AN UPDATE ON THE MOLNIYA ORBIT IMAGER

Lars Peter Riishojgaard

University of Maryland Baltimore County
and
Goddard Space Flight Center

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 latitudes poleward of 65 degrees, the timeliness of delivery of these data is not optimal, the coverage does not fully complement that of the geostationary satellites, and the operational future of this type of observations is uncertain, especially as far as the water vapor channel imagery is concerned. A concept for a high-latitude quasi-geostationary imager 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 reports on the current status and future prospects of the mission.

INTRODUCTION

At the 7th International Winds Workshop in Helsinki 2004, the concept for the Molniya Orbit Imager was presented to an international scientific audience of experts on satellite winds for the first time (Riishojgaard, 2004). The concept was received favourably both by the satellite winds community and by the operational meteorological community at large. The user community was especially supportive of the prospect of ongoing real-time access to high-latitude winds. However, a number of questions were raised concerning the technical feasibility and the overall costs of operating in an orbit that has never been used for civilian remote sensing, and a number of alternative orbits were proposed to be investigated for high-latitude winds. Over the course of the two years that have passed, most of these questions have been answered, and our technical understanding of the Molniya Orbit Imager has made substantial progress. In this paper we briefly review the scientific rationale for the mission, our current understanding of the technical feasibility of the mission, the considerations that led to the selection of this particular orbit as the best choice for high-latitude imaging, and finally the current programmatic context of the mission.

SCIENTIFIC RATIONALE

The mid- and low-latitude regions have been well served for a multitude of applications by the high temporal and spatial resolution imagery provided by satellites in geostationary orbit since the late 1970's. The Molniya orbit (e.g. Kidder and Vonder Haar, 1990) provides a suitable vantage point for similar high resolution imagery of those regions in the high northern latitudes that cannot be seen from geostationary orbit. The main characteristics of the orbit are summarized in Figure 1.

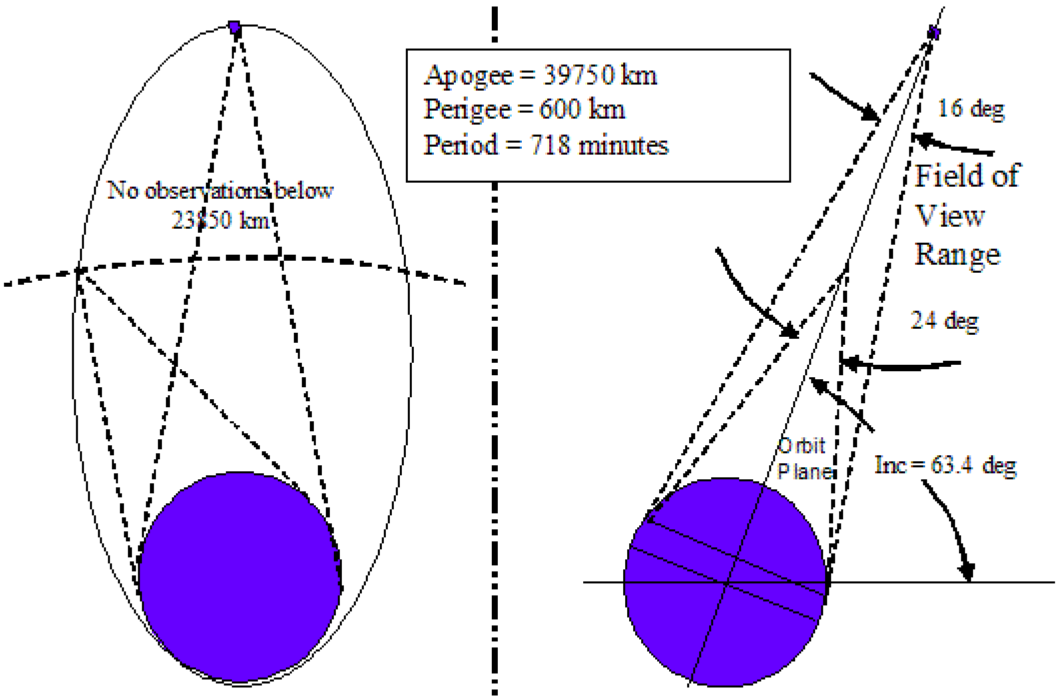

Figure 1. Main elements of the Molniya orbit. Imaging is performed during the roughly 500-minute apogee dwell period (67 percent of the total duration of the orbit) when the satellite is above the curved line in the left panel.

The need for high-latitude winds for numerical weather prediction (NWP) purposes with improved coverage and timeliness characteristics continues to be the primary science driver for the Molniya Orbit Imager. However, since the concept was first announced, groups interested in a number of additional applications have contacted the proposal team to express their interest in the data. The expanded list of applications includes:

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). The broader scientific interest in the mission is reflected in the preliminary list of data products given in table 1.

TECHNICAL FEASIBILITY

A Pre-phase A study carried out by the Goddard Space Flight Center with support from a number of industrial partners has led to a solid mission baseline. It is important to point out that the existence of a baseline does not imply that this is what will 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.

Table 1. Molniya Orbit Imager data products and appropriate channels (microns)

Product	Channels	Status
Aerosols/dust/smoke	VIS, 11, 12	TBD
Calibrated images	VIS, 3.9, 6.3, 7.1, 11, 12	Core
Cloud mask	VIS, 3.9, 6.3, 7.1, 11, 12	Core
Cloud-top microphysics	VIS, 3.9, 11, 12	Intended
Cloud-top pressure/temperature	3.9, 11	Core
Fires/hot spots	VIS, 3.9, 11, 12	Core
Land skin temperature	3.9, 7.1, 11 12	Intended
Low cloud and fog	3.9, 11	Core
Derived motion (atmosphere)	6.3, 7.1, 11, 12	Core
Sea ice motion	VIS, 11	Core
Sea ice temperature	11,12	Core
Sea ice concentration	VIS, 11	Core
Sea surface temperature	3.9, 11, 12	Intended
Snow detection (cover)	VIS, 3.9, 11	TBD
Volcanic ash product	VIS, 3.9, 7.1, 11, 12	Core

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).

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

Following two solicitations issued by the Goddard Space Flight Center to industry concerning satellite bus designs to accommodate the imager, it was established that the bus could be based on any of a number of commercially available designs with roughly similar performance and launch requirement characteristics. The final selection concerning the 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. 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.

Apart from the overall cost of the mission, the most important challenges are (i) image navigation and registration (INR) and (ii) the radiative environment imposed on the observatory by the orbit, with (i) being by far the more significant obstacle of the two. The basic approach to INR consists of oversampling the earth disc while 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 the oversampled image to be resampled 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.

This INR approach is very similar to what is planned for GOES-R, and the Molniya Orbit Imager therefore stands to reap the benefits of the substantial investment in INR research and development work under the GOES program.

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 on the order of 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.

ORBIT CONSIDERATIONS

The 11h 58min 63.4 degree inclination Molniya orbit was already familiar to many in the space flight community - and to a slightly lesser degree also in the meteorological community - by the time the concept for the Molniya Orbit Imager was launched. However, numerous questions about the suitability of the orbit for the intended imaging applications and about the technical and economic feasibility of the mission had to be addressed during the early study phases. The most important findings are summarized here.

Molniya vs. LEO

While the requirement for polar winds is enjoying broad support in the meteorological community, a recurring question asked of the Molniya Orbit Imager team initially from the space agencies in particular was the following: “Why not instead continue on the path of the MODIS winds and deploy a series of suitable imagers in the well-known sun-synchronous low-earth orbit?” The background for this question is that an affirmative answer would allow the agencies to adjust their already existing programs incrementally rather than force them to face a series of new technical issues related to an orbit largely unknown to them.

Figure 1 provides an illustration of the answer to this question. The satellite winds retrieval requires three images of the same scene, obtained at intervals that are neither too long - since this would violate the assumption about features being advected passively between images - nor too short - this would lead to insufficient displacement of features. The left panel shows the data coverage of satellite winds from a hypothetical four-satellite LEO system, accumulated over a six-hour period. The right panel shows the near-instantaneous coverage provided by the Molniya Orbit Imager at its western apogee. It is clearly seen that the LEO winds coverage is leaving a significant latitudinal gap with respect to the GEO winds (locations shown in red), whereas the Molniya winds provide a full complement to the GEO winds, even on the side of the Earth that faces away from the current apogee.

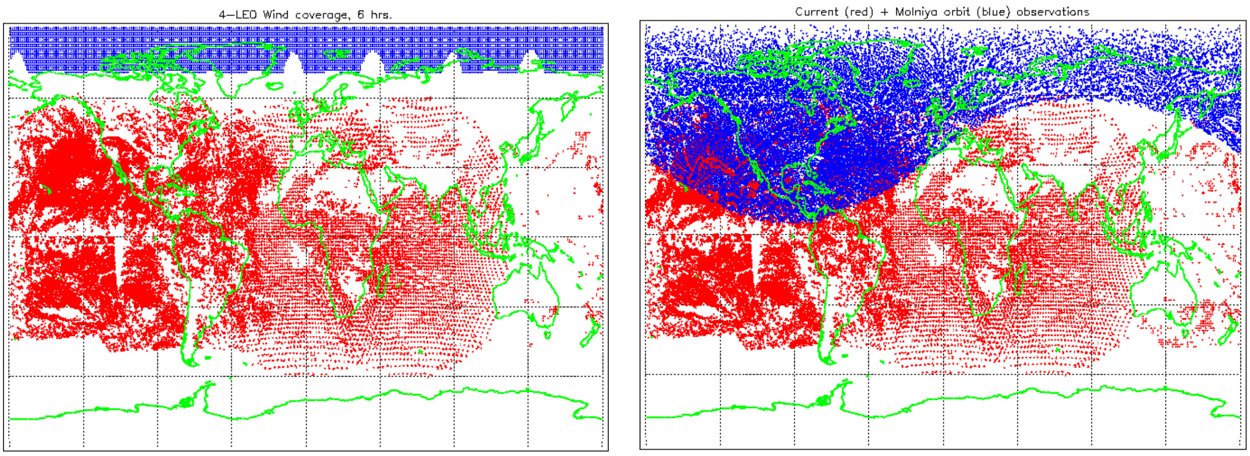

Figure 2. Six-hour accumulated image triplet winds coverage from a hypothetical 4-LEO imaging constellation (left panel), and from the Western apogee of a one-satellite Molniya system (right panel) in blue. Geostationary winds coverage shown in red.

Molniya vs. MEO

A constellation of satellites in a 6-hour circular 90-degree inclination middle earth orbit (MEO) has been proposed as an alternative option for obtaining high-latitude images (Dittberner et al., 2005). A continuous view of the high latitudes in both hemispheres would require a four-satellite MEO system. In terms of coverage specifically targeted for satellite winds, a one-satellite MEO system appears to be at a significant disadvantage compared to the Molniya Orbit imager, since the former does not provide a staring perspective. The viewing angle of a given cloud or water vapor feature will therefore undergo significant changes from image to image, something which is not the case for an imager in a Molniya orbit.

In order to be able to compare the amount of high-latitude coverage each of these two candidate systems would provide for applications other than satellite winds, a figure of merit was defined as follows: *Fraction of the area N of 60 deg N, imaged with a satellite elevation angle of 23 degrees or higher, averaged over 24 hours*. The cut-off elevation angle of 23 degrees was chosen based on where experience tells us that the geostationary images cease to be useful for winds retrieval. With the coverage thus defined, it was found that one Molniya orbit satellite achieves roughly 74% of full coverage for the high northern latitudes. The corresponding figure for one MEO satellite is 23%, or roughly one third of the coverage provided by the Molniya satellite. This is primarily due to the fact that any satellite in a circular 90-degree inclination orbit will spend two thirds of its total flight time over latitudes lower than 60 degrees irrespective of the orbit height. However, a MEO satellite does offer equivalent coverage for the high latitudes in both hemispheres, whereas a Molniya orbit satellite is targeted to one hemisphere only.

Apogee height

The current mission baseline calls for a 12-hour Molniya orbit with an apogee height of 39750 km. In the early phases of the project, 8-hour as well as 16-hour versions of the orbit were studied. The former has slightly worse coverage characteristics than the 12-hour orbit but offers the potential of a less expensive launch vehicle and a smaller aperture of the main imager for a given horizontal resolution. The 16-hour orbit offers improved temporal coverage at the expense of a larger aperture and a more expensive launch. It was found that the 12-hour orbit represents the best trade-off, to a large extent due to the fact that already existing designs for geostationary imagers will work from this orbit with minimal modifications.

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 variety 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 Molniya orbit imaging mission appears to be a prime candidate for international collaboration. A number of international and national organizations from countries outside the US have expressed varying degrees of interest in having access to the data and/or in participating in the mission itself.

There are many possible permutations of mission partners, and the list of conceivable specific scenarios is too lengthy to go through here. However, at the time of writing (May 2006), discussions with the Finnish Meteorological Institute, with the Canadian Space Agency, and with 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, a team will be formed among the interested parties that is strong enough to take the Molniya Orbit Imager to the respective funding agencies and come up with 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 areas 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 concept continues to mature and evolve. 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 science community supporting the mission continues to expand, both within the NWP area and in other earth science disciplines. It therefore now appears that the main challenge in getting mission off the ground is no longer technical but rather identifying the right teaming of organizations with the combined willingness and capability to do this, either nationally or internationally.

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