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Continuous coverage of the Arctic: Two-satellite Highly Elliptical Orbit (HEO) system is better than two dozen of LEO polar orbiters

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Polar Communication and Weather (PCW) mission (POLARSAT) on Highly Elliptical Orbit (HEO)

Major planned PCW Payloads

The Canadian Space Agency (CSA) in collaboration with other Canadian Government Departments is preparing for Phase B studies defining a 2-satellite HEO system – the Polar Communication and Weather (PCW) mission, which is also known as POLARSAT. Satellite will include an imager with very similar characteristics to ABI on GOES-R.

Operational Instruments

- **Meteorological payload – Multispectral Imager**
- **Space Weather Payload – Suit of particle detectors**
- **Communication payload**

Potential Research Instruments

Fourier Transform Spectrometer (FTS) proposed by ABB Bomem. Some other payloads in the areas of atmospheric remote sensing, geophysical imaging, and near-Earth space environment applications are under evaluation.

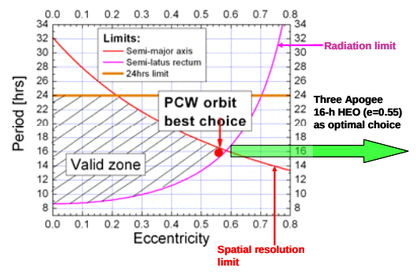
PCW Imager – Main Meteorological Payload

Band No.	Wavelength (microns)	Heritage	Priority	GSD (km) Goal	GSD (km) Max	Main applications
1	0.45-0.49	ABI,FCI	1	0.5	1.5	Surface, clouds, aerosols
2	0.59-0.69	ABI, FCI	1	0.5	1.5	Wind, clouds, ice mapping
3	0.704-0.714	MERIS-09	2	0.5	1.5	Water quality, chlorophyll
4	0.85-0.89	ABI, FCI	1	0.5	1.5	Wind, aerosols, vegetation
5	1.04 – 1.06	SGLI SW1	2	1.0	3.0	Snow grain and clouds
6	1.37-1.39	ABI, FCI	2	1.0	3.0	Cirrus detection
7	1.58-1.64	ABI, FCI	1	0.5	1.5	Snow-cloud distinction, ice cover
8	2.22-2.28	ABI, FCI	1	1.0	3.0	Aerosol, smoke, cloud phase
9	3.80-4.00	ABI, FCI	1	2.0	3.0	Fog, fire detection, ice/cloud separation, wind, phase.
10	5.77-6.60	ABI, FCI	1	2.0	3.0	Wind, high level humidity
11	6.75-7.15	ABI, MTSAT	2	2.0	3.0	Wind, mid level humidity
12	7.24-7.44	ABI, FCI	1	2.0	3.0	Wind, low level humidity,SO_2
13	8.30-8.70	ABI, FCI	1	2.0	3.0	Total water, cloud phase
14	9.42-9.80	ABI, FCI	2	2.0	3.0	Total ozone
15	10.1-10.6	ABI, FCI	2	2.0	3.0	Cloud, surface, cirrus
16	10.8-11.6	ABI, HIRS	1	2.0	3.0	Cloud, SST, ash
17	11.8-12.8	ABI, FCI	1	2.0	3.0	Ash, SST
18	13.0-13.6	ABI, FCI	1	2.0	3.0	Cloud height
19	13.5-13.8	MODIS,HIRS	2	2.0	6.0	Cloud height, low level temperature
20	13.8-14.1	MODIS,HIRS	2	2.0	6.0	Cloud height, mid level temperature
21	14.1-14.4	MODIS,HIRS	2	2.0	6.0	Cloud height, high level temperature

HEO orbit optimization

Frequently suggested orbit for HEO Polar mission is a classical Molniya 12-h orbit (Kidder and Vonder Haar, 1990). It provides good solution for spatial and temporal coverage of polar region above 50^{0}N (Trishchenko and Garand, 2011). However, this orbit exposes spacecraft and payload to very harsh proton radiation environment.

Optimization analysis points to **T**hree **AP**ogee (**TAP**) 16-h orbit as an optimal choice for PC 2-sat HEO system (**Figure 1**).



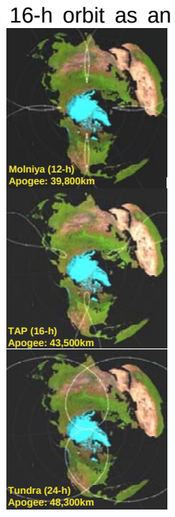


Figure 1. Orbit optimization: a) minimization of proton radiation doze, b) spatial resolution, c) orbit maintenance, d) data reception,- points to 16-h TAP HEO orbit.

References

Kidder, S.Q. and T.H.Vonder Haar, 1990: On the use of satellites in Molniya Orbits for Meteorological Observation of Middle and High Latitudes. *J. Atm. Oceanic Tech.*, 7, 517-522.

Trishchenko, A.P., L.Garand, 2011: Spatial and Temporal Sampling of Polar Regions from Two-Satellite System on Molniya Orbit. *J. Atm. Oceanic Tech*. Vol. 28(8), pp. 977-992.

Trishchenko, A.P., L.Garand, L.D.Trichtchenko, 2011: Three Apogee 16-h Highly Elliptical Orbit As Optimal Choice For Continuous Meteorological Imaging Of Polar Regions. *J. Atm. Oceanic Tech*. Vol. 28(11), pp. 1407-1422.

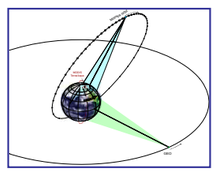
Trishchenko, A.P. and L.Garand, 2012: Observing Polar Regions from space: Advantages of a satellite system on a highly elliptical orbit versus a constellation of low Earth polar orbiters. *Canadian Journal of Remote Sensing*. Vol. 38, No. 2, 13pp, In press.

WMO, 2009: Vision for the Global Observing System (GOS) in 2025" adopted by the sixty-first session of the WMO Executive Council (EC-LXI).

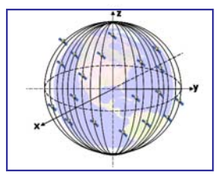
Issue

A constellation of numerous LEO satellites fails to achieve coverage requirements in polar regions, while a minimal 2-salellite HEO constellation can. Can we objectively and quantitatively evaluate that advantage ?

HEO - Highly Elliptical Orbit



LEO - Low Earth Orbit



Applications and refresh rate requirements

- The key atmospheric applications include a number dynamic phenomena
  - Atmospheric Motion Vector (AMV) retrievals
  - Ice/snow monitoring
  - Volcanic ash, smoke and aerosol dynamics
  - Atmospheric stability indices and aircraft icing threat
  - Radiative fluxes and surface albedo
  - Forest fire monitoring
  - Large number of other atmospheric, terrestrial and oceanic parameters
- Typical GEO refresh rate for next generation systems:
  - 1-min for local rapid scan
  - 5-min to regional rapid scan
  - 15-min for entire Earth disc
- Motion vectors are normally retrieved from image triplets=> 10-15 min refresh rate is optimal

2-satellite HEO spatio-temporal coverage

100% coverage above 60^{0}N can be achieved from HEO

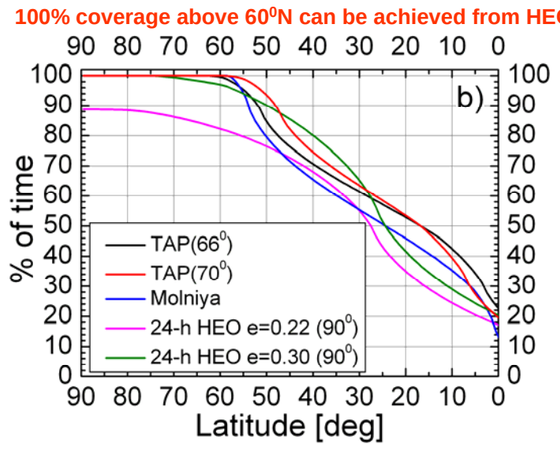
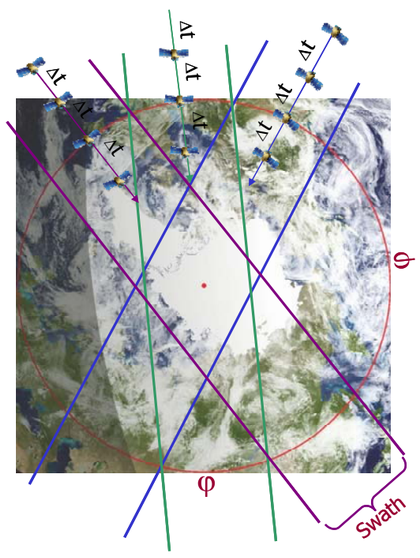


Figure 2. Zonal mean temporal coverage for TAP (66^0 and 70^0), Molniya (12-h) and 24-h HEO (e=0.22 and 0.30, inclination *i*=90^0) (data reception in Yellowknife with antenna elevation at > 5^0).

Spatial coverage from LEO system



Swath width

$$S = 2R_E\left[\arcsin[(1+\frac{h}{R_E})\sin\beta]-\beta\right]$$

Period

$$T = 2\pi\frac{a^{1.5}}{\sqrt{GM}}$$

Number of satellites (orbital planes) to cover latitude circle φ

$$M = \frac{2\pi R_E\cos\varphi}{S}$$

Number of satellites to maintain revisit time Δt

$$m = f\frac{T}{\Delta t}$$

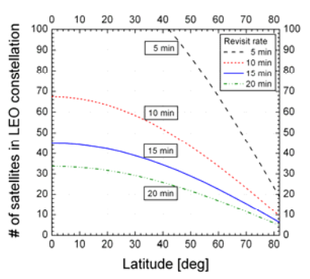
Total number of satellites

$$N = M \times m$$

Number of LEO satellites that provides revisit rate Δt at latitude circle φ

$$N = \tilde{N}(h,\beta)\frac{\cos\varphi\ \sin i}{\Delta t} \quad (*) \quad \tilde{N}(h,\beta) = \pi^2\frac{(R_E+h)^{1.5}}{\sqrt{GM}\left[\arcsin[(1+\frac{h}{R_E})\sin\beta]-\beta\right]}$$

h - orbit altitude; β – max scan angle; R_E – Earth radius; GM – gravitational constant; *i* – orbit inclination



at 60º latitude

Δt	Number of sats
20 min	17 LEO satellites
15 min	23 LEO satellites
10 min	34 LEO satellites
5 min	68 LEO satellites

LEO satellite orbits are similar to NOAA/JPSS

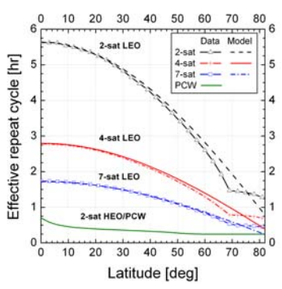


Figure 3. Left panel: The number of LEO satellites as function of latitude and revisit rate from Expression (*)
Right panel: Comparison of analytical results and precise orbit/image simulations for repeat cycle.

Realistic LEO configuration

To compare simple analytical LEO model with observations, we analyzed the realistic operational satellite constellation

Baseline NOAA/AVHRR LEO configuration

- AM & PM primary satellites (currently METOP-A and NOAA-19)
- AM & PM secondary and back-up (NOAA-15,16,18)
- VIIRS imager on NPP/Suomi (2012) was not included

MODIS on Terra & Aqua (frequently used for various applications)

Therefore,

Baseline LEO includes 4 satellites imagers

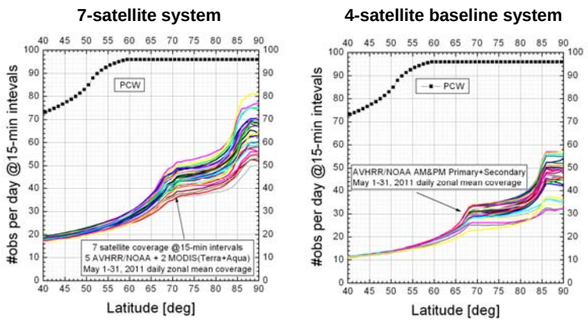
Extended LEO configuration can include up to 7 imagers

Calculations were conducted using *precise orbit navigation and image geolocation modeling*, as described by Trishchenko (1994)

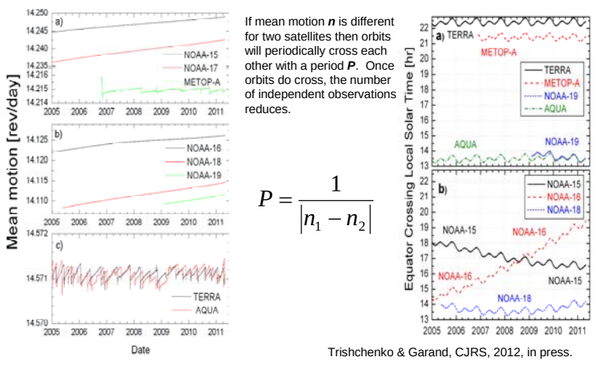
Zonal mean number of observations

Daily means for May 1-31, 2011 @15-min

(max possible is 96)



Variability in spatial coverage is due to mean motion *n* and Equator crossing time



If mean motion ***n*** is different for two satellites then orbits will periodically cross each other with a period ***P***. Once orbits do cross, the number of independent observations reduces.

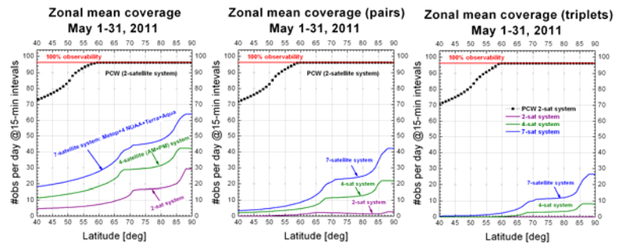
$$P = \frac{1}{|n_1 - n_2|}$$

Trishchenko & Garand, CJRS, 2012, in press.

Monthly mean zonal coverage

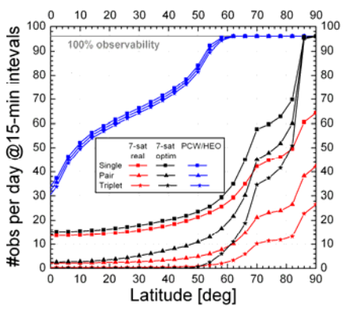
Example for May, 2011 with daily statistics averaged over 1 month period

Single images | **Image pairs** | **Image triplets**



Significant reduction of statistics for image pairs relative to single images (30% - 50% or more), and image triplets relative image pairs for LEO constellations (>50%). HEO statistics is not affected above 60degN, and very slightly reduced below 60degN.

LEO system can be optimized for better high-latitude coverage



- An optimized LEO constellation is designed to minimize the impact of image overlaps on spatio-temporal coverage.
- All ***N*** satellites have identical orbital period ***T*** and other elements, except for the Right Ascension of Ascending Node (RAAN) , which are equally spaced at the equatorial plane.

$$\Delta\Omega = 180^0 / N$$

- The crossing time of the equatorial plane for two consecutive satellites in the constellation differs by the interval ***T/N***
- An optimized system of 7 LEO satellites can improve coverage @15-min refresh rate to 100% of HEO only above 86^{0}N
- Still 8% -30% of HEO performance at 60^{0}N

Average efficiency of the PCW HEO system relative to LEO over 60^{0}N-90^{0}N region (for 15 min imagery)

Type of image statistics	Type of LEO constellation: 2-satellite	4-satellite	existing 7-satellite	optimized 7-satellite
Single	8.2	3.7	2.5	2.0
Pairs	52.2	10.9	5.9	2.9
Triplets	-	82.8	15.2	4.8

Efficiency is

$$\frac{(\#obs\ PCW)}{(\#obs\ LEO)}$$

Conclusions

- **PCW 2-satellite HEO system is significantly more efficient for observing Polar Regions than constellation of LEO polar orbiters;**
- **17/23/34/68 LEO satellites are required to update imagery every 20/15/10/5 min at 60^{0}N , respectively. Corresponding numbers in the vicinity of the North Pole are 5, 7, 10 and 20.**
- **Data reception/data collection issues for LEO system increase product latency and further reduce efficiency of polar LEO system in comparison to PCW.**
- **This result strongly support the idea of a HEO constellation to fill the spatio-temporal gap in the global Earth Observation System in support of WMO's vision to observe the global weather at any point and any time (WMO, 2009).**

Canada