ARCTIC WEATHER EVERY 10 MINUTES: DESIGN AND OPERATION OF ABI FOR PCW

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ABSTRACT

This paper discusses the key weather observation performance objectives for the Canadian Polar Communication and Weather (PCW) mission and how they drive the design and operation of a PCW imager.

The decreasing ice in the Arctic is leading to more personnel, ships, and operations, resulting in a greater need for more accurate, timely weather predictions. The US, Japanese, Korean, and European meteorological agencies are all upgrading their geostationary weather imagers to provide much more frequent Full Disk Earth images (every 5 to 10 minutes). Arctic weather observation, however, is still limited to a few passes a day from low Earth orbit (LEO) satellites, many of which are well beyond their intended operational life.

The Canadian Polar Communication and Weather (PCW) mission concept is to provide Arctic weather observations with the same temporal fidelity and spectral resolution as equatorial and mid-latitude weather, and similar spatial resolution. This paper discusses how the key performance objectives drive the design and operation of a PCW imager. Key mission decisions include number of satellites, orbit (LEO vs. HEO; Molniya, TAP, Tundra), coverage, image collection interval, types of images (Full Disk, storm watch, etc.), spectral bands, spatial resolutions, etc.

Exelis' Advanced Baseline Imager (ABI) will fly on GOES-R East, GOES-R West, Himawari (Japan), and GEO-KOMPSAT-2A (Korea), providing these missions the additional capability for interleaved mesoscales delivering storm observations every 30 to 60 seconds. ABI's operational flexibility also makes it an ideal solution for the PCW mission.

The Advanced Baseline Imager is a NOAA funded, NASA administered meteorological instrument program. This document does not reflect the views or policy of the GOES-R Program Office.

ARCTIC DESERVES SAME QUALITY OF WEATHER PREDICTIONS AS CONUS

Geostationary weather satellites have continuous coverage of their region of the Earth, providing high temporal resolution and the ability to monitor rapidly evolving severe weather events. The U.S., Japanese, Korean, and European weather agencies are all making significant upgrades to their geostationary weather imagers, enabling Full Disk Earth images every 10 minutes instead of every 30 minutes. The U.S., Japanese, and Korean imagers will also have the capability to interleave storm watch collections every 30-60 seconds. However, due to the curvature of the Earth none of these missions provide adequate spatial resolution above 60° latitude. Hence, the Arctic must rely on data from low Earth orbiting (LEO) weather satellites.

LEO weather satellites cover the entire Earth but even in the Arctic region they provide data for any given spot on the Earth only a few times per day. Their low altitude provides excellent spatial resolution but the orbit results in poor temporal resolution and no ability to monitor rapidly evolving severe weather.

A key factor in the accuracy of weather model predictions is the consistency of the initial conditions. For models driven by geostationary satellite data, all of the data is collected within 30 minutes (soon to be 10 minutes). On the other hand, for the Arctic's weather models the initial conditions are provided by data collected over 4-6 hours. So much of the "initial" condition data is actually quite old ("aging pixels"), which affects the accuracy of the results of the model.

Unfortunately, many LEO weather satellites are well beyond their design life and few are scheduled to be replaced. In the near future the amount of weather data for the Arctic will be significantly reduced – a marked difference from significant improvement in weather data for regions covered by the geostationary weather imagers, such as the continental United States (CONUS).

At the same time, the decreasing ice in the Arctic is leading to a need for more accurate weather forecasting. There is an increase in commercial shipping, commercial operations, and permanent residents. The decreasing ice is also causing more severe weather and greater variability in the weather.

The solution to this problem is the proposed Canadian Polar Communication and Weather (PCW) satellite. The PCW mission concept is to provide Arctic weather observations with the same temporal fidelity and spectral resolution as equatorial and mid-latitude weather, and similar spatial resolution.

Additionally, with the retirement of Meteosat-7 in 2016, there will be a significant coverage gap over the Indian Ocean (IO) region. Severe storm systems are common in this area and the observational gap will be detrimental to warfighter operations and to the nations in that region. PCW will also address this issue, providing significant temporal resolution for the Indian Ocean region for much of the day.

MISSION-LEVEL OPTIMIZATION

The goal of engineers is to produce an optimized design, where "optimum" is defined within the context of the system. Most optimization efforts are focused on a component (e.g. temperature sensing circuit) or assembly (e.g. power supply) but the same techniques can be applied to a space mission.

The first step in mission optimization is to identify the fundamental mission objective. In the case of a space-based weather imager, the objective is to produce high quality weather data products.

In the end, the payload, satellite, and ground station are merely the means by which these high quality weather data products are obtained. Optimizing each individually will not necessarily lead to an optimum mission. It is necessary to optimize the system as a whole.

However, there is more to a mission than just technical success. Missions are not flown unless they are affordable and timely. So the true objective of mission-level optimization is to ***maximize the quality and quantity of weather product data at minimum cost and risk***.

The key parameters for obtaining high quality weather data products are:

- Spatial resolution
- Coverage – both area and repetition interval (i.e. temporal resolution)
- Spectral bands
- SNR
- Radiometric Accuracy

These could be optimized individually but at the mission level there are trade-offs between them. The optimum solution depends upon the mission.

A key mission parameter derived from these data product parameters is orbit. The PCW mission will be used as a case study to show how mission-level optimization leads to a different orbital choice than just focusing on spatial resolution or coverage.

PCW MISSION CONCEPT

The PCW mission concept is to put two satellites in a highly elliptical orbit such that they provide continuous coverage of the Earth above 65°N latitude – both weather and communication. The weather data is to be comparable to that of the next generation geostationary imagers (ABI, AHI*, AMI†, FCI‡). This paper is focused on the weather mission but its conclusions are also applicable to the communication mission.

OPTIMUM ORBIT FOR PCW

Data Quality Assessment

Two fundamental data quality requirements drive the choice of the orbit:

- Coverage: 100% observation above 65°N latitude
- Spatial Resolution: Comparable to ABI, AHI, AMI, and FCI

The coverage requirement means a highly elliptical orbit (HEO) is required. There are many choices of HEO orbits. Three candidates that span the spectrum are:

- Molniya
- Three Apogee (TAP)
- Tundra

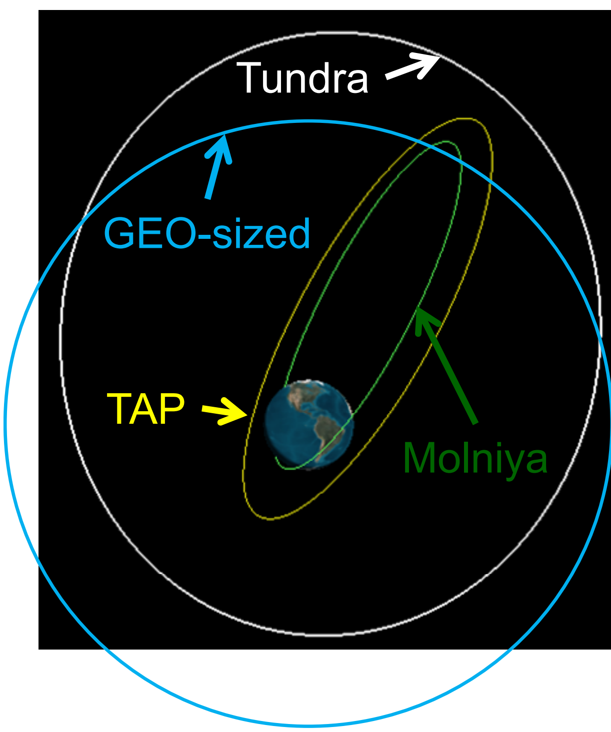


Figure 1 Molniya, TAP, and Tundra orbit geometries (the geostationary orbital radius is provided as a reference)

The orbit geometry for these three orbits is shown in Figure 1. Each will meet the 100% coverage requirement above 65°N latitude but their different apogees result in different ground resolution, as shown in Table 1. For ease

* AHI = Advanced Himawari Imager, which flies on Japan's Himawari satellite

† AMI = Advanced Meteorological Imager, which will fly on Korea's GEOKOMPSAT-2A satellite

‡ FCI = Flexible Combined Imager, which will fly on Europe's Meteosat Third Generation satellite

of comparison, the geostationary orbital parameters are also provided and the ratio of apogee to the geostationary orbital height is provided. Spatial resolution is inversely proportional to satellite height.

Table 1 Comparison Between PCW Candidate Orbits

	GEO	Molniya	TAP	Tundra
Perigee (km)	35,786	531	8,100	23,144
Apogee (km)	35,786	39,819	43,500	48,442
Apogee/GEO	100%	111%	122%	135%
Orbital period	24 hours	12 hours	16 hours	24 hours
Radiation	Moderate	Severe	Severe	~GEO
ABI Lifetime	15 years	5 years	7 years	15 years

If spatial resolution were the only criterion, then the Molniya orbit would be the clear winner. Its worst case resolution is only 11% greater than geostationary compared to 22% greater for the TAP orbit and 35% greater for the Tundra orbit.

However, “better” needs to be put in the proper context. The numbers in Table 1 are for a spot on the Earth directly below the satellite (the sub-satellite point, a.k.a. nadir). The geostationary missions, however, are not flown to collect data at nadir. The primary mission for GOES-R ABI is to collect data for the continental United States (CONUS). As can be seen in Figure 2, the orbital position of GOES-R East is on the equator at 75°W longitude, whereas CONUS is located north and west of this location. When PCW is at apogee in the Tundra orbit, it is centered within its region of interest.

As can be seen in the graph in Figure 3, the center of CONUS lies at latitude ~40°N. At this latitude an ABI “1 km” pixel will have a ground sample distance (GSD) of 1.5 km. (Note: this does not account for the offset in longitude between the orbital position of GOES-R and the location of the center of CONUS, which would result in an even larger GSD.) For a PCW imager in the Tundra orbit at the center of the region of interest, a “1 km” pixel would have a ground sample distance of 1.35 km. Hence, even the worst case PCW orbit has a better resolution at the center of its region of interest than the geostationary ABI has at the center of its region of interest. So while Molniya may be “better”, Tundra meets the requirement of providing resolution comparable to the geostationary imagers. In addition, the Molniya orbit at apogee is not located above the North Pole. So while its nadir GSD is 22% better than the Tundra orbit, its worst case GSD over the PCW region of interest will not compare as favorably.

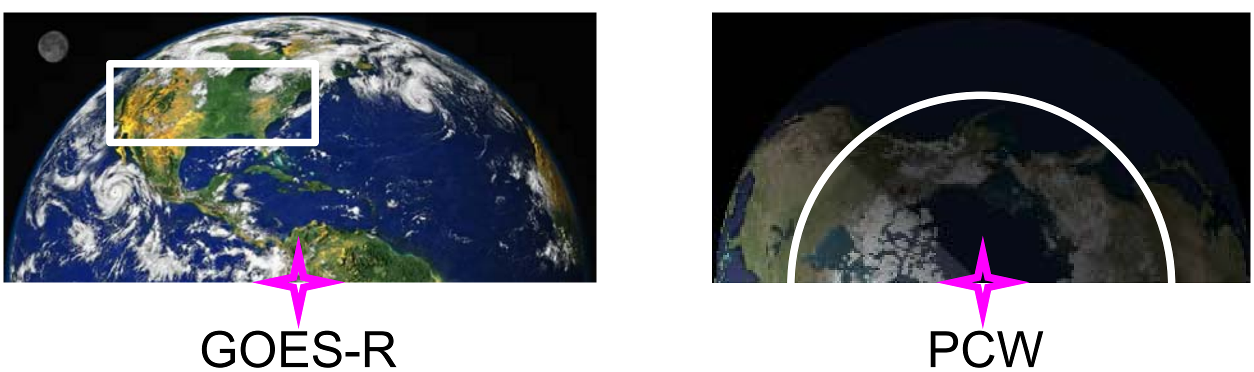


Figure 2 Orbital locations (pink star) for GOES-R and PCW (at apogee) relative to their primary region of interest (denoted by the white border)

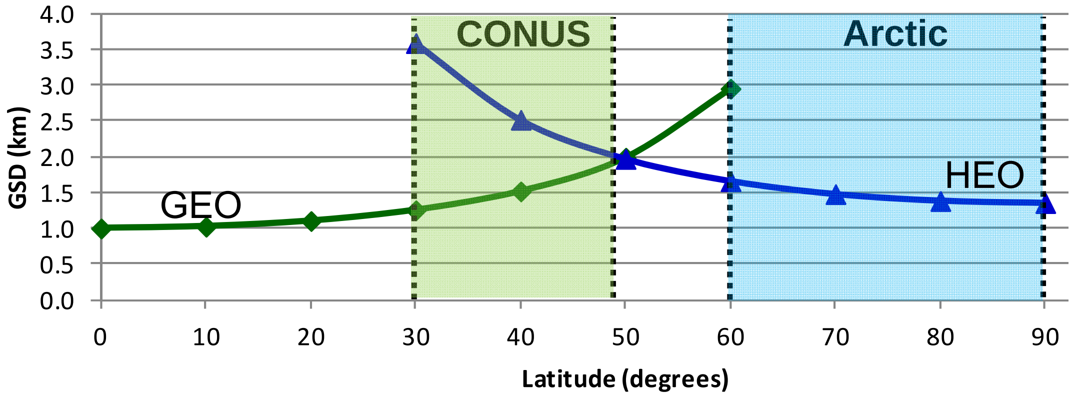


Figure 3 Comparison of the GSD for a "1 km" pixel between GOES-R East and PCW over their respective primary areas of interest (PCW at apogee)

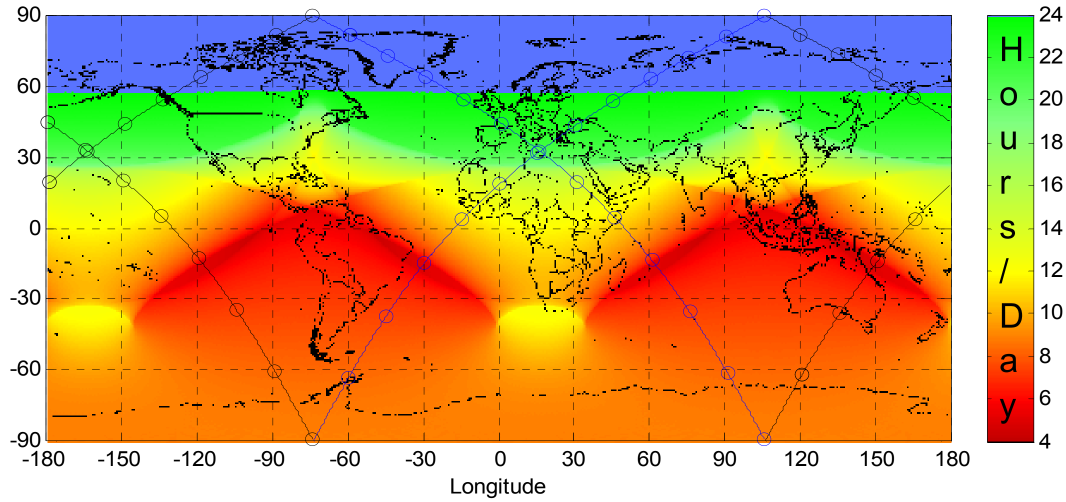
When it comes to "better" resolution, the importance must be measured in terms of the quality of the weather data products. An assessment performed during the ABI formulation phase trades studies for NASA concluded resolution needed to be improved by a factor of two in order to make a significant impact upon weather data products. The square root of 2 is 1.4, so anything less than a 40% improvement in resolution is really not significant. The Molniya orbit resolution is only 18% better than Tundra, which is less than half the level at which resolution improvement is considered significant. The TAP orbit resolution improvement is only 10% better than Tundra, which is even less significant. So while it is true that Molniya and TAP orbits provide "better" resolution, this improvement does not offer much value to the end user.

Another way to evaluate whether "better" resolution is really beneficial is to consider the ultimate use of this data, which is to drive the polar weather models. The US National Weather Service (NWS) models use grids of 3 km or larger. Environment Canada, European Centre for Medium-Range Weather Forecasts (ECMWF), and the United Kingdom Meteorological Office all use grids of 2.5 km or larger.

Currently these models are fed by data from the polar orbiting imagers, the newest of which is VIIRS. Comparing the GSD of VIIRS with that of an ABI instrument in PCW's Tundra orbit at apogee one finds that they have comparable resolutions as shown in Figure 6[§]. VIIRS' GSD is better at nadir but it is not uniform – there is a saw tooth variation based on the aggregation levels utilized, which requires distortion correction post-processing. ABI's resolution is smoothly varying. Both instruments, however, have sufficient resolution to support the standard polar weather models. So the "better" resolution of the Molniya and TAP orbits will yield no net improvement over the Tundra orbit because the data is all going to be mapped to the coarser grid of the weather models.

Like a LEO instrument, PCW will provide coverage for the entire globe. Unlike a LEO instrument, it can provide persistent coverage of the Arctic. Figure 4 shows the global coverage for PCW when flying in a Tundra orbit with one possible set of ground tracks. Figure 5 shows ground tracks optimized for the Indian Ocean region (providing 12-16 hours of coverage in the region), which will be of particular importance with the planned retirement of Meteosat-7 in 2016. The blue region is 24 hours of coverage per day. Every spot on the earth is observed for more than 4 hours per day and Antarctica is observed for more than 8 hours per day.

[§] Although ABI's final images are at 0.5, 1 and 2 km GSDs (at nadir), this is after resampling. The detector samples are collected on a finer grid. This is why the GSD at nadir in Figure 6 is less than the 1.35 km shown in Figure 3.



Telesat Tundra Orbit – Notional Equator Crossings

	LONG 1(LAT 0)	LONG 2(LAT 0)
Satellite 1	-129.95	162.341
Satellite 2	-17.659	50.051

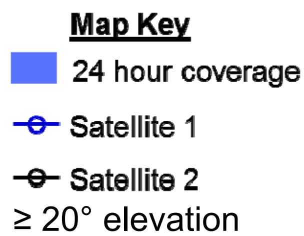


Figure 4 In addition to providing 100% coverage above 60°N latitude, ABI on PCW in the 90° inclination Tundra orbit will provide more than 4 hours of coverage everywhere on the Earth.

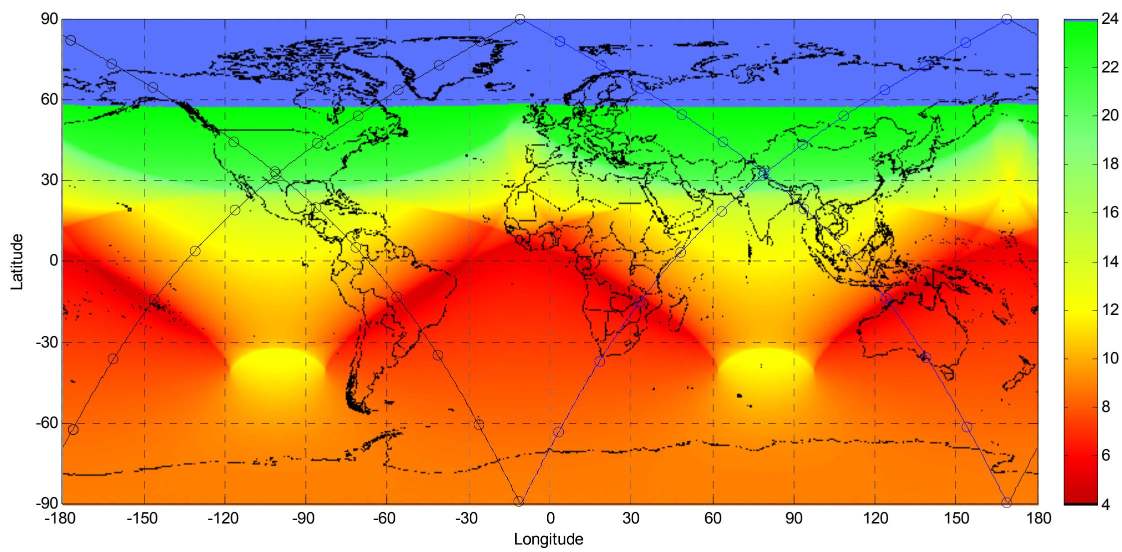


Figure 5 Choice of ascending nodes has no effect upon Arctic coverage but will affect the amount of coverage for regions near the equator. In this example the ascending nodes have been shifted to 67°W and 113°E, which provides improved coverage of the Indian Ocean (currently covered by the aging Meteosat-7, which will be taken out of service in 2016)

In Figure 6 one can also see the significant difference between the swath width of VIIRS and that of ABI in a PCW Tundra orbit. It is this difference in field of regard that provides the significant coverage advantages of PCW over current polar imagers.

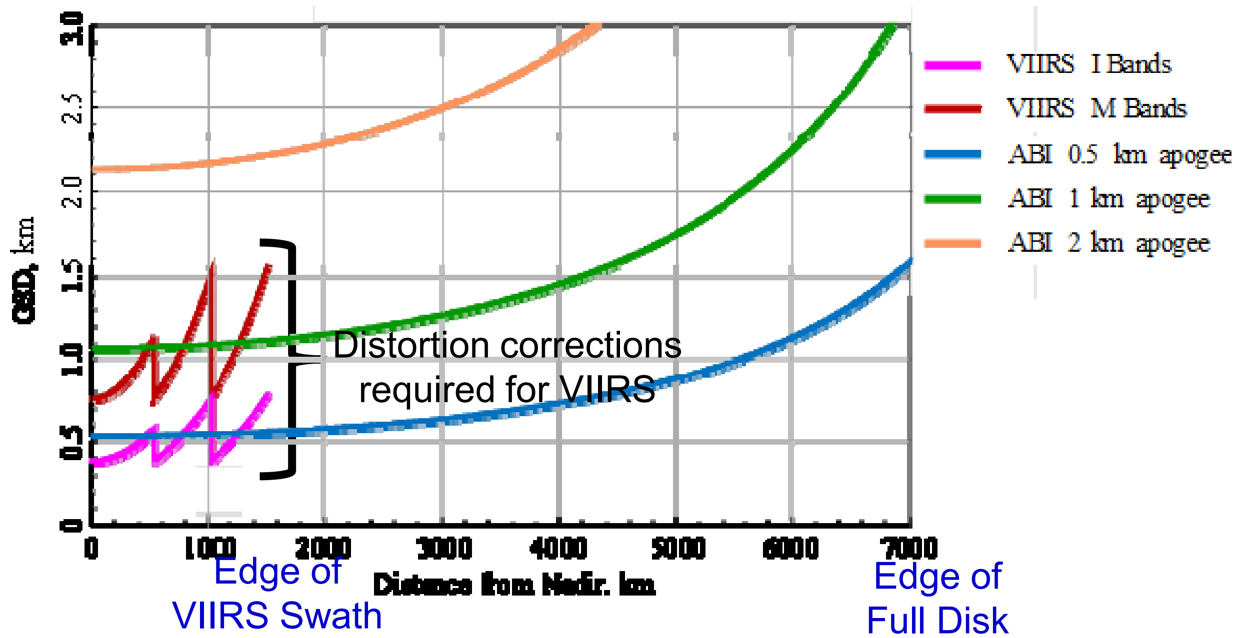


Figure 6 Comparison between the GSD of VIIRS in LEO and that of ABI in a PCW Tundra orbit

Life Cycle Cost

The final factor of the mission-level trade study for orbit is life cycle cost. There is a significant difference in the radiation environments between the Molniya, TAP, and Tundra orbits. This leads to a significant difference in expected mission life of the imager. Shown in Table 1 are the estimated lifetimes of the ABI payload in all three orbits. As can be seen, the "better" resolution Molniya orbit comes at a cost three times that of the Tundra orbit mission, requiring six satellites to be built and launched to accomplish a 15 year mission (a pair of satellites every five years). The TAP orbit is twice the cost, requiring four satellites whereas the Tundra orbit only requires two satellites. Hence, the Tundra orbit has a very significant life cycle cost advantage over the other two orbits.

Tundra Orbit Optimum for PCW Mission

Since all three orbits meet the resolution requirements, the Tundra orbit is the clear winner in terms of mission optimization. Although its resolution is slightly worse than that of the other two orbits, this difference makes no difference in the quality of the weather data products, whereas it's significantly better radiation environment means significantly lower mission life cycle costs.

Additional Comments:

- There are many variants possible within the Tundra orbit class. The 90° inclination Tundra orbit was analyzed for this document. It is also optimum for the communication portion of the PCW mission.
- There are many variants possible within the TAP orbit class. The 16-hour orbit was analyzed for this this document. Some of the other options offer better radiation environments and hence would offer a much lower mission life cycle cost. However, they are not as good from the communication aspect of the mission as the 90° inclination Tundra orbit.

While the Tundra orbit is not the best answer for all missions, it is the optimum orbit for the PCW mission as it is currently defined today.

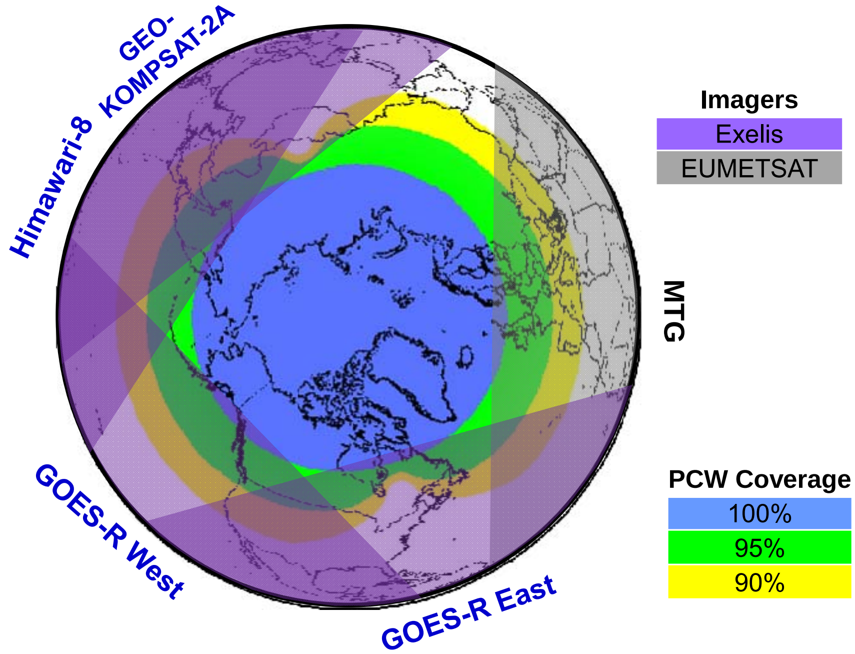


Figure 7 PCW will provide the Arctic the same coverage as the next generation geostationary imagers

OPTIMUM METEOROLOGICAL PAYLOAD FOR PCW IS ABI

Exelis' Advanced Baseline Imager (ABI) was developed for the GOES-R program. The flexibility of this design in terms of spectral channels and coverage enabled it to also be used for Japan's Advanced Himawari Imager (AHI) and Korea's GEOKOMPSAT-2A Advanced Meteorological Imager (AMI). To date, of the seven ABI-class imagers ordered, four have been delivered to their customers and AHI-8 is currently operating in orbit on Himawari-8.

Spectral Channels

The missions of GOES-R, Himawari, GEO-KOMPSAT-2A, and PCW are the same - collecting weather data. However, the regions they cover have different needs, which leads to a different optimum mix of spectral channels. The GOES-R program conducted trade studies during the ABI formulation phase and concluded that the sixteen ABI channels shown in Table 2 were the optimum set for the US mission. In Table 3 the primary usage for each band is provided.

The ocean plays a significant role in the economies and weather of Japan and Korea. For this reason, it was important for both Himawari and GEO-KOMPSAT-2A to have true red/green/blue imagery (Figure 8), which required adding a 1-km 0.51 μm (green) channel. Adding this channel meant eliminating one of the existing ABI channels in order to utilize the space-qualified design. The spectral bands for AHI and AMI are shown in Table 2.

The prime area of interest for PCW is the Arctic, where snow and ice play a significant role. There are 12 required channels and 9 optional channels identified for the PCW imager[1], one of which is the 1.05 μm channel used to better understand the snow. One possible mix of channels for PCW is provided in Table 2. The design of ABI utilizes separate bandpass filters for each channel, permitting easy customization for all four of these missions.

Table 2 Spectral channels for ABI, AHI, AMI, and one possible set for PCW demonstrate the design flexibility of ABI to accommodate different missions. Green-highlighted cells are spectral channels present on ABI but collected with different focal plane arrays (FPAs). Purple-highlighted cells are spectral channels not present on ABI.

FPM	FPA	Resolution (km)	Center wavelength (µm)			
			ABI	AHI	AMI	PCW
VNIR	A047	1	0.47	0.47	0.47	0.47
	A064	0.5	0.64	0.64	0.64	0.64
	A086	1	0.865	0.51	0.51	0.865
	A138	2	1.378	1.61	1.378	1.61
	A161	1	1.61	0.865	0.865	1.05
	A225	2	2.25	2.25	1.61	2.25
MWIR	A390	2	3.9	3.9	3.9	3.9
	A618	2	6.185	6.185	6.185	6.185
	A695	2	6.95	6.95	6.95	6.95
	A734	2	7.34	7.34	7.34	7.34
	A850	2	8.5	8.5	8.5	8.5
LWIR	A961	2	9.61	9.61	9.61	9.61
	A1035	2	10.35	10.35	10.35	10.35
	A1120	2	11.2	11.2	11.2	11.2
	A1230	2	12.3	12.3	12.3	12.3
	A1330	2	13.3	13.3	13.3	13.3

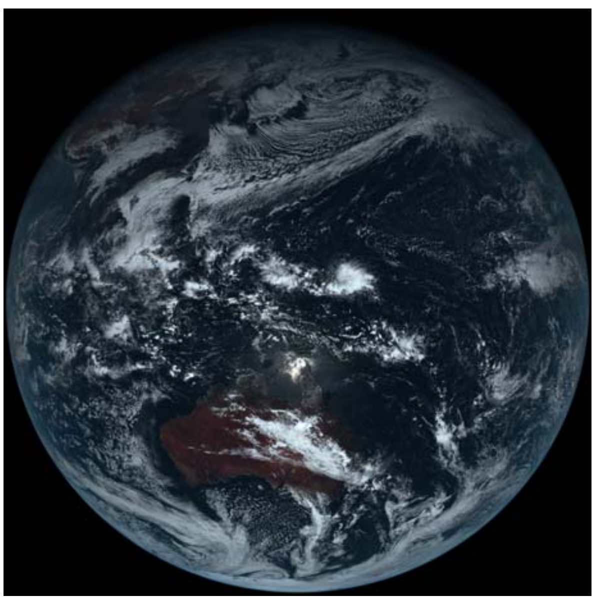


Figure 8 Himawari-8 first image – true-color (red/blue/green composite)[2]

Table 3 Data products from each spectral band (descriptions from ABI formulation phase and PCW RFI)

Band	Data Products
0.47	Blue: Surface, clouds, aerosols
0.51	Green: daytime green for true color
0.64	Red: Wind, clouds, ice mapping
0.87	Wind, aerosols, vegetation
1.05	Snow grain and clouds
1.38	Cirrus detection
1.61	Snow-cloud distinction, ice cover
2.25	Aerosol, smoke, cloud phase
3.9	Fog, fire detection, ice/cloud separation, wind
6.19	Wind, high-level humidity
6.95	Wind, mid-level humidity
7.34	Wind, low-level humidity
8.5	Total water, cloud phase
9.61	Total ozone
10.4	Cloud, surface, cirrus
11.2	Cloud, SST, ash
12.3	Ash, SST
13.3	Cloud height

Coverage

Although the weather missions are very similar between GOES-R, Himawari, GEO-KOMPSAT-2A, and PCW, their coverage requirements are quite different. ABI has two principal modes of operation[3]

- Flex Mode (Scan Mode 3)[**]: One Full Disk Earth image every fifteen minutes, one CONUS every five minutes, and one mesoscale (storm watch) image every 30 seconds – all interleaved into a single 15 minute timeline
- Continuous Full Disk (Scan Mode 4): One Full Disk Earth image every five minutes

Himawari collects a Full Disk Earth image every ten minutes, Japan regional images every 150 seconds, a rapid scan region (for storm watch or other purposes) every 150 seconds, and two landmarks every 30 seconds – all interleaved into a single 10 minute timeline[4]. GEO-KOMPSAT-2A will have its own unique timelines as well.

Even though GOES-R, Himawari, and GEO-KOMPSAT-2A have very different image collection scenarios, a standard ABI-class imager can support all three missions. Exelis' ABI-class imager was designed to easily support a wide variety of coverage missions. Its paradigm-shifting approach to image collection is to schedule the collection of swaths (a single constant-velocity scan maneuver to collect image data) rather than scenes (e.g. Full Disk, CONUS, mesoscale). Scenes are defined as a set of swaths and timelines define when each swath of each scene is to be collected. Scene and timeline definitions are both table uploads that can be updated at any time during the mission.

This scan flexibility permits ABI to also meet the coverage needs of the PCW mission. The PCW requirement is a Full Disk Earth image at least every 20 minutes and the goal is to be comparable with the next generation geostationary imagers, which means a Full Disk image every ten minutes plus regional observations. ABI can easily achieve the goal. Unlike GOES-R, Himawari, or GEO-KOMPSAT-2A, there is no local region (CONUS, Japan, or Korea) to be collected. There is a need, however, for rapid scan (one minute repetition) data of evolving severe weather or other areas of interest. ABI's interleaved scene collection permits these rapid scan images to be accomplished as part of a ten-minute Full Disk Earth image timeline.

[**] Exelis has also designed an ABI timeline that collects one Full Disk Earth image every ten minutes, a CONUS image every five minutes, and a mesoscale image every thirty seconds – all interleaved in a ten minute timeline.

Unlike the geostationary imagers, PCW will be moving north-south relative to the Earth's surface and the Earth will be rotating east-west under the satellite. Therefore, every scan of the Earth will be conducted from a slightly different geometry. The combination of the relatively slow orbital motion of the Tundra orbit, ABI's rapid image collection, and the large amount of swath-to-swath overlap offered by ABI ensures all data can be collected without any gaps in the imagery. Snapshots of the view of ABI from PCW for various times in the Tundra orbit are shown in Figure 9 along with ABI's ability to provide rapid scan updates.

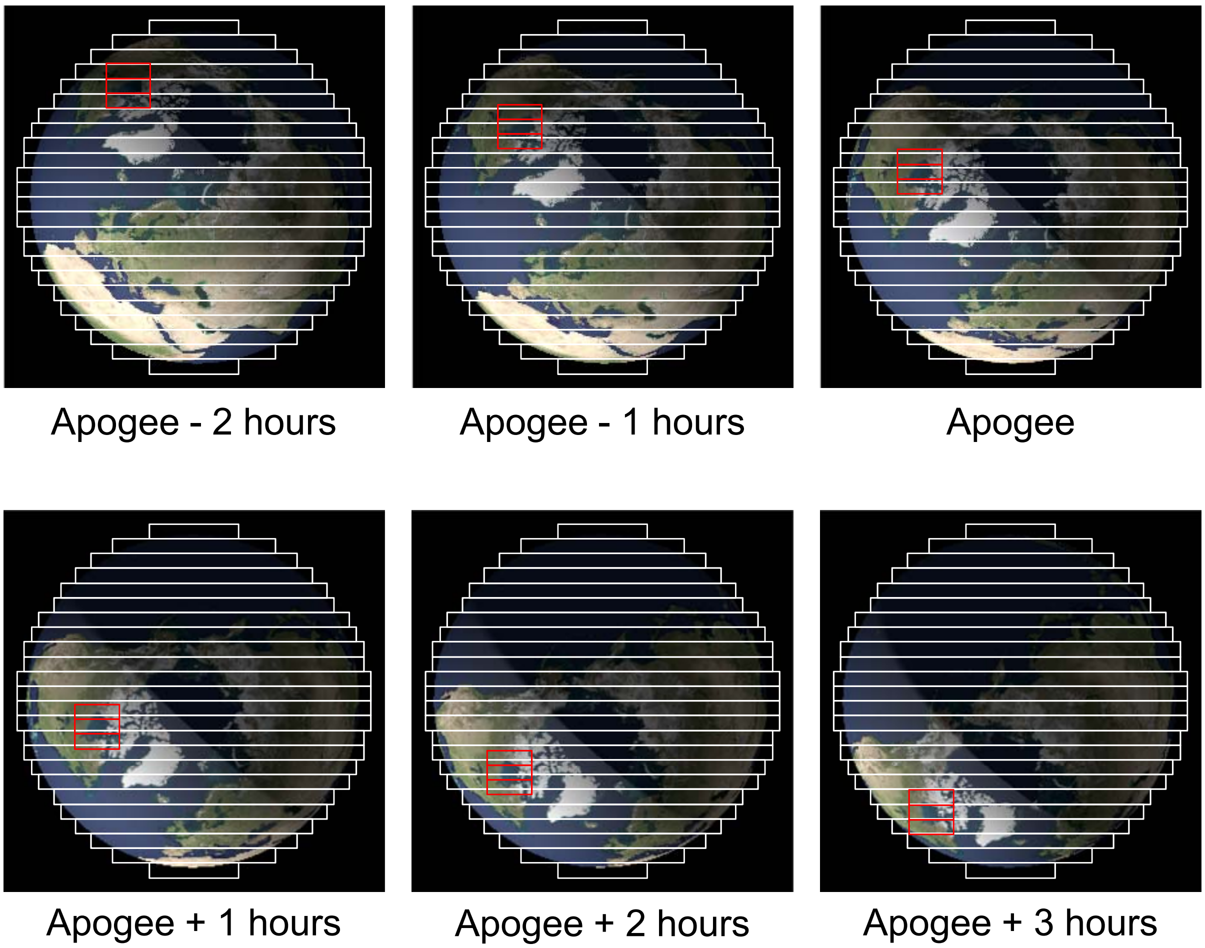


Figure 9 Example of ABI coverage over the course of the PCW orbit for one of the two satellites. Ten-minute Full Disk Earth image is collected using 24 swaths and rapid scan regional area (red square) is collected every minute using three swaths. For illustrations purposes, the rapid scan has been centered on Hudson Bay but it could equally well be Alaska, the North Pole, or another area of interest.

CONCLUSION

A total mission-level optimization can yield different mission parameter results than simply optimizing for a single data quality metric, as shown by the PCW orbit trade study. It is also critical to understand when differences in performance matter and when they don't, in order to avoid letting insignificant differences drive a trade study result to a less optimal solution.

Exelis' ABI-class imager provides the lowest risk and highest capability solution for the PCW mission. It is designed to deliver the spatial resolution and spectral bands required for PCW, has the flexibility to provide the coverage collection goals desired by the mission, and is low risk because it is currently operating on orbit on the Himawari-8 satellite (TRL-9).

Additional Information on ABI

1. GOES-R Advanced Baseline Imager, http://www.goes-r.gov/spacesegment/abi.html

Additional Information on PCW

1. Trichtchenko, L.D., L.V. Nikitina, A.P. Trishchenko, and L. Garand, 2014: Highly elliptical orbits for Arctic observations: Assessment of ionizing radiation. J. Adv. Space Res., 54, 2398–2414,
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4. Garand, L., J. Feng, S. Heilliette, Y. Rochon, and A. P. Trishchenko, 2013: Assimilation of circumpolar wind vectors derived from highly elliptical orbit imagery: impact assessment based on observing system simulation experiments. J. Appl. Meteor. Climatol., 52, 1891-1908.

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[1] Polar Communications and Weather (PCW) Project Request for Information (RFI), Solicitation W6369-04DC01/A, Public Works and Government Services, 1/11/2013 (https://buyandsell.gc.ca/procurement-data/tender-notice/PW-13-00535594)

[2] True-color composite (Band 1 (blue), Band 2 (green), Band 3 (red)) from Japan Meteorological Agency website http://www.jma.go.jp/jma/jma-eng/satellite/news/himawari89/20141218_himawari8_first_images.html

[3] ABI Modes of Operation, GOES-R website http://www.goes-r.gov/spacesegment/abi.html

[4] Himawari 8/9 imager (AHI) observation area and periodicity from Meteorological Satellite Center (MSC) of JMA website http://www.data.jma.go.jp/mscweb/en/himawari89/space_segment/spsg_ahi.html