THE MOLNIYA ORBIT IMAGER
a high-latitude quasi-geostationary mission concept

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Abstract

The successful assimilation of polar winds from MODIS has led the meteorological user community to push more aggressively for continued access to high-latitude satellite winds. Regions at latitudes higher than 55-60 degrees cannot be seen from geostationary orbit under a viewing angle that is adequate for generating feature tracking winds. While data from NASA's MODIS sensors are used to retrieve winds for some regions poleward of 65 degrees, the timeliness of delivery of these data is not optimal, the horizontal coverage is incomplete, and the operational future of this type of observations is uncertain, especially as far as the water vapor channel imagery is concerned. The Molniya Orbit Imager, a concept for a high-latitude quasi-geostationary mission that would be ideally suited for multitemporal imaging e.g. for satellite winds purposes without most of the disadvantages of the low-earth orbit imagers, has been under development at the Goddard Space Flight Center since 2004. This paper provides an introduction to the mission concept, along with an update on its current status and prospects for proceeding to an implementation phase.

SCIENTIFIC BACKGROUND

As demonstrated by the GOES and Meteosat systems and related efforts in other countries over the last three decades, one of the most versatile types of satellite observations is continuous, rapid repeat rate imagery of the cloud and atmospheric water vapor fields and of the earth's surface. Images – and in particular animated sequences of images – are unparalleled in their ability to convey the dynamical nature of weather systems and to alert a human observer to changes or unusual features in the state of the atmosphere and the surface. The list of applications for geostationary imagery includes nowcasting for the transportation sector and the general public, numerical weather prediction, severe weather, tropical weather, and monitoring of surface phenomena such as volcanic eruptions and forest fires. It is worth noting that these data have contributed to major breakthroughs in our understanding of a range of atmospheric phenomena, e.g. hurricanes, squall lines and mesoscale convective systems, breakthroughs that would have been difficult to imagine without the combination of a large synoptic field of view and high spatial and temporal resolution that is unique to geostationary imagery.

From a global perspective, a major shortcoming of the geostationary satellite system is the limited coverage of the mid-latitudes and the complete lack of coverage of the high latitudes. The useful imaging disc for a satellite in geostationary orbit reaches up to about 60 degrees of latitude in either hemisphere, but only at the sub-satellite longitude. As the longitudinal distance to the satellite increases, the latitude up to which coverage can be provided decreases. Over certain areas in the Pacific, the area of useful coverage thus only extends up to about 40 degrees of latitude.

Since July 2002, wind observations for the regions poleward of 65 degrees of latitude have been derived from images obtained by NASA's two MODIS sensors, using an adaptation of the feature tracking algorithms originally developed for geostationary data (e.g. Key et al., 2003). Both in early tests and in subsequent operational implementations, these winds have had a very significant positive impact on forecast skill in a number of different assimilation systems. The positive impact is seen not only in the observed high-latitude regions, but throughout the extratropical portions of the forecast domain. This is consistent with the experience that the root cause of bad forecasts over the US often is found in poor initial conditions over the Alaska region. In general, the MODIS winds have a larger impact on bad forecasts than on good ones, so the improvement in average skill is caused mostly by reducing the severity of the busts.

The bulk of the MODIS winds dataset - and most of the beneficial impact - comes from the imagery in the 6.7 micron water vapor channel. The operational follow-on to MODIS, the VIIRS instrument scheduled to fly on NPP – the NPOESS Preparatory Project - and later on NPOESS itself, was not designed to include a water vapor channel. As a consequence of the success of the MODIS winds and the resulting push from the user community, the NPOESS program has been investigating ways to include one or more water vapor channels in later VIIRS flight models. The ultimate fate of this effort is unknown at the time of writing, but the earliest date by which water vapor images could become available from NPOESS is in 2018. The two MODIS instruments were launched in 1998 and 2002, respectively, and even though they are hoped to exceed their design lifetime of six years, it is unlikely that the Aqua and Terra missions will remain in operations until NPOESS can take over. The user community will therefore be faced with a multi-year gap during which no high-latitude water vapor imagery will be available.

It is worth noting that satellite winds were not a part of the originally planned MODIS product suite, and neither the instrument itself nor its orbit were designed with this application in mind. The image repeat period is equal to the orbital period of the platform, roughly 100 minutes. Since the wind retrieval algorithms are based on image triplets, the total data acquisition time is close to three and a half hours. The assumption that the cloud field in particular acts as a passive tracer is somewhat problematic on such a long time scale, especially in critical situations with rapidly developing weather systems. The image repeat cycle for the next generation of geostationary sensors is typically 15 minutes; from rapid-scan experiments it is known that a repeat of 10 or 5 minutes is better yet in terms of both the quality and quantity of the derived winds.

This acquisition mode also introduces a substantial delay in the dissemination of the final data product. Assuming that the nominal observation time is the valid time for the central of the three images used, the observation itself will already be more than 100 minutes old by the time the satellite has completed the necessary measurements. The total delay with respect to real time of the final delivered product generally amounts to four hours or more. This is too late to meet the cutoff for many operational global data assimilation system and for almost all regional or limited area systems.

An additional problem is introduced by the viewing geometry. MODIS is flying at an altitude of roughly 700 km, and the instrument scans out to an angle of 55 degrees off nadir on either side of the flight track. In order for the algorithm to calculate a wind vector, it must correctly identify and geolocate a given feature in the cloud or clear-sky water vapor field in each of three successive images. Generally, the angle under which this feature is seen will vary between images. A given feature may be seen close to one edge of the scan in the first image, close to nadir in the second, and close to the opposite extreme of the scan in the third image. This imposes a very stringent requirement on the image navigation and rectification (INR), and any errors here will limit both the number and the accuracy of the observations. In contrast, the angle under which a given cloud feature is seen from geostationary orbit remains essentially constant from image to image.

Finally, there remains a data void between the regions covered by the geostationary satellites (up to 40 to 60 degrees of latitude, depending on longitude) and those covered by MODIS (starting at 65 to 70 degrees of latitude, depending on longitude). In order to reduce the mid-latitude forecast errors in the two to five-day range, good observational coverage of this region is critically important.

THE MOLNIYA ORBIT IMAGER

It is clear that almost all of the limitations of the MODIS winds listed in the previous section could be eliminated, if it would be possible to fly an imager in an orbit that would let it view the high-latitude regions continuously, in the same way the geostationary platforms provide continuous views of the lower latitudes. As it turns out, the so-called Molniya orbit (Fig. 1) matches this requirement very well.

The Molniya (Russian for lightning) orbit is highly eccentric, and the orbital elements are chosen such that the sub-satellite location of the perigee and apogee are stationary in longitude and latitude. The inclination is 63.4 degrees, and the orbital period is half a sidereal day – or about 11h 58m. Seen from the ground, the satellite will hover in a nearly stationary position in the sky at an altitude between 25000 and 40000 km above the selected apogee location for about two thirds of that time. During this period, an onboard imager will be able to obtain multiple successive images of the whole visible earth disc. During the 8-hour period within apogee ±4 h – the so-called apogee dwell - the sub-satellite point will travel back and forth along a path of less than 1800 km in length along the surface of the Earth. The sub-satellite surface location of two successive apogees will be 180^o apart in longitude. The polar cap (N of about 60^o latitude) will thus be visible roughly 16 hours per day from a single satellite, while longitudinally opposite portions of the lower latitudes will be visible for 8 hours at a time.

A single satellite in a Molniya orbit would therefore allow us to extend geostationary-type imaging all the way to the north pole for a total of 16 hours per day. Two satellites would ensure 24-hour coverage of the entire northern hemisphere, and four satellites would extend the continuous coverage to the entire globe.

Currently, the MODIS winds are generated using imagery from two different channels, 11 µm (IR) and 6.7 µm (water vapor). As already mentioned, the water vapor channel provides both the better quality and the larger number of wind vectors. However, both the horizontal locations of the targets and the height assignment of the retrieved winds differ between them, and the two channels are therefore complementary in this sense. A baseline imager including both of these channels, supplemented by an additional water vapor channel sensitive at lower altitudes and two additional window channels (e.g. 3.9 and 12 micron) for better height assignment and other applications is adequate for meeting the main goals of the mission. A visible channel for image navigation and registration and for surface and day-time cloud and sea ice applications completes the channel line-up.

Since the Molniya Orbit Imager will be nearly stationary seen from the ground during the active parts of its orbit, real-time data transfer is much simpler to achieve than it is for LEO satellites. The ground segment can be simple: A single high-latitude station primary receiving station receives the data that are being transmitted to the ground from the satellite in real time. The exact location of the ground station is unimportant: any location N of 60 degrees of latitude will have a line of sight to satellite during the entire apogee dwell. With an image repeat cycle of 15 minutes, the time delay in the availability of the images and derived products for operational use would be comparable to that of the GOES and Meteosat winds, both of which are routinely disseminated early enough not only for numerical weather prediction but also for operational nowcasting use.

The need for high-latitude winds for numerical weather prediction (NWP) purposes with improved coverage and timeliness characteristics is the primary science driver for the Molniya Orbit Imager. However, in a wider context the mission could be seen as a pathfinder toward a high-latitude extension of the GOES/Meteosat system, and user communities interested a range of non-NWP applications have therefore expressed interest in and support for the mission.

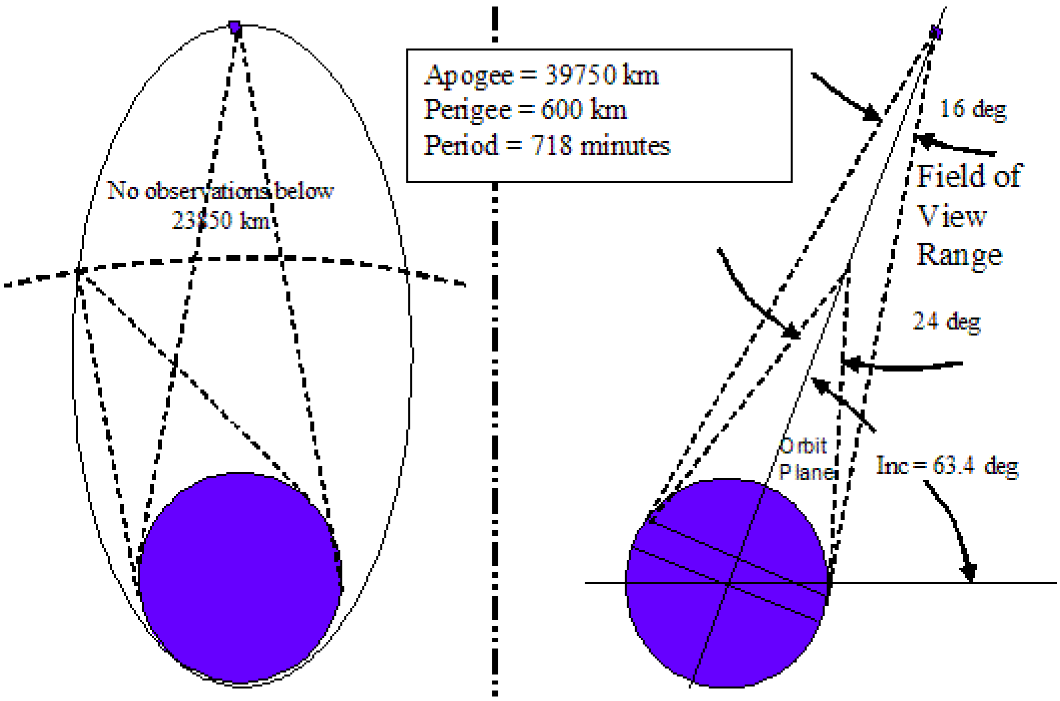

Figure 1. Main elements of the Molniya orbit. Imaging is performed during the roughly 500-minute apogee dwell period (67 percent of the total duration of the orbit) when the satellite is above the curved line in the left panel.

Among the most promising of these non-NWP applications are:

1. Volcano monitoring (aviation safety)
2. Vegetation and forest fire monitoring
3. Polar weather (non-NWP) applications
4. Sea ice monitoring and model validation
5. Snow cover and albedo monitoring
6. Surface radiation balance and soil-vegetation-atmosphere transfer (SVAT) model validation
7. Regional water quality
8. Cloud physics and cloud dynamics

Some of these are primarily of scientific interest (5, 6, 7, 8), at least one is predominantly of interest to operational users (1), and some have both scientific and operational aspects (2, 3, 4).

TECHNICAL FEASIBILITY AND IMPLEMENTATION

There is a close correspondence between Molniya orbit apogee height (39,740 km) and geostationary orbit height (35,800 km). A Molniya orbit mission can therefore be put together in a cost-effective way by building on the very substantial investment in successive generations of geostationary satellite systems. Experience in all of the most challenging areas of such a mission – instrument design, attitude control, image navigation and registration, radiation effects on flight hardware – can be carried over from the geostationary missions.

Since August 2004, the Molniya Orbit Imager team at Goddard has been developing a mission concept to obtain the measurements outlined in the previous section. The first step was to define a set of high-level performance requirements for the imaging sub-system. This process took several

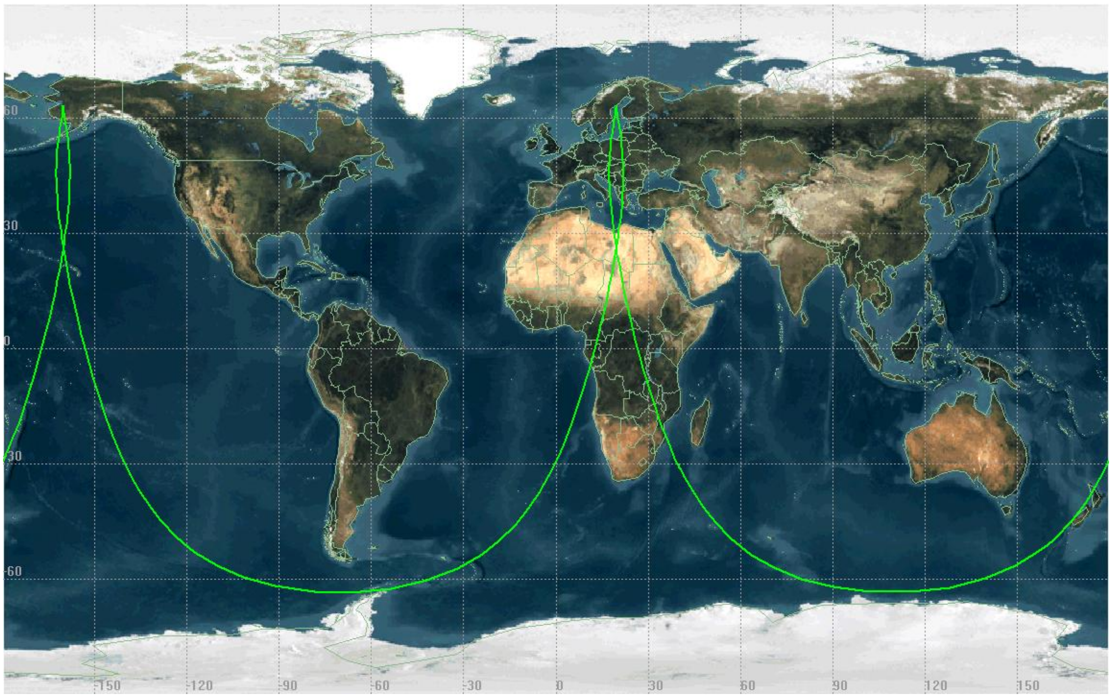

Figure 2. Example ground track of a Molniya orbit satellite. The satellite will alternate between the two apogee points in the respective cusps of the orbital track. Any ground station N of 60 degrees N will be able to see the satellite during the entirety of both apogee dwell periods.

iterations involving discussions both with the interim science team for the mission (Appendix I) and with representatives from instrument vendors with experience in imaging from geostationary orbit.

Following the establishment of the initial set of requirements, a Pre-phase A study carried out by the Goddard Space Flight Center with support from a number of industrial partners has now led to the development of a well-defined baseline mission. It is important to point out that the existence of a baseline does not imply that this is what would be selected for implementation. The primary role of the baseline is to serve as a clear demonstration of the technical feasibility of the Molniya Orbit Imager and to provide a realistic straw-man budget and schedule.

A solicitation for instruments concepts issued by the Goddard Space Flight Center to industry resulted in a number of highly competitive proposals. The main instrument requirements as expressed in the solicitation are summarized in Table 2. The preliminary decision made by the evaluation team was that under the baseline scenario, the main imager will be a close relative to the Japanese Meteorological Imager (JAMI) developed by Raytheon SBRS under contract to SS/Loral for the Japanese MTSAT-1R mission. In the MOI primary acquisition mode, the instrument will provide full earth-disc images every 15 minutes at horizontal resolutions of 2 km (IR) and 1 km (VIS).

Following two solicitations issued by the Goddard Space Flight Center to industry concerning satellite bus designs to accommodate the imager, it has been established that the bus can be based on any of a number of commercially available designs with roughly similar performance and launch requirement characteristics. The final selection of bus design and manufacturer has been deferred until a point in time at which the final payload composition and the available launch options are better defined.

The baseline launch vehicle is a Delta-II 7424-9.5. Substantial savings would result from using a smaller launch vehicle, e.g. from the Taurus line. However, this would preclude the use of an existing bus design, requiring instead the development of a mission-specific lightweight structure. Based on overall budget and risk considerations, such a development was not included as part of the baseline.

A broader international collaboration on the mission could open alternative launch options, some of which are currently being investigated further.

Table 2. Main instrument system requirements for the Molniya Orbit Imager

Lifetime	36 months (goal: 60 months)
Orbit	718 min Molniya
Visible Channel	0.55-0.80 micron 1 km horizontal resolution
IR Channels	3.9 (3.8-4.0) micron 6.3 (5.8-6.8) micron 7.1 (6.8-7.4) micron 11.0 (10.7-11.3) micron 12.0 (11.5-12.5) micron 2 km horizontal resolution
Radiometric Precision	VIS: SNR 500:1 @ 100% albedo IR: 0.2 K @300K, 0.5 K @ 250K
Radiometric Accuracy	VIS: 6% IR: 1 K
Field of View	>24 degrees + star field
Time to image a complete scene	<15 minutes
Input Power (baseline)	< 180 W (including 20% cont.)
Mass (baseline)	<136 kg (including 30% cont.)
Volume (baseline)	<0.9 m x 1.2 m x 1.3m

Apart from the overall cost of the mission, the two most important challenges are Image Navigation and Registration (INR) and the radiative environment imposed on the observatory by the orbit, with the former being by far the more significant obstacle of the two. The basic approach to INR consists of having the imager oversample the earth disc, and using off-disc star sightings performed by the main imager combined with a Kalman filter algorithm to maintain accurate knowledge of the boresight direction at the time each individual pixel was measured. This will allow us to resample the oversampled data to a fixed geolocated grid, much the same way the MODIS images are resampled to a fixed grid before winds processing in order to compensate for the large variation in pixel resolution across the scan lines and between the individual images in the triplets used for processing the winds.

The overall approach just described is very similar to what is planned for GOES-R, and the Molniya Orbit Imager is therefore in a good position to reap the benefits of the substantial investment of the GOES program in INR research and development work.

The radiative environment of the orbit is now well characterized and understood, and according to the preliminary studies carried out by both the Goddard Integrated Design Center and our industrial partners, a combination of judicious parts selection and 4 to 5 mm of aluminum shielding the most sensitive parts of the electronics will be sufficient to guarantee a 3-year mission life in this orbit.

PROGRAMMATIC CONTEXT

Under the baseline mission scenario, NASA would fully fund a one-satellite demonstration or pathfinder mission under its Earth System Science Pathfinder (ESSP) Program. The current calendar for ESSP is highly uncertain, and a range of alternative mission scenarios therefore remain under exploration. As already mentioned above, a high degree of interest in the mission has been expressed from the meteorological community as well as from other constituencies, representing both operational and research interests.

Discussions with NOAA/NESDIS have been ongoing since the early phases of the project. From the point of view of the mission team, a strong involvement from NESDIS in the ground operations, data reception, algorithm development and data processing parts of the mission in particular would be highly desirable. This would strengthen the case for obtaining funding for the mission and would ultimately increase the likelihood of its success in terms of timely delivery of high-quality data products to the end users. As mentioned earlier, there is synergy between geostationary imaging and Molniya orbit imaging not only as far as observational data coverage is concerned, but also on the instrument side. Discussions are ongoing regarding a potential closer link to the GOES program that would let us exploit this.

Since the Molniya orbit is longitudinally “blind” - i.e. all regions of the high northern latitudes are imaged about equally well regardless of where exactly the apogee points are located - a mission in this orbit is an excellent candidate for international collaboration. A number of international and national organizations from countries outside the US have expressed interest in having access to the data and/or in participating in the mission itself.

At the time of writing (June 2006), discussions with the Finnish Meteorological Institute, the Canadian Space Agency and EUMETSAT seem to be particularly promising in terms of finding common ground for future collaboration. It is the hope that over the next couple of years, the interested parties will be able to form a team strong enough to take the Molniya Orbit Imager to the respective funding agencies and develop a workable implementation plan.

Finally, it should be mentioned that the benefits to continuous imaging of the high latitudes are not unique to viewing the Earth’s surface and lower atmosphere in the visual and IR wavebands as envisaged for the Molniya Orbit Imager. Aurora imaging in the UV, or ionospheric imaging in the extreme UV are but two examples of other scientific applications that would benefit from having access to a similar vantage point. Discussions are ongoing with a Canadian/Finnish research team about including a UV Aurora imager as a secondary scientific payload on the Molniya Orbit Imager.

SUMMARY

The Molniya Orbit Imager provides a path toward a natural high-latitude extension of the geostationary imaging capabilitites. Primarily due to the initial investment in Pre-phase A studies by the Goddard Space Flight Center, most of the technical issues surrounding the implementation of the mission are now well understood. The initial driver behind the mission was the unmet user requirement for continued access to real-time high-latitude cloud-track and water vapor winds, but the scientific community supporting the mission continues to expand, also in other earth science disciplines. Discussions on are ongoing with a number of prospective partners, both in the US and abroad, and it is the hope that a teaming arrangement can be found over the course of the next couple of years.

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