Ever Wonder What's in Molniya? We Do.

John T. McGraw
J. T. McGraw and Associates, LLC and
University of New Mexico
Peter C. Zimmer
J. T. McGraw and Associates, LLC
Mark R. Ackermann
J. T. McGraw and Associates, LLC

ABSTRACT

Molniya orbits are high inclination, high eccentricity orbits which provide the utility of long apogee dwell time over northern continents, with the additional benefit of obviating the largest orbital perturbation introduced by the Earth's nonspherical (oblate) gravitational potential. We review the few earlier surveys of the Molniya domain and evaluate results from a new, large area unbiased survey of the northern Molniya domain. We detect 120 Molniya objects in a three hour survey of ~ 1300 square degrees of the sky to a limiting magnitude of about 16.5. Future Molniya surveys will discover a significant number of objects, including debris, and monitoring these objects might provide useful data with respect to orbital perturbations including solar radiation and Earth atmosphere drag effects.

1. SPECIALIZED ORBITS

Earth Orbital Space (EOS) supports many versions of specialized satellite orbits defined by a combination of satellite mission and orbital dynamics. Surely the most well-known family of specialized orbits is the geostationary orbits proposed by science fiction author Arthur C. Clarke in 1945 [1] that lie sensibly in the plane of Earth's equator, with orbital period that matches the Earth's rotation period. Satellites in these orbits, and the closely related geosynchronous orbits, appear from Earth to remain constantly overhead, allowing continuous communication with the majority of the hemisphere below. Constellations of three geostationary satellites equally spaced in orbit (~ 120° separation) can maintain near-global communication and terrestrial surveillance.

Geosynchronous satellites with non-zero orbital inclination describe analemmas about a nominal geostationary equatorial position. The significant difference is that true geostationary satellites have 0° inclination relative to the celestial (and thus Earth's) equator, while geosynchronous satellites, centered on the same altitude, have orbits inclined to the equator, allowing them to move north and south of the equator, thus describing an analemma on the celestial sphere as observed from Earth. Each of these orbits clearly takes advantage of special conditions with respect to Earth orbital physics.

The specialized highly elliptical Molniya (mōhl'-nē-uh - Russian "lightning") orbits provide oversight and communication to fixed regions on Earth, as do the geosynchronous satellites, but do so by using (rather clever!) orbital mechanics. Molniya orbits are highly inclined at about 65° with high eccentricity of about 0.75 and periods of one-half day. At apogee, the Molniya satellites are at high altitude and latitude, with their lowest orbital velocity, thus longest dwell time above, say, Russia. Thus Russian satellites can provide communications and/or acquire imagery over all of Russia, most of Europe, and south into the Indian subcontinent. Because they are in half-day orbits, they reach a second daily apogee 180° in longitude from the primary service position, or in this example, above the USA. Three Molniya satellites provide continuous communications capability to half the globe, with good coverage to high latitudes.

Molniya orbits take advantage of the inclination dependence of the largest perturbation to Earth's nominally spherical geopotential to "zero-out" the effect and minimize the necessity for station-keeping.

2. THE CLEVERNESS OF MOLNIYA ORBITS

Earth-orbiting satellites are probes of the planet's gravitational potential. That is, while Earth is sensibly spherical, large-scale physical structures on Earth, such as continents and oceans, create corresponding structures sensed as stationary, modified acceleration in the geopotential. That is, the geopotential structure incorporates gravitational acceleration induced by terrestrial features (land and sea masses, for example). Note that Earth's gravitational field formally carries no information about what creates it, only that density and range of surface and subsurface topological features modulates the acceleration experienced by the satellite.

Since 1957 satellites have been used to measure (in many innovative ways) Earth's gravitational potential, and geodesists relate these measurements to Earth features. Some of these measurements are crucial to our current understanding of Earth, its structure, and the rate of change of that structure. That is, geodesy is spatially and time dependent at multiple scales. The geopotential is also spatially and time dependent but, for multiple physical reasons, the angular, range and time-dependence of the geopotential "sums" acceleration vectors, and does not necessarily correspond in detail to Earth structures.

Earth-orbiting satellites respond to Earth-induced accelerations, and geodesists interpret these in terms of surface and subsurface terrestrial structure. Satellite operators, on the other hand, simply need to know what effects the geopotential structures have on satellite orbits.

Components of acceleration vectors produced by gravitating features on Earth add to form the geopotential in which satellites orbit.

One example of this is the non-spherical, low-frequency elements of the geopotential that lead to the 12 hour period Molniya (and 24 hour period Tundra) orbits.

The geopotential is canonically represented by Legendre polynomials, with the modal shape described by spherical harmonics e.g. Beutler[2].

In the series of Legendre polynomials describing the aspherical components of the Earth's gravitational field, the J2 Legendre term is measured to be larger than the J3 term by a factor of ~ 500 – it is by far the largest perturbative coefficient of the series that currently best describes the field.

For inclined, eccentric orbits, such as the Molniya orbit, perturbations introduced by passing through Earth's non-spherical potential are a function of the inclination of the orbit. The change in eccentricity introduced by a change in the inclination of the orbit as measured by the lowest-order periodic Legendre polynomial (i.e. Earth's gravitational "equatorial bulge"):

$$\Delta\omega = -2\pi \frac{3J_2}{\mu p^2}\left(\frac{5}{4} sin^2\, i - 1\right)$$

By zeroing the change of the argument of perigee, $\Delta\omega$, this "J_2 term" formally goes to zero. That is, the argument including the inclination, $\left(\frac{5}{4} sin^2\, i - 1\right) = 0$, which occurs for $i = 63.43°$, and perigee is not perturbed, but remains constant at ω. Herein lies the utility of the Molniya (and Tundra) apogee dwelling orbits: at this inclination the primary perturbation introduced to an elliptical Earth orbit is cancelled by crossing the Earth's gravitational equatorial bulge at the "correct" angle, resulting in a stable orbit requiring little station keeping, and with maximum dwell time at high latitudes above northerly countries such as Russia and the USA, for example.

Launching satellites into highly elliptical orbits at this inclination thus allows communications satellites to dwell at high northern latitudes.

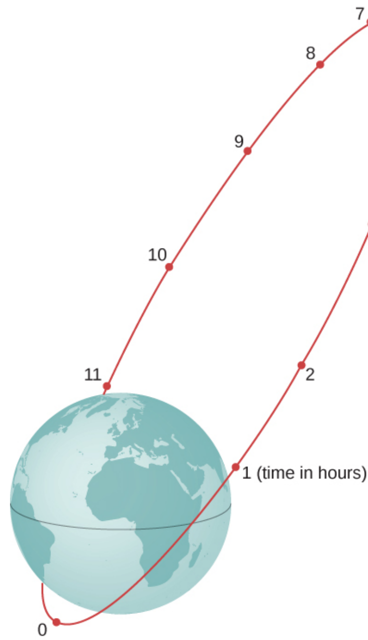

Fig. 1. The Molniya orbit crosses Earth's equator at an inclination angle i = 63.4° with perigee at -90°. Russian Molniya communications satellites had apogee near 40,000 km and period of one-half a synodic day.

Three Molniya satellites occupying sensibly the same orbit ensures virtually complete temporal coverage of a large sector of a hemisphere. A constellation with apogee in the northern hemisphere centered on Russia, for example, provides near-continuous communications and/or imaging of a large fraction of Europe and Asia. Because the period is one-half a day, a second apogee for each satellite occurs 180° away in longitude, or over North America. This orbital geometry is shown in Figure 2.

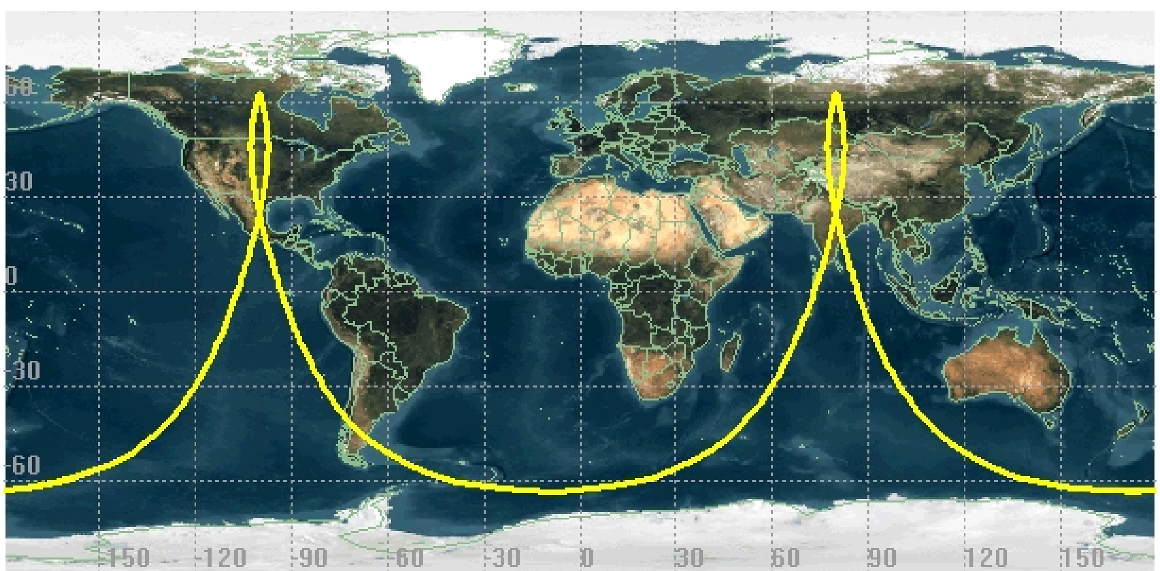

Fig. 2. A Molniya satellite has a period of one-half a synodic day, which puts successive apogees over Russia and the USA. Both Russia and the USA have excellent communications coverage from the satellite. The accurately repeating orbit ensures contact with the satellite family's ground stations.

The related Tundra orbits, with a period of one synodic day, operate by the same physical mechanism, but each orbit reaches apogee at a single longitude.

Apogee for the Molniya orbit can be ~ 40,000 km, while perigee is ~ 500 km. In essence, these satellites traverse all nominal orbital space from LEO through GEO twice a day.

3. INVENTORY AND SURVEY OF MOLNIYA ORBITAL SPACE

Molniya orbits thus “sample” virtually all of the extent of EOS twice a day. Molniya (and Tundra) satellites are “stable” in the sense that a primary orbital perturbation - the change in perigee - has been minimized by choice of inclination. An hypothesis is that objects, including debris, that are launched or injected into a Molniya orbit might be expected to dwell there for appreciable duration. [3]–[5]

While the perigee, ω, remains sensibly constant by this stratagem, the right ascension of the ascending node, Ω, also a function of J_2, will change with time at a rate of -0.0742° per orbit for an orbital period of one-half a synodic day, the target period for a true near-stationary Molniya orbit.

Objects on Molniya-like orbits experience almost the full range of non-gravitational physical perturbations that, with time, modify orbits. At the low perigee, Molniya-orbiting objects experience the variable drag of Earth’s atmosphere. At apogee, these objects are gravitationally perturbed by Earth’s moon and the sun, as well as by solar radiation pressure.

One might hypothesize that monitoring objects in Molniya orbits provides synoptic measurement of these parameters and their effects on orbits. Monitoring the long-term variable solar radiation field by its effect on satellites of various area-to-mass ratios might be particularly useful, for example. These are, however, small perturbations which thus require a sufficiently large number of objects to make significant measurements.

A second hypothesis is that as external (i.e. not gravitational) perturbations affect Molniya orbits, one might consider the effect of inclined orbits being preferentially perturbed in azimuth. That is, with inclination remaining near 65°, the right ascension of the ascending node, because it is not constrained, might change synoptically, resulting in equatorially near-parallel orbits propagating across the celestial sphere.

Recently, observers and theoreticians have instituted programs to predict, survey and understand debris and satellites crossing MEO in near-Molniya orbits. [3], [4], [6]–[8] The result of these investigations is to indicate that objects in Molniya-like orbits are expected to be rather ubiquitous, that the primary decay mechanism is atmospheric drag-induced depopulation, and that further research into the orbital population and evolution of these objects is warranted.

Hinze et al.[7], Schildknecht et al.[7] and Silha et al.[3] for example, analyzed observational data on objects with Molniya-like orbits obtained at the ESA Space Debris Telescope located at the Optical Ground Station (OGS) at the La Teide Observatory on Tenerife. Observations of selected Molniya objects obtained from the USSTRATCOM catalog as of January 2012 were made at OGS in 2013. The ESA Space Debris Telescope (ESASDT) is a 1-m modified Ritchey-Chretien f/4.47 reflector with a nominal one degree field of view (FOV). The detector is mosaic of four 2048 x 2048 pixel CCDs with pixel resolution of 0.6 arcsec and FOV of 0.7° x 0.7°. The shortest readout time for the multiplexed outputs is 19 s. It is stated that this telescope can thus detect objects at 20 – 21 mag at GEO, corresponding to 20 – 10 cm diameter objects.

The observational strategy used at OGS was to observe a field for an 11 minute integration time at the anti-sun right ascension and +55° declination. Detected satellite “tracklets” were follow up with same-night second epoch observations.

During the 13 night OGS observation sequence used to acquire the data set on which the dynamical research is based, 30 uncorrelated targets (UCTs) were detected, with a limiting magnitude of ~ 19. The majority (22) of objects was discovered in the magnitude range 16 – 18, with individual objects often showing significant brightness variability.[3]

The conclusion of the research based upon these data is that there exists a large population of objects, including debris, in Molniya-like orbits, and that more extensive surveys to discover and characterize this population of objects is required to fully understand the nature of the objects and to gain insight into the evolution of Molniya-like orbits.

4. A WIDE-AREA SURVEY TO UNDERSTAND THE POPULATION AND EVOLUTION OF MOLNIYA-LIKE ORBITS

The next step in investigation of the Molniya family of orbits is accomplished by a statistically complete uncued survey to faint limiting magnitude that provides statistics describing the number of Molniya objects as a function of magnitude, as well as orbital elements. We describe a preliminary survey designed to address this goal.

The survey we propose is based on an uncued, wide-field survey, as opposed to classical pointed, single field-of-view observations. This survey , which is designed and we are now implementing, is one example of the utility and efficiency of complete, cost-effective SoS based upon WFOV surveillance telescopes accomplishing uncued, wide field-of-view observations as described by JTMA [9]–[11] and included references.

A baseline survey of Molniya-like orbits designed to be compared to previous surveys of this family of orbits was accomplished using a C-14 telescope with HyperStar focal reducer and a 4k x 4k cMOS camera on a Software Bisque Taurus mount shown in Fig. 3.

Fig. 3. The COTS telescope system used for this Molniya detection experiment: a Celestron C-14 with a HyperStar focal reducer and camera on a Software Bisque Taurus mount. Data are acquired and analysis of “tracklets” of Molniya-like objects are identified on-site.

The resulting detected FOV is 1.88° x 1.88° with 1.65 arcsec pixels. This telescope is located at a site in Placitas, New Mexico (+35° 18', 106° 27'), approximately 40 km north of Albuquerque.

An uncued test survey of three hours duration was acquired with the telescope tracking at the sidereal rate. The survey, covering the range of -30° to +30° in azimuth and +50° to +70° in altitude, was executed to assess detectivity of uncued targets in Molniya orbits. The survey includes a total of 2028 surveyed square degrees on an overlapping grid of 575 uncued observations, 41 pointings in azimuth and 14 pointings in altitude, with alt/az step size of 1.5°. The total (non-overlapping) area surveyed area on the sky is 1291 square degrees. This survey used a total integration time of eight seconds for the first third of exposures, and 12.8 seconds for the remaining two-thirds of exposures. The longer exposures reached a faint limiting magnitude of 16.8 for stars and slow-moving objects.

This test survey detected 120 total Molniya-like targets. Of these, 24 were previously cataloged objects, 15 were un-correlated definite detections and another six were categorized as un-correlated probable detections.

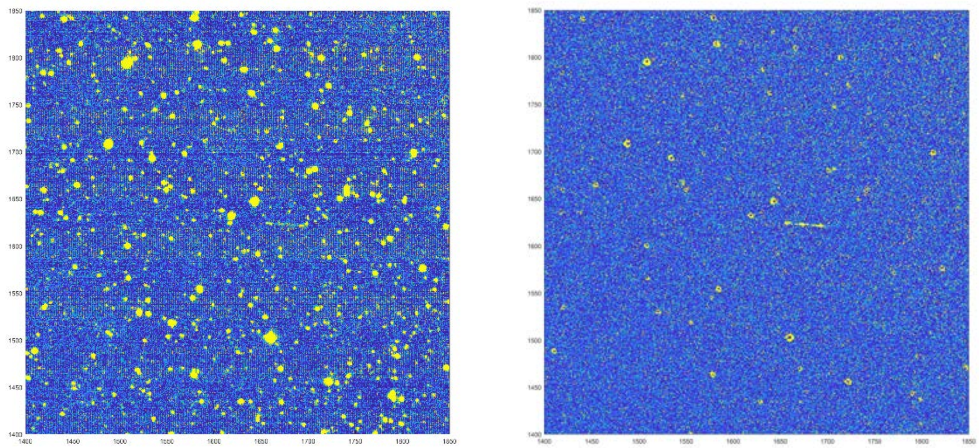

Fig. 4. The left image shows the raw data resulting from a 12.8 s exposure. The processed image more clearly shows the un-cataloged Molniya object at good signal-to-noise.

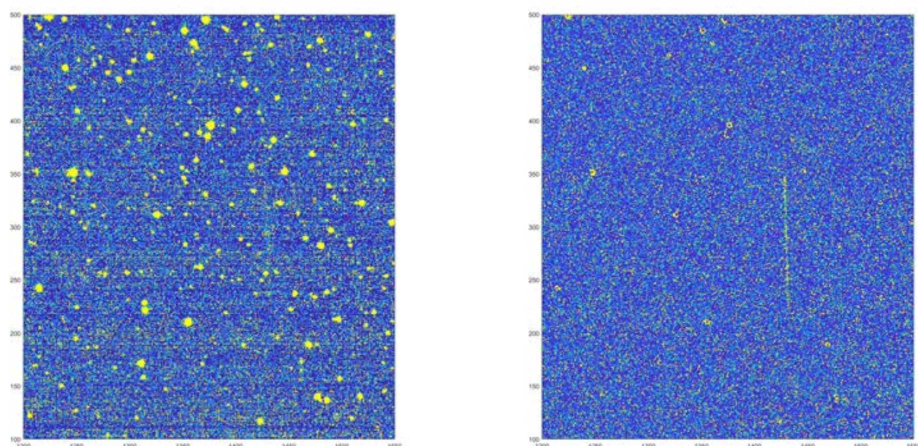

Fig. 5. Fainter streak image of another un-cataloged Molniya appears with good signal-to-noise after image processing.

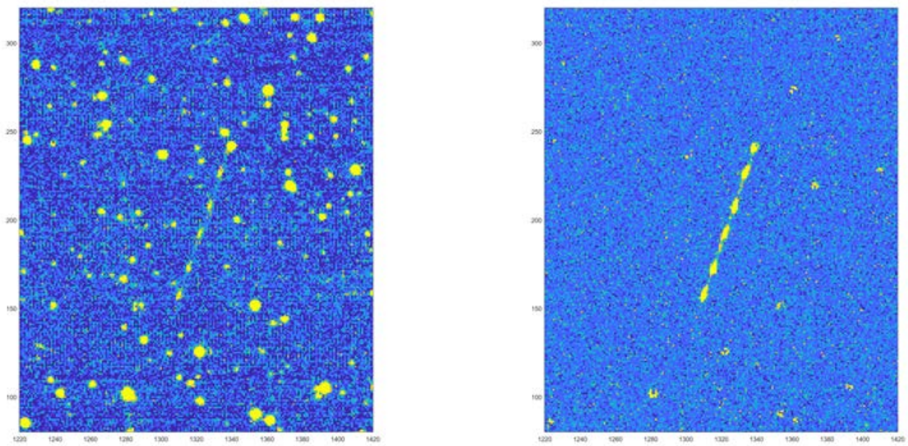

Fig. 6. Molniya satellite streak image detection with resolved variability.

With detections, radiometry, and angular rate determinations we can evaluate the orbital population statistics of the 120 detected objects. Fig. 7 shows the angular motion rate expressed as arcsec/sec for all 120 detections, with blue data showing <u>all detections</u>, and overlying brown entries are previously <u>uncorrelated</u> detections. Within the limits of the survey statistics these detections reflect the same population, legitimately classified as Molniya objects.

Fig. 8 shows the magnitude histogram for this sample. Again, the distribution of magnitudes appears similar. The previously uncorrelated entries overlying brown) trend towards fainter detection magnitudes, which may be consistent with them not being previously correlated. This diagram also suggests that the fainter Molniya objects will be discovered by well-designed surveys extending to fainter limiting magnitudes. If this hypothesis is correct, there might well be a significant number of objects, possibly some population of debris, orbiting in Molniya-like orbits

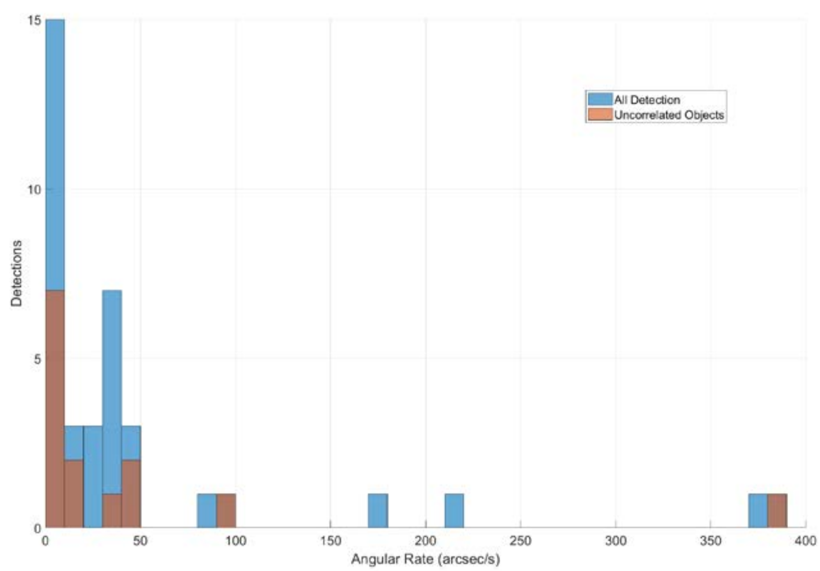

Fig. 7. Angular rate histogram for Molniya objects detected in this survey. Blue entries indicate rate values for all detections, while overlying brown entries indicate uncorrelated detections. E.g. the 0 – 10 arcsec/sec angular rate bin contains 15 total detections, of which seven are uncorrelated.

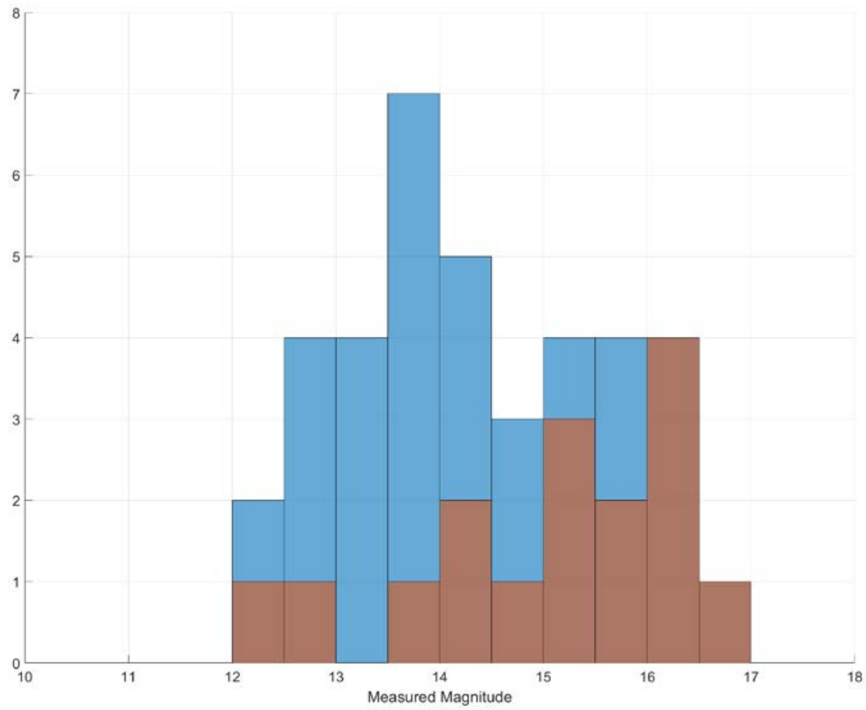

Fig. 8 Magnitude histogram of the 120 Molniya objects detected in this prototype survey. Blue entries represent all detections, and brown entries represent uncorrelated objects.

It is clear that the detection scenarios used to analyze data from the optical telescope assembly (OTA) described herein provide a useful survey technique for Molniya-class objects. While the detection limit is currently about magnitude 16.5 for this 0.35 m telescope, the grid survey, camera operation and survey techniques implemented for this test provide high efficiency for satellite detection, in general, and application of motion constraints effectively and efficiently isolated Molniya-class satellites.[9]–[11] Comparing this prototype survey to previous surveys with larger aperture telescopes reaching fainter limiting magnitudes (e.g. [3], [7], [8]) indicates that both wider field and fainter limiting magnitudes will provide significant data about the currently incomplete knowledge of the population and extent of objects in Molniya-like orbits.

Detection and long-term monitoring of satellites and debris in Molniya orbits provide data not only on the functional and derelict satellites occupying this space, but long-term monitoring of objects in these orbits can provide information and insight into the Earth's gravitational potential and its correspondence to current models, as well as external effects including solar irradiance and atmospheric drag.

To discover and quantify what is in Molniya-like orbits, the answer is probably best obtained by synoptically observing Molniya space. We suggest that the survey techniques presented herein, especially extended to fainter limiting magnitudes, effectively and efficiently provides a direct inventory of Molniya, and other related regimes of Earth orbital space

5. REFERENCES

[1] Clarke, Arthur C., “The 1945 Proposal by Arthur C. Clarke for Geostationary Satellite Communications,” 1945. [Online]. Available: http://lakdiva.org/clarke/1945ww/. [Accessed: 05-Sep-2017].

[2] G. Beutler, *Methods of Celestial Mechanics*. 2005.

[3] J. Silha, T. Schildknecht, A. Hinze, T. Flohrer, and A. Vananti, “An optical survey for space debris on highly eccentric and inclined MEO orbits,” *Adv. Space Res.*, vol. 59, pp. 181–192, Jan. 2017.

[4] E. Kuznetsov and P. Zakharova, “Dynamical evolution of space debris on high-elliptical orbits near high-order resonance zones,” presented at the 40th COSPAR Scientific Assembly, 2014, vol. 40.

[5] E. Kuznetsov and P. Zakharova, “Long time dynamical evolution of highly elliptical satellites orbits,” presented at the Journées 2014 “Systèmes de référence spatio-temporels,” 2015, pp. 108–111.

[6] T. Schildknecht, A. Vananti, A. Hinze, and J. Herzog, “Long-Term Evolution of High Area-to-Mass Ratio Objects in Different Orbital Regions,” presented at the Advanced Maui Optical and Space Surveillance Technologies Conference, 2012, p. 10.

[7] A. Hinze, T. Schildknecht, T. Flohrer, and H. Krag, “Results of Space Debris Survey Observations on Highly-Eccentric MEO Orbits,” presented at the 6th European Conference on Space Debris, 2013, vol. 723, p. 140.

[8] T. Schildknecht, T. Flohrer, A. Hinze, A. Vananti, and J. Silha, “An optical survey for space debris on highly eccentric and inclined MEO orbits,” presented at the 40th COSPAR Scientific Assembly, 2014, vol. 40.

[9] J. McGraw, P. Zimmer, and M. Ackermann, “Multiple Observing Modes for Wide-field Optical Surveillance of GEO Space,” presented at the Advanced Maui Optical and Space Surveillance Technologies Conference, 2016, p. 24.

[10] P. Zimmer, J. McGraw, and M. Ackermann, “Affordable Wide-field Optical Space Surveillance using sCMOS and GPUs,” presented at the Advanced Maui Optical and Space Surveillance Technologies Conference, 2016, p. 25.

[11] M. Ackermann, D. Cox, J. McGraw, and P. Zimmer, “Lens and Camera Arrays for Sky Surveys and Space Surveillance,” presented at the Advanced Maui Optical and Space Surveillance Technologies Conference, 2016, p. 58.