The Polar Communications and Weather Mission: Addressing remaining gaps in the Earth Observing System

Louis Garand[1], Alexander P. Trishchenko[2], Larisa D. Trichtchenko[2], and Ray Nassar[3]

[1]Environment Canada, Dorval, Qc
[2] Natural Resources Canada, Ottawa, On
[3]Environment Canada, Downsview, On

ABSTRACT

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 on highly elliptical orbits (HEO) appears to be the most practical way of achieving the goal of observing the Earth at any moment and time 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 is an all-of-government enterprise which could be realized in about five years after funding is approved.

INTRODUCTION

Space technology is progressing at an accelerated pace. Hundreds of satellites are contributing to communications between humans. A very significant number are also contributing to Earth observation, notably for meteorology (World Meteorological Organization, see www.wmo-sat.info/oscar/). Despite these great advances, there are still significant spatio-temporal gaps in global communications and Earth observations, especially as these apply to 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 several factors. Space industry is still relatively young. Individual governments or the private sector align their priorities to needs of their own population or targeted clients. Coordination is not ideal, for example, on the positions of geostationary (GEO) satellites around the globe for meteorological applications. There is sometimes no backup satellite ready to replace a failing one within a short time. 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. The situation can be summarized as follows: GEO satellites cover relatively well communications needs up to 75° N/S, and meteorological observation needs up to 55° N/S. For high latitudes, LEO satellite networks are simply insufficient or not designed to provide continuous services in terms of coverage, data rate, or communication frequencies needed for civilian and defence operations (Trishchenko and Garand, 2012a).

The Polar Communications and Weather (PCW) mission was initiated by Canada in 2007 to address the high latitude gaps noted above, both for communications and operational meteorology. Space weather instruments would complement the suite to monitor the ionizing radiation environment at the satellite. The initial concept was based on a classical 12-h "Molniya" orbit (apogee ~39,900 km, perigee ~500 km, inclination 63.4^o). This type of elliptical orbit has been utilized extensively by the Russian Federation for their communications. The life of these satellites was typically quite short (usually less than 3 years). Today, Russia is proposing a mission similar to PCW, but with different satellites for communications and meteorology.

Elliptical orbits have not been used so far for meteorological imaging, at least for civilian applications. Kidder and Vonder Haar (1990) showed that two satellites in 12-h highly elliptical orbits (HEO) would be sufficient to satisfy coverage requirements for meteorology in the northern polar area. These requirements include essentially full coverage of the entire circumpolar domain above 60^o N with a repeat cycle of 15 min or less. A key motivation for this mission is that meteorological imaging characteristics available from GEO orbits would be extended to polar areas. It then appeared natural to align the requirements associated with the meteorological instrument to those planned for the upcoming generation of imagers, such as the Advanced Baseline Imager (ABI, Schmit et al, 2005) on US geostationary satellite GOES-R (launch date in 2016). Detailed PCW requirements are provided in the Users Requirements Document (Garand and Morris, 2011). Briefly, the PCW imager would have between 12 and 20 channels covering the spectral range 0.45-17 µm, with ground sampling distance of order 1 km for visible channels and 2-3 km for infrared channels. A PCW "Phase A" study led by the Canadian Space Agency (with MacDonald, Dettwiler and Associates as a prime contractor) was completed in 2012, assuming a 12-h orbit constellation. It was again confirmed that requirements for 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 propositions for added science instruments. Orbits in range 12-hr to 24-hr were evaluated extensively recently, presenting a more complete analysis of tradeoffs. At this time, the orbital configuration for PCW is not yet settled, but mission configurations better aligned to the meteorology and communication components are well understood, as described below.

ORBIT CHARACTERISTICS

The selection of the elliptical orbit presents a range of possibilities. Following previous experiences of the Russian Federation, the 12-hr orbital period was first examined, at the so-called critical inclination of 63.4^o. That inclination is preferred because maintenance of the orbit is minimized. The Sirius radio constellation of three satellites in 24-hr elliptical orbits is at critical inclination. Using a 12-hr 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. Lowering the eccentricity does allow a lower apogee height, but at the expense of degraded spatial coverage for a two-satellite system. The study of Trishchenko and Garand (2011), expanding on the work of Kidder and Vonder Haar (1990), presented a detailed analysis of 12-hr orbit characteristics. The two satellites should preferably be in the same orbital plane, resulting in four apogees, 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.

Trishchenko et al. (2011) evaluated the advantages of a 16-hr orbit characterized by three apogees (referred to as "TAP" orbit) repeated every two days. In contrast to 12-hr orbit, satellites in the same plane, 8-hr apart, follow the same ground track. While the apogee height is higher, 43,500 km with eccentricity of 0.55 and inclination 66^o, the main advantage is that the much higher perigee (7,500 km versus 500 km) allows avoiding the area with dangerous high energy protons linked to the inner radiation belt (details in Space Weather section). Due to that potential danger, the 12-hr orbit is no longer considered by the Canadian industry as a preferred choice for the mission. The 24-hr orbit is perceived as safer due to its higher perigee (23,500 km) and apogee (48,500 km) heights. However, the latter results in a degraded resolution in direct proportion to the height ratio. The single track favors specific regions for nadir viewing. An advantage of the 24-hr orbit is that it allows partial extension of services in the Southern Hemisphere, owing for the slower speed of the spacecraft near perigee.

A new analysis conducted by Trichtchenko et al. (2014) suggests that from the viewpoint of Earth observation, the 14-hr orbit has a slight edge in comparison to orbits with longer periods (Table 1). First, as indicated in Table 1, it is possible to have a slightly lower apogee (42,200 km) using a lower eccentricity, while maintaining 100 % coverage above 60^o N, this with the satellite at critical inclination. This compromise is more difficult to achieve for longer orbiting periods. Secondly, the 14-hr period is characterized by as many as 12 apogees for each satellite, 30^o 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 1 are presented in Figure 1. The zonal mean coverage, defined as percentage of imaging time with satellite viewing zenith angle VZA $<70^0$, 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 Figure 2. It turns out that all orbits can image the northern latitudes about 16-hr per day, which implies up to 8 hours per day of dual imaging (maximum at the pole). As noted in Table 1, the orbit inclination has to be above the critical value $i=63.4^0$ for HEO orbits with eccentricity smaller than ~0.6 in order to maintain 100% coverage of the 60^0-90^0 region with two spacecrafts. The inclination 70^0 is required for the 18-hr orbit and an inclination of 90^0 is required for 21-hr and 24-hr orbits. Orbit maintenance may imply significant overheads for orbits at non-critical inclinations. For these orbits, the satellite starts imaging the polar regions from a lower latitude (Figure 2c) in comparison to shorter orbits. This may present additional difficulties for data reception in Canada.

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 (Dittberner et al., 2006), which would raise significantly mission costs if these were to be assumed by a single nation. However, such a constellation would cover the needs of both polar regions, this at a constant resolution and lower 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 mission on various aspects: scientific, social, economic, and political. The value of extended services to Arctic populations was evaluated by the Canadian Space Agency (CSA). Economic returns, notably for transportation, are seen as substantial despite the limited population. The Department of National Defense (DND) has obvious operational needs linked to Arctic sovereignty and security. Here we focus on the meteorological component. Trishchenko and Garand (2012a) compared the spatio-temporal coverage of PCW and LEO systems. It was shown that in order to meet the requirement of 15 min repeat cycle at 60^{o} 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). 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, Lazzara et al. (2014) attempted to partially address that issue from complex GEO-LEO compositing. These gaps are exacerbated by the lack of important water absorption channels in some future 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^{0}-90^{0} N, and still allow the production of AMVs 16-hr 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. Garand et al. (2013) conducted observing system simulation experiments (OSSE) to evaluate, via data assimilation, the added value of HEO AMVs in comparison to the impact resulting from the current coverage. The conclusion is that HEO AMVs would improve predictability at days 2-3 by several hours at latitudes 50-90^{o}, 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, winds), navigation (fog, sea ice), road conditions (precipitation, visibility). For numerical weather prediction, the assimilation at high temporal rate of radiances (notably from water vapor sensitive channels) represents a high potential. Environmental monitoring applications such as volcanic ash and forest fires will also be facilitated in a major way. 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), as shown by Trishchenko and Garand (2012b).

SPACE WEATHER

Space Weather or 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 (700-10,000km) populated by protons and electrons, the outer radiation belt (13,000-65,000km) populated by electrons, and the region between these belts, as schematically shown in Figure 4.

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 the 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 degrees), 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. Recent extensive analysis covering the range of HEO orbits from 6-hr to 24-hr was carried out by Trichtchenko et al. (2014) using statistical models AE8/AP8 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, computed in assumption of the shielding geometry as the aluminum sphere. 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 is decreasing rapidly with longer orbital periods (negligible beyond 15-hr), while for electrons it is increasing until a period of ~ 16-hr 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 [Trishchenko et al 2011, Trichtchenko, 2012] 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 space environment for future HEO-orbiting missions.

OTHER SCIENCE OPPORTUNITIES

The Canadian Space Agency 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 FY-4 China satellite in 2017 and METOP-S in 2021. As well UV-VIS-NIR instruments specifically designed for air quality remote sensing are planned on several GEO platforms (METOP-S from Europe, TEMPO from U.S., GEMS from S. Korea). McConnell et al. (2012) engaged in Phase 0 an A studies investigating imaging versions of these two types of 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 shortwave infrared retrievals from the FTS, together providing columnar amounts of CO_2, O_3, NO_2, CH_4 as well as aerosol optical depth. Nassar et al. (2014) studied 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 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 Earth Observing system as well as global communication systems in terms of spatio-temporal coverage. HEO systems such as PCW represent a practical and elegant solution to address this pressing issue, in a context of rapid climate change and economic development in the Arctic. 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 in the near future. The Canadian space industry, various governmental departments, and the university community are ready to take up the challenge.

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TABLE

Period (hr)	Inclination (deg)	Apogee height (km)	Perigee height (km)	Number of apogees	Repeat pattern (days)	Longitude step (deg)	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	8	7	45	0.31
24	90.0	48,500	23,500	1	1	0	0.30

Table 1. 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 apogee height < 44,000 km, where possible.

FIGURES

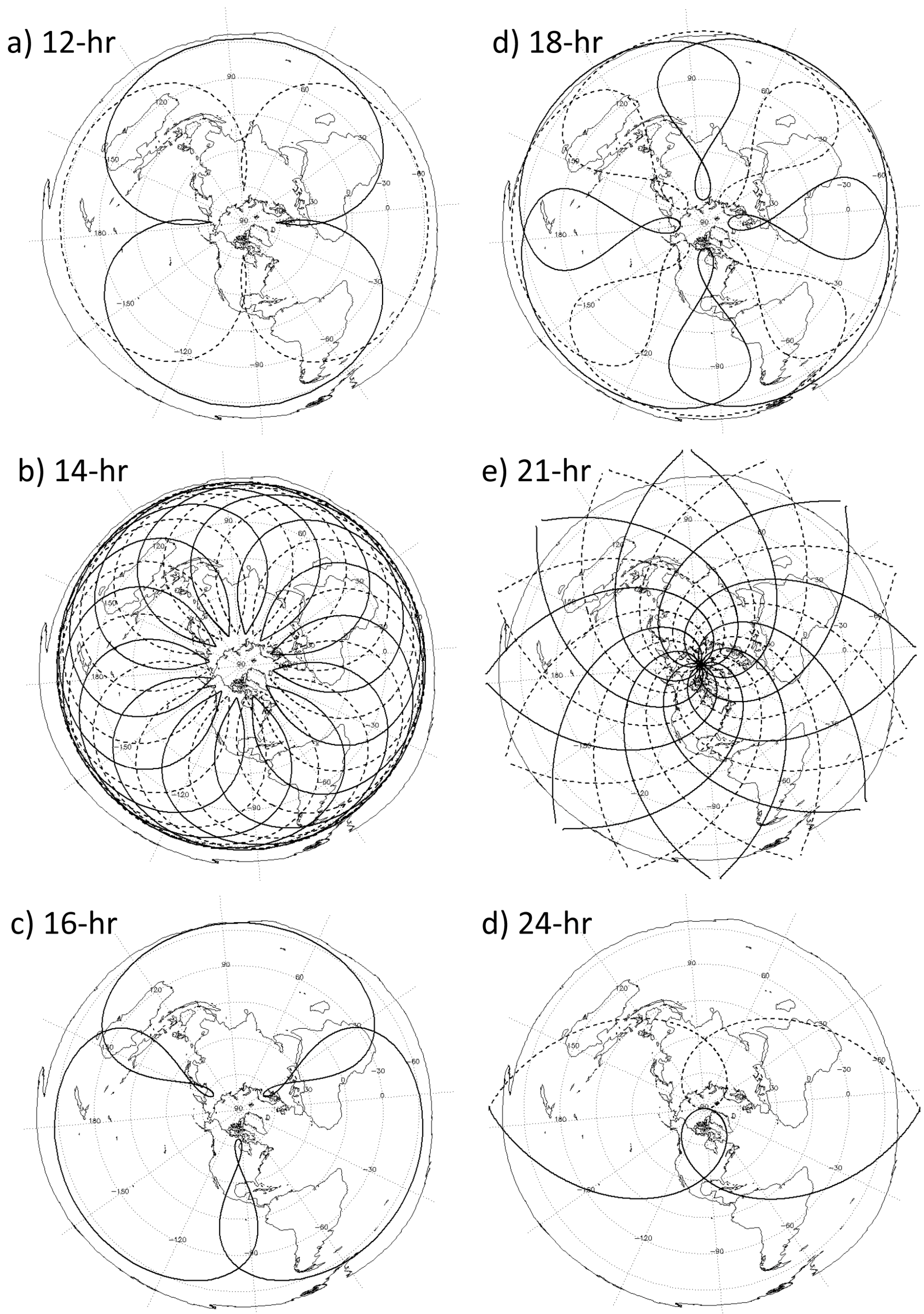

Figure 1. Ground track of each satellite (solid, dashed) for HEO orbits listed in Table 1. Satellites in 16-hr orbit have the same ground track.

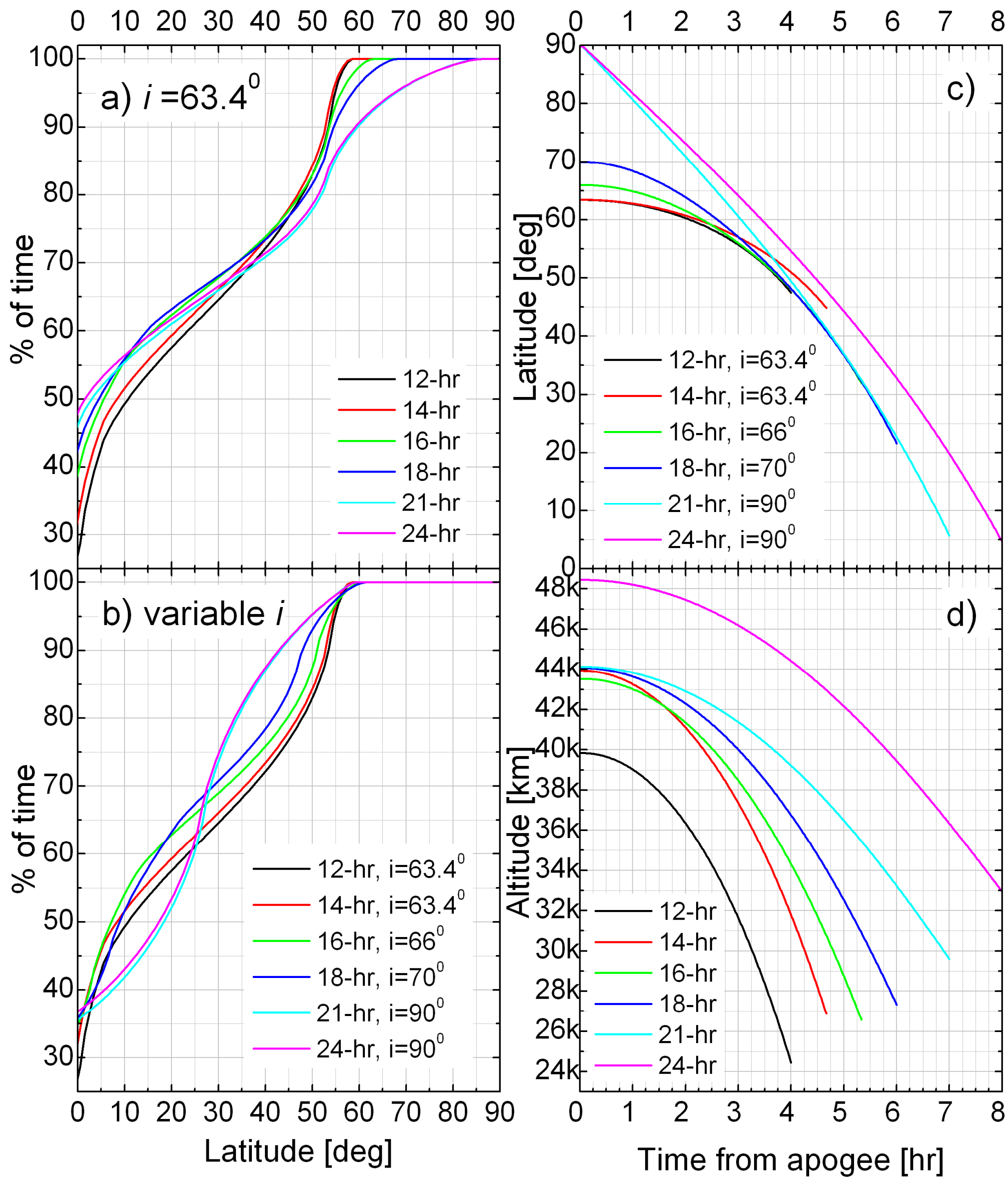

Figure 2. Zonal mean coverage for HEO orbits (Table 1) a) for critical inclination i=63.4^0 and b) inclinations needed to meet 100% coverage at 60^0; c) Latitude and d) height as functions of time from the apogee point corresponding to panel b).

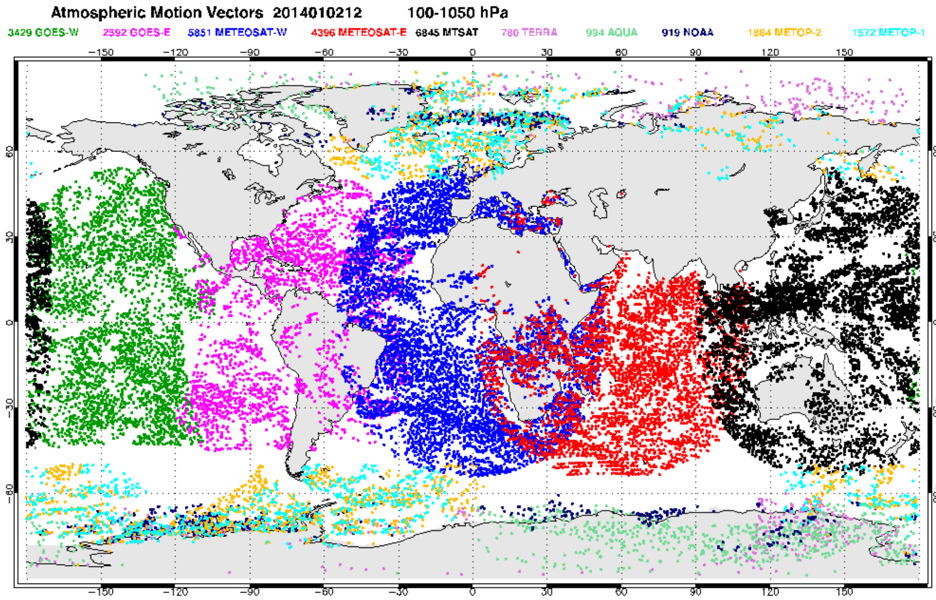

Fig. 3. AMVs available for assimilation at the Canadian Meteorological Center on January 2, 2014, for the period 9-15 UTC, after thinning and quality control. The 10 data sources (5 GEO and 5 LEO) are identified by a color code.

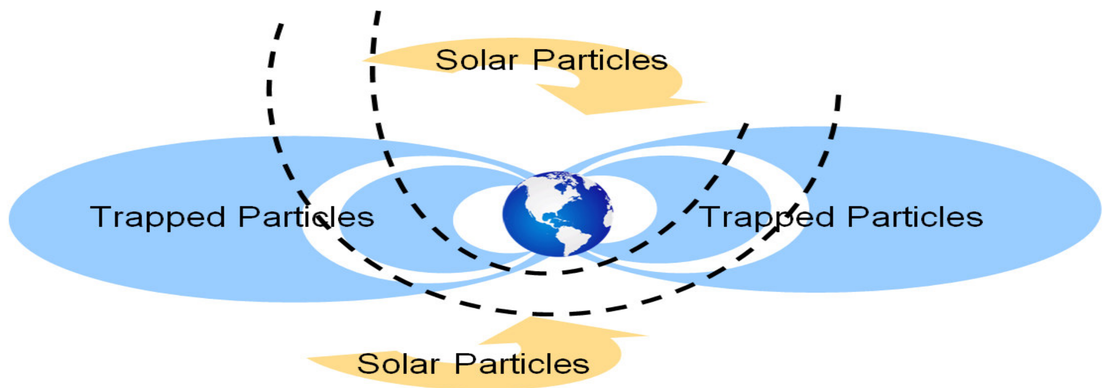

Figure 4, Schematic representation of two populations of ionized particles in the vicinity of the Earth. Trapped particles are pictured in the inner and outer belts (blue). The in-between region, called "slot", is indicated in white. Arrows (yellow) depict solar energetic particles entering the system.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

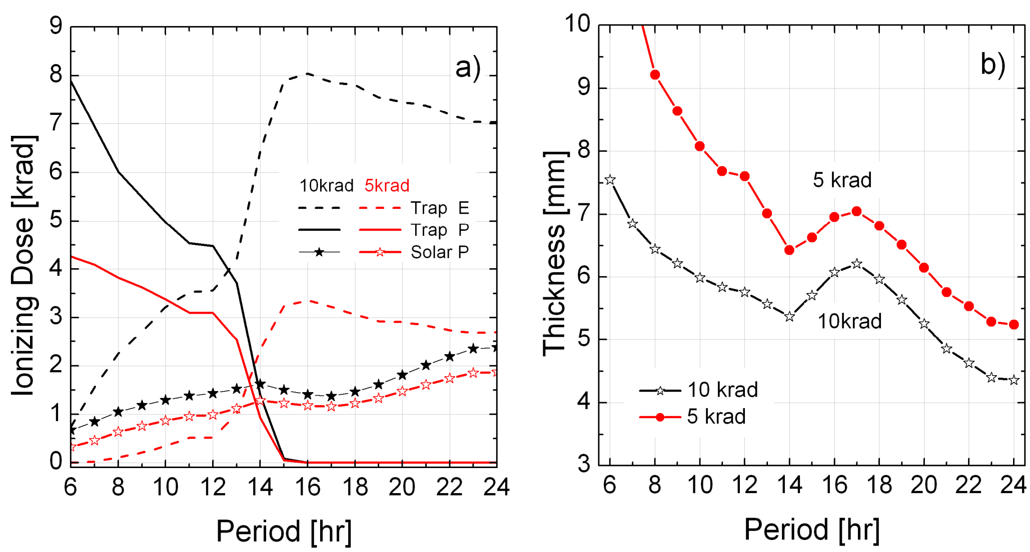

Fig. 5. For various orbital periods: a) contribution of trapped protons, trapped electrons and solar protons to an assumed total ionizing dose of 5 or 10 krad/yr; b) shielding (aluminum thickness, mm) required to keep the total ionizing dose at 5 and 10 krad/yr. The AE8/AP8 models implemented in the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