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Space Weather Payload for Canadian Polar Communication and Weather Space Mission

L. Trichtchenko

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CONTENTS

INTRODUCTION

Canadian Space Agency, in partnership with Environment Canada, Department of National Defence, Natural Resources Canada and other Government Departments and Canadian industry has completed a study on the development of communications, weather and climate satellite system known as the Polar Communications and Weather (PCW) mission.

Canadian Space Weather Forecast Centre (CSWFC) of Natural Resources Canada's Geomagnetic Laboratory has been participating in the study since its start in 2007 through to the finalising of the space weather payload specifications for mission requirement document in 2012.

The aim of PCW mission is to provide Canadian Arctic region with continuous communication services and meteorological observations for improving the quality of weather forecasts and other weather services in Canada and globally, thus closing a gap that currently is not covered by LEO or GEO satellites.

The unique characteristics of the proposed PCW candidate orbits will also provide opportunities for advancing Canadian space weather forecasts and other service applications by contributing to the monitoring, understanding and forecasting of space weather to reduce its hazardous impacts on space-borne and ground based infrastructure, navigation and human health. Thus, the operational Space Weather instruments are listed as one of the primary (main) payload for PCW satellites together with meteorological and communication payload.

Because space weather and space environment will have a strong influence on the mission operations, the use of space weather payload has also been proposed as a diagnostic tool for overall mission health. It has been defined therefore, that operational space weather payload will serve two purposes. The first purpose is to provide PCW satellites anomaly identification (i.e. if mis-operation is caused by space weather or by purely instrumentation malfunctioning) and the second one is to provide multiple users with continuous data on space weather and space environment for monitoring and forecasting purposes.

The report documents author's development on definition of the space environment and operational space weather payload during tenure as a member of the PCW User and Science team in 2007-2012.

PART 1. MAIN FEATURES OF NEAR-EARTH SPACE ENVIRONEMENT

Space Weather or Space environment refers to the continuously changing conditions of the electromagnetic environment and energetic particle fluxes in the vicinity of Earth which affect satellite operations and quality of services provided by the on-board instruments.

To design a successful space mission, possible impacts of the space environment have to be assessed. One of the most important components of environmental assessment for space is the accurate evaluation of the satellite radiation environment.

The space environment can generally be split into two parts, trapped population of radiation belts where charged particles are permanently trapped by the Earth's magnetic field and transient particles penetrating along open magnetic field lines in polar areas.

1.1. Trapped Radiation

Particles stably trapped in radiation belts are energetic (MeV) protons, electrons and heavy ions. Their distribution is not uniform splitting into the inner radiation belt (700-10000km) populated by protons and electrons, the outer radiation belt (13000-65000km) populated by electrons, and the slot region between them. The distribution of protons (with energies> 10 MeV) and electrons (with energies >1 MeV) in radiation belts are shown in Figs 1.1 and 1.2, respectively (Vette, J.I., 1991 available at http://nssdc.gsfc.nasa.gov/space/model.html), with black line representing one of candidate orbits for PCW mission.

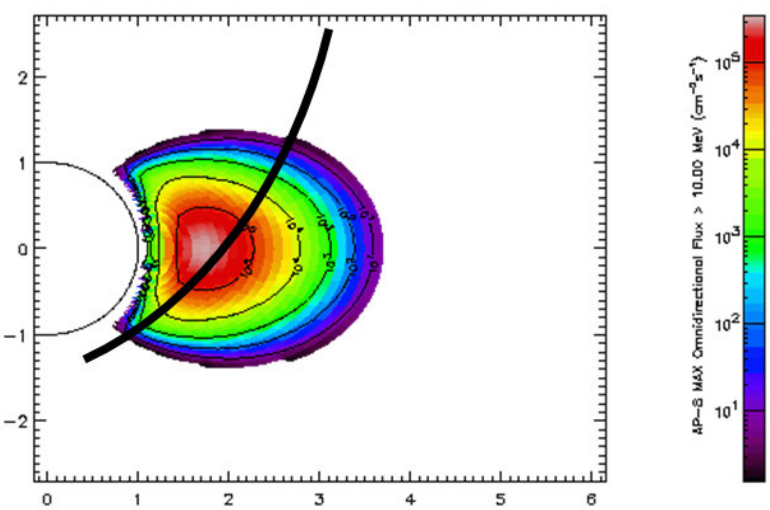


Figure 1.1 Modelled trapped proton omnidirectional fluxes for protons with energies>10 MeV. Coordinates are distances in Earth radius units. Black line represents candidate orbit.

The radiation belts are dynamic features, highly varying in time due to changes in the guiding geomagnetic field and the external sources of energetic particles. For example, fluxes of relativistic electrons through radiation belts can suddenly increase or decrease by a factor of 100 or more. These enhancements are well above the levels modeled by existing radiation belt models.

Changes in the Earth magnetic field due to solar events (coronal mass ejections, high speed solar wind streams) are especially strong in the auroral and polar regions, where the planned PCW satellites will traverse most of the time. They induce significant variations in the trapped radiation population and create enhanced fluxes in the slot region or additional short-lived inner radiation belt.

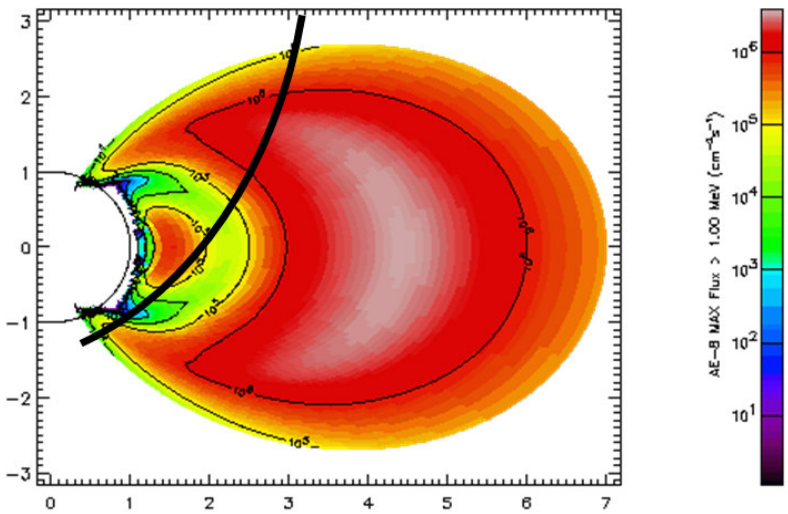


Figure 1.2. Modelled trapped electron omnidirectional fluxes for electrons with energies>1 MeV. Coordinates are distances in Earth radius units. Black line represents candidate orbit.

1.2. Solar energetic particles and cosmic rays.

The transient particle population is produced by galactic cosmic rays and energetic particles accelerated by the solar eruptions (flares, coronal mass ejections) or by solar wind shocks. These particles can enter the satellite orbit at different latitudes, depending on their energy and on shielding provided by the geomagnetic field. Solar energetic protons most easily can penetrate down to the ionosphere levels through open geomagnetic field lines in the polar region.

Changes in the geomagnetic field during geomagnetic storms change the cut-off rigidity for the transient population. The northern hemisphere cut-off rigidity maps of protons are presented in Fig. 1.3 for two levels of geomagnetic activity: quiet time (global geomagnetic activity index Kp =0) and geomagnetic storm (Kp=9).

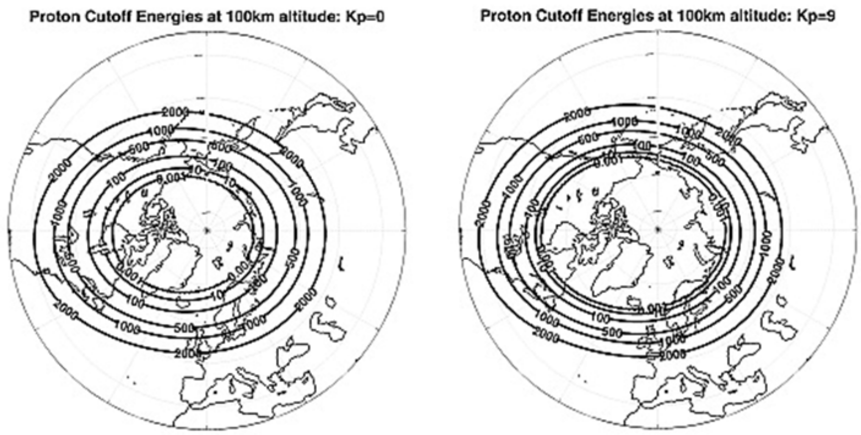


Figure 1.3. Contour plots showing the location of rigidity energy cut-offs at 100 km (from Roger C., J. Cliverd et al, 2006).

These maps show that protons with energies >10MeV can penetrate into the ionosphere as far south as 55^{o} during geomagnetic storms and to ~60 ^{o} during quiet time. Thus, high energy solar particles will affect the PCW satellites most of their orbital time.

Energetic particles, particularly from radiation belts and from solar particle events cause radiation damage to satellite electronic components, solar cells and materials. Energetic ions from cosmic rays and solar particle events can damage memory element, leading to so-called 'single event upset'. Energetic particles may interfere with payloads, producing 'background' signal which might not be distinguishable from the main signal or overload the detector systems. Energetic electrons can cause internal build up of charges in dielectric materials, such as cables, circuit boards and others. All these possible effects should be monitored on-board of PCW mission by properly defined SW payload.

PART 2. ORBIT DEFINITION

To provide continuous 24/4 service to such high-latitude country as Canada would require for PCW mission orbit to pass over high latitudes and be able to spend most of the time dwelling over high latitudes.

Three optimal candidate orbits for mission were chosen by User and Science Team based on thorough analysis of the coverage of services provided by two satellites operated on the candidate orbits. These are: 12-hours Molniya orbit [Capderou, M., 2005], 16-hours three apogee orbit [Trishchenko, A.P. et al, 2011] and 24-hours Tundra orbit [Capderou, M., 2005].

World map projections of examples for each orbit are shown in Figures 2.1-2.4, for 12-hours Molniya, 16-hours Three Apogee (TAP) and 24-hours Tundra orbits respectively with color representing the altitude. The details of orbits are presented in Table 2.1.

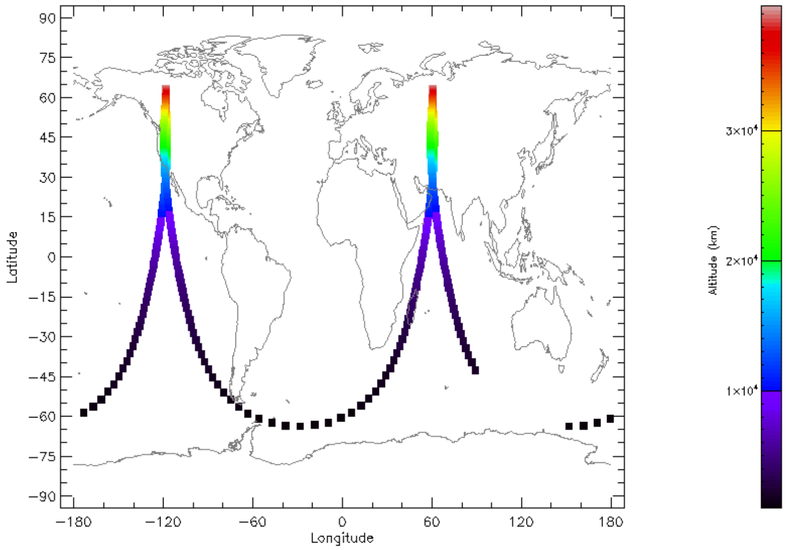


Fig. 2.1. World map projection of Molniya orbit

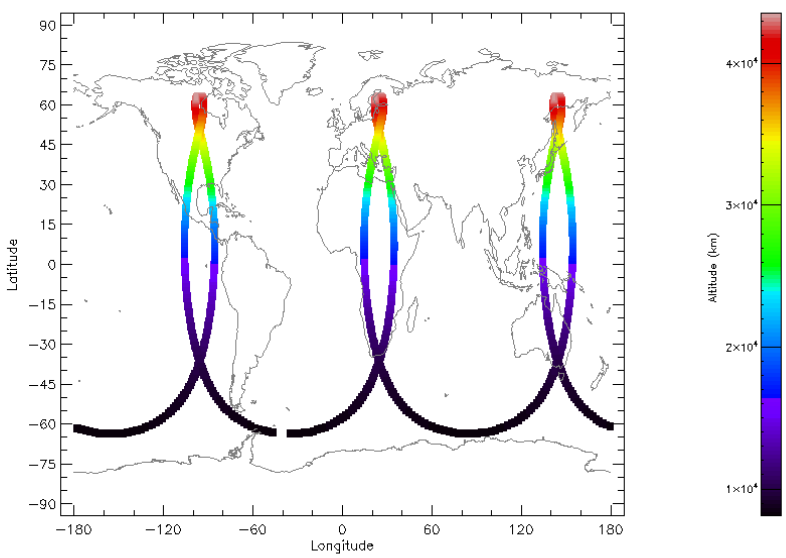


Fig. 2.2. World map projection of TAP orbit

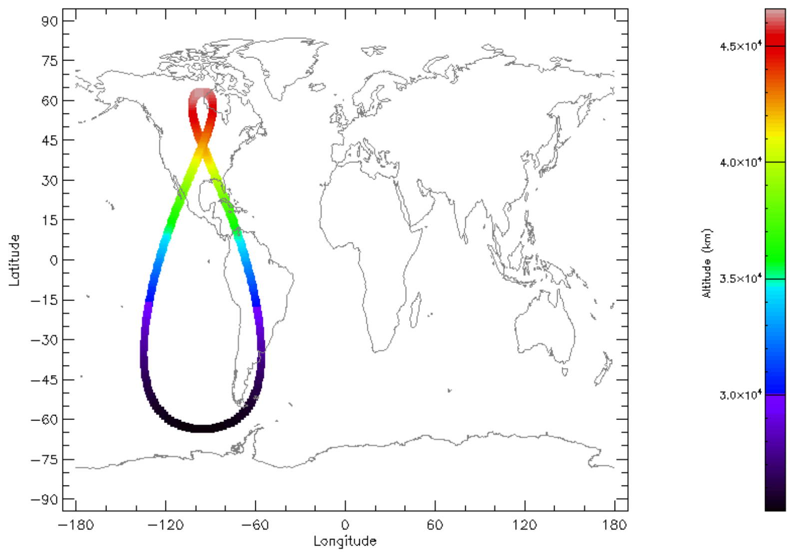


Fig. 2.3. World map projection of Tundra orbit

Table 2.1 Parameters of orbits presented in Figs. 2.1-2.3

Orbital Parameter	**Molniya**	**TAP**	**Tundra**
Apogee	39380.00 km	43500.14 km	46577.68 km
Perigee	972.00 km	8107.72 km	25007.13 km
Inclination	63.40°	63.44°	63.44°
R.A. of Ascending Node	45.00°	212.79°	152.63°
Argument of Perigee	270.00°	270.00°	270.00°
True Anomaly	0.00°	0.00°	0.00°
Period	11.96 hrs	15.95 hrs	23.93 hrs
Number of Orbits	2.00	3.00	1.00
Duration	1.00 days	1.99 days	1.00 days
Eccentricity	0.72	0.55	0.26

The first two orbits are better meteorological payload, while the third one is chosen due to its low exposure to trapped particles population, but less suitable for meteorological payload.

PART 3. SPACE ENVIRONEMENT ON PCW CANDIDATE ORBITS

PCW satellites in their operational cycle will pass through the polar high altitude regions opened to transient particles which are high energy protons and electrons and interplanetary cosmic rays. As well, they will be affected by trapped radiation consisting of protons and electrons of radiation belts, except perhaps for Tundra orbit which will be higher than inner proton radiation belt. Following set of figures show the examples of the modeled radiation environment at Molniya, TAP and Tundra orbits.

3.1. Trapped radiation

This type of radiation is presented by the distributions of the proton and electron fluxes with energies >2 MeV along the PCW orbit and its orbital time dependence as shown in Figs. 3.1-3.3 for protons and 3.4-3.6 for electrons.

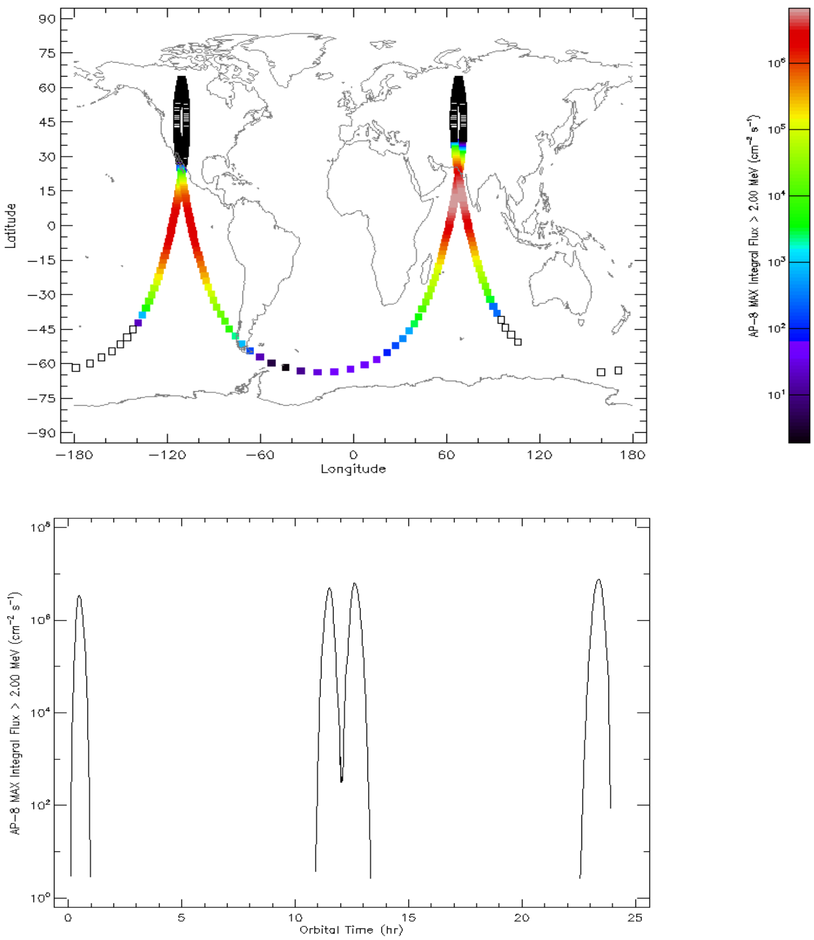


Fig. 3.1. Exposure of Molniya orbit to > 2 MeV trapped protons: top- along the orbit, bottom-orbital time dependence.

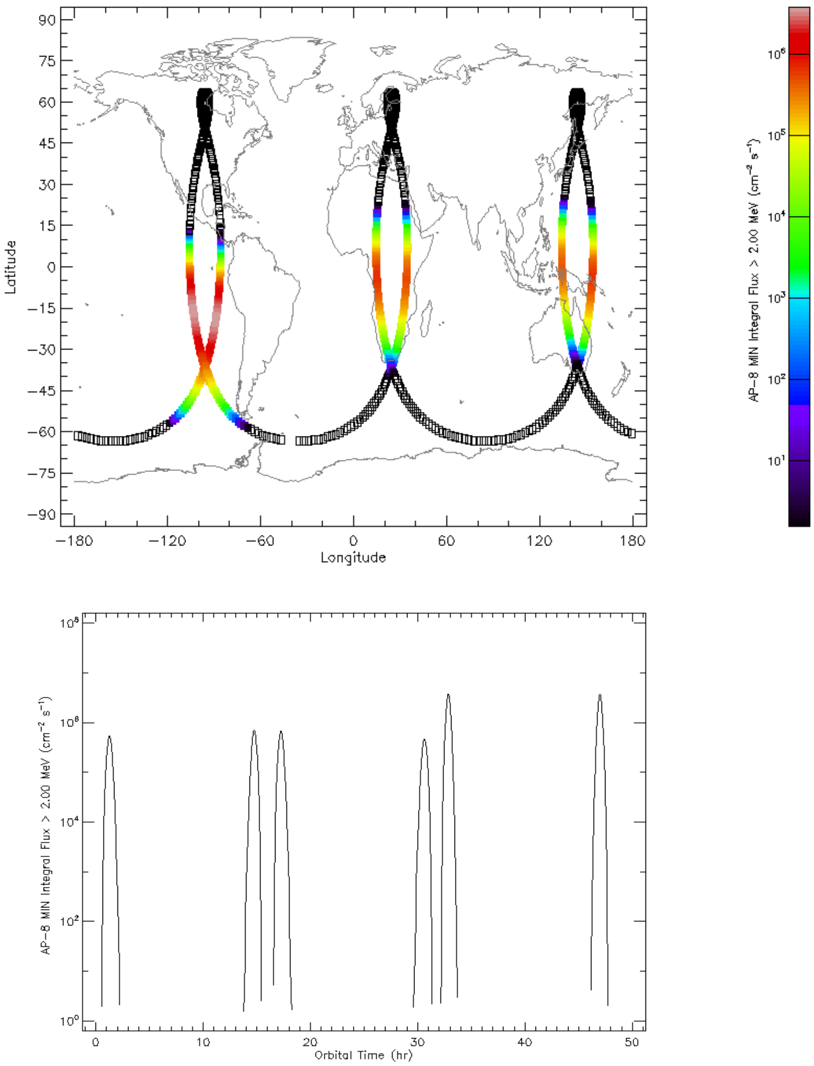


Fig. 3.2 Exposure of TAP orbit to > 2 MeV trapped protons: top- along the orbit, bottom- orbital time dependence.

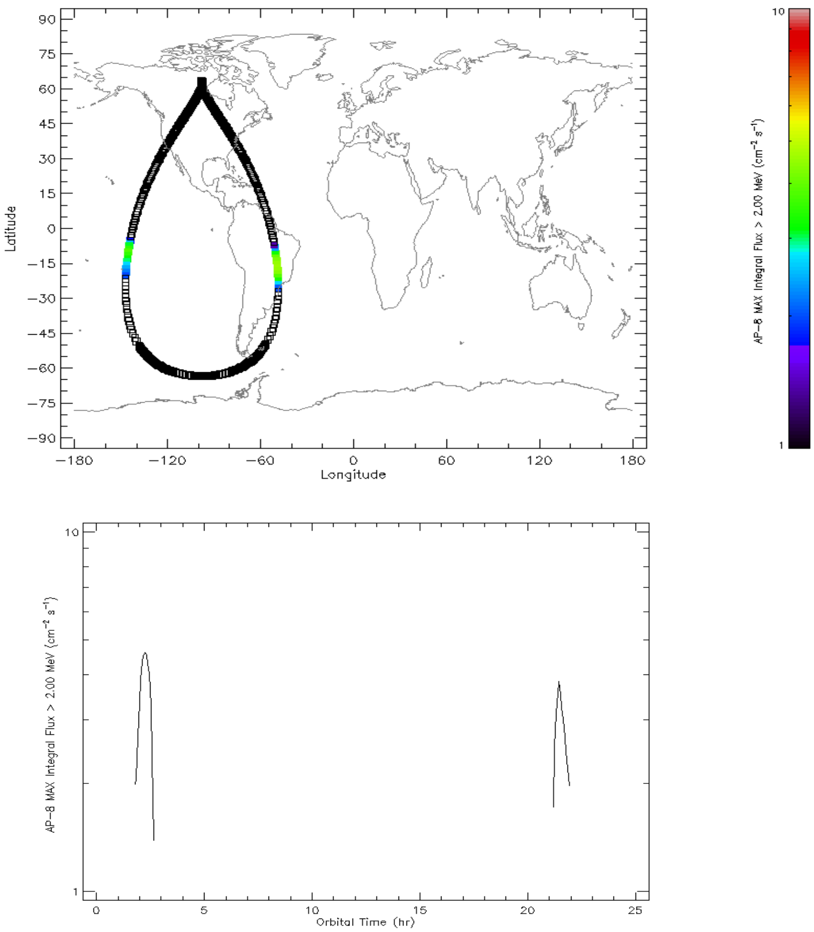


Fig. 3.3 Exposure of Tundra orbit to > 2 MeV trapped protons: top- along the orbit, bottom- orbital time dependence.

From these samples it follows that protons are present at all orbits with the proton radiation belt 24-hours exposure for Molniya orbit being the highest, diminishing for Tundra orbit.

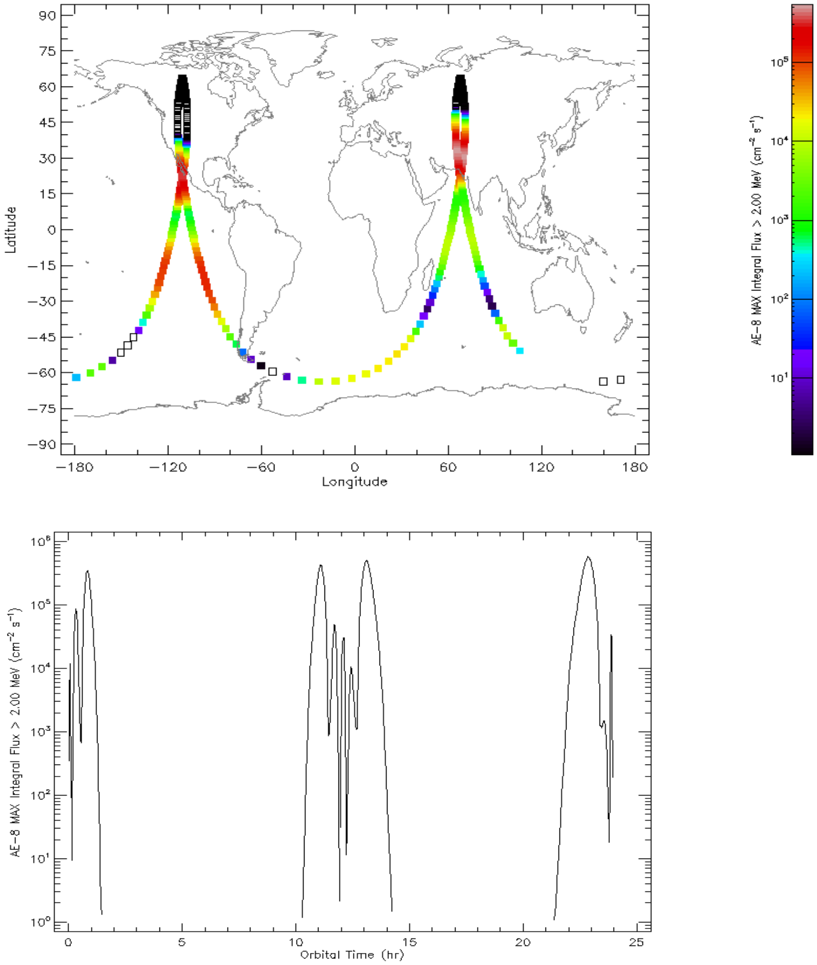


Fig. 3.4. Exposure of Molniya orbit to > 2 MeV trapped electrons: top- along the orbit, bottom- orbital time dependence.

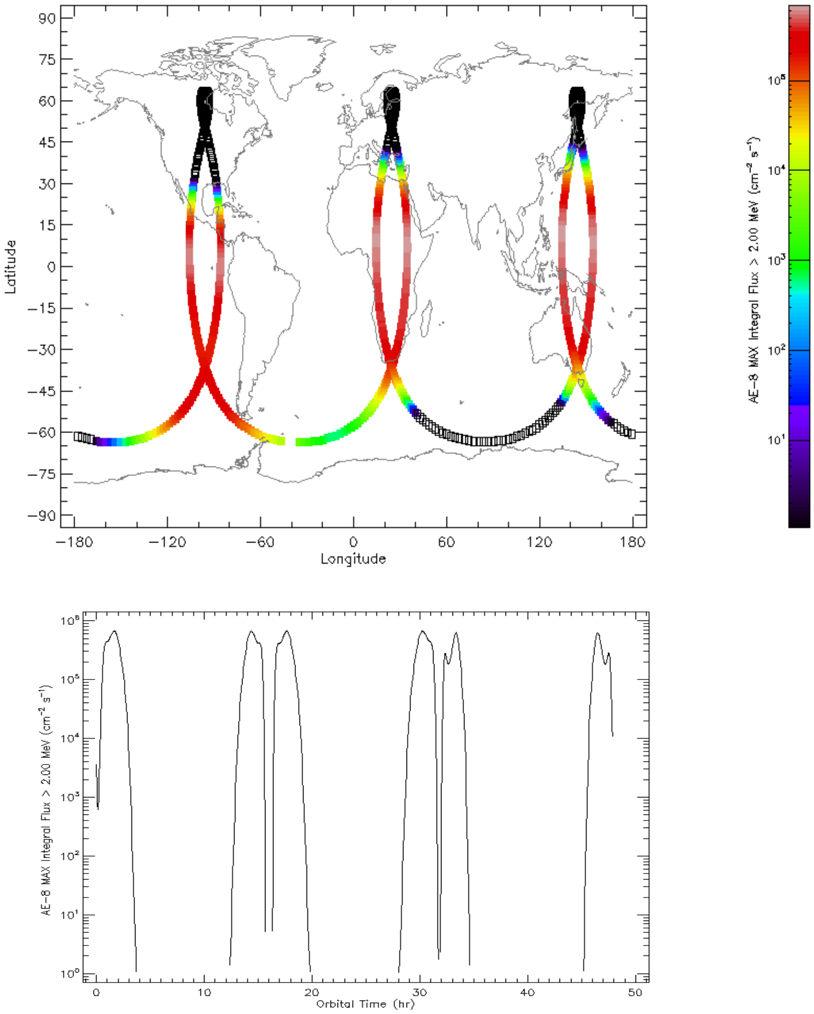


Fig. 3.5. Exposure of TAP orbit to > 2 MeV trapped electrons: top- along the orbit, bottom-orbital time dependence.

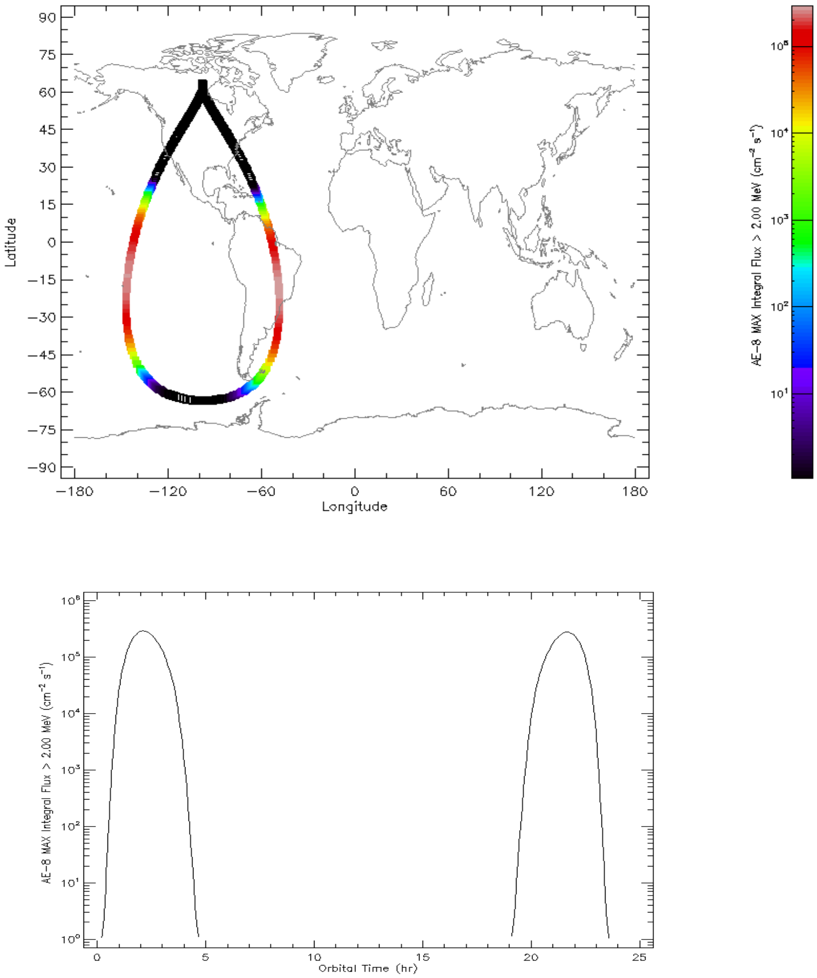


Fig. 3.6. Exposure of Tundra orbit to > 2 MeV trapped electrons: top- along the orbit, bottom-orbital time dependence.

From these samples it follows that electrons are present at all orbits with the electron radiation belt exposure for Molniya and TAP orbits higher than for Tundra orbit.

3.2. Transient (solar energetic protons)

Fluxes of transient energetic protons with energies > 2 MeV on PCW candidate orbits are presented on Figs 3.7-3.9. The top panels are showing the attenuation factor of the solar protons along the orbits for protons, where attenuation of 1 means no shielding by geomagnetic field, 0 means totally protected by geomagnetic field; bottom panels show the time dependence of the attenuation factor along the orbit. It can be seen that for the significant time during each orbit, PCW satellites will not be shielded from solar transient particles and cosmic rays.

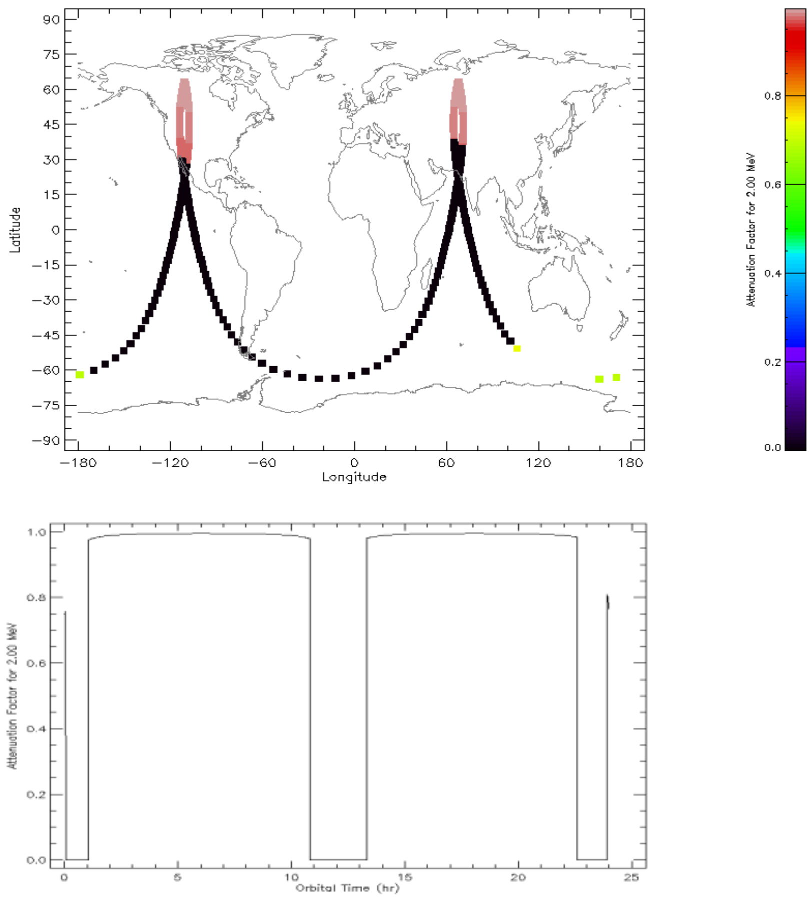
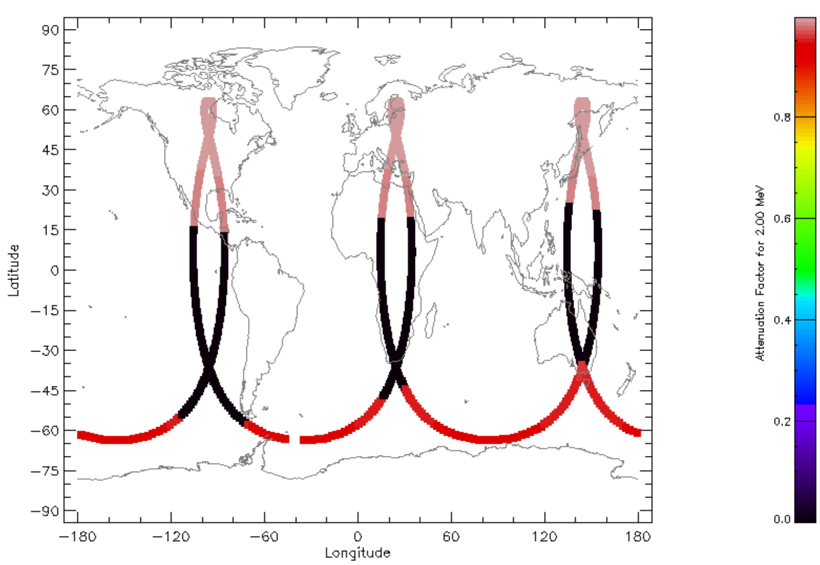


Fig. 3.7 Exposure of Molniya orbit to > 2 MeV solar protons: top- along the orbit, bottom- orbital time dependence.



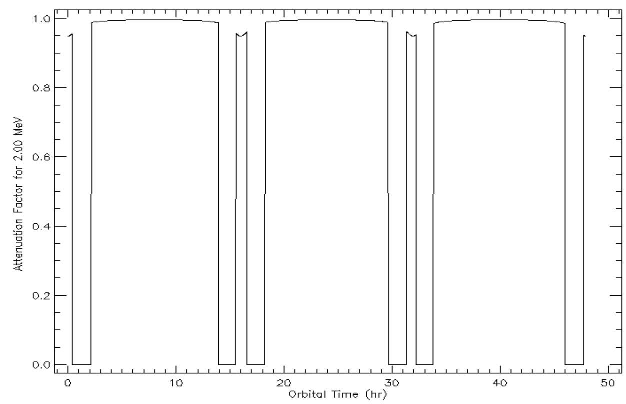


Fig. 3.8 Exposure of 16-hrs orbit to > 2 MeV solar protons: top- along the orbit, bottom- orbital time dependence.

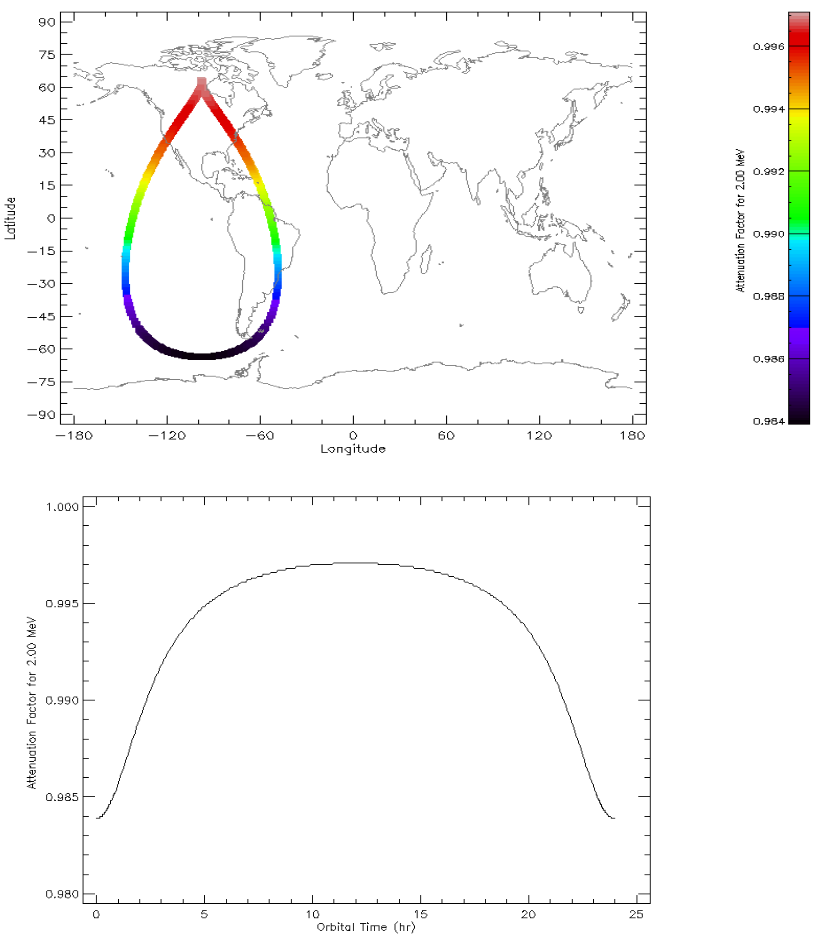


Fig. 3.9 Exposure of Tundra orbit to > 2 MeV solar protons: top- along the orbit, bottom- orbital time dependence.

It is evident that exposure time for Tundra orbit to the transient solar energetic particles and cosmic rays will be the largest among all three candidate orbits.

More details on space environment for these three orbits can be found in the complimentary GCS Open File #7252, 2012.

All these examples were calculated using the standard radiation models of the space environment used by satellite designers. At the same time these standard models (e.g. AE8, AP8 and others available from SPace ENVIronment System on http://www.spenvis.oma.be/models.php) were mainly developed in 1970s and later assimilated data only from measurements on GEO (GOES, LANL) and LEO (NOAA POES, DMSP) satellites mostly low latitude near-circular orbits. However, there are very limited amount of space environment data for high-inclination Molniya orbit and no measurements were done for other two candidate orbits. Thus, the modeled predictions of satellite environment might potentially differ by orders of magnitude from actual conditions.

PART 4. EFFECTS OF SPACE ENVIRONMENT ON MISSION PERFORMANCE.

As has been shown above (Part 3), space environment on PCW orbits will be diverse, subjecting the satellite and its payload to the hazardous effects of trapped radiation as well as transient high energy particles from the outer space.

One of the goals for space weather payload measurements would be to provide data on particles which might have negative effects on mission performance.

In order to choose proper energy bands for instruments to record particle fluxes, the particular energies of particles were identified together with the sources producing these particles or accelerating them. These parameters are summarized in Table 4.1. The first column lists the environment (particles or magnetic field), the second lists vulnerable satellite components, the third provide information on the origins of the particles, the forth is the energy requirement for the instrument to detect the effect, and the fifth describes the time resolution needed. The last column cites the type of space weather product which could be developed using data provided by measurements in the particular energy band.

Space Environment Characteristics	**Potentially affected satellite elements**	**Sources**	**Energy requirement**	**Time resolution requirement**	**Space Weather Product**
Solar protons and ions	SEE's and TID that affect microelectronics, solar cells, CCDs	Flares, shocks, cosmic rays	several bands from ~1 MeV to ~500MeV	4-20 sec	nowcast, forecast
Trapped	SEE's and TID	Radiation	several bands	<~4-60 sec	nowcast

protons (Single Event Upset, ionising dose	that affect microelectronics, CCDs	belts+ external (flares)	>1 MeV		
Trapped electrons	TID that affects surface charging, dielectric charge	Radiation belts+ external (magnetic storms)	several bands >0.5 MeV	<~4-60 sec	nowcast forecast
Magnetic field Disturbances due to solar sources	AODCS	Solar	N/A	<1min	nowcast, forecast
Magnetic field Disturbances due to solar source	100MHz-4GHz scintillations	Solar+ ionospher e	N/A	<1min	nowcast, forecast

Table 4.1. Effects of Space Weather on Satellite subsystems and SW payload requirements. Abbreviation used: SEE: Single Event Effects; TID: Total Ionizing Doze; CCD: Charge Coupling Device; AODCS: Attitude and Orbit Determination and Control systems

Space weather effects to be monitored on PCW mission will also provide a new set of data for advancing many aspects of space weather services, in particular of radio communications.

HF radio communication in the Arctic is strongly affected by Polar Cap Absorption (PCA) events caused by high energy protons guided by open magnetic field lines and penetrating to the D region of the polar ionosphere. The penetrating particles cause the strong absorption of HF (3-30 MHz) signal that can last for several days. The affected area is located pole-ward of 55^{o} latitude. Forecasting PCA events is quite challenging because for high energy particles it takes only 1-2 hours from their detection to the initiation of the effect on the ionosphere. High energy proton data from PCW space weather suite would facilitate advancing the now-cast and development of the forecast of PCA events.
Table 4.2 provide the summary of the effect and instrument requirements.

Space Environment Characteristics	**Affected systems/ Operations**	**Sources**	**Energy requirement**	**Time resolution requirement**	**Product**
Solar Protons	3-30 MHz Polar Cap Absorption	Solar+ ionosphere	from ~1 MeV to ~500MeV	~ 4-60 sec	nowcast, forecast

Table 4.2. Effects of Space Weather on signal propagation and SW payload requirements.

Even non-direct data can provide valuable input to monitoring space weather effects on signal propagation. For example, the high latitude ionospheric irregularities, such as patches, blobs and others (tens of km scales) are likely to cause signal fading for Molniya-type PCW communications. Because the PCW ground-to satellite links will be exclusively polar and auroral ionosphere, these scintillation effects will be a particular concern. To monitor this effect, data on the quality of radio communication signal can provide important information on the conditions of the ionosphere for space weather research.

PART 5. SPACE WEATHER PAYLOAD REQUIREMENTS

5.1 Targeted Information

Information is required on energetic particles: electrons with energies greater than 500 KeV, protons with energies greater than 1 MeV.
Data from high energy proton detectors (>1MeV) on Canadian PCW satellite are an important input for monitoring a wide range of solar energetic particles effects on PCW satellites (Table 4.1, second column). They will also be used in developing services of space weather effects on HF communications in Canadian Arctic.
Data from electron detectors on Canadian PCW satellites are needed for monitoring such hazardous effects as surface charging and deep dielectric charging (Table 4.1, second column).

Some additional information can be obtained from monitoring the signal strength for PCW-to-ground radio communication link, which together with geomagnetic activity and in-situ space weather data can facilitate characterization of scintillation dynamics of the ionosphere, the. The conditions which might have an effect on quality of the PCW satellite communication itself.

In principle the PCW mission could be expanded to include additional capabilities and hardware items. If so, it is preferable that additional capabilities contribute to the mission's primary objectives, but not mandatory. It should be assumed that funding to develop/procure and operate additional equipment will be from sources outside PCW's core mission budget, and that incorporation of additional hardware and functional capabilities will not be allowed to compromise PCW's core function and objectives.

5.2. Coverage and Payload Location

Space weather data shall be recorded continuously throughout the orbit by identical space weather payload in each satellite. Sensors should be placed outside of the spacecraft with their view non-obstructed by other parts.

The number of instruments and their location on each spacecraft depend on the field of view of the detectors and engineering possibilities. To cover all directions of particles arrivals at the non-spinning PCW satellites, two instruments with 180 FOV on each satellite is the best option.

One of the SWP detectors should located on the spacecraft so that it "looks" in the same direction as optical axis of the meteorological spectroradiometer when pointing to nadir.

Consequently the SW detector will provide information on the particle flux impinging on the spectroradiometer where the first internal elements to be encountered will be the baffles and scanning mirror assembly.

Provision of the data from co-located measurements of magnetic field (if satellite design permits) will give complimentary information on magnetic field variations and magnetic storm progression at satellite position.

5.3 Timeliness and Data Latency

Latency of information from the satellite should be in near real time NRT (goal) or less than 1 minute, in order to produce timely forecast of transient events. When the satellite downlink is available the data shall be downloaded in "real time". When the satellite downlink is not available due to the location of the satellite, space weather data should be stored internally and sent to the ground as soon as downlink becomes available.

5.4 SWP Availability Requirement

The required availability for SW data is 90%.

5.5 End Use

Satellite radiation monitoring data will be directly used for monitoring and forecasting space weather conditions by NRCan CSWFC that will include PCW satellites as one of primary objects. The information from space weather instruments on-board PCW spacecraft will be extremely important in facilitating the safety of PCW operations. As well, using this information, NRCan's CSWFC will modify its services currently provided for geostationary orbit to accommodate the high latitude PCW orbits, and will develop new Space Weather products and services dedicated specifically to the PCW mission (see Tables 4.1,4.2). Data from space weather detectors will be used to develop, evaluate and improve operational forecast of space environment at HEO orbit, which currently is not well described by existing models and services.

Data from space weather detectors will also be used to improve forecast of space weather effects on communications and, therefore, will benefit all users of HF radio links in the Arctic region.

PART 6. CANDIDATE INSTRUMENTS

The exact components of the PCW space weather payload have not been finalized yet because the orbit is still to be determined. At the same time, the set of instruments should have filght experience, i.e. the individual instruments should be identical or similar to SW instruments that have flown on other missions. Thus, the list of existing instruments which might serve as samples of candidate instruments at the time of writing the report is provided below. These are:

1. European Standard Radiation Monitor (SREM), ESA , http://srem.web.psi.ch/docs/SREM_ASR_2008.pdf.gz

http://www.oerlikon.com/ecomaXL/index.php?site=SPACE_EN_radiation_monitors

2. ICARE (CNES) http://craterre.onecert.fr/radiation_monitors/ICARE.html

3. EPT (currently undergoing tests at ESA, phase C)) http://www.spaceradiations.be

4. GOES-R SEISS (Magnetospheric Particle Sensor, MEPED, Energetic Heavy ion sensor, EHIS and Solar and Galactic Proton Sensor, SGPS), details are not available due to ITAR.

5. GOES-8-13, O, P SEM suite (Energetic Particle Monitor, EPS, High Energy Proton and Alpha detector, HEPA) http://goes.gsfc.nasa.gov/text/GOES-N_Databook_RevC/Section05.pdf

6. NOAA POES Space Environment Monitor SEM-2. (Total Energy Detector, TED and Medium Energy Detector MEPED, high energy alpha particle detectors) http://www.ngdc.noaa.gov/stp/NOAA/noaa_poes.html

7. New monitors currently under development in Europe, (Paul Scherrer Institute, Switzerland, developers of European SREM), sizes 30x30x50mm3, weight 200-300 gramms. Planned for Swiss micro-satellite, (private communication).

Table 6.1 contains some details for inter comparisons of lists somethe existing instruments which may be satisfactory for PCW, based on the requirements outlined above and their performance specifications available for the several space weather for other space missions. Note this list may be revised if/when new or upgraded instruments are developed which might better satisfy the requirements listed in Tables 4.1 and 4.2.

Parameters	**Requirements**	**Available**	**Instrument**	**Comments**
Proton energy thresholds	>1 MeV	0.8-500MeV/ 350-700MeV; >2MeV; 1-500 MeV; 8-300 MeV; 4-500MeV; 5-45 MeV	EPS/HEPAD EHIS SGPG SREM EPT ICARE	GOES(O, P), GEO GOES (R), GEO GOES (R), GEO ESA, multiple orbits, HEO as well Under development at ESA, CNES, polar LEO
Proton Bands	several	3 / 3 N/A	GOES(O, P), GOES-R	Bands are not specified in URD

Parameters	Requirements	Available	Instrument	Comments
		8 18 2 (?)	SREM EPT ICARE	to provide more flexibility with choice of instruments
Electron energy thresholds	>0.5 MeV	>0.6 >2 MeV 0.3-6 MeV 0.2-10 MeV 0.1-3 MeV	GOES(O, P), GOES-R SREM EPT ICARE	
Electron Bands	several	3 N/A 2 (TBC) 18 5 (?)	GOES(O, P), GOES-R SREM EPT ICARE	Bands are not specified in URD to provide more flexibility with choice of instruments
Alpha-particles and heavy ions	desirable	Exist Exist Exist Exist Exist	GOES(O, P), GOES-R SREM EPT ICARE	Not specified, see above
FOV	360°	? N/A (ITAR) ±20° 90° 90°	GOES(O, P), GOES-R SREM EPT ICARE	FOV is not specified in URD to provide more flexibility with choice of instruments
Sampling rate	4 sec-60 sec	Different for different particles, from 4 to 32 sec N/A (ITAR); Detection rate 100kHz; 0.1-10 sec; resolution 4 to 256 sec	GOES(O, P), GOES-R SREM EPT ICARE	
Weight	For information	N/A N/A 2.5 kg <5 kg 2.4 kg	GOES(O, P), GOES-R SREM EPT ICARE	

Parameters	Requirements	Available	Instrument	Comments
Power		N/A N/A ~2W <6W 2.5W	GOES(O, P), GOES-R SREM EPT ICARE	
Size		N/A N/A 95x122x217 mm^3 110x110x200 mm^3 71x281x155 mm^3	GOES(O, P), GOES-R SREM EPT ICARE	

Table 6.1. Comparative characteristics of existing and developing SW instruments.

The list of space weather instruments currently available can be changed as soon as new modifications or new instruments will be developed which better satisfy the requirements to monitor the environment described in Tables 4.1 and 4.2, columns 4 and 5 and more suitable for developing services described in the last column of the above cited Tables.

Magnetic storms cause extreme changes in the population of transient and trapped particles of all energies. These changes can be short (minutes) or long lived (weeks). Provided that the radiation environment is monitored by PCW satellites and supported by ground-based magnetometers, on-board magnetometers may not be required.

CONCLUSIONS

The space weather payload is intended to be a compact suite of instruments to monitor *in situ* particle fluxes and ionizing radiation.

Space Weather Payload will operate continuously through the orbit to provide the information about *in situ* ionizing radiation in near real-time.

Real-time monitoring of the local (to the satellite) space environment will provide diagnostics of satellite anomalies or communication degradation, in support of overall PCW mission objectives.

With space weather suite of instruments on both satellites, the substantial hazards to the mission operations can be monitored and to some extent predicted

Space Weather Payload will provide added knowledge on the behaviour of space weather variables in relation to Molniya the PCW orbit. It will help to fill existing gaps in data and models of the space environment parameters at high inclination HEO and serve follow-on PCW high latitude missions.

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