NOTES AND CORRESPONDENCE

On the Use of Satellites in Molniya Orbits for Meteorological Observation of Middle and High Latitudes

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ABSTRACT

Time and space sampling is an increasingly critical aspect of Earth observation satellites. The highly eccentric orbit used by Soviet Molniya satellites functions much like a high-latitude geostationary orbit. Meteorological instruments placed on a satellite in a Molniya orbit would improve the temporal frequency of observation of high-latitude phenomena such as polar lows. Consideration of this new sampling strategy is suggested for future systems such as the "Earth Probe" satellites in the Mission to Planet Earth program as well as for operational meteorological satellite programs.

1. Introduction

As satellite payload capabilities and the sophistication of remote sensing systems continue to increase, we find time and space sampling to be an increasingly critical aspect of Earth observation satellites. Today's meteorological satellites are primarily in nearly circular orbits of two types: geostationary orbit (GEO) and low-earth orbit (LEO).

GEOs orbit over the equator in synchrony with the Earth so that they appear stationary over a selected meridian. Their main advantage is that points in their field of view can be observed as frequently as instruments allow. The areas they observe (Fig. 1) are restricted, however, to about 60° great circle arc from the subsatellite point. Four or five geostationary satellites usually operate around the globe, so the equatorial regions are well observed. Points poleward of about ±50° are observed poorly or not at all due to increasing atmospheric path length and perspective problems arising from the oblique view.

If they are in orbits with inclination angles close enough to 90° (such as the sunsynchronous NOAA satellites), LEOs can observe the entire globe, but only the polar regions are observed frequently (once each orbit, or approximately once each 100 min). Other locations are observed as infrequently as twice per day (Fig. 2).

The latitude zones between roughly 50° and 80° are not well served by these two orbits. It is the purpose of this paper to point out that an orbit pioneered by Soviet communications satellites could be used to bring the advantages of geostationary satellites to this latitude zone, which contains substantial numbers of people and scientifically interesting, rapidly changing meteorological conditions.

2. The Molniya orbit

The Soviet Union began launching Molniya (Russian: *lightning*) communication satellites in 1965, and they continue to be launched (seven in 1988; Thompson 1989).

The Molniya orbit is highly eccentric and inclined 63.4° from the equator. The perigee is chosen to keep the satellite above most of the atmosphere to avoid drag. The Soviets have chosen the perigee to be about 600 km above the Earth's surface. The apogee is then chosen such that the satellite completes exactly two orbits while the Earth makes one complete rotation (see Appendix). The period for this orbit is 717.74 min. The apogee is 39 750 km above the Earth's surface, compared to the height of a geostationary orbit of 35 787 km. The resulting semi-major axis is 26 553 km, and the eccentricity is 0.737.

The oblateness of the Earth causes changes in Keplerian orbital elements. The semi-major axis, inclination angle, and eccentricity are nearly unaffected by Earth's oblateness. However, the orbital period changes slightly, and both the right ascension of ascending node and the argument of perigee (Fig. 3) change linearly in time due to this perturbation (see Appendix). At an inclination angle of 63.4° $[\sin^{-1}(0.8^{1/2})]$, the argument of perigee becomes stationary; thus the apogee is fixed at a given latitude.

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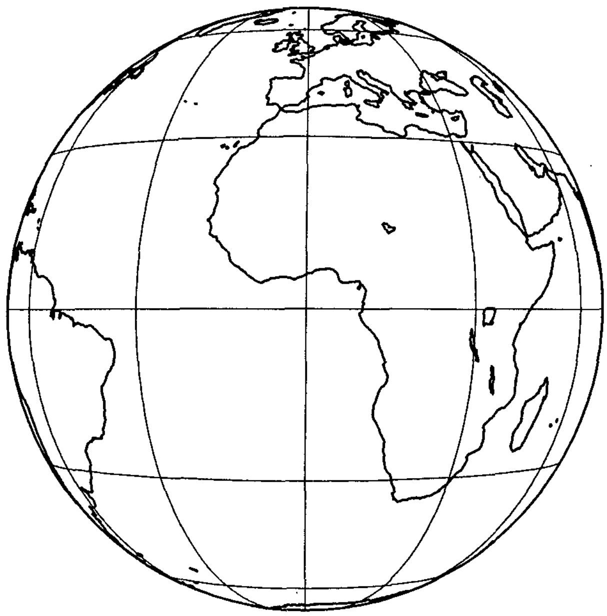

FIG. 1. The area viewed by the geostationary METEOSAT.

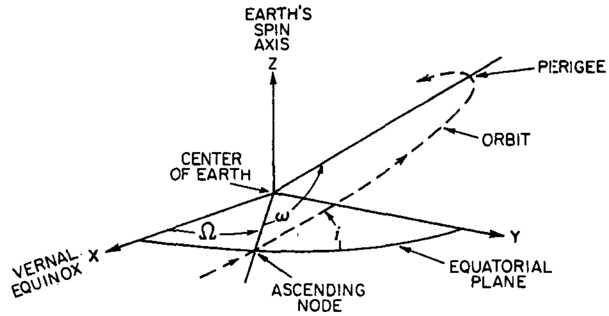

FIG. 3. Sketch of Keplerian orbital elements: i = inclination angle, ω = argument of perigee, Ω = right ascension of ascending node.

Figure 4 shows the Molniya orbit as viewed perpendicular to the orbital plane. The satellite moves very slowly near apogee and rapidly near perigee. Figure 5 shows the remarkable ground track of a satellite in a Molniya orbit with apogee at latitude 63.4°N and longitudes 0° and 180°. Two complete orbits are shown; succeeding orbits follow the same track. Within about 4 h of apogee, the subsatellite point is nearly stationary. Thus the satellite approximates a high-latitude geostationary satellite.

Figure 6a shows the views of such a satellite when its apogee is at the prime meridian. Comparing Fig. 1 with Fig. 6a, the improvement in observation of northern Europe is quite obvious.

During the nearly four hours centered on perigee, the satellite rapidly tours the Southern Hemisphere and rises on the opposite side of the Earth. The view from the second apogee is shown in Fig. 6b. The case for international cooperation in the use of such a satellite is apparent.

For comparison, the view of a satellite in a Molniya orbit such that its apogee occurs at ±90° longitude are shown in Fig. 7.

Between 1966 and 1968, eight Soviet Molniya satellites carried television cameras to transmit cloud-

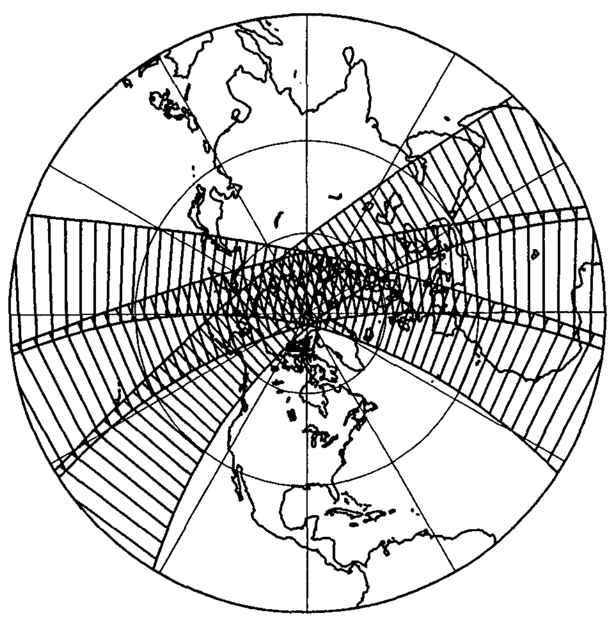

FIG. 2. The coverage of the NOAA 9 Advanced Very High Resolution Radiometer (AVHRR) on three consecutive orbits. The ascending portion of the orbits is on the left, and the descending portion is on the right. The satellite makes about 14 orbits per day; thus each point will be viewed at least once ascending and once descending.

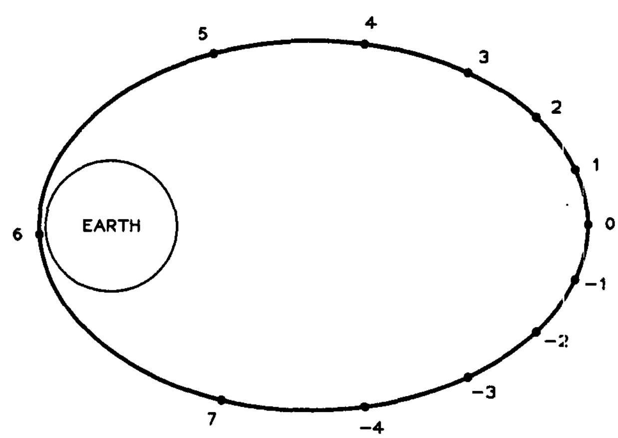

FIG. 4. A Molniya orbit (600 km perigee height) viewed perpendicular to the plane of the orbit. A dot is placed every hour. The labels are hours from apogee.

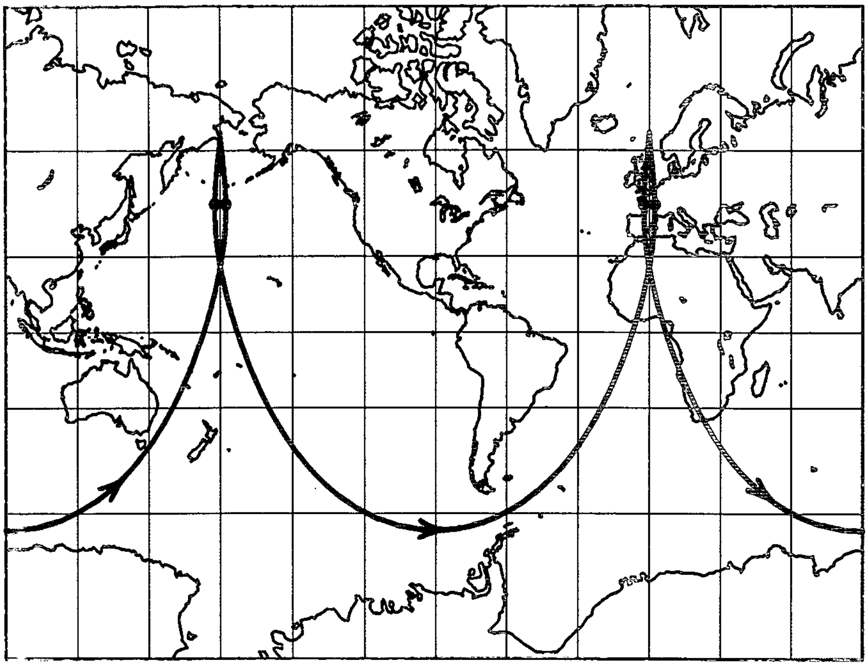

FIG. 5. Ground track of a satellite in a Molniya orbit with apogee at latitude 63.4°N and longitudes 0° and 180°. A dot is placed 4 h before and 4 h after apogee. The satellite spends two-thirds of its time north of the dots, which occur at 46.8°N and ±2.3° longitude from apogee.

cover pictures (Dubach and Ng 1988). We have been unable to determine the overall quality, usefulness, or reason for termination of these experiments.

3. Problems

There are a few problems associated with meteorological satellites in a Molniya orbit. First, a very accurate attitude control system, perhaps involving star imaging, would need to be used for accurate navigation of the resulting images. This requirement is reinforced by the differing distances with which the area of interest would be observed. (The altitude of the satellite 4 h before and after apogee is about 60% of its height at apogee.) Each image would require normalization to a standard viewing perspective or remapping into a standard map projection. This requires accurate navigation of each pixel.

Second, each satellite observes a given location for only about 8 h per day. The rest of the time is spent near perigee or on the opposite side of the Earth. Continuous 24-h coverage can be realized by placing three satellites in similar orbits with the right ascensions of ascending node separated by 120° and synchronized so that their apogees are 7.97 h apart.

4. Alternatives

Are there alternative orbits or strategies that could improve observation of high latitudes?

Six coordinated sunsynchronous LEOs could observe every point on Earth approximately every 2 h, but three satellites in a Molniya orbit could observe a given point in the Northern (or Southern) Hemisphere continuously.

A satellite in a high-inclination, circular orbit could be used. It would have the advantage of observing both the Southern and Northern Hemisphere high latitudes, but it would spend roughly half its time near the equator.

Satellites synchronized such that they complete m orbits for each rotation of the Earth could be used, but only Molniya orbits ($m = 2$) have ground tracks with cusps which approximate geostationary satellites. The ground tracks for satellites in orbits for which $m = 1$ and $m = 3$ are shown in Fig. 8.

5. Conclusions

It is concluded that a Molniya orbit offers unique advantages for weather and climate observations of middle and high latitudes. We believe that the launch of an experimental meteorological satellite in a Molniya orbit is both timely—in view of the recent trend in international cooperation—and scientifically interesting for the study of polar lows, the circumpolar vortex, ozone variation, and other high latitude phenomena. Consideration of this new sampling strategy is suggested

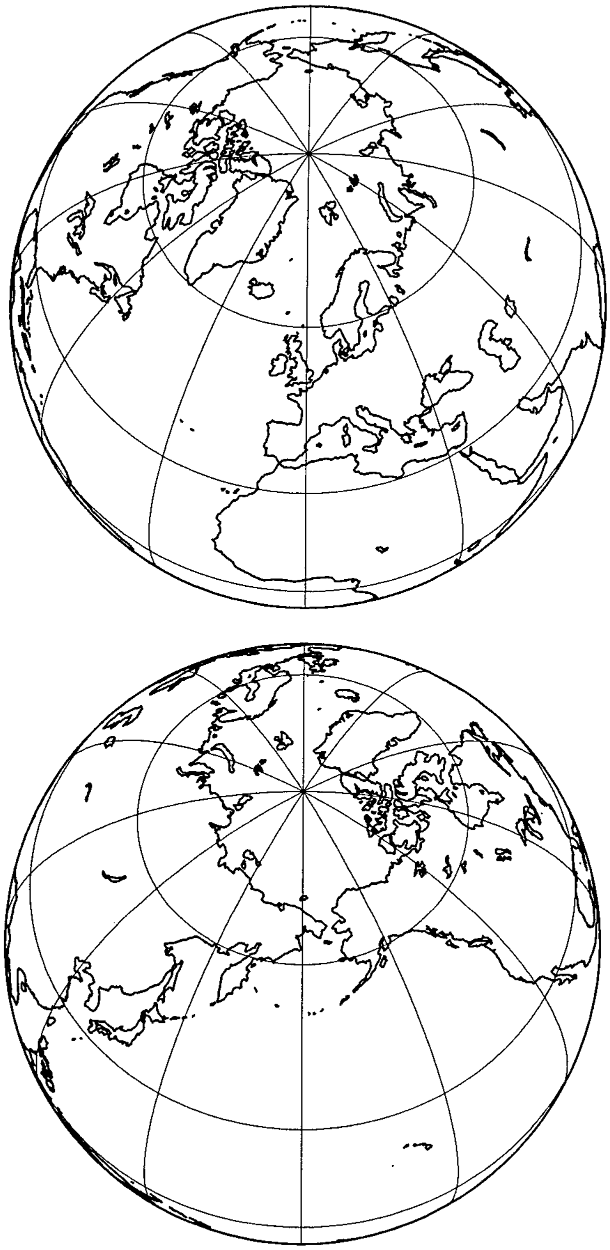

FIG. 6. The views of a satellite at the apogee of a Molniya orbit: (a) when the satellite is at 0°, and (b) one orbit later when the satellite is at 180°.

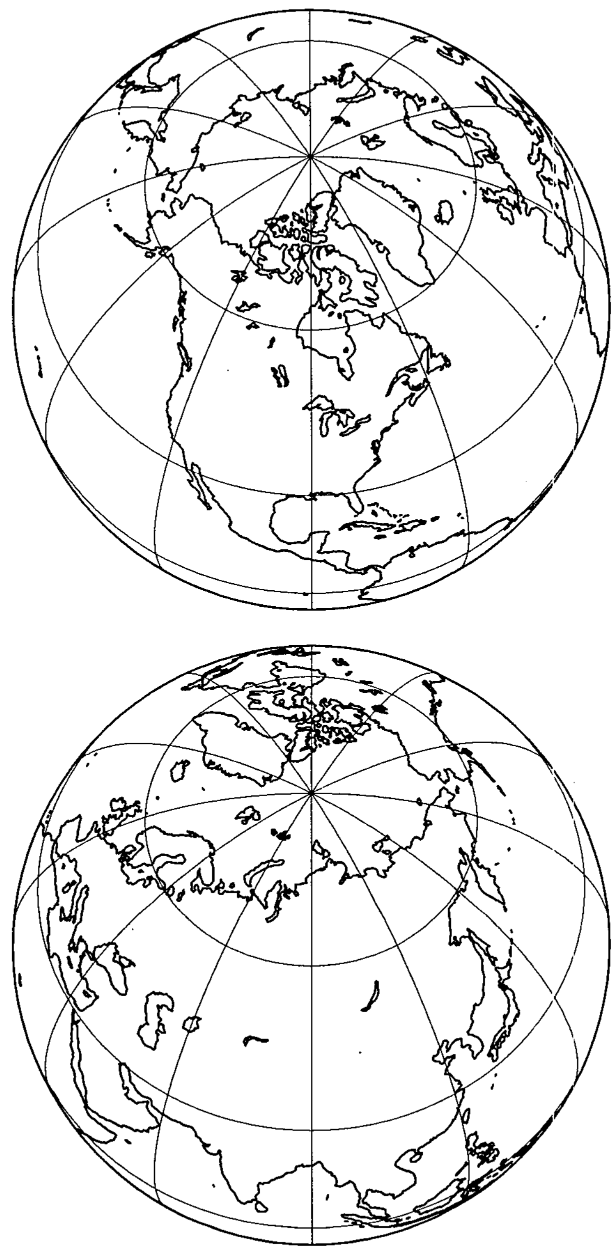

FIG. 7. As in Fig. 6 except that the orbit has been rotated so that the apogee occurs at ±90° longitude: (a) satellite at 90°W longitude, (b) satellite at 90°E longitude.

for future systems such as the "Earth Probe" satellites in the Mission to Planet Earth program as well as for operational meteorological satellite programs.

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APPENDIX

Orbit Calculations

Escobal (1965) gives the following formulae for the time rate of change of orbital elements in an orbit perturbed by a quadrupole gravitational field:

$$n = (Gm_e)^{1/2}a^{-3/2}[1 + 1.5J_2(R_e/a)^2(1 - \epsilon^2)^{-3/2} \times (1 - 1.5\sin^2 i)], \quad \text{(A1)}$$

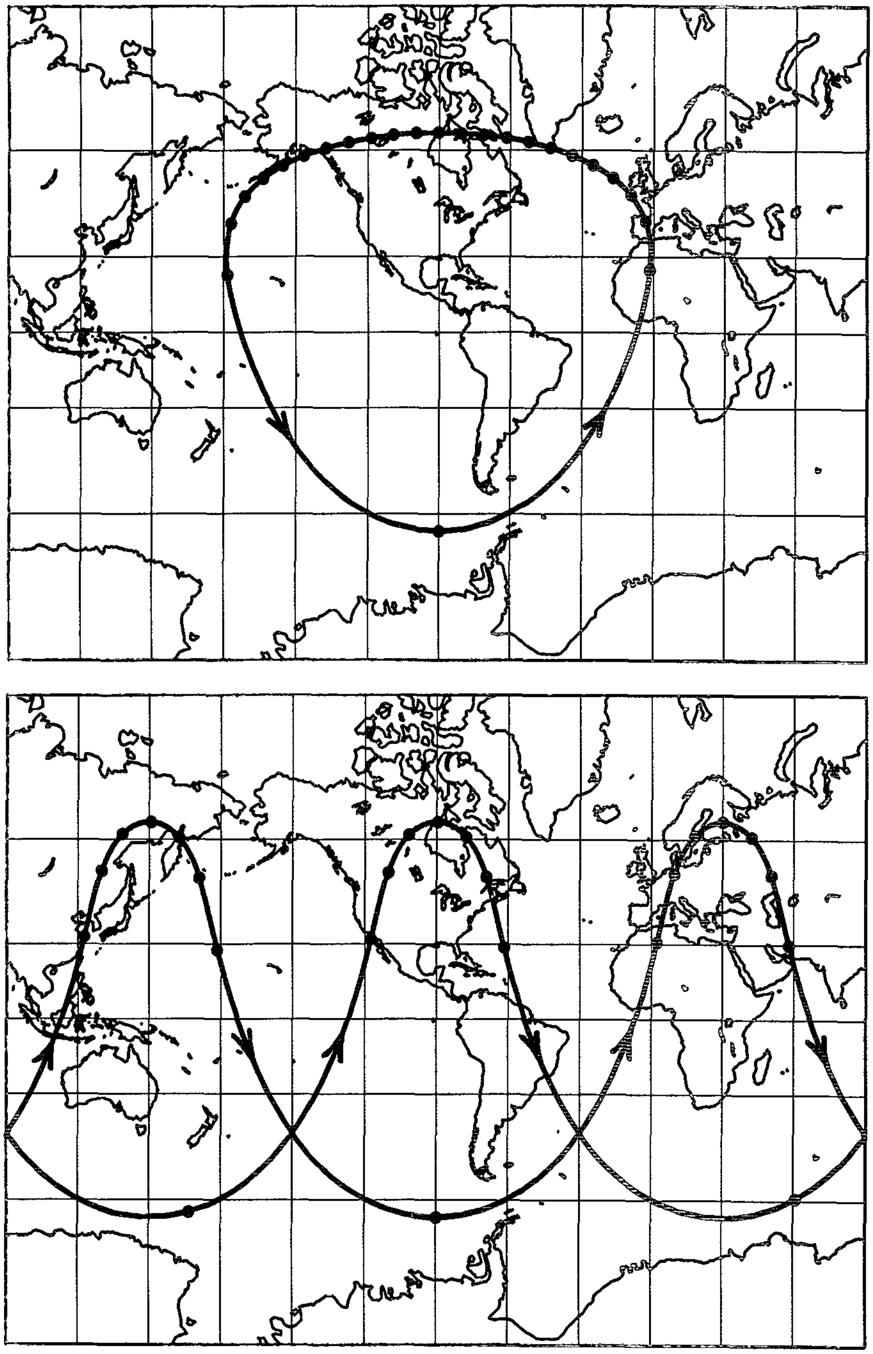

FIG. 8. The ground track of satellites in synchronous orbits such that they make (a) one and (b) three orbits for each rotation of the Earth. Dots are placed each hour.

$$d\Omega/dt = -n[1.5J_2(R_e/a)^2(1-\epsilon^2)^{-2}\cos i], \quad (A2)$$

$$d\omega/dt = n[1.5J_2(R_e/a)^2(1-\epsilon^2)^{-2}(2-2.5\sin^2 i)], \quad (A3)$$

where n is the anomalistic mean motion constant (time rate of change of the mean anomaly) in radians per second, $d\Omega/dt$ the time rate of change of the right ascension of ascending node in radians per second, $d\omega/dt$ the time rate of change of the argument of perigee in radians per second, J_2 the coefficient of the quadrupole term of the Earth's gravitational field (1.08228×10^{-3}), G is the Universal Gravitation Constant, m_e the Earth's mass ($Gm_e = 3.98579 \times 10^{14}$ m^3 s^{-2}), R_e

the equatorial radius of Earth (6.378214×10^6 m), a the orbital semi-major axis in meters, ϵ the orbital eccentricity, and i the orbital inclination angle.

The nodal period of a satellite (time between ascending nodes) is approximately given by

$$T = 2\pi/(n + d\omega/dt). \qquad (A4)$$

If $d\Omega_e/dt$ is the rotation rate of the Earth with respect to the fixed stars (7.292116×10^{-5} rad s^{-1}), then $d\Omega_e/dt - d\Omega/dt$ is the rotation rate of the Earth with respect to the satellite's orbital plane. If the satellite is to complete m orbits while the Earth turns once, then,

$$mT = 2\pi/(d\Omega_e/dt - d\Omega/dt), \qquad (A5)$$

or, equivalently,

$$n + d\omega/dt = m(d\Omega_e/dt - d\Omega/dt). \qquad (A6)$$

Assuming a value of the inclination angle [$\sin^{-1}(0.8^{1/2})$] which makes $d\omega/dt = 0$, and assuming a perigee [$a(1 - \epsilon)$] of R_e + 600 km, Eq. (A6) can be solved iteratively for the apogee [$a(1 + \epsilon)$].

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