The "Boreas" concept for imaging polar winds from the Iridium-NEXT constellation

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ABSTRACT

The Iridium communications satellite constellation is a swarm of 66 LEO satellites in 6 pole-crossing orbits. Iridium LLC plans a NEXT generation to be launched 2013-16, and has invited secondary "bolt and go" payloads from Earth-observing agencies. A swarm of infrared imagers on Iridium-NEXT could track water vapor and clouds to estimate the unobserved winds above the 55-60 degree latitude limit of geosynchronous satellite imagery. This kind of polar overpass data has been demonstrated to significantly improve medium-range weather forecasts by tracking water vapor features at 6.7 microns in successive images near the pole from NASA's MODIS instruments. A "Boreas" instrument design is proposed for a push-broom imager combining two miniature sensors: uncooled microbolometric cameras gathering 4-band infrared radiometry, and small star trackers providing attitude information. An autonomous instrument package has been designed with low mass, power, and data rate. The "Boreas" instrument would use the Iridium constellation itself to relay the raw imagery from 3 successive images to ground stations that would navigate the data and extract wind vectors. Wind vectors could be generated automatically for the polar caps every few hours, and delivered for assimilation into numerical weather models during Iridium-NEXT operations, during 2016-2030.

Keywords: polar wind, data assimilation, microbolometer, Iridium-NEXT

1. INTRODUCTION

Global wind data improve medium-range weather forecasting. Active 3-D wind measurements from space using doppler lidar are expected to fill the need decades from now. Meanwhile, passive wind measurements using cloud- and water vapor-tracked features at low- to mid-latitudes in time-series images from geosynchronous satellites are assimilated into the operational weather forecast systems, with sufficient success to warrant the effort. Consequently, feature-tracked polar wind measurements would be valuable space-based observations in the next decade.

1.1 Satellite-based winds

The IR spectral band at 6.7 microns observes in the heart of a strong water vapor absorption feature that limits viewing to the upper-middle troposphere, where the jet streaks appear as vivid dry slots. The 6.7 micron band is used operationally by the geosynchronous wind-determination systems. In the thermal infrared, the water vapor features can be tracked in clear air, day and night, at all latitudes. Years of experience with the geosynchronous imagery indicates that feature-tracked winds are reliably determined from a time-series of at least 3 images taken 15 to 60 minutes apart, with a few-hour cadence that matches the assimilation cycle of numerical forecast systems. However, the geosynchronous system is unable to track winds poleward of 55-60 degrees, and so weather forecasts fail whenever unobserved polar events influence the mid-latitudes, a common event since the polar regions are one-sixth of the Earth's surface.

1.2 Experimental polar winds from MODIS

NASA's Earth Observing System (EOS) of Terra (EOS AM) and Aqua (EOS PM) satellites carry a Moderate Resolution Imaging Spectroradiometer (MODIS) that passes near each pole at an altitude of 705 km once every 99 minutes. MODIS has 10 bands in the thermal IR, including a 6.7 micron channel which reveals polar weather as vivid as seen at lower latitudes. Retrospective experiments with feature-tracked winds using the MODIS 6.7 micron channel near the poles have successfully prevented "busted" 5-to-7 day forecasts and improved hurricane-track predictions.[1][2][3] The unexpected impact of experimental image-tracked polar winds upon medium-range forecasts has aroused interest in developing an operational space-based system.

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However, the requirement for 3 overlapping scenes at moderate time-intervals restricts MODIS coverage to features poleward of 70 degrees and with several hours latency. Indeed, any single low-altitude polar-orbiting satellite imager, such as the Visible/Infrared Imager/Radiometer Suite (VIIRS) on the National Polar-orbiting Operational Environmental Satellite System (NPOESS), will suffer the same limitations of not measuring winds in real time near 60 degree latitude. Because VIIRS also lacks a 6.7 micron spectral band, any scheduled operational polar wind product must wait for the post-NPOESS era, after 2030.

The following figure illustrates space-based feature-tracked wind-determination coverage from GEO and LEO satellites. In particular, it illustrates the gap in wind data between 60 and 70 degrees latitude.

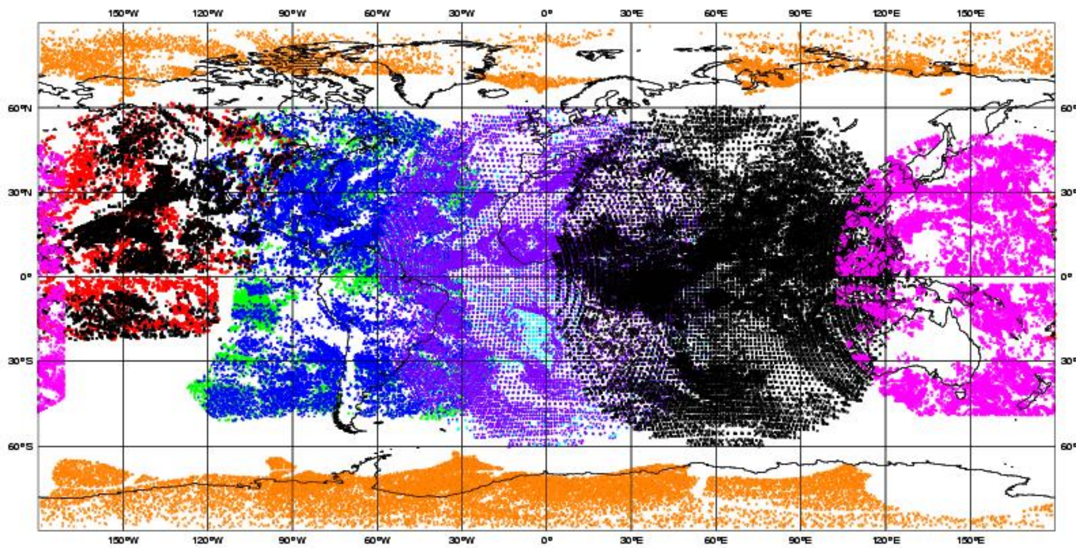

Fig. 1. Illustration of the global extent of feature-tracked wind coverage by the geosynchronous satellites at low-/mid-latitudes, and the experimental polar coverage by MODIS .

1.3 The Molniya option

One approach to achieving timely coverage down to 60 degrees latitude would be to replicate the geosynchronous imaging approach in a highly inclined orbit.[4] Indeed, an elliptical (e=0.75) 12-hour orbit with apogee just above geosynchronous altitude and inclined at 63.4 degrees to the equator is naturally stable, with 8-hour loiter times near apogee that keep the entire polar cap in view. The orbit and satellites are named Molniya (lightning). The Molniya orbit has been used for decades by Russia to maintain slow-moving communications satellites above the horizon in their northern latitudes.

Molniya's long loiter times would make it possible to mount a scanning infrared imager similar to the geosynchronous instruments to image the poles at 15-to-60 minute intervals and derive feature-tracked winds.[5] A single satellite would be operational for 8 out of every 12 hours, and deliver imagery in real time. Geosynchronous imager designs would have to be somewhat modified for a wider field of view, but they would be relieved of the stress of pointing near the Sun every day. Engineering design studies have found that a dedicated Molniya imaging mission would be feasible, with a cost and schedule comparable to a geosynchronous mission. The major cost of a dedicated Molniya imaging mission would be for "getting there", for spacecraft and launch, not for instrumentation and operations.

1.4 The LEO option

An Earth-observing satellite in a low-earth orbit (LEO) typically has an altitude of 700 km, an orbital period 100 minutes, and an instantaneous field-of-regard for useful imaging of 2000 km. Indeed, dozens of cross-track push broom or scanning imagers gather pictures of the Earth every day, as it rotates beneath them. To achieve more frequent imaging for feature-tracking, more satellites are needed as a train in the same orbit. At a minimum, 3 imagers in one orbit would gather strips of cloud-tracked winds, with any place on the surface viewed once every 12 hours.

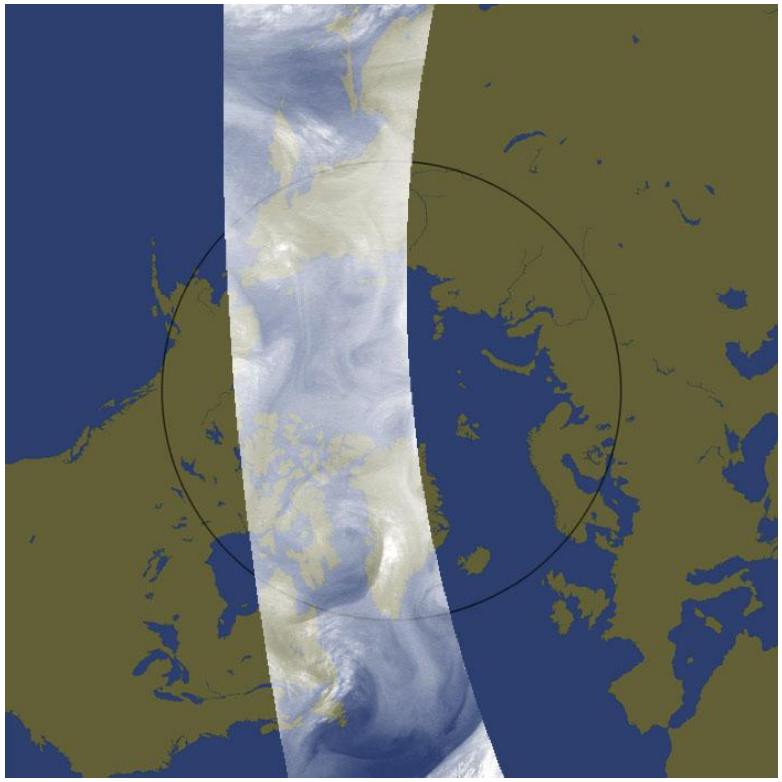

Fig. 2. Illustration of the mid-tropospheric water vapor features seen by a wide-angle imager (MODIS) during a single polar overpass by a polar-orbiting LEO spacecraft (Terra).

The infrared imaging instrument on a polar-orbiting LEO satellite could be a simplification of an existing earth-observing design. However, infrared science instruments have cryogenic cooling systems and moving parts that are expensive to design and build for a decade of reliable operations. In addition to observing IR pixels, the instrument would have to know where it is (orbit) and where it is pointing (attitude), in order to register successive images accurately to surface coordinates and measure motion. Once again, "getting there" is the major expense for a dedicated multi-satellite mission.

1.5 The Iridium-NEXT option

The Iridium communications satellite constellation is a swarm of 66 LEO satellites in 6 pole-crossing orbits designed to keep at least one satellite above the horizon at all times to provide telephone services. Iridium LLC plans a NEXT generation to be launched 2013-16, with significantly greater payload and communications capabilities. Iridium LLC has invited secondary "bolt and go" payloads from Earth-observing agencies. This is an opportunity to minimize the cost of "getting there" with a swarm of imagers to feature-track polar winds. The multiple orbit planes also present the opportunity to derive winds every few hours, instead of every 12 hours. Figure 1 illustrates a fully instrumented 66-satellite Iridium constellation, which would be able to assemble a complete image of the polar cap every 10 minutes and measure feature-drift winds every 30 minutes.

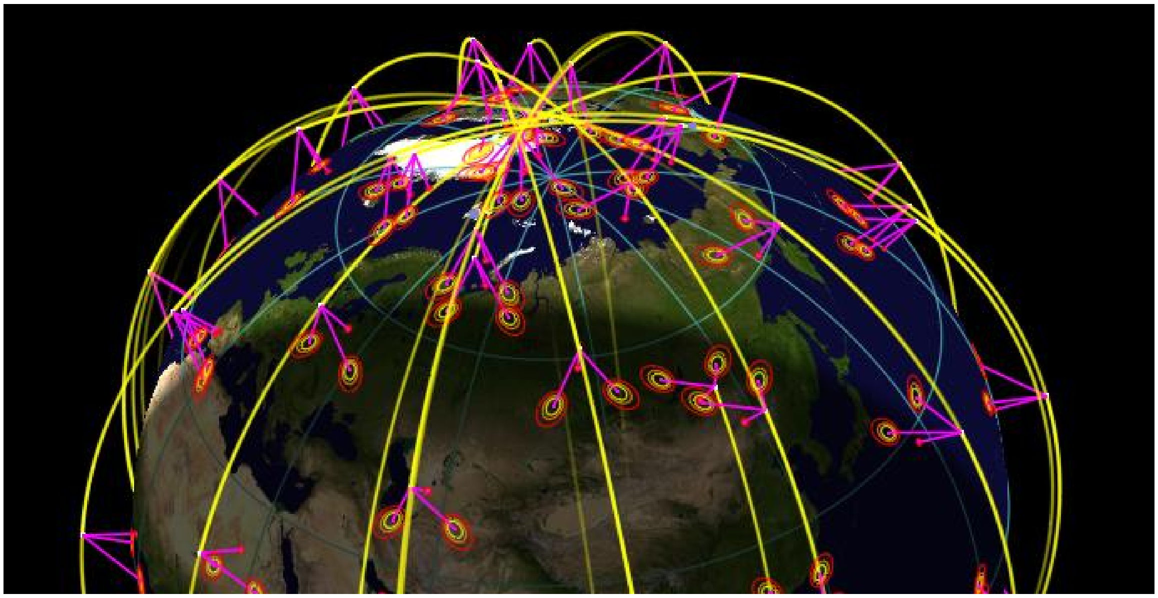

Fig. 3. Illustration of the 6 Iridium orbits populated with 66 satellites, each carrying an imager. Footprints have been simulated for two side-looking cameras on each satellite. The camera swaths converge by a factor of 2 at 60 N and overlap, providing pixels that could be assembled into a complete image of the polar cap.

2. THE BOREAS INSTRUMENT REQUIREMENTS

To take advantage of the polar imaging opportunity offered by IRIDIUM-NEXT, one needs an instrument to meets the satellite's "bolt and go" requirements, while providing accurate enough imaging to determine feature-drift winds operationally for 10 years. The design presented here is called "Boreas". It is based upon small, robust radiometers and star trackers available commercially.

2.1 Iridium-NEXT payload constraints

The Iridium-NEXT satellites significantly limit the resources available to the guest instruments: mass ~25 kg (<50 kg); power ~50 W (<200 W); voltage 28 VDC (22 to 36 VDC unregulated); size <20x24x15 cm external and <30x40x15 cm internal; data rate <1 Mbps; data protocol USB 1.2; thermal self-control (-20C to +60C); vibrations 5 G; shock 10 G; no moving parts allowed. The Iridium-NEXT satellites are expected to provide accurate time, GPS-quality orbit data, and smooth attitude changes.

2.2 The Boreas instrument requirements

The imager needs to detect thermal infrared features with 2 km resolution and similarly navigated accuracy. This implies that it must both have quiet, stable radiometry (normalized, but not necessarily calibrated) and it's own attitude-determination system, both with 10-year expected lifetimes.

The radiometric design goals were: push broom imaging to 60 degrees from nadir; spectral bands at 5.8-7.3 and 10.2-11.2 microns (more bands if low impact); single-sample noise <0.5 K @ 250 K (TDI allowed); 1 km sampling foot print at nadir; 2 km resolution "level-1b" pixels (resampled, navigated); >95% operable detectors; radiometric drift <1.0 NEDT/min.

The attitude design goals were: attitude knowledge with respect to stars <1.0 mrad (3 sigma); updates >1.0 Hz; autonomous recovery of attitude after turn-on or sun-view; rare outages due to sun/moon/earth-view.

To have a design that is robust and affordable, follow the precepts: use commercially available space-qualified parts; adopt single-string, redundant subsystems; survive the LEO radiation environment; keep it simple.

3. THE BOREAS INSTRUMENT DESIGN

Modern focal planes make the compact Boreas instrument feasible. The Instrument Design Laboratory (IDL) at NASA's Goddard Space Flight Center (GSFC) found it possible to meet the Boreas performance requirements within the Iridium-NEXT constraints. Because the imager has to perform low-noise radiometry in the thermal infrared without the luxury of cryogenic focal planes, the designers turned to commercial microbolometers. Likewise, the need for a small, smart star tracker is enabled by the development of commercial active-pixel focal planes.

3.1 Microbolometer telescopes

Today, 2-D microbolometer focal planes are sold by the thousands for monitoring industrial processes and surveillance, where robust, low-noise and moderate resolution images are required at television (30 to 60 Hz) refresh rates. The tiny changes in resistance with temperature of silicon pads in focal planes with 640x480 pixels can be operated with 0.05 K NEDT at room temperature. A complete IR telescope -- lens, spectral filter, focal plane, and readout electronics -- can be assembled in a package with the dimensions of a 12 oz soda can, drawing 3 W and weighing <200 gm.

One microbolometric telescope with Boreas-customized lenses, IR strip filters for spectral bands, and rad-hard electronics has a 90 degree cross-track field-of-view across 640 detectors. Three such telescopes, one pointed at nadir, and the other two pointed left-/right of nadir, constitute a push broom instrument with raw spatial resolution of 1-2 km. Four strip filters over the 480 pixels in a column provide generous TDI within 1 micron wide spectral bands at 6.7, 8.5, 10.5 and 11.5 microns.

3.2 Miniature star trackers

The need for modest attitude knowledge in a small package for space-based imaging has spurred the development of ever-smaller star trackers, now the size of a cup of coffee. Using an Active Pixel CMOS imager, the star tracker has an array of 1,000 by 1,000 pixels and is sensitive up to 4th magnitude stars. A star catalog of almost 600 stars is used, requiring very little processing power for pattern recognition. The star tracker has a 30° field of view, a tracking update rate of 1 Hz, and a mass of only 300 grams and power <2 W. Assuming uniform star distribution, an average of about ten stars are in any field in the sky. Two such star trackers, pointed "horizontally" with respect to nadir, and at least 90 degrees apart, assure <0.4 milliradian attitude knowledge in the Molniya orbit except for rare simultaneous appearances of the sun and moon in both star trackers.

3.3 Other Design Features

A dedicated field programmable gate array (FPGAs) for each telescope manages TDI, along-track data compression, and digital formatting for the USB serial data packet transfer to the spacecraft.

Radiation tolerance is assured by using space-qualified parts, typical mass shielding for LEO orbit, and focal planes with FPGAs that are inherently rad-hard.

Thermal control in the low-power Boreas instrument is managed by the usual wrap of multi-layered insulation (MLI) and radiation to space by perimeter sun shields.

Molecular contamination of the optics and lens damage during handling is minimized by the use of deployable lens caps.

3.4 Boreas design summary

One Boreas instrument consist of:

- 3 infrared cameras for horizon-to-horizon imaging
- 2 star trackers pointing 90 degrees apart
- field-programmable gate arrays to handle data
- 4 IR strip filters 1 micron wide at 6.7, 8.5, 10.5 and 11.5 microns per 640x480 microbolometer
- 2000 cross-track 10-bit radiometric samples with TDI, losslessly compressed to ~500 Mbps
- 15 kg, 10 W, 0.6 Mbps in a "bread box"

3.5 Boreas illustrated

The following figure shows the 3 canted cameras, 2 star trackers, and 1 electronics box mounted on a frame ready to "bolt and go" (MLI wrap not shown).

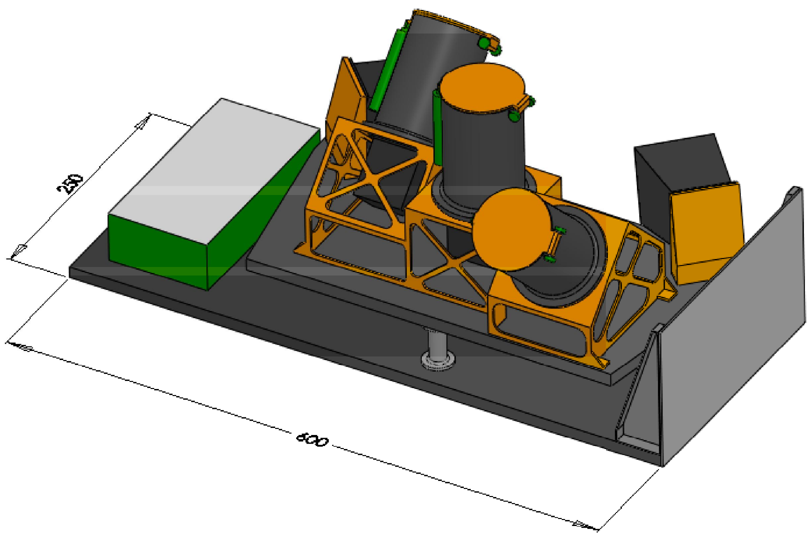

Fig. 4. Illustration of the Boreas instrument, with bolometric cameras looking at nadir (up) and left/right of nadir. Two star trackers are looking "horizontally", 90 degrees apart. The sensor data is processed by FPGAs in the adjacent electronics box.

4. BOREAS ON IRIDIUM MISSION OPTIONS

While it would be interesting to equip every one of the 66 Iridium-NEXT satellites with a Bores instrument, it is easy to minimize the population to save cost without compromising a 10-year operational mission.

4.1 Risk Mitigation

The Boreas instrument design itself is forgiving. It can still produce useful data if some detectors fail, some of 4 channels fail, if 1 or 2 cameras fail, if a star tracker fails. To make the constellation just as forgiving, the mission should somewhat over-populate the Iridium-NEXT swarm to tolerate the failure of a Boreas instrument or even an entire orbital group.

4.2 Sparse orbital population

By sparsely populating both the orbits and the orbital groups of Iridium-NEXT, the constellation can observe polar winds with sufficient redundancy to survive the risk of satellite or orbital failures. Consequently, we suggest a baseline design of Boreas instruments on 4 of the satellites in an orbital plane, for 3 of the orbital planes, as illustrated below. This requires only the launch and operation of 12 instruments.

In this case, one instrument/satellite failure in an orbit does not lose the functionality of the orbit, and 2 of the 3 orbits can fail without losing at least 12-hour intervals winds over the poles. The orbital groups can be phased to either arrive all at the same time over the same pole, or sequentially over the pole, depending upon the trade between simultaneous or continuous wind observations. Likewise, Boreas instruments an orbital group can be either tightly bunched or spread out over the orbit, depending upon the trade between detailed feature-identification or longer baseline motion tracking. In any case, the longest interval between wind-determination at 60 N latitude is less than 4 hours for 3 orbits each populated with 3 Boreas instruments.

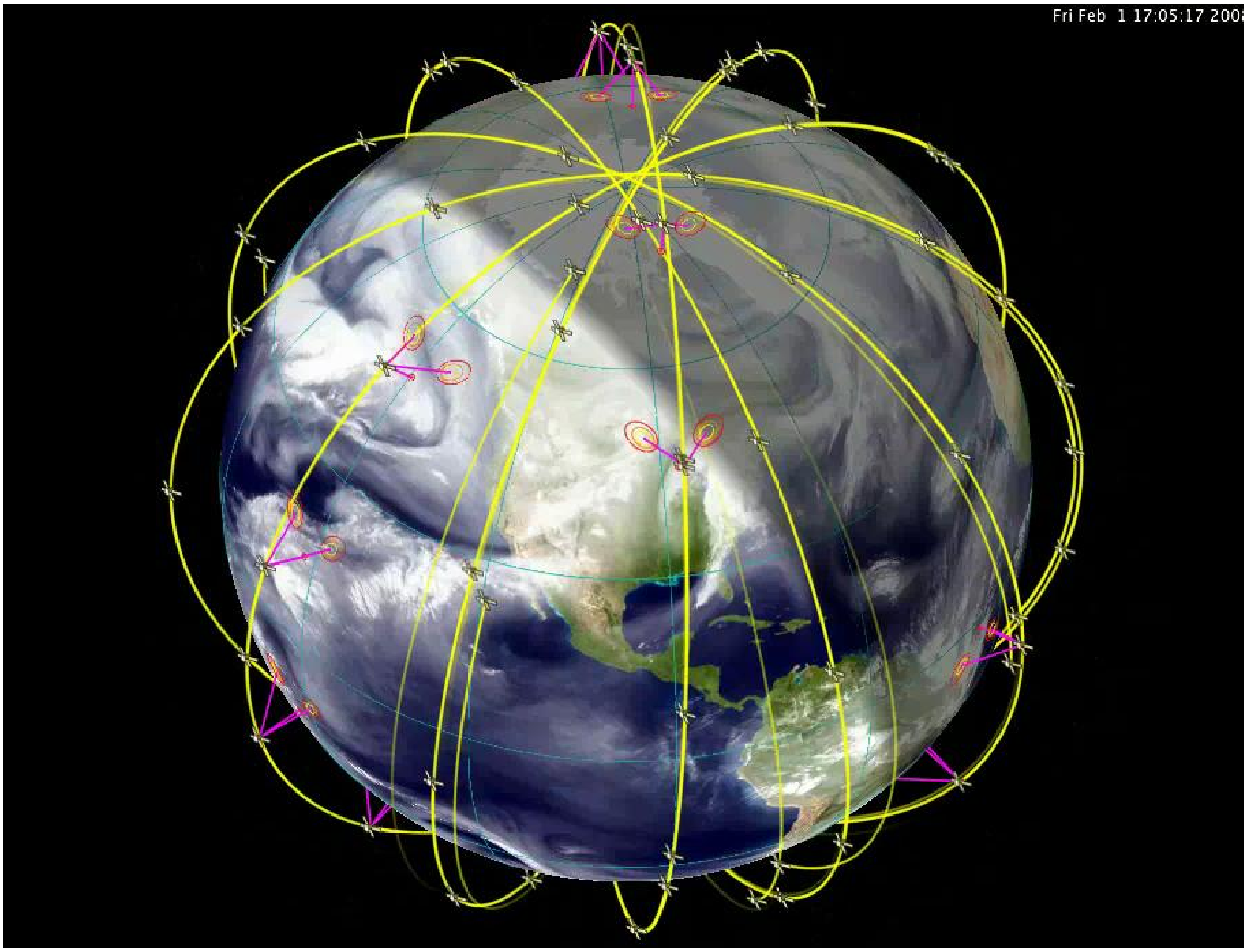

Fig. 5. Illustration of the Boreas-on-Iridium constellation, with 4 instruments on satellites in 3 orbits.

4.3 The financial benefits of polar winds

After the discovery of significant impact on medium-range weather forecasts using retrospective polar winds from MODIS, NOAA commissioned a standard benefit-impact study by the Mitre Corporation.[6] Using accepted values for the cost of polar aircraft transport and for avoidable hurricane evacuations, they found that the improved medium-range forecasts provided by a single MODIS-quality polar orbiter would provide approximately $10M/year in savings, assuming 2007 prices. Consequently, there is a definite financial incentive to operate polar wind imagers on the Iridium-NEXT constellation.

Finally, while considering the options for flying government-funded remote sensors on commercial spacecraft, the National Research Council recently declared: "In some cases, sensors can be manifested on already-planned missions to capitalize on surplus satellite performance capability. Flights of opportunity might leverage planned NASA or NOAA missions, or take advantage of so-called secondary-payload capability on planned commercial flights. Repeated commercial flights, such as those of Intelsat (GEO) and Iridium NEXT (LEO), offer potential opportunities for one-of-a-kind or extended lines of climate instruments to be flown at negotiated costs. Each platform will bring its own electromagnetic interference environment, pointing control and knowledge capabilities, and accommodation parameters. And each provider will have tight timelines, presenting a challenge to government programs when decision making and procurement occur over years, rather than months. However, these opportunities can provide cost-effective mechanisms for access to space for appropriate climate sensors and measurements, and should be considered."[5]

5. SUMMARY

A small, robust infrared imaging instrument called "Boreas" has been designed to fly on the Iridium-NEXT communication satellites in the next decade, and provide operational feature-tracked polar wind measurements that would improve medium-range weather forecasts and hurricane tracks. The instrument has no significant technical risks, and can be mass-produced from commercially available parts. The implementation of such a mission will require multi-government decision making and unusual commercial arrangements.

REFERENCES

[1] Key, J.R., D. Santek, C.S. Velden, N. Bormann, J.N. Thepaut, L.P. Riishojgaard, Y. Zhu, and W.P. Menzel, "Cloud-Drift and Water Vapor Winds in the Polar Regions from MODIS," IEEE (2003).

[2] Bormann, N, and J.N. Thepaut, "Impact of MODIS Polar Winds in ECMWF's 4DVAR Data Assimilation System," American Meteorological Society, pp 929-940 (2004).

[3] Riishojgaard, L.P., M. Sienkiewicz, and G.P. Lou, "The impact on forecast skill of water vapor and window channel winds from MODIS", Eight International Winds Workshop (2006).

[4] Riishojgaard, L.P., "Report on Molniya Orbits", WMO report CBS/OPAG-IOS/ODRRGOS-7/Doc. 7.5(1) (2004).

[5] Riishojgaard, L.P., and D. Chesters, "GOES to the Pole", GOES-R Users Conference VI (2005).

[6] Reining R., J. Sterling, G. Dittberner, and E. Miller, "Economic Benefits of Polar Winds from MODIS and GOES-R Winds", American Meteorological Society (2007).

[7] "Ensuring the Climate Record from the NPOESS and GOES-R Spacecraft: Elements of a Strategy to Recover Measurement Capabilities Lost in Program Restructuring", National Research Council, ISBN: 0-309-12185-X (2008).