THE "BOREAS" CONCEPT FOR IMAGING POLAR WINDS FROM THE IRIDIUM-NEXT CONSTELLATION

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Abstract

The Iridium communications satellite constellation is 66 LEO satellites in orbits that swarm over the poles. Iridium LLC plans a NEXT generation to be launched 2013-16. They have invited "bolt and go" secondary payloads from Earth-observing agencies. We propose a dozen infrared imagers on Iridium-NEXT to track water vapor and clouds and measure the winds above the 55-60 degree latitude limit of geosynchronous satellite imagery. This kind of polar overpass data has already 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 to deliver imagery in 4 thermal IR bands with low mass, power, and data rate, suited to the Iridium-NEXT platform. The Boreas instrument has no significant technical risks, and can be mass-produced from commercially available parts at an estimated cost of $60M(US) for a set of 12 instruments, including the NRE required to develop the first flight model. Costs for accommodation and operation are to be determined. A robust constellation would be 3 Iridium orbits, each populated with 4 Boreas instruments. They would relay imagery from frequent successive overpasses to user ground stations that would navigate the data and extract wind vectors in real time. Wind vectors could be generated automatically for both polar regions, and delivered for assimilation into numerical weather models during Iridium-NEXT operations, 2016-2030. The financial benefit of operational polar winds has been estimated to be worth $27M(US 2007) per year to global aviation and disaster management. The implementation of such a mission will require decisions by several government agencies, and unusual arrangements for the commercial delivery of operational weather data to weather forecasting systems.

POLAR WINDS FROM POLAR SATELLITES

The satellite-measured global winds significantly improve medium-range weather forecasts. Passive wind measurements using cloud- and water vapor-tracked features at low- to mid-latitudes in time-series images from geosynchronous satellites are currently assimilated into the operational forecast systems, with sufficient success to warrant the effort. The geosynchronous winds are limited to low and mid-latitudes, unable to see one-sixth of the Earth's surface near the poles. Consequently, 5-to-7 day forecasts are regularly "busted" by the effect of unobserved high-latitude weather systems. In addition, the growing commercial development of arctic resources and transportation requires better weather observations and forecasts for efficient operation and disaster avoidance.

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. 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(US)/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 US National Research Council (NRC) 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."

Polar wind measurements are a well-recognized un-met requirement by the metrological community. Despite the demonstrated value of satellite-derived polar winds, there is no space mission planned to observe them for the next few decades.

BOREAS SENSORS AS PART OF THE IRIDIUM CONSTELLATION

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 pushbroom imaging instruments on 4 of the satellites in an orbital plane (3 operational imagers plus one spare), in 3 of the orbital planes. This requires the launch of 12 instruments and operation of 9 imagers when over the poles, for 1/3rd of each orbit. On average, then, 3 imagers are downlinking their data. Figure 1 illustrates one possible constellation.

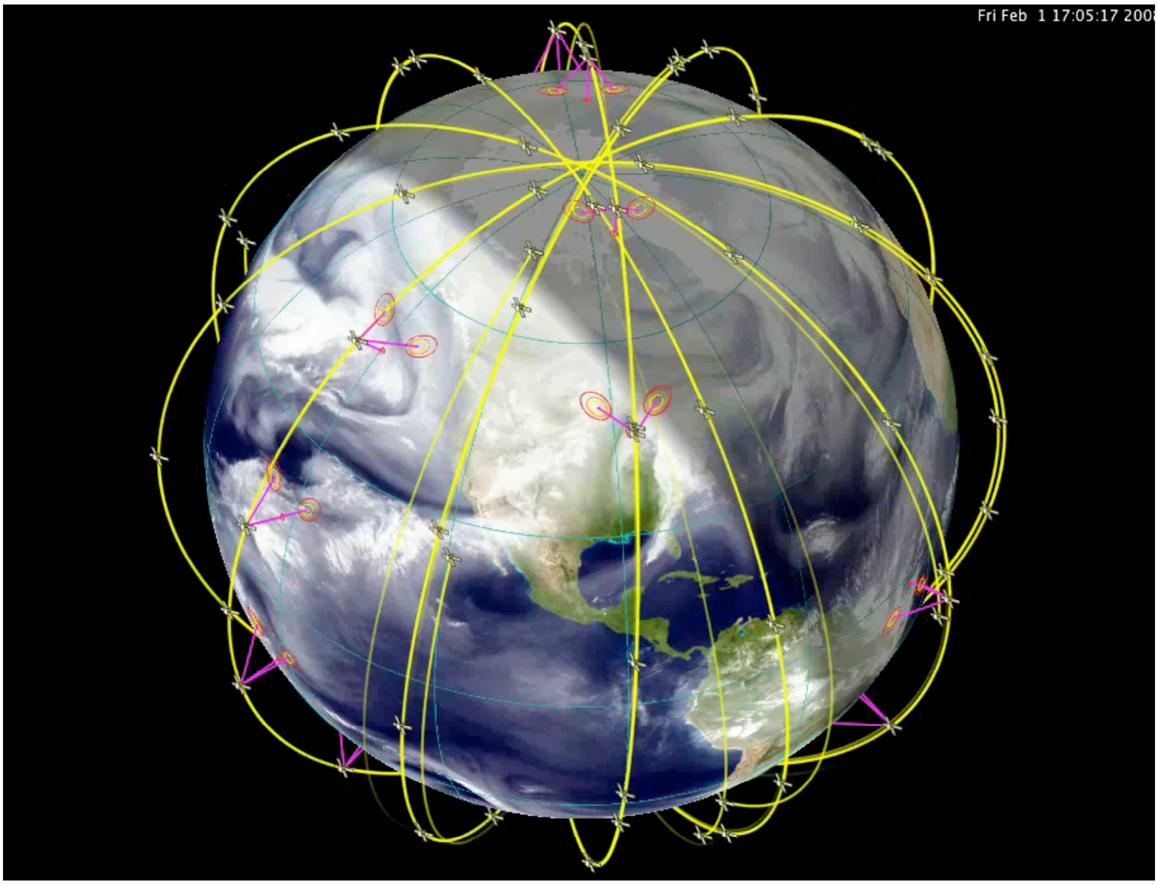

Figure 1: **A constellation of 4 Boreas instruments in 3 alternating Iridium orbits, with 2 camera footprints simulated. In this case, the 4 instruments are bunched together in each orbit, but the 3 bunches arrive over the poles separately, instead of simultaneously.**

With 3+1 instruments per orbit, 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 trades 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 degrees latitude is less than 4 hours for 3 orbits each populated with 3 Boreas instruments.

BOREAS INSTRUMENT PERFORMANCE SPECIFICATIONS

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, 0.1 km orbit data, and smooth attitude changes.

The Boreas 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 are: 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 are: 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: use commercially available space-qualified parts; adopt single-string, redundant subsystems; survive the LEO radiation environment; keep it simple.

BOREAS INSTRUMENT DESIGN

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.

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.

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 except for rare simultaneous appearances of the sun and moon in both star trackers.

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.

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"

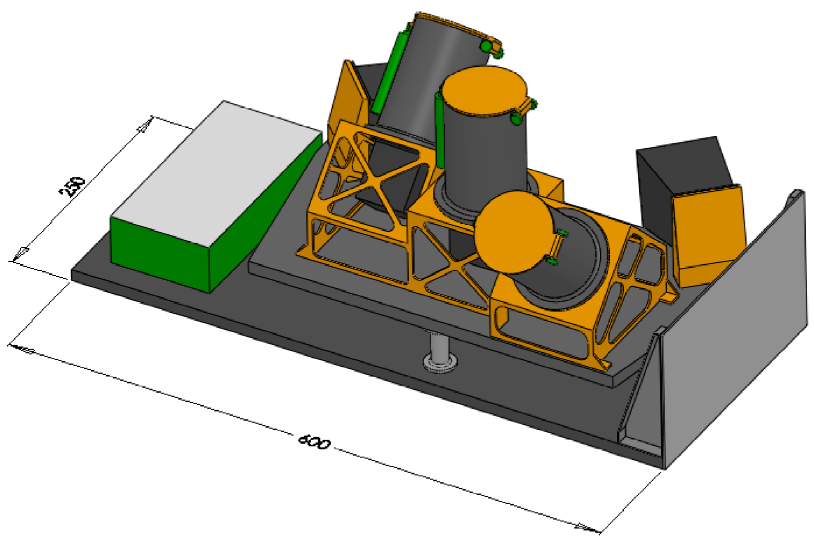

Figure 2: **The Boreas design consists of 3 canted cameras, 2 star trackers, and 1 electronics box mounted on a frame ready to "bolt and go". The cameras (with lens caps closed) are pointing up at nadir and left/right of nadir. The star trackers are looking "horizontally", 90 degrees apart. The sensor data is processed by FPGAs in the adjacent electronics box. The MLI and sun shields are not shown.**

The Boreas instrument is designed to be inexpensive and robust: no moving parts, no cryo-cooler, all space-qualified technology. The mission is also robust: it can survive the loss of a satellite or instrument in each orbit, of a camera in an instrument, of a channel in a camera, of detectors on a focal plane.

FLIGHT SEGMENT

The development of the Boreas instruments is proposed in two phases, development and production. The development phase leads to the delivery of the first flight model in 2012, and includes the NRE required to design and test the instrument. The production phase involves the commercial construction of 12+2 copies of the first flight model for delivery in 2013-15. The 2 spare instruments allow for a full launch complement of 12, even if 1 or 2 are not performing well.

Costs were estimated using validated financial and schedule models for NASA flight hardware, and include 30% contingency. Costs are minimized by using readily-available, high-heritage components (Janos lens, BAE microbolometer array, AeroAstro Miniature Star Tracker).

The cost of accommodation and operation on Iridium-NEXT is to be negotiated. Boreas' mass and power are less than half the accommodation capacity planned on Iridium-NEXT, so ride-sharing with other small instruments may be possible. The on-orbit design is for continuous autonomous operation, with the data flow to the ground to be enabled poleward of 60 degrees. On average, 3 instrument are operating at any one time, each delivering 600 Mbps, so the communications cost is for a 2 Mbps global connection, comparable to a streaming video. The raw data stream from Boreas would be delivered to an internet connection at Iridium's ground stations.

GROUND SEGMENT

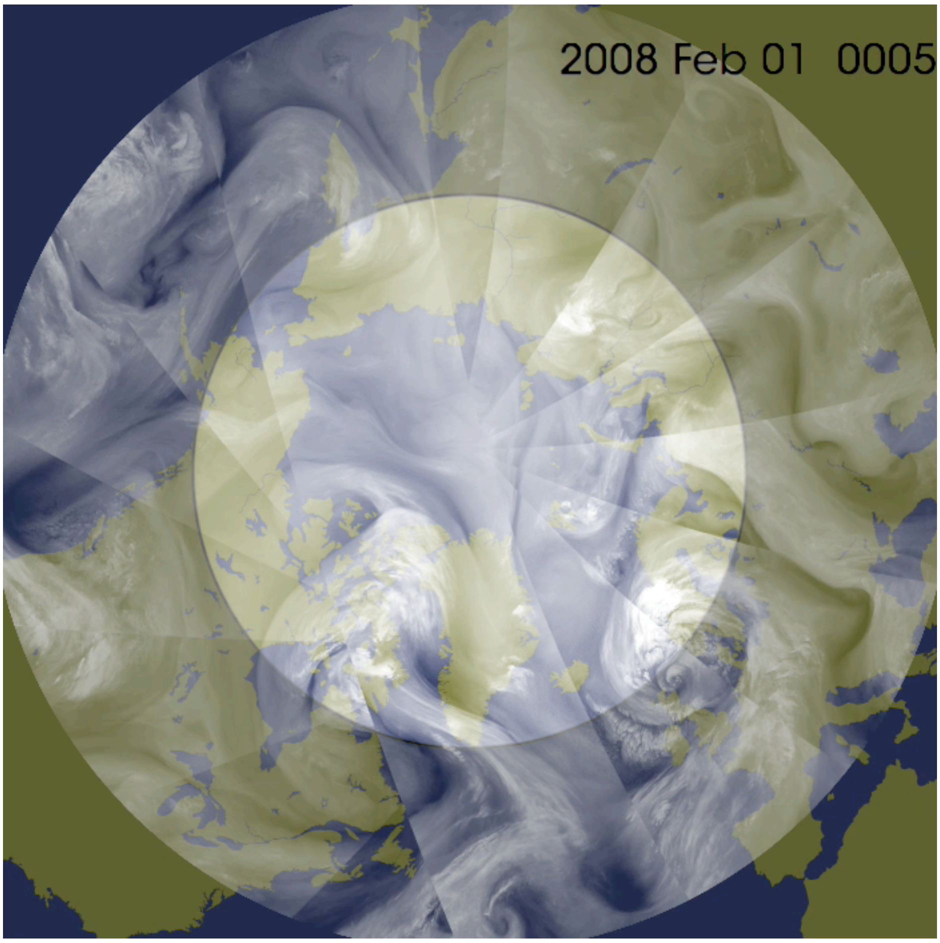

Figure 3: **Example of water vapor imagery around the North Pole, derived from 12 hours of successive MODIS overpasses. The brighter area near the center of the image is above 60 degrees of latitude, not observable from the operational geosynchronus satellite imagers. The structure of mid-tropospheric winds is as apparent over the poles as over the lower latitudes.**

Boreas will require a dedicated site to resample and navigate the raw imagery to a navigated fixed-grid using the attitude and orbit data in the data stream. This process is well-developed for the current polar-orbiting weather satellites, which processes much larger volumes of imagery in real time.

Likewise, Boreas will require a site that identifies and tracks cloud and water vapor features in successive image swaths. Once again, this process is well-developed for the geosynchronous imagers and was used with MODIS to demonstrate the utility of satellite-tracked water vapor polar winds. Production throughput in real time will not be difficult, since the data rates and computational methods are about the same as for one of the current geosynchronous weather imaging satellites. Delivery of another wind-set to the medium range forecast centers will be routine, as will be the ground-truth verification of satellite-derived winds.

Using Boreas, it will be possible to patch together images of the clouds and water vapor over the pole for delivery every few hours for real time "nowcasting" weather conditions and planning polar transportation. For example, Figure 3 shows overlapping swaths of water vapor imagery from 12 hours of MODIS overpasses. A Boreas system could deliver a similar, but completely fresh image every 3 to 4 hours, with new imagery above 70 degrees every 2 hours.

SUMMARY

In 2016-2030, Iridium-NEXT could be equipped with inexpensive "Boreas" infrared imagers that would measure real-time wind vectors poleward of 60º.

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1. No footnotes, but endnotes please
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