A QUASI-GEOSTATIONARY VIEW OF THE ARCTIC AND ENVIRONS: PCW/PHEMOS FOR ARCTIC WEATHER, CLIMATE AND AIR QUALITY

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Abstract

The PCW (Polar Communications and Weather) mission proposes to use two satellites each in a highly eccentric orbit with apogee ~ 42,000 km and a period in the 12-24 hour range. Orbits with these eccentricities are quasi-stationary for ±3 to 6 hours about apogee. With this system there is the potential to have 24x7 (continuous) coverage of the Arctic region in the Infra-red and more temporally limited coverage in the UV-Visible spectral region. The baseline meteorological instrument which would deliver meteorological data to the forecasting community is a 21-channel spectral imager similar to MODIS or ABI. The CSA is also exploring the possibility of additional instruments for atmospheric and auroral science. A Phase A study led by ABB Bomen, COM DEV and a group of atmospheric scientists from university and government commenced in the summer of 2011 including several international collaborators. This brief report presents the status of the development of a suite of innovative vertical sounding instruments with an imaging capacity. The instruments are an FTS with 4 bands from the NIR to MIR and a UV-Vis spectrometer to provide essential Arctic weather, climate and air quality data from the PCW satellite. Science goals of the instruments which will be used in concert with the PCW multi-spectral imager are the provision of basic weather information (temperature and water vapour), synoptic-scale air quality (gas and aerosol) measurements over the Arctic to better understand the impact of industrial and agricultural pollution and boreal forest burning on the Arctic and the acquisition of column abundance data on methane and CO₂ over the Arctic to assess perturbations due to their increasing release from the permafrost and from shallowly buried clathrates.

INTRODUCTION

The Canadian Space Agency, in partnership with Environment Canada and the Department of National Defence is planning an innovative mission called PCW (Polar Communications and Weather) that will combine communications and meteorology over the Arctic region. This mission will provide high capacity, continuous communication services throughout the Canadian Arctic as well as meteorological Earth observations which will lead to improved weather forecasting for the Arctic region. The PCW mission will also play a role in addressing issues of economic development in the North, environmental stewardship and sovereignty that are Canadian government priority areas. The PCW mission includes an imaging spectroradiometer (PCW/ISR) much like the MODIS or ABI imagers. It is planned to have ~21 channels overlapping with standard meteorological imaging channels to cover the visible, NIR and MIR. The spatial resolution of the shortest wavelength visible channel is ~ 0.5x0.5 km². The communications and meteorological goals of 24x7 coverage will be achieved using 2 satellites in tandem in a highly elliptical orbit (HEO) with an apogee ~ 42,000 km and an orbital period to be chosen between 12 and 24 hours. The 12 hour, or Molniya orbit is perhaps better for Earth observations since it has a lower apogee but with its lower perigee ~ 500 km the instruments are subjected to more intense high energy proton and electron radiation as the satellite crosses the Van Allen belts. A TAP (Three apogee orbit) (Trishchenko et al., 2011) with a 16 hour period is also being considered as well as a modified Tundra orbit (24 hour period, inclination > 80 deg.). Both orbits have reduced radiation hazards as compared with the Molniya orbit as their perigees are higher. The PCW/ISR is designed to cover the planet from apogee ± 3-4 hours (12-h period) up to
6-8 hours (24-h period). This should provide meteorological observations 24 h/day, 7 days/week of entire northern latitudes with high temporal resolution (of the order of 15 minutes) at MIR wavelengths and reduced coverage in the solar reflected light channels during the Arctic winter. This should provide more timely weather advisories and, more specifically, information about tropospheric winds using cloud images. The current paucity of knowledge of the tropospheric 3D wind field in the Arctic is a serious gap that cannot be addressed by LEO or GEO satellites.

PHEMOS

The PHEMOS (Polar Highly Elliptical Molniya Orbital Science) Weather, Climate and Air Quality instrument suite and science mission is an essential complement to the PCW meteorological mission. The proposed instruments will enhance the PCW meteorological mission by adding vertical sounding measurements to the suite of meteorological information gathered by the PCW meteorological imager. The basic instruments are an FTS operating in the near-IR (NIR) and Mid-IR (MIR) and a UV-Vis (ultraviolet-visible) spectrometer. The FTS will allow measurement of temperature and water vapour vertical profiles and a number of other species essential for understanding and prediction air quality in the Arctic and environs and monitoring changes in climate gases while the UVS instrument will provide additional critical measurements on air quality. Figure 1 shows the preliminary design of the PCW satellite.

![Figure 1: Potential design for the PCW satellite with payload](image)

**Weather, Climate Change and Air Quality Monitoring**

Changes in the Arctic region such as the rapid disappearance of multi-year ice (Wang and Overland, 2009) appear to be a harbinger of early climate change and global temperature changes are amplified at polar latitudes by changes in surface albedo, water vapour amount and possibly changes in the Arctic Ocean currents. As temperatures increase and summer multi-year ice recedes, ice melts for longer periods, the ocean warms and there is more moisture in the air which can lead to reduced radiative cooling, increasing the potential for storm formation. The increased radiative forcing also accelerates the melting of the ice.
The Arctic region is a fundamental driver critical for the development of winter storms in boreal latitudes. And as all major forecast centres use global models to drive higher-resolution, regional forecasts, this data set will be a major contribution to this international effort. Studying climate change at high latitudes requires a better understanding of weather and climate processes, such as convection, ice formation and precipitation and interaction with the changing snow and ice surface in polar regions.

It is important to monitor greenhouse gases (GHGs) in the atmosphere to understand and quantify their sources and sinks and this is no less important in the Arctic and high latitudes. In fact, there are concerns that methane could be released as a pulsed source from either warming permafrost or possible release from shallowly buried clathrates off the polar shelf (e.g. Shakova et al., 2010). In addition, there is an awareness of the potential for the rapid release of methane which would accelerate global warming around the world. The potential increase in release of CO₂ from permafrost thaw or other manifestations of Arctic climate change is also an issue. Although in wetter permafrost regions, methane is the dominant GHG released, CO₂ dominates in drier elevated regions and understanding the balance between emissions of these two GHGs in a changing Arctic will continue to be important (Schurr et al., 2008). Canadian and international groups will be able to use the PHEMOS GHG data in concert with ground-based and aircraft data to better estimate GHG emission sources and sinks.

With the decrease in the polar multi-year ice the summer time Arctic becomes much more accessible to shipping and to mineral and gas exploration under the cold Arctic waters. Already large ships are making their way across the Arctic Ocean and this is likely to increase dramatically over the next 10-20 years (Corbett et al., 2010). As a result one anticipates that the air quality of the north will degrade and there will be a need for continuous monitoring of many species related to air quality (see below). Some of the emissions expected from shipping and drilling will be volatile organic compounds and NOx and so, in sunlight, ozone, a GHG, will be generated. In addition, SO₂ and NO₂ and particulate levels are expected to increase during the summer shipping and exploration period. Furthermore, with the potential drying of the boreal forest it is anticipated that the number of incidents of air pollution from the burning of the boreal forest impacting the Arctic will increase. PHEMOS measurements will provide an unprecedented view of air quality and, because of its flexibility of viewing, will also be able to monitor severe air quality incidents at mid-latitudes as necessary.

**Instruments**

In order to provide meteorological, climate and air quality data to complement the PCW/ISR imager, instruments with an imaging capacity are essential. The total mass, power and volume available for the PHEMOS instrument package are 50 kg, 100 W and 27,000 cm³, respectively. These tight constraints impose strict limitations on telescope size, spectral and spatial resolution. One of the innovations is to house the FTS and UVS within the same structure as shown in Figure 2.

![Figure 2. Preliminary design for the FTS/UVS instrument combination for PCW/PHEMOS.](image)

The objectives call for an observation quality for species and temperature to be at least as good as currently available from an LEO. Thus an FTS was chosen with spectral range 0.7 to 14 µm, with 4 bands, listed in Table 1. There are two MIR bands viz., band-1 from 6.7 to 14.2 µm and band-2 from
3.7 to 5.6 µm and two NIR bands, Band-3 ~1.6 µm and Band-4 at 0.76 µm. The goal for the FTS spatial resolution is 10x10 km². The spectral resolution is 0.25 cm⁻¹ for bands 1 to 3, and 0.5 cm⁻¹ for band-4. Information on the sensitivity is given in Table 1 and is slightly better than the current version of IASI flying on METOP-2. The UVS instrument is a grating spectrometer with 1 nm spectral resolution in order to retrieve the target AQ gases listed in Table 2 (see below). The goal for the spatial resolution of the UV-Vis instrument is 8x8 km². The S/N details are given in Table 1. To achieve the S/N requirements the FTS is required to stare at the same ground spot for ~ 100 seconds during which it is estimated that cloud movement in the image will not be a serious problem. The UVS instrument will only stare for a few seconds during which it will take many images of the same spot to satisfy detector constraints. The main challenge is to make the instruments relatively compact and with relatively low mass.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Spectral Range</th>
<th>Spectral Resolution</th>
<th>Sensitivity Goal (G), Threshold (T)</th>
<th>Ground IFOV</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTS – Band 1</td>
<td>700 – 1500 cm⁻¹</td>
<td>0.25 cm⁻¹ ±2 cm OPD</td>
<td>NEDT cm⁻¹ 700-1500 cm⁻¹ 0.33K (T) 700-1500 cm⁻¹ 0.075K (G) 700-1000 cm⁻¹ 0.1K (G) 1000-1200 cm⁻¹ 0.2K (G) 1200-1500 cm⁻¹ 10x10 km² Contiguous</td>
<td></td>
</tr>
<tr>
<td>FTS – Band 2</td>
<td>1600 - 2700 cm⁻¹</td>
<td>0.25 cm⁻¹ ±2 cm OPD</td>
<td>NEDT cm⁻¹ 1.0(G) 1800-2000 cm⁻¹ 1.0(T), 0.5(G) 2000-2200 cm⁻¹ 2.0(T), 1.0(G) 2200-2700 cm⁻¹ 10x10 km² Contiguous</td>
<td></td>
</tr>
<tr>
<td>FTS – Band 3</td>
<td>5990 - 6450 cm⁻¹</td>
<td>0.25 cm⁻¹ ±2 cm OPD</td>
<td>&gt; 450 for 0.4 albedo at 60° SZA SNR(T)=300, (G)=500</td>
<td></td>
</tr>
<tr>
<td>FTS – Band 4</td>
<td>13060-13168 cm⁻¹</td>
<td>0.5 cm⁻¹</td>
<td>&gt; 500:1 for 0.4 albedo at 60° SZA 10x10 km² Contiguous</td>
<td></td>
</tr>
<tr>
<td>UVS</td>
<td>270 – 600 nm</td>
<td>1.0 nm</td>
<td>SNR(T)=1250, (G)=2000 nm SNR(T)=300, (G) = 600, 350 nm 2-D scan 8x8 km² Contiguous</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Target values for the PHEMOS System Characteristics (G-goal; T-Threshold)

It is anticipated that the Field of Regard (FoR), an area ~ 3400x3400 km² at apogee, will be imaged by both instruments. During the viewing period the spacecraft antenna will be pointing at the ground receiving station in Northern Canada and it is anticipated that for a Molniya orbit that observations will be taken ±3 hours of apogee which may be extended to ±4 hours under certain circumstances. During the descent the spatial resolution will improve by about 30%. In addition, during this period the ground track of the spacecraft will move at < 300 m/s.

Viewing Strategy

A zero order viewing strategy is that the field of regard (FOR) for both PHEMOS instruments will overlap with that of the PCW/ISR. However, for a significant part of the year the Arctic region will be in darkness and only the MIR channels of the PCW/ISR and the FTS can collect data (except perhaps for nightglow and auroral emissions). Thus it is planned to design viewing flexibility that the UVS and also FTS can be targeted at a different location from the PCW/ISR. For simplicity the imaging UV and FTS have a fixed range of viewing angles and a fixed number of pixels within this range. The highly elliptical orbit has significant variation of altitude as a function of time before and after the apogee point. As a result the FOR on the ground of these instruments changes over time being the smallest at apogee and increasing as much as 33% 5 hours before and after apogee. It is also planned to design flexibility into the viewing/scanning system so that special events can be tracked more rapidly with the PHEMOS instruments but with reduced spatial coverage. It is anticipated that boreal forest fires, volcanic eruptions, east coast pressure bombs or regional air quality events will be targeted.

As stated earlier the multiband imager will scan the full earth disk and hence provide the maximum arctic coverage in addition to extensive coverage at lower latitudes. On the other hand the imaging UV and FTS instruments have a limited field of regard and hence will concentrate nominal viewing in the high arctic region.

Species
The species to be measured by the PHEMOS instruments are important for weather (W), climate (C), and air quality (AQ) applications and the target species are listed in Table 2. Although the instruments for PCW/PHEMOS are science (as opposed to operational) instruments some of the anticipated products may be assimilated by weather forecast centres. In particular, it is anticipated that measurements of the tropospheric temperature and water vapour profiles using FTS measurements from Bands 1 and 2 will be important in improving Arctic weather information and this could lead to more accurate forecasting of winter storms that break out from the Arctic. It is anticipated that the radiances will be assimilated by the forecast centres rather than retrieved profiles.

<table>
<thead>
<tr>
<th>Data Product</th>
<th>Vertical Resolution (km)</th>
<th>Precision or column amount</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>W H₂O profile</td>
<td>2 km</td>
<td>10%</td>
<td>FTS, bands 1,2</td>
</tr>
<tr>
<td>W Temperature profile</td>
<td>2 km</td>
<td>1°C</td>
<td>FTS, band 1</td>
</tr>
<tr>
<td>C CH₄ partial column</td>
<td>4%</td>
<td>FTS Band 2</td>
<td></td>
</tr>
<tr>
<td>C CH₄ Total column</td>
<td>4%</td>
<td>FTS Band 3</td>
<td></td>
</tr>
<tr>
<td>C CO₂ partial column</td>
<td>1%</td>
<td>FTS Bands 1,</td>
<td></td>
</tr>
<tr>
<td>C CO₂ Total column</td>
<td>1%</td>
<td>FTS Band 3</td>
<td></td>
</tr>
<tr>
<td>C Ps NA 0.1%</td>
<td>FTS, Band 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C, AQ Aerosol OD O₂-A Band</td>
<td>Total Column</td>
<td>0.03 15%</td>
<td>FTS, Band 4</td>
</tr>
<tr>
<td>AQ Ozone Strat and trop columns</td>
<td>0.8x10⁻⁸ – 3x10⁻⁹</td>
<td>UVS, FTS band 2</td>
<td></td>
</tr>
<tr>
<td>AQ NO₂ Strat and trop columns</td>
<td>10⁻⁵ - 10⁻⁶</td>
<td>UVS</td>
<td></td>
</tr>
<tr>
<td>AQ CO Partial column</td>
<td>1.3x10⁻⁹</td>
<td>FTS, band 2</td>
<td></td>
</tr>
<tr>
<td>AQ Al Total column</td>
<td>0.03 15%</td>
<td>UVS</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Target PHEMOS Level 2 Products for weather, climate and air quality

In addition, the spectral range of the FTS will allow measurements of CO₂ and CH₄ columns in both the NIR and MIR. The NIR measurements will measure the total columns of these GHGs while the MIR kernels contain abundance information from the mid-troposphere. In order to be useful for source inversion the assigned precision requirements for CO₂ and CH₄ are high. The NIR Band 3 of the FTS has been allocated for these measurements. A critical support measurement for GHG retrievals is the O₂ A-band in the FTS band-4. The resolution targeted (Table 1) will allow the retrieval of surface pressure for converting the GHG column densities to column-averaged mixing ratios (XCO₂ and XCH₄), along with an assessment of the amount of aerosol or thin cirrus present.

Tropospheric air quality (AQ) products are also targets for PHEMOS and are also listed in Table 2. In this case it is anticipated that the vertical resolution will be ~5-10 km, so that in effect, vertical columns will be measured by the UV-Vis instrument and partial columns by the MIR channels of the FTS. Also for NO₂ and ozone the stratospheric columns (SC) have generally larger amounts than the tropospheric columns and care must be taken to extract the SC with sufficient accuracy that the tropospheric column (TC) has useful accuracy, hopefully for assimilation in air quality models in the post-2017 era. In addition, to ozone and NO₂ as target species we also intend to include CO as a target species in the MIR. Although the kernel is not optimised for full TC amounts measurements of MOPITT and IASI (Clerbaux et al., 2009) have shown that useful profile information can be extracted. As noted above aerosol information can be obtained from the O₂ A-band. But useful aerosol information can be obtained from the Aerosol Index (AI) (Guan et al., 2010) which yields information on the aerosol amount and aerosol location in the vertical.

There are many more species in addition to those listed in Table 2 than can be obtained with the PHEMOS instruments. These include in the UV-Vis BrO, HCHO, Al, (HCO)₂, in the MIR HNO₃, PAN,
CH$_3$OH, HCOOH, HCN, NH$_3$, CH$_3$COOH, and SO$_2$ is available in both the UV-Vis and MIR while CH$_4$, CO$_2$ can be measured in both MIR and NIR. Figures 3 and 4 below using model results give an appreciation of the distribution of species accessible to the PHEMOS instruments.

Some of these species will only be accessible by temporal and/or spatial averaging. Other species will only be available for special events such as, for example, a volcanic eruption where SO$_2$ was measured by IASI (Karagulian et al., 2010) using SO$_2$ bands at 4 and 7.3 µm, or as HCN emissions, for example, from forest fires species (e.g., Lupu et al., 2009) or Arctic Spring ozone depletion events when marine boundary layer BrO in the Arctic becomes very abundant (e.g., Toyota et al., 2010).

Synergy with the Meteorological Imager

There is a strong potential for an important synergy between the PCW/ISR and the PHEMOS instruments. PCW/ISR has higher surface spatial resolution, and a more rapid repeat viewing period, but its spectral resolution is much lower and, as compared to the FTS instrument in the mid-IR, there is a reduced capacity for vertical information. For example the PCW/ISR aims to have column ozone amounts, but the product derived from both the UV and mid-IR instruments will have height information and promises also be more quantitative. One of the important uses of the imager using the highest spatial resolution visible channel is for cloud clearing (see below).

Cloudiness Issues

Cloudy pixels are an issue for both instruments, although sometimes cloudiness can be turned to an advantage. For example if the cloud top height is known then the amount of material above that level is known and if there is a nearby cloud-free pixel then the differing amount of material lies beneath the cloud level. However, generally cloudiness poses a problem if it is not 100% or less than some small number depending on the retrieval problem. To some extent the spectral information in the MIR also contains useful information cloud clearing information. However, it will also be useful to have the more detailed spatial information available from the PCW/ISR.

Nadir observations can be adversely affected by clouds in the field of view. Krijger et al. (2007) studied the effect of sensor resolution on the number of cloud-free observations. However, if MIR channels with a higher altitude weighting function, such as at 14.5µm (~ 100 hPa) are chosen then much more temperature data becomes useful (e.g., McNally and Watts, 2003). Also the ECMWF are now using completely cloudy pixels (McNally, 2009). Given the 10x10 km$^2$ ground pixel, approximately 18% of the pixels would be cloud-free globally, 21% would be at the 5% threshold and 26% would be at the 20% threshold. Given a 3x3 km ground pixel, approximately 25% of the pixels would be cloud-free,
25% would be at 5% threshold and 27% would be at 20% threshold. As stated above, the PCW/ISR imager data would be used for selecting the cloud-free ground pixels.

Aerosols

The PCW/ISR has the potential for retrieving AOD much like MODIS but, as for MODIS, it will be difficult to get accurate absolute amounts. However, the combination of the imager with the UV-Vis data and also the O$_2$ A-band (band-4) data can yield more quantitative product. As well, in combination with other information such as ground-based sunphotometer data or lidar data, the aerosol optical depth product can be improved. With the high spatial resolution of the ISR, there will be detailed information on the spatial dispersion of plumes from biomass burning, aerosol plumes from dust storms and also poor air quality as well as volcanic plumes. And combined with the measurement of species data it may be possible to extract improved information on fire emissions.

Conclusions

The PCW mission is an innovative mission to provide communications and meteorological data for the Arctic and environs. These meteorological goals will be enhanced the PHEMOS science instruments. In addition, they will also obtain critical information for the Arctic and environs on GHGs and air quality species, essential for monitoring the atmosphere during an era of anticipated dramatic change.

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