# The case for launching a meteorological imager in a Molniya orbit

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## 1. Introduction

In spite of continuing improvements in the average quality and reliability of numerical weather prediction (NWP) output, the frequency of abnormally bad forecasts ("busts") remains relatively high. The steady increase in the use of NWP products as basis for decision-making with often very substantial financial ramifications have contributed to making such busts increasingly costly for society. As a consequence, the focus of the operational weather agencies now tends to be shifting away from merely attempting to raise the average skill scores toward specifically diminishing the frequency and the severity of the forecast busts.

It is interesting to note that forecast busts in most cases seem to be directly traceable to errors in the initial conditions rather than to errors in the subsequent model forecast. In some cases, shortcomings in the analysis methods seem to be the likely cause of these errors while in others they can be attributed to a lack of data – either of data in general or perhaps only of data of a certain kind - over a specific region at the initial time of the forecast. With this in mind we therefore ask ourselves the following question: Which additional observations could help the operational weather services to further improve the quality of weather forecasts over the major population centers in the mid-latitudes? And in particular, which observations would contribute the most toward decreasing the frequency of bad forecasts (busts) in the two to seven day range?

## 2. Numerical weather prediction and the global observing system

While it is generally true that abnormally large forecast errors can be traced back to errors in the initial conditions, busts over North America in particular are often traceable to errors in the initial conditions in the high northern latitudes, especially over Alaska and the regions north and west thereof. The analysis methods used in modern NWP systems are global in nature, thus we have no reason to expect them to perform particularly poorly over any one region. The indications are therefore that additional observational information for the high latitudes in general and for the Alaska region in particular would be highly desirable as we strive to improve the initial conditions in these areas.

Both in terms of number of observations provided and in terms of contribution to forecast skill, the global observing system is now dominated by satellite data. This is especially true for remote areas over the oceans and in the high latitudes where other observing systems are largely absent and often prohibitively expensive to operate.

In terms of the geophysical quantities measured from space, the mass field continues to be much better observed than the flow field due to the proliferation of infrared and microwave sounders. At least in principle, the mass field is measured from the polar orbiters no less than twice daily everywhere over the three-dimensional global domain. However, difficulties in interpreting the measurements under certain conditions contribute to significantly reducing the actual data coverage provided by the satellite sounders. In contrast, the upper air wind field is only observed from space in the low and mid-latitude regions visible from geostationary orbit, and generally at most at a single level for each horizontal location. The exception to this rule is the experimental MODIS wind product available poleward of $65^o$ latitude in both hemispheres (section 3).

Infrared soundings tend to work best in cloud-free areas over the oceans. However, several studies have indicated that there is a prevalence of clouds over the "sensitive regions", i.e. those regions in which more accurate initial condition would contribute the most to decreasing the forecast error. Combined with the generally extensive cloud cover over the Arctic region, this severely limits the potential impact of the infrared sounders there.

Microwave sounders are unaffected by non-precipitating clouds, and they are therefore often more suitable for extracting information in the sensitive regions. However, the microwave emissivity of snow and ice surfaces varies strongly with partly unknown characteristics such as age and temperature of the snowpack, crystal size etc., and the microwave soundings therefore tend to be less reliable in high latitudes.

Generally speaking, inferring information about the atmospheric flow from the mass (or temperature) observations is most relevant at larger scales where the flow is at least approximately obeying certain balance conditions that can be built into the data assimilation system. In order to detect unbalanced flow components associated with rapid pressure changes and potentially "new weather", it is necessary to obtain direct (i.e. non mass-inferred) observational information about the atmospheric flow. This is expected to become increasingly important as operational NWP continue its progress toward assimilating and predicting on smaller scales.

## 3. MODIS winds

Since July 2002 wind observations for the regions poleward of $65^o$ latitude have been derived from MODIS imagery much the same wind vectors are derived from geostationary imagery. Both in early tests and in subsequent operational implementation, these winds have shown 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 observation made in the introduction that the root cause of bad forecasts over the US is often found in poor initial conditions over the Alaska region. Interestingly enough, the MODIS winds seem to have more of an impact on the bad forecasts than on the good forecasts. In other words, the improvement in average skill seems to be caused mostly by a reduction of the severity of the forecast busts.

A significant problem with deriving feature tracking winds from polar orbiting instruments such as MODIS is the inherent data acquisition mode. The basic idea is that the imagery can be used for calculating winds for those high-latitude regions where the same ground location is seen from subsequent overpasses due to the convergence of the orbital tracks near the poles. The image repeat period is therefore equal to the orbital period of the platform - roughly 100 minutes. Since the wind retrieval algorithms are based on image triplets, the total 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 situations with rapidly developing weather systems. The image repeat cycle for the current 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 data acquisition mode also introduces a substantial delay in the dissemination of the observations. 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. Once the onboard storage, downlinking, and subsequent data transfer and processing is added, the total delay with respect to real time 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 unique to low earth orbit (LEO) imagery is the viewing geometry. MODIS is flying at an altitude of roughly 700 km, and the instrument scans out to $55^{o}$ off nadir on either side of flight track. In order for the algorithm to calculate a wind vector, it must first correctly identify and geolocate a given feature in the cloud and/or water vapor field in each of three subsequent images. Generally, the angle under which this feature is seen will undergo substantial variations from one image to the next. One can thus imagine a scenario in which the feature is 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 and it will limit both the number of wind vectors that can be retrieved and the accuracy of the retrieved vectors. In contrast, the angle under which a given cloud scene is viewed from geostationary orbit remains essentially unchanged from one image to the next.

These various drawbacks of using LEO platforms for polar winds notwithstanding, the MODIS winds have demonstrated a considerable amount of potential in research and operational implementations. Most recently, this has led to WMO adopting a formal recommendation that an operational capability to generate polar winds be developed for the post-MODIS era. As already mentioned, the vast majority of the MODIS wind vectors are derived using the 6.7µ water vapor channel. The NPOESS operational imager VIIRS is built on the MODIS heritage, but unfortunately the first three flight models of this sensor will not include a water vapor channel, and from the nominal end of the MODIS missions in 2008 until at least 2015, there will be no water vapor imagery available beyond the regions of geostationary coverage.

4. Proposed solution: A meteorological imager in a Molniya orbit

The MODIS winds have been highly successful in improving forecast skills well outside the observed region, especially due to the water vapor channel, and especially via their impact on the sub-par forecasts. We now recapitulate some of the main problems with the current and planned global observing system identified in the two previous sections.

- There is a general lack of reliable observations for the high northern latitudes, evidenced by mid-latitude forecast busts caused by bad initial conditions in the high latitudes
- In particular, there is a lack of wind observations in the high latitudes
- Success with the MODIS winds is achieved in spite of the fact that neither the data acquisition mode nor the viewing geometry imposed by the platform seems to be well suited for obtaining satellite winds
- Required timeliness of high-latitude winds based on low earth orbiting imagers is difficult or impossible to achieve
- There remains a coverage gap between roughly 58$^o$ (upper limit for geostationary) and 65$^o$ (lower limit for MODIS) of latitude
- Once the MODIS missions have ended in 2008, the NWP community will have no access to high-latitude water vapor imagery until at least 2015.

It is immediately clear that all of the issues in this list could be addressed if one could simply launch a geostationary-class imager with a suitable channel line-up into an orbit that would let it view the high northern latitudes continuously, much the same way that the current geostationary platforms provide continuous views of the lower latitudes. As it turns out, the so-called Molniya orbit (Fig. 1) comes very close to meeting this requirement.

A Molniya orbit (prounounced Mol-neeh-yah; from the Russian word for lightning) is a highly eccentric orbit for which the elements are chosen such that the sub-satellite location of the perigee and apogee are stationary in longitude and latitude. The inclination is 63$^o$.4, and the orbital period is half a sidereal day – or about 11h 58m. As seen by an observer on 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 any given scene within its viewing 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 65$^o$ 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.

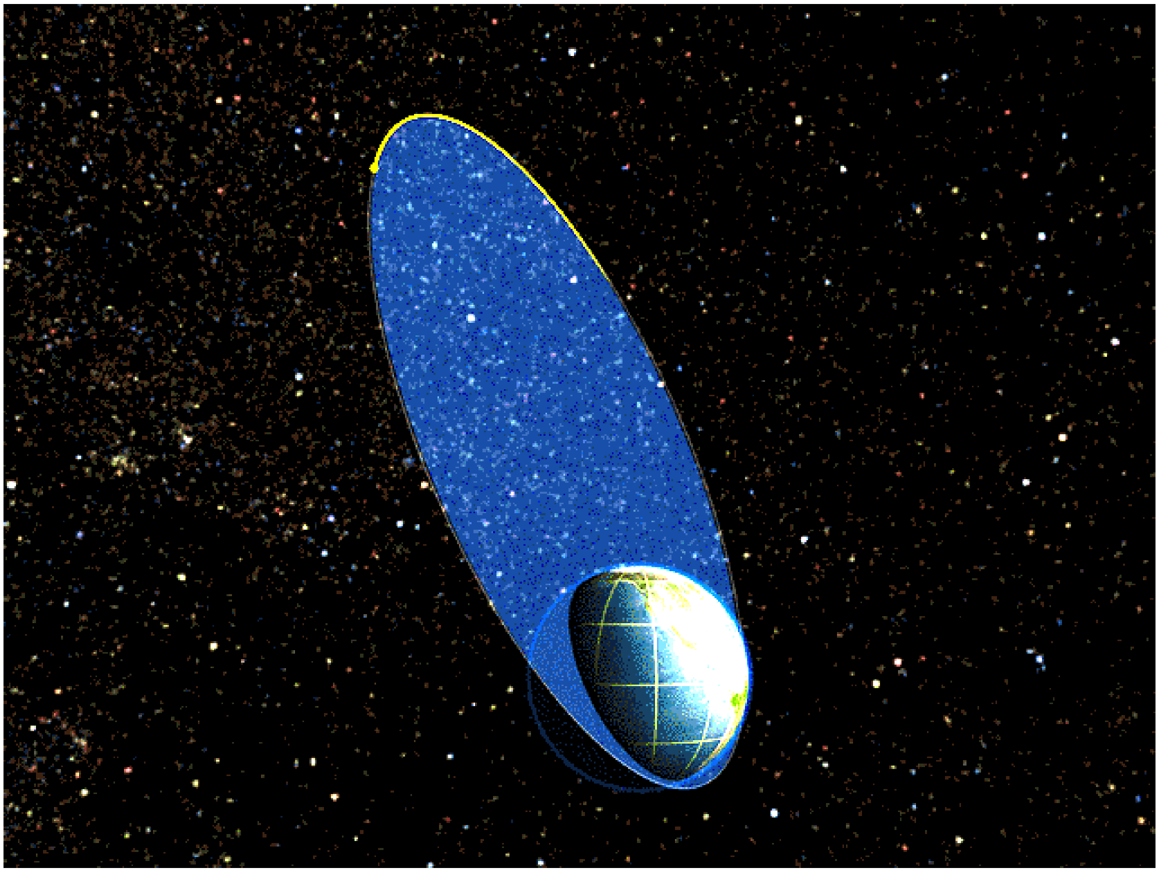

*Fig.1 The Molniya orbital plane. Due to the second Kepler Law, the satellite spends most of the time in the near-apogee part of the orbit (yellow trace), from where it will provide a quasi-stationary view of much of the northern hemisphere, including the high latitudes.*

A single satellite in a Molniya orbit would therefore allow us to extend the geostationary imagery all the way to the pole in one hemisphere for 16 hours per day. Two satellites would ensure around the clock coverage in one hemisphere, and four satellites would extend the coverage to the entire globe, 24 hours a day.

Currently, the MODIS winds are generated using imagery from two different channels, 11 µm (IR) and 6.7 µm (water vapor). Of these two, 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 basic Molniya orbit imager with these same two channels, supplemented by an additional vapor channel sensitive at lower altitudes and one or two IR channels (e.g. 3.6 and 8.7µm) for better height assignment and other applications is considered adequate for meeting the main goals of the mission. A visible channel for image navigation and registration and for surface and day-time cloud applications would complete the channel line-up. The

Molniya apogee height is 39750 km. This is close enough to geostationary orbit height (roughly 36000 km) that an "off the shelf" geostationary imager can serve as a suitable baseline for the instrument, and there are in fact designs available that could be reused "as is" or be adapted with minimal modifications to meet these requirements.

Since the imager will be nearly stationary seen from the ground during the most important portion of its orbit, real-time data transfer is much simpler to achieve than it is for polar orbiters. A primary ground network consisting of two mid-latitude (45$^o$ to 60$^o$ latitude) receiving stations - one in each hemisphere serving the appropriate apogee location – will be sufficient. As an alternative, the possibility of using a single high-latitude station - e.g. Kiruna or Svalbard - could be considered.

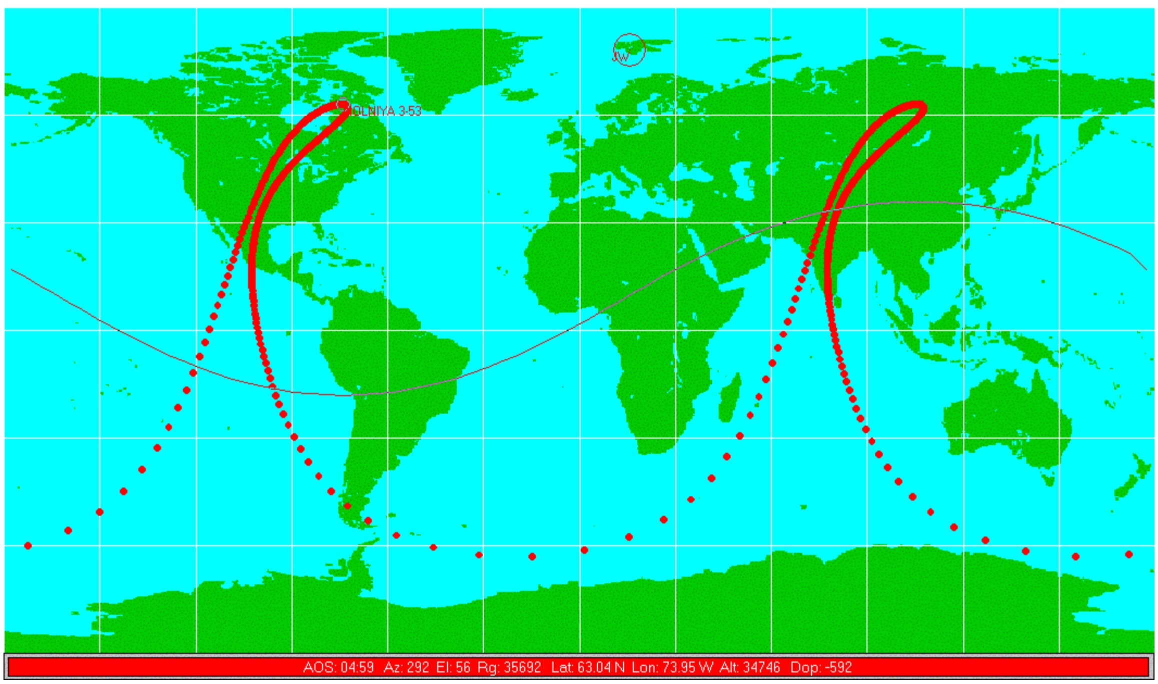


*Figure 2. Example of a near-Molniya orbit (Russian Molniya 3-53 satellite). Location plotted in red every 100 s; all areas N of solid line are visible from the western hemisphere apogee location indicated by satellite name.*

As an example the orbit of the Russian Molniya 3-53 communications satellite is shown in Figure 2. The sub-satellite point is calculated once every 100 seconds and indicated by a red marker. It is easy to see that the satellite spends most of the time in or near the cusps of the orbit. This particular orbit is visible from Svalbard (indicated by a circle) more than 85% of the time, and the entire imaging portion of the orbit could thus be covered using just one ground station for real-time date reception. The actual location of the ground station is not particularly critical. All areas north of the solid line are visible from the western cusp of the orbit (location indicated by the satellite name), and it is thus evident that either of the cusps will provide excellent coverage of the high northern latitudes.

With an image repeat cycle of 15 minutes, the time delay in the availability of the winds for operational use would be essentially equivalent 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.

## 5. Feasibility

As far as the orbit itself is concerned, at least two countries (USSR and the US) have been using it for communications purposes for more than 25 years, so launching and operating satellites in this orbit does not present any significant unknown challenges or risks.

The spacecraft technology will build mostly on the heritage from the GOES satellites, since the requirements on pointing knowledge and accuracy, power consumption, communications etc. are very similar. One aspect that does need careful consideration in the design phase is the fact that the spacecraft will traverse the Van Allen radiation belts several times per day. However, given the relatively short amount of time spent in the radiation belts, this is not considered to impact the feasibility of the design.

The instrument payload can be replicated or adapted with minor modifications from already existing or proposed geostationary imagers. The fundamental driver behind the mission is to extend the geostationary type of coverage to the entire northern hemisphere, and since the Molniya apogee height and the geostationary orbit height are roughly similar, most of the requirements on the imager - concerning sensitivity, horizontal, spectral and temporal resolution, radiometric accuracy, etc - are close to identical.

Due to the fact that the platform is quasi-stationary during the active imaging part of the orbit, the ground segment can be much simpler than what is typical for low earth orbiters. A single primary ground station is sufficient for real-time downlinking and dissemination of the data, similar to the standard practice for the geostationary platforms.

However, a Molniya orbiting imager will not be geostationary in the strict sense of the word, and subsequent images will have slightly varying perspectives and slightly different viewing areas. It is therefore envisaged that the data be remapped to a fixed grid in the first step of the processing. The feasibility of this has been demonstrated both on data from geostationary imagers and on MODIS data. Both the viewing areas and the viewing angles of the latter are subject to variations that greatly exceed anything that would be encountered from Molniya orbit, and there is therefore no reason to question the feasibility of the necessary image rectification.

## 6. Mission timeline

At the time of writing, polar winds are being generated based on imagery from two NASA research satellites, Terra and Aqua. Terra was launched in December, 1999, while Aqua was launched in May, 2002. The projected duration is six years for both missions. Nominally, the NWP and nowcasting/forecasting communities will therefore lose their access to high-latitude water vapor imagery by mid-2008.

The successful application of the MODIS water vapor imagery has lead to a sustained effort to add a similar channel on VIIRS, the operational MODIS follow-on flying first on the NPP satellite in from 2006, and then on the operational NPOESS satellite series starting in 2009. Development of the first three VIIRS flight models has already proceeded beyond a stage where the channel line-up could be altered. Even under the most optimistic assumptions – namely that a water vapor channel will be added starting with Flight Model 4 - water vapor imagery from VIIRS will not become available until 2015, by the time NPOESS-3 is launched.

Beginning in 2005, EUMETSAT will fly AVHRR/3 on the operational METOP series in a 9:30 AM equatorial crossing time orbit. The impact of the MODIS imagery has lead to a similar similar push within EUMETSAT toward adding a water vapor channel or alternatively replace the imager payload on METOP. In the most optimistic scenario, this could be accomplished beginning with METOP-3 which is currently scheduled for a 2014 launch.

The most likely scenario is therefore that there will be at least a six-year gap (2008-2014) during which no water vapor imagery will be available outside the latitude bands that are visible from geostationary orbit.

A Molniya-orbiting imager with a water vapor channel could help fill this gap for the northern hemisphere, and in order to provide continuity after the end of the MODIS period, a launch as close as possible to the nominal end of the MODIS mission would be highly desirable. Ideally, the mission duration would be six years in order to provide coverage until VIIRS will have the water vapor capability. This will be difficult to achieve within the financial envelope provided by ESSP. However, in order to properly evaluate the impact of the retrieved data on the target applications, a minimum duration of three years would be desirable. Other agencies or user groups interested in maintaining access to such observations beyond the projected lifetime should be invited to contribute resources toward prolonging the duration of the mission.