E)	Used for astronomic and solar corona observations http://secchirh.obspm.fr/instruments.php
18-1 800 MHz	Solar Radio Spectrograph	R	Australia	Culgoora observatory (Narrabri)	Need quiet environment within at least 30 km, preferably 200-300 km. Risk of interference with aircrafts, ground repeaters, or remote ground sources in case of temperature inversion over sea. http://www.ips.gov.au/Solar/2/2
25-180 MHz	Solar Radio Spectrograph	R	Australia	Learmonth	Same comment as Culgoora http://www.ips.gov.au/Solar/3/2
25-2 500 MHz	Solar Radio Spectrograph (HIRAS)	R	Japan	NICT Hiraiso Observatory	Solar radio burst and solar flare monitoring
30-500 MHz	Solar Radio Spectrograph	R	Rep. of Korea	RRA KSWC Jeju	http://www.spaceweather.go.kr/observation/ground/spectrum
30-2 500 MHz	Solar Radio Spectrograph	R	Rep. of Korea	RRA KSWC Icheon	
45-450 MHz	e-Callisto spectrograph	R	Belgium	Humain	Monitoring solar flares and CMEs http://sidc.oma.be/humain/
45-450 MHz	e-CALLISTO spectrograph	R	Rep. Korea	Daejeon	Monitoring solar flares and CMEs http://kswrc.kasi.re.kr/en/about/facilities/e_callisto/
20-650 MHz	Solar Radio Spectrograph (ARTEMIS)	R	Greece	Thermopyle (38.47°N, 22.41°E)	http://secchirh.obspm.fr/instruments.php
70 MHz-9.0 GHz	Solar radio spectrograph	R	Japan	Yamagawa radio observation facility	Solar radio burst and solar flare monitoring In test phase. Routine operation will start in 2016.
130-1 000 MHz	Solar Radio Spectrograph (ORFEES)	R	France	Nançay	
300-3 000 MHz	Solar Radio Spectrograph	R	Belgium	Humain	In commissioning http://sidc.be/humain
232-258, 389-431 MHz, 0.5–18 GHz	Solar Radio Spectrograph (KSRBL)	R	Rep. Korea	Daejeon	Solar radio burst and solar flare monitoring http://kswrc.kasi.re.kr/en/about/facilities/ksrbl/

IV. Solar Observations (Discrete frequencies)					
Frequency range	**Application**	**T/R**	**Country**	**Location**	**Comments**
150-450 MHz (specifically 150, 236, 327, 410 and 432 MHz)	Radio Heliograph	R	France	Nançay (47°N, 2°E)	http://secchirh.obspm.fr/instruments.php Solar 2D and 1D images at selected frequencies
245 MHz-15.4 GHz (specifically 245, 410, 610, 1 415, 2 695, 4 995, 8 800, 15 400 MHz)	Solar radio flux monitoring	R	Australia	Learmonth	http://www.ips.gov.au/Solar/3/4 Solar Electro-Optical Network (SEON)
245 MHz-15.4 GHz (specifically 245, 410, 610, 1 415, 2 695, 4 995, 8 800, 15 400 MHz)	Solar radio flux monitoring	R	USA	Sagamore Hill, Mass.	Solar Electro-Optical Network (SEON)
245 MHz-15.4 GHz (specifically 245, 410, 610, 1 415, 2 695, 4 995, 8 800, 15 400 MHz)	Solar radio flux monitoring	R	USA	Palehua, Hawaï	Solar Electro-Optical Network (SEON)
245 MHz-15.4 GHz (specifically 245, 410, 610, 1 415, 2 695, 4995, 8 800, 15 400 MHz)	Solar radio flux monitoring	R	Italy	San Vito	Solar Electro-Optical Network (SEON)
1 400-1 427 MHz (*) 1 660-1 670 MHz (*) 2 750-2 850 MHz (**) 4.990-5.000 GHz (*) 8.275-8.375 GHz 10.600-10.700 GHz(*)	Solar radio flux monitoring	R	Canada	Dominion Radio Astrophysical Observatory (DRAO) near Penticton, 49.32° N 119°62° W	(*): Radio-astronomy band (**): 10.7 cm solar radio flux. This frequency lies in a band allocated by ITU to the Radiolocation Service (radar) http://www.nrc-cnrc.gc.ca/eng/solutions/facilities/drao.html
1 400-1 427 MHz (*) 1 660-1 670 MHz (*) 2 750-2 850 MHz (**) 4.990-5.000 GHz (*) 8.275-8.375 GHz 10.600-10.700 GHz(*)	Solar radio flux monitoring	R	Belgium	Humain (Planned)	Similar to Canada / DRAO
2 801 ±5% MHz (**) 4 542 ±5% MHz 9 084 ±5% MHz	Solar radio flux monitoringt	R	China	Shandong Shidao Xinjiang Taxian	Protection: no radio emission within 1 km in these frequencies. (**) 10.7 cm solar radio flux, see above.

2.8 GHz	Solar radio flux monitoring	R	Japan	NICT Hiraiso Observatory	Monitoring 10.7 cm solar radio flux
2.8 GHz	Solar radio flux monitoring	R	Rep. of Korea	Icheon	Monitoring 10.7 cm solar radio flux http://spaceweather.rra.go.kr/observation/ground/solarflux