THE POLAR COMMUNICATIONS AND WEATHER MISSION: ADDRESSING REMAINING GAPS IN THE EARTH OBSERVING SYSTEM

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Earth observation from space is currently based on instruments onboard geostationary and polar orbiting satellites. The idea of using, in addition, imagers and sounders onboard satellites in highly elliptical orbits (HEO) appears to be the most practical way of achieving the goal of observing the Earth at any moment and location at latitudes above ~55°. Communication gaps are also significant at high latitudes. This motivated Canada to initiate the Polar Communications and Weather (PCW) mission in 2007. This short paper highlights recent studies linked to PCW, and unique capabilities and characteristics of HEO observations. PCW could be realized in about six years after funding for next phases is approved.

INTRODUCTION

A large number of satellites are contributing to communications and Earth observation (see www.wmo-sat.info/oscar/ for meteorology). Despite this, there are still significant spatio-temporal gaps in global communications and Earth observations, especially for high latitude regions. The basic requirement of reliable, seamless observation and communication for all areas of our planet is still not satisfied. This situation is due to various socio-economic factors, rather than available technology. Individual governments or the private sector align their priorities to needs of their own population or targeted clients. Economic constraints impose limitations on the number of low Earth orbiting (LEO) meteorological satellites, the only ones which at present observe the polar regions. Only a handful of nations commit to satellite systems which are suitable for operational meteorology. At this time, Canada is not part of these contributing nations. The situation can be summarized as follows: GEO satellites cover communications needs up to about 75°N/S, and meteorological observation needs up to 55°N/S relatively well. For high latitudes, LEO satellite networks are simply insufficient or not designed to provide continuous services in terms of coverage [1], or the communication frequencies and data volumes needed for civilian and defense operations. With the rapid climate change observed in the Arctic and the perspective of strong economic development in this area, the need to address these gaps becomes more and more pressing.

SUMMARY

The Polar Communications and Weather (PCW) mission proposes a constellation of two satellites in highly elliptical orbits to address spatio-temporal gaps of the Earth Observing System. Services similar to those available from geostationary satellites will then be extended to the circumpolar Arctic region.

In view of the above, the Polar Communications and Weather (PCW) mission was initiated in 2007, focusing on the Northern Hemisphere polar area. Main departments involved were the Canadian Space Agency (CSA), Environment Canada, the Department of National Defence, and Natural Resources Canada. Following a study dating back to 1990 [2], the initial concept was based on a classical 12-h "Molniya" highly elliptical orbit (HEO, apogee ~39,900 km, perigee ~500 km, inclination 63.4°). Elliptical orbits have not been used so far for meteorological imaging, at least for civilian applications. The reference study showed that two satellites in Molniya orbits would be sufficient to satisfy coverage requirements for meteorology in the Arctic. These requirements include essentially full coverage of the entire circumpolar domain above 60°N, with imagery refresh rate of 15 min or less. A clear advantage is that meteorological imaging characteristics available from GEO orbits would be extended to polar areas. It then appeared natural to align the requirements of the meteorological instrumentation to those planned for the upcoming generation of imagers, such as the Advanced Baseline Imager [3] on the US geostationary satellite GOES-R (planned launch date in early 2016). Detailed PCW requirements are provided in the Users Requirements Document [4]. Requirements for military and civilian communications include various frequencies for different applications and users (X, Ka, and UHF bands). Key requirements linked to the meteorological instrument are presented in Table 1. PCW first generation satellites are required to provide

TABLE 1

KEY REQUIREMENTS LINKED TO THE METEOROLOGICAL IMAGING INSTRUMENT. PRODUCT DEVELOPMENT, DISTRIBUTION AND ARCHIVING IS THE RESPONSIBILITY OF ENVIRONMENT CANADA.

Temporal	20 min imagery refresh rate, 10–15 min expected from Phase A. Latency: 15 min.
Spatial	100% above 65°N, still >70% at 45°N, with viewing angle <70°.
Spectral	12–21 channels 4.5–14.5 µm, 16–18 expected from Phase A.
Resolution	Goal/needed 0.5/1.5 km VIS, 2.0–3.0 km IR.
Key derived products	Winds, cloud height/amount, fog, visibility, forest fires, volcanic ash, surface temperature, albedo, emissivity, vegetation index, leaf area index, ice/snow cover, aerosol optical depth.

services for a minimum of 15 years. A PCW "Phase A" study (with MacDonald, Dettwiler and Associates as a prime contractor) was completed in 2012. It was confirmed that the requirements for both communications and meteorology could be met from a constellation of only two satellites. This short paper reviews several studies conducted to support PCW, including analyses of orbital characteristics, simulations demonstrating the added value for global weather, implications of space environment (space weather) on orbit, and proposals for added science instruments. Orbits in the range of 6-h to 24-h were evaluated in detail recently [5], presenting a more complete analysis of tradeoffs, as showed below.

ORBIT CHARACTERISTICS

The selection of the orbit presents a range of possibilities. As mentioned, the 12-h orbital period was first examined, at the so-called critical inclination of 63.4°. That inclination is preferred because maintenance of the orbit is minimized (see [6] for details). As an example, the Sirius radio constellation of three satellites in 24-h elliptical orbits is at critical inclination. As shown in Table 2, using a 12-h orbit allows a higher eccentricity, which translates into improved coverage of the targeted polar region while at the same time keeping the apogee height no higher than 40,000 km. It was shown that the two satellites in 12-h orbits should preferably be in the same orbital plane [6], resulting in four apogee positions (two per satellite separated by 180°), more uniform polar coverage and improved dual views, rather than forcing the same ground track using different planes, thereby limiting the number of apogees to two. Data reception at a single station located in Canada such as Yellowknife is possible.

The PCW Science Team then evaluated the advantages of a 16-h orbit characterized by three apogees (referred to as the "TAP") repeated every two days [7]. In contrast to the 12-h orbit, satellites launched in TAP orbit in the same plane, 8-h apart, follow the same ground track. While the apogee height is higher, 43,500 km with an eccentricity of 0.55 and an inclination 66°, the main advantage is that the much higher perigee (7,500 km versus 500 km) avoids the altitudes with dangerous high energy protons linked to the inner radiation belt (see details in Space Weather section). Due to that potential danger, the 12-h orbit is no longer considered by Canadian industry as a preferred choice for the mission. The 24-h orbit is perceived as safer due to its higher perigee (23,500 km) and apogee (48,500 km) heights. The higher apogee results in a slightly degraded resolution in comparison to orbits such as

TABLE 2

CHARACTERISTICS OF HIGHLY ELLIPTICAL ORBITS WITH DIFFERING PERIODS.

Longitude step refers to distance (westward) between consecutive apogees. Eccentricity is set to the maximum value allowing an apogee height <44,000 km, where possible. The 21-h orbit would have 8 apogees separated by 45° if the inclination was less than 90°.

Period (h)	Inclination (°)	Apogee height (km)	Perigee height (km)	Number of apogees	Repeat pattern (days)	Longitude step (°)	Eccentricity
12	63.4	40,000	500	2	1	180	0.74
14	63.4	42,200	4,000	12	7	150	0.65
16	66.0	43,500	7,500	3	2	120	0.55
18	70.0	44,000	13,500	4	3	90	0.45
21	90.0	44,000	21,000	1	7	0	0.31
24	90.0	48,500	23,500	1	1	0	0.30

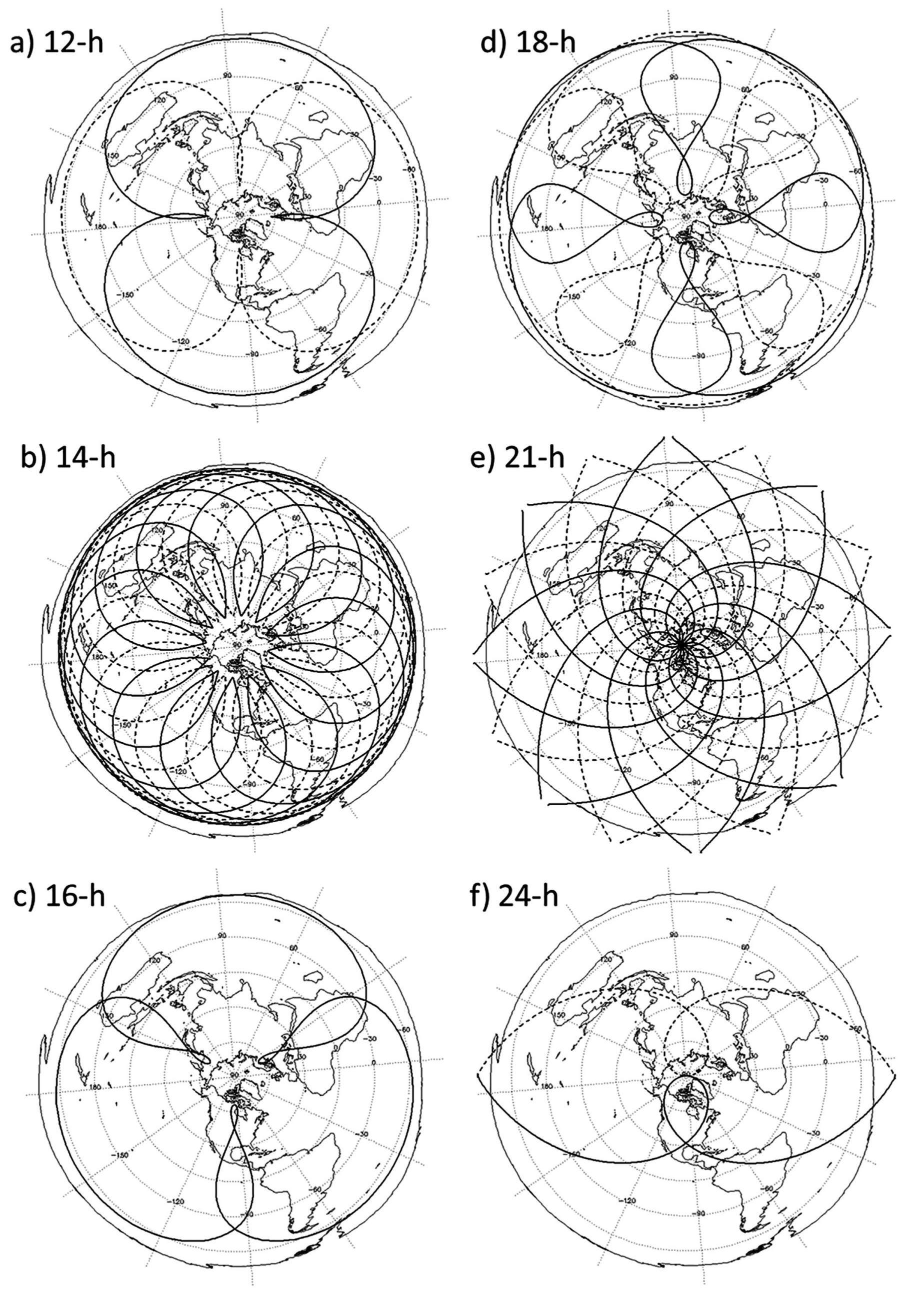

Fig. 1 Ground track of each satellite (solid, dashed) for HEO orbits listed in Table 1. Satellites in a 16-h orbit have the same ground track.

A more recent analysis suggests that from the viewpoint of Earth observation, a 14-h orbit presents interesting characteristics in comparison to orbits with longer periods [5]. First, as indicated in Table 2, it is possible to have a slightly lower apogee (42,200 km) using a higher eccentricity, while maintaining 100% coverage above 60°N, this with the satellite at critical inclination. This compromise is more difficult to achieve for longer orbital periods. Secondly, the 14-h period is characterized by as many as 12 apogees for each satellite, 30° apart. Therefore, near nadir viewing conditions are distributed uniformly around the circumpolar region, which is a valuable characteristic, provided this does not complicate ground reception.

The ground tracks of the HEO orbits listed in Table 2 are presented in Fig. 1. The zonal mean coverage, defined as percentage of imaging time with satellite viewing zenith angle smaller than 70°, the satellite latitudinal position, the height above the surface, and the latitude of the satellite position as a function of time from apogee are displayed in Fig. 2. All orbits can image the northern latitudes about 16 hours per day, which implies up to 8 hours per day of dual imaging (maximum at the pole). As noted in Table 2, the orbit inclination has to be above the critical value for HEO orbits with eccentricity smaller than ∼0.6 in order to maintain 100% coverage of the 60°–90° region with two spacecrafts. 70° inclination is required for the 18-h orbit and an inclination of 90° is required for 21-h and 24-h orbits. Orbit maintenance may imply significant overheads for orbits at non-critical inclinations. A satellite in 24-h orbit starts imaging the polar regions from a lower latitude (Figure 2c) in comparison to orbits with shorter periods. For example, imaging starts 4-h from apogee for a 12-h orbit, at about 45°N and 25,000 km altitude, while imaging starts 8-h from apogee, at about 5°N and 33,000 km altitude, for a 24-h orbit. This may present additional difficulties for data reception in Canada.

TAP (by about 10%). The 24-h orbit has to be at 90° inclination to satisfy coverage requirements. The single track favors specific regions for nadir viewing. An advantage of the 24-h orbit is that it allows partial extension of services in the Southern Hemisphere (about eight hours per day), owing to the lower speed and higher altitude of the spacecraft at perigee in comparison to orbits with shorter orbital periods.

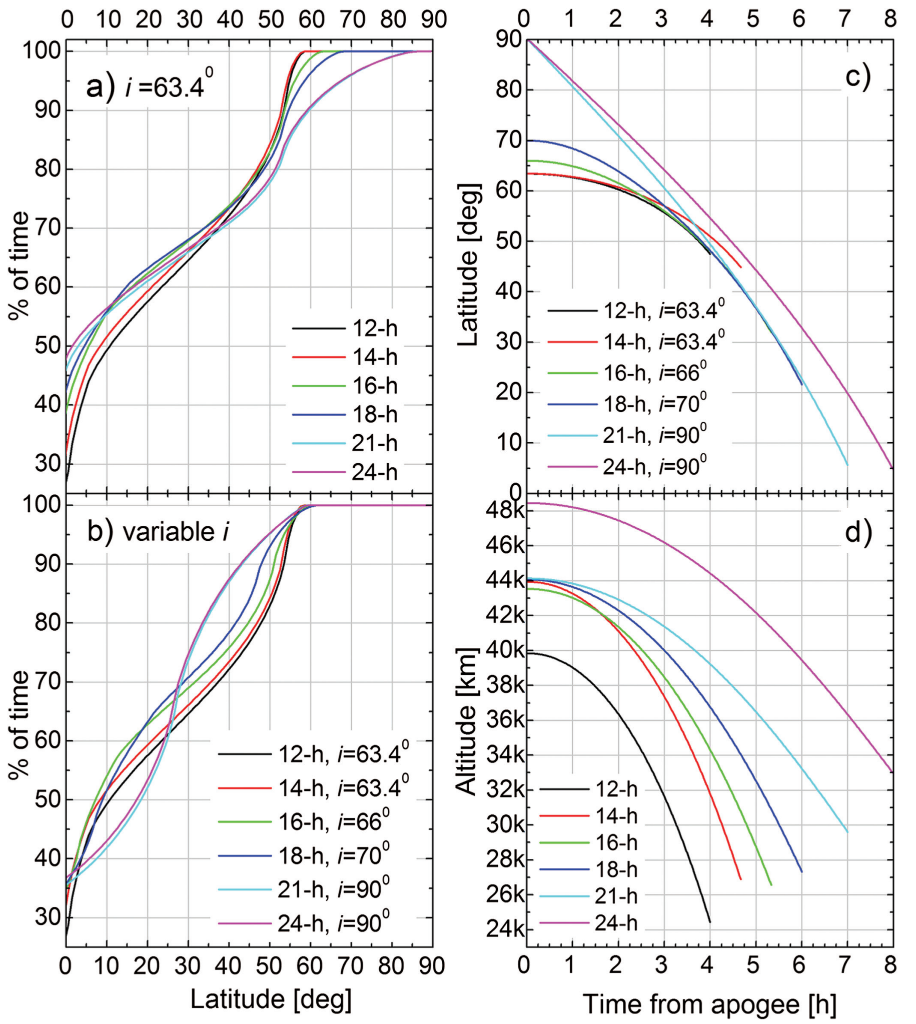

Fig. 2 Zonal mean coverage for HEO orbits presented in Table 2: a) for critical inclination $i = 63.4^{\circ}$ and b) inclinations needed to meet 100% coverage at 60°N; c) latitude and d) altitude as functions of time from the apogee point corresponding to panel (b).

For completeness, the option of using circular orbits at medium heights (MEO, i.e. between LEO and GEO) can be considered. In that case, a minimum of four satellites would be needed to meet coverage requirements [8], which would significantly raise mission costs. However, such a constellation would cover the needs of both polar regions, from a lower and constant altitude. Reiterating, HEO and MEO systems both require four satellites to cover the two polar regions, but the HEO option satisfies the needs of each polar region separately with two satellites.

IMPACT FOR OPERATIONAL METEOROLOGY

The operational nature of PCW implies a long term commitment and a substantial investment. There is a need to determine the added value of the various aspects of the mission: scientific, social, economic, and political. The value of extended services to Arctic populations from PCW was evaluated by the CSA (internal report). Economic returns, notably for transportation, are seen as substantial despite the limited population. The Department of National Defence has obvious operational needs linked to Arctic sovereignty, security and interoperability with Allies. Here we focus on the meteorological component. The spatio-temporal coverage of PCW and LEO systems were compared [1]. It was shown that in order to meet the requirement of 15 min imagery refresh cycle at 60°N, as many as 23 LEO satellites would be needed as opposed to two HEO satellites. The LEO option also implies a rather cumbersome compositing exercise. That study also evaluated the capabilities to get image triplets, ideally at 15 min intervals, needed for cloud tracking and the production of atmospheric motion vectors (AMV, also called “satellite winds”). Currently, polar winds derived from LEO satellites are based on triplets at 90 min intervals (LEO orbital period), which is far from ideal (AMVs should preferably be produced from 15 min imagery [9]). The worst situation is in the latitude band 55°–70°N/S, as shown in Fig. 3. The figure shows that despite the contribution of 10 satellites to the AMV product, there remain substantial gaps. Recently, work was accomplished to partially address that issue from complex GEO-LEO compositing [10]. These gaps are exacerbated by the lack of important water absorption channels in some polar imagers such as the Visible Infrared Imaging Radiometer Suite (VIIRS). In the absence of such channels, AMVs cannot be estimated in clear sky areas. The Advanced Very High Resolution Radiometer (AVHRR) present on current LEO satellites does not have a water vapor channel either. In contrast to the current LEO capability, PCW would cover at all times the domain 60°–90°N, and still allow the production of AMVs 16-h per day at 35°N. In effect, the combination of HEO + GEO would be sufficient for the global production of AMVs if two additional HEO satellites cover the Antarctic region. Observing system simulation experiments (OSSEs)

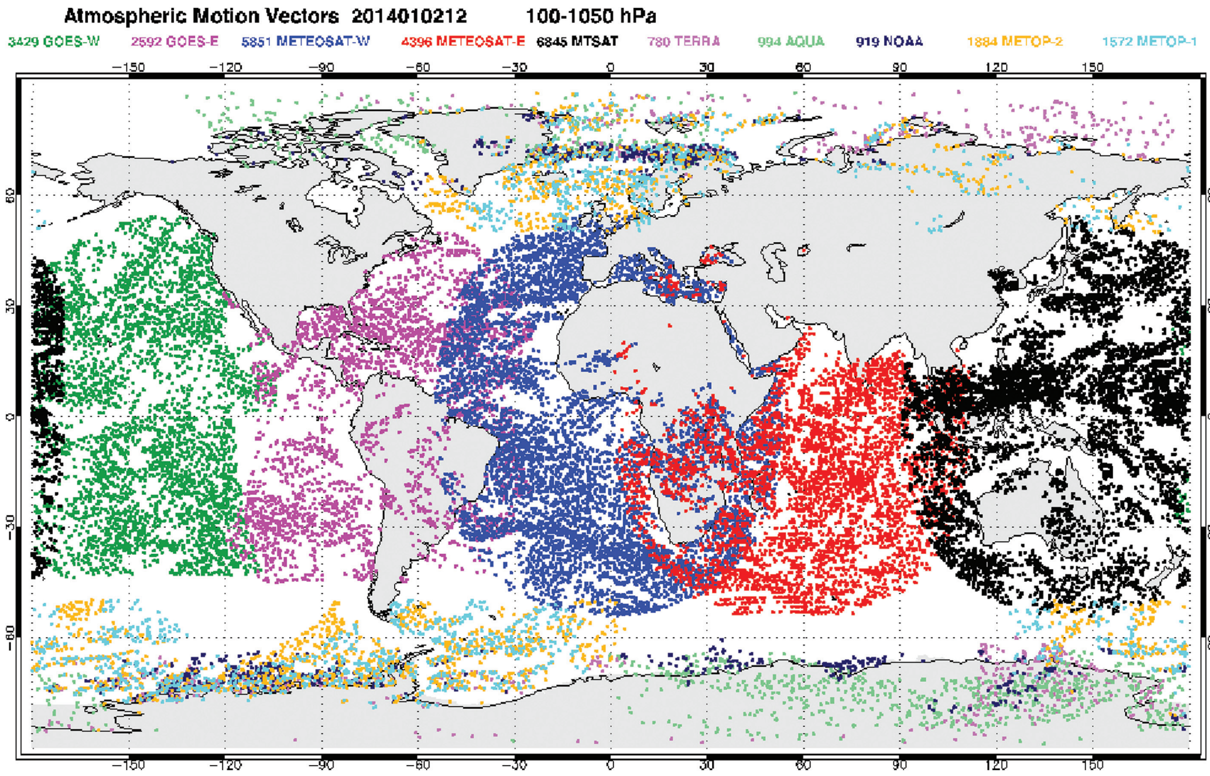

Fig. 3 AMVs available for assimilation at the Canadian Meteorological Center on January 2, 2014, for the period 9–15 UTC, after thinning and quality control. The 10 data sources (5 GEO and 5 LEO) are identified by a color code.

were conducted to evaluate, via data assimilation, the added value of HEO AMVs in comparison to the impact resulting from the current coverage [11]. The conclusion is that HEO AMVs would improve predictability at days 2–3 by several hours at latitudes 50°–90°, with a larger impact in the Southern Hemisphere where AMV gaps are more severe.

In addition to AMV, there are numerous applications requiring frequent imagery. These include nowcasting operations in support of aviation (icing), navigation (fog, sea ice), and road conditions (precipitation, visibility). For numerical weather prediction, the assimilation at higher temporal rate of radiances (notably from water vapor sensitive channels) represents a high potential to improve forecasts. Environmental monitoring applications such as volcanic ash and forest fires will also be facilitated. The monitoring of key essential climate variables related to the surface and atmosphere (vegetation index, clouds, radiative fluxes, snow and ice cover) would benefit from a unique source of data covering the circumpolar domain. For proper detection of climate signals, it remains important to capture the diurnal cycle. Bi-directional reflection models could be improved significantly from available dual views. Finally, the PCW multispectral imagery, by overlapping with that from all other weather satellites, notably GEO, can contribute significantly to and benefit from the Global Space-based Inter-calibration System (GSICS) [12].

SPACE WEATHER

Space Weather or the Space Environment refers to the continuously changing conditions of the electromagnetic environment and energetic particle fluxes (protons, electrons, ions) in the vicinity of the Earth, which may affect satellite operations and quality of services. Natural Resources Canada is the lead federal agency providing monitoring and forecast services linked to space weather. Of particular concern are charged particles permanently trapped by the Earth's magnetic field and transient particles associated with solar eruptions. 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 (700–10,000 km) populated by protons and electrons, and the outer radiation belt (13,000–65,000 km) populated by electrons, with a less active region in between (referred to as the slot), as schematically shown in Fig. 4.

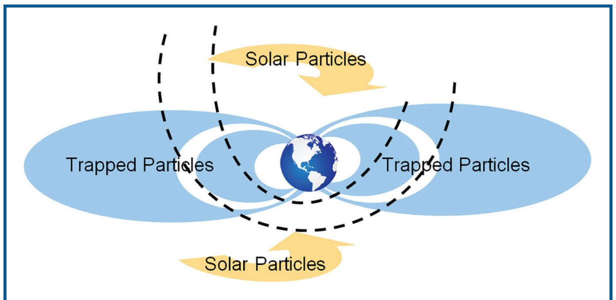

Fig. 4 Schematic representation of two populations of ionized particles in the vicinity of the Earth. Trapped particles are pictured in the inner and outer belts (blue). The in-between region, called the "slot", is indicated in white. Arrows (yellow) depict solar energetic particles entering the system. Dashed lines illustrate potential HEO orbits.

The transient particle population is produced by background galactic cosmic rays and energetic particles accelerated by solar eruptions (flares, coronal mass ejections) or interplanetary shocks. These can enter the satellite orbit at different latitudes, depending on their energy and on natural shielding provided by the geomagnetic field, but most easily through open geomagnetic field lines in the polar regions, where each PCW spacecraft will spent most of its time. Changes in the Earth magnetic field due to solar eruptions are especially strong in the auroral region (typically above 55°), producing significant variations in the trapped particle population. For example, fluxes of relativistic electrons can suddenly increase or decrease by two orders of magnitude or more.

To design a successful space mission, possible impacts of the radiation environment have to be assessed. An extensive analysis covering the range of HEO orbits from 6-h to 24-h was carried out [5] using statistical models AE8/AP8 and AE9/AP9 implemented in the European Space Agency's (ESA) Space Environment Information System (SPENVIS) software tool (www.spenvis.oma.be). Some of the results of assessment are presented in Fig. 5. Assumed average total ionizing doses of 10 krad and 5 krad were decomposed to evaluate the specific impacts of trapped protons, trapped electrons and solar particles for missions with different orbital periods (Fig. 5a). It is noted that the risk of proton-originating ionizing radiation rapidly decreases with longer orbital periods (negligible beyond 15-h), while for electrons it is increasing until a period of ~16-h and then decreasing slightly. Corresponding estimates of the thickness of the shielding needed to keep the total dose below 5 krad and 10 krad per year are shown in Fig. 5b. These effects have to be taken into account in the orbit definition [7,13] as well as in the design of the payload and satellite components, especially for an operational mission to provide 15 years of service as is the case for PCW.

As a result of space environment studies, it has been recommended that space weather payloads be installed on all satellites to monitor in-situ the ionizing dose and fluxes of energetic protons and electrons continuously throughout the orbit, with data reception provided in near real time. These data will serve as a diagnostic tool for overall mission health and anomaly identification, and allow developing more realistic statistical models of the space environment for future HEO-orbiting missions.

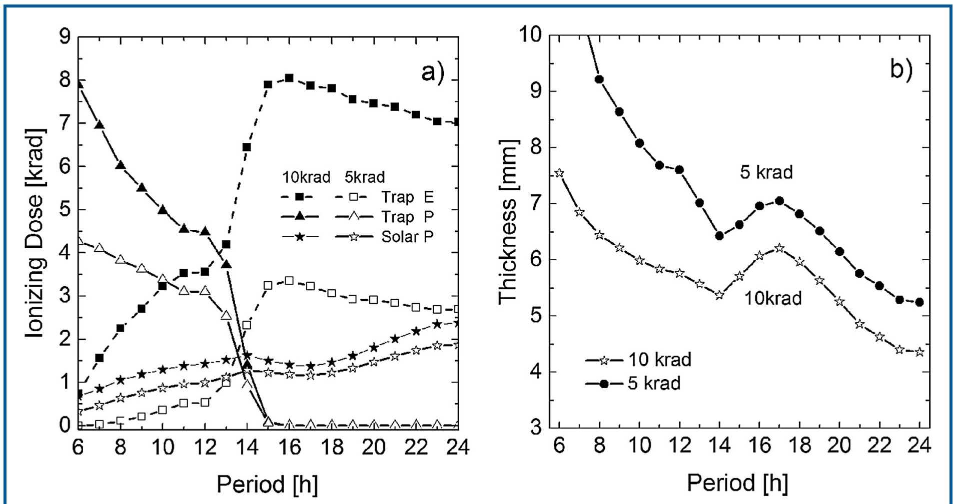

Fig. 5 For various orbital periods: a) contribution of trapped protons, trapped electrons and solar protons to an assumed total ionizing dose of 5 or 10 krad/yr; b) shielding (aluminum thickness, mm) required to keep the total ionizing dose at 5 and 10 krad/yr. The AE8/AP8 models implemented in the ESA SPENVIS software tool were used to compute dose and thickness.

OTHER SCIENCE OPPORTUNITIES

CSA provided several contracts to support potential additional science instruments on PCW, subject to technical readiness and costs. Strong constraints were imposed on mass and volume. This initiative is defined as the "enhanced" mission as opposed to the core mission. At the present time, hyperspectral infrared sounding instruments such as the Infrared Atmospheric Sounding Interferometer (IASI, on METOP, 4.5 to 15.5 μm) are only available on LEO satellites. However this situation will change in the near future, e.g. on Fengyun-4 China satellite in 2017 and METEOSAT Third Generation (MTG-S) in 2021. As well UV-VIS-NIR instruments specifically designed for air quality remote sensing are planned on several GEO platforms (Sentinel-4 and MTG-S from Europe, TEMPO (Tropospheric Emissions: Monitoring of Pollution) from U.S., GEMS (Geostationary Environmental Monitoring Spectrometer) from S. Korea). A science team led by late Jack McConnell [14] engaged in studies investigating imaging versions of two instruments for PCW: a Fourier Transform Spectrometer (FTS) covering various parts of the spectrum between 0.76 and 14.2 μm, and a UV-VIS grating spectrometer. Industrial partners were ABB, Quebec, for the FTS and COMDEV, Cambridge, Ontario, for the UV-VIS. Atmospheric soundings (temperature, humidity) and greenhouse gas, ozone and carbon monoxide retrievals would be available approximately every hour as opposed to every three hours on average in the Arctic region (assuming two LEO versus two HEO satellites). The same is true (in day light) for air quality retrievals from the UV-VIS instrument (spectral range 280–650 nm), and short-wave infrared retrievals from the FTS, together providing columnar amounts of CO_2, O_3, NO_2, CH_4 as well as aerosol optical depth. Environment Canada led a study [15] evaluating the capability of using column CO_2 observations from the FTS for the estimation of CO_2 surface fluxes over the boreal and Arctic regions, demonstrating the advantages of HEO viewing versus LEO. Universities of Waterloo and Dalhousie also proposed a UV-VIS-NIR instrument based on Fabry-Perot 2D imaging spectrometers (MPB Inc Technology, Pointe Claire), with the goal of directly assimilating greenhouse gases and air quality variables in near-real time in atmospheric model analyses.

The University of Calgary has been involved for a long time in auroral imaging from space and from the ground. PCW offers truly unique capabilities for the continuous observation of auroras from space. They proposed a dual band UV imager (160–175 nm, 140–160 nm) with spatial resolution of 40 km, allowing estimates of the auroral energy fluxes. Finally, the University of Alberta proposed to use the PCW orbit to investigate plasma-physical processes controlling mass and energy transport in the mid-altitude magnetosphere. Various heritage instruments would be used such as fluxgate and search coil magnetometers, an ion imager, and an electrostatic spectrum analyzer. Again, HEO characteristics provide great opportunities for atmospheric science applied to the high latitudes.

CONCLUSION

There is an obvious need to complete the Global Observing System (GOS) as well as global communication systems in terms of spatio-temporal coverage. An HEO system as envisioned for PCW represents a practical and elegant solution to address this pressing issue. With PCW, Canada would become an active participant among nations providing satellite observations for operational meteorology. Clearly, the private sector and the atmospheric science and physics communities in Canada would highly benefit from this mission. Not only does PCW extend GEO-type observing capabilities to high latitudes, but it opens up new areas of research linked to the cryosphere, cloud physics, air quality, radiative fluxes, space weather and high atmosphere physics. It is hoped that a decision to proceed with the next phases will be made shortly by the Canadian Government, with the perspective of a launch in 2021. The Canadian space industry, various governmental departments, and the university community are ready to take up the challenge.

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