

US/Russian micro-satellite for calibration of active ground-based optical collectors

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Abstract

A micro-satellite, designed to aid ground-based laser imaging, ranging, and sensing systems as a calibration target, has been constructed and is scheduled to be launched in the fall of 2000. This low-earth orbit satellite carries a set of retroreflectors (for visible and near-infrared wavelengths) that present a spatially extended target to sites on the ground. Several of the reflectors also impart a polarization signature to the reflected laser light. This paper discusses the specifications of the retroreflectors, positioning of the reflectors on the satellite structure, passive control of the vehicle orientation, and ground-pattern characteristics of the reflected light.

Keywords: satellite, micro-satellite, retroreflector, corner-cube, laser ranging, laser imaging, laser remote sensing, satellite illumination

1. INTRODUCTION

The United States Air Force Research Laboratory, Directed Energy Directorate, Surveillance Technologies Branch (AFRL/DEBS) and the Institute for Precision Instrument Engineering (IPIE) of Moscow, Russia have developed a micro-satellite designed to aid in the calibration of ground-based laser imaging, ranging, and sensing systems.^{1,2} The satellite (referred to as the Retroreflector Ensemble for Laser Experiments, Calibration, Testing & Optical Research, or REFLECTOR) is a free-flying, passive (un-powered) spacecraft that carries a number of small retros spaced apart on a tree-like structure. The satellite is expected to be deployed into a 1018 km altitude, 99.6 degree inclination orbit by a *Zenit-2* launch vehicle in the fall of 2000.

The development, structural design, and launch considerations of REFLECTOR have been discussed previously.^{3,4} In this paper we detail the optical characteristics of the satellite.

The design of REFLECTOR was based on criterion related to its function as an optical calibration and imaging target. First, REFLECTOR needed to present a target of separated retros to sites on the ground. Currently all the satellites in low-earth orbit that carry multiple retros have the reflectors clumped in a group so they are not particularly interesting imaging targets. The second criterion was that the orientation of REFLECTOR must be known when it is orbit so the apparent positions of the retros as seen from the ground are known. This allows any imaging results to be compared with the known target. A third requirement was that the satellite target be “visible” from a reasonably wide ground path about the orbit track. Since the satellite will rarely pass directly over a given ground station, it must present a useful retro pattern when illuminated from small side angles. A key consideration for this specification is the angular acceptance of the retroreflectors. Finally, for cost reasons, the satellite needed to be passive and have a very low mass.

A diagram of the REFLECTOR satellite is shown in Fig.1. After release from the launch vehicle, the center boom telescopes to the position shown in the photograph in Fig.2 and stabilizes the vehicle gravitationally. The length of the vehicle with the boom extended is 1430 mm. Retros are clustered at the top of the boom, near the center of the vehicle and at the four corners of the base. The vehicle base is 460 mm wide between the retros along the diagonal. The total weight of the spacecraft is 6 kg. The triangular fins on the base increase the vehicle’s Radar and optical cross sections for ground tracking purposes. It is estimated that during terminator periods sunlight reflected from the vehicle will result in a brightness at the ground of between 6 and 8 visual magnitude.

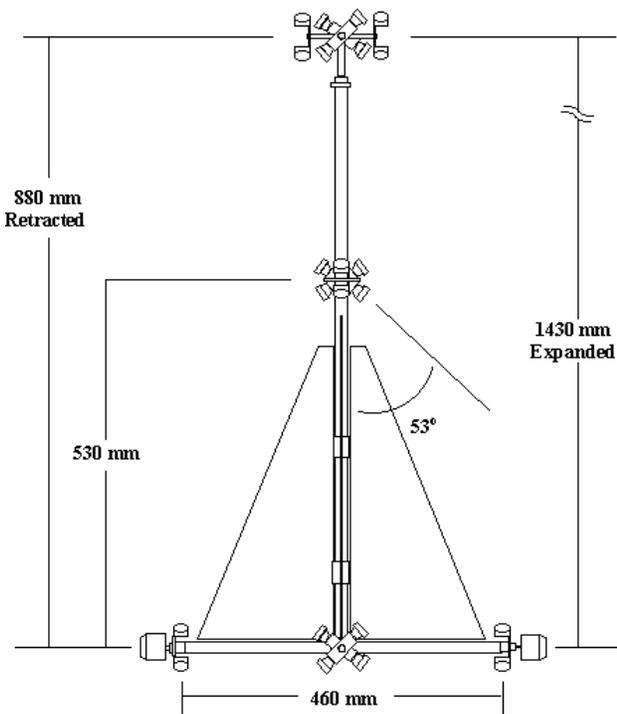


Figure 1. Diagram of the REFLECTOR microsatellite



Figure 2. Photograph of REFLECTOR with boom extended

2. RETROREFLECTORS

A close-up of the retroreflector assembly on the top of the boom is shown in Fig.3. Upon release from the launch vehicle REFLECTOR could stabilize with the boom either away or toward the earth, so retros were placed pointing both “up” and “down”. Therefore, regardless of eventual stabilization orientation, four reflectors at the top of the boom, four at the center of the spacecraft and two from each corner of the base of the craft will point toward the ground.



Figure 3. Photograph of top retroreflector assembly

The specifications of the retroreflectors carried on REFLECTOR are:

- Fused silica prism, 1.4607 index of refraction at $\lambda = 532$ nm
- Aluminum reflective coating on side facets
- Reflection coefficient at $\lambda = 532$ nm is 0.62
- Input aperture = 28.2 mm x 16 mm (rectangular shape)
- Diffraction-limited angular extent of return pattern = 4 x 6.1 arc sec (FWHM)
- Acceptance angle approximately ± 36 degrees (half-max reflected power)

Similar retroreflectors were built by SRIPDE and have been installed on various other satellites including GLONASS (Russia), ETALON (Russia), GEOIK (Russia), METEOR-3 (Russia), SALUT (Russia), RADUGA (Russia), ZEYA (Russia), GPS-36, -36 (USA), GFZ-1 (Germany), and WESTPAC (Australia).

The basic retroreflector provided by SRIPDE has a hexagonal shaped aperture of 28.2 mm diameter so the diffraction-limited beam returned from one of these retros is a roughly symmetric pattern of about 4.0-arc sec (FWHM) in angular extent. However, to address the effects of the relativistic velocity aberration,⁵ that dislocates the return beam along the orbital ground path, the retros on REFLECTOR were modified to improve the efficiency of light returning to the illuminating site. This was done by placing a 16 mm wide rectangular aperture

across the face of each retroreflector. The slits can be seen on the reflector faces in Fig. 3. When the spacecraft is in orbit, the slits will be oriented orthogonal to the orbit direction. The slits cause two effects - diffraction from the slit elongates the pattern along the orbital direction (to about 6.1 arc sec, FWHM) but the slit also limits the input acceptance angle to the retroreflector. The net effect is an improvement in energy returned to the illumination ground site but a limitation on the acceptable illumination angles.

To make REFLECTOR more useful to the general laser ranging and remote sensing community the group of retros at the mid-section of the vehicle were modified to cause a polarization change to the reflected light. Polarization sensitive measurements using laser systems is a growing approach for sensing applications. In most cases, retroreflectors have little effect on the polarization of the incident light. We are not aware of any retroreflectors currently in orbit that provide a specific polarization signature to the returning light. For REFLECTOR, $\frac{1}{4}$ wave plates were placed over entrance apertures of the 4 center retros. The fast axis of the $\frac{1}{4}$ wave plate was aligned with the vehicle's central body tube. Light returned from these retros will pass through the $\frac{1}{4}$ wave plate twice, once on the way in to the retroreflector and once on the way out. The polarization change imparted to the light will depend on the incident angle, which will be a relatively complicated but predictable function of the vehicle orbit parameters and the ground site position. Bench measurements with and without the $\frac{1}{4}$ wave plates in front of a test retroreflector showed no significant effects on the divergence of the return beam.

3. VEHICLE ORIENTATION

The orientation of REFLECTOR in orbit must be maintained in a known manner for two reasons. First, the slit apertures over the retros must be oriented orthogonal to the velocity vector, and second, the target needs to be known for imaging experiments. The boom on REFLECTOR ensures a gravity-stabilized position, which minimize pitch and roll motions. Controlling yaw motion (horizontal spin) is more difficult. Part of the solution for REFLECTOR was to place two weights at opposite ends of one of the cross member on the base of the spacecraft (Fig. 4). The weights and cross member will tend to orient along the orbit direction due to a centripetal force created by the effective rotation of the satellite in the orbit plane (in

effect, the satellite rotates in the orbit plane once each orbit). A small mass for the weights was important to minimize launch cost, although, it requires more time for the craft to stabilize in orbit after release from the launch vehicle with the smaller mass. So in addition to relatively small weights (1.2 kg each), a second passive damping approach was included in the design. Rods were installed along the fins at the base of the craft that have a hysteresis interaction with magnetic fields (Fig. 5). As the spacecraft wobbles in its initial orbit and passes through the earth's magnetic field, the rods will exert a small force on the vehicle that acts to damp any oscillatory motion. With the combination of the weights and the rods, it is expected that 3 weeks after the launch the craft will settle in the proper orientation with a wobble of a few degrees in any direction.

If short-pulse ranging (normal for the current SLR stations) is used, the two possible states of gravitational orientation (boom pointed towards the zenith or towards the nadir) may be determined from the relative positions of return pulses in time. E.g., if during a high-culmination pass of the REFLECTOR satellite a single return pulse is followed by a more or less compact group of two or three pulses, it means the boom is pointing towards the nadir. Simulated return signatures may be obtained for any observation angle, and comparison with actual signatures may help to determine the satellite's actual orientation and its variations in time.

4. RETROREFLECTOR GROUND COVERAGE

Because the retros have a limited acceptance angle, several groups of retros needed to be pointed different directions to cover a reasonable ground path. The angled mounting of the retros is apparent in Figs. 2 and 3. The retros point in one of four directions; along the direction of orbit, either direction transverse to the orbit, or backward from the direction of orbit.

Therefore, on the top of the boom – one retroreflector points in each of the four directions; in the middle of the boom – one points in each direction; and on the base – two point in each direction. So the 16 retros observable from the ground are grouped in four similar groups of four. All the retros are angled out at 53 degrees from nadir. If an observer were illuminating the satellite from the side (and below), directly into one group of the retros, the retros that would return light are indicated in Figure 6.

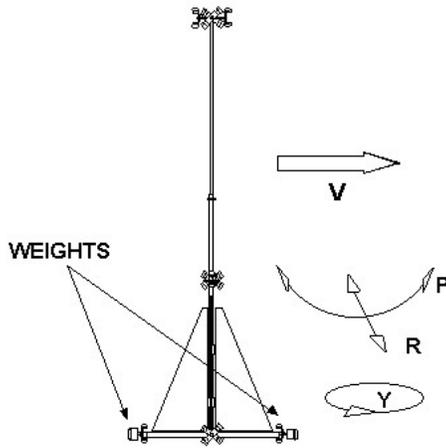


Figure 4. Orientation is maintained by gravity boom and weights. Pitch (P), roll (R), and yaw (Y) motions are shown schematically.



Figure 5. Magnetic hysteresis rods on fins damp vehicle's rotational oscillations

The question of which group of retros will be seen from various ground positions is a function of the retroreflector mounting, acceptance angle, and diffraction pattern as well as the orbit parameters and the velocity aberration. Figure 7 is a map showing which of the four retroreflector groups will return light to the observing site at various positions around the satellite's projected ground point. The map is scaled in degrees from zenith. The choice of the 16 mm slit aperture for the retros leads to the full coverage characteristics of the map with little overlap between retroreflector groups. This map shows the approximate coverage zones but further analysis will need to be done to determine the expected return signal contours within these zones. Figure 8 is a simulation that shows a sequence of visualizations of the REFLECTOR micro-satellite as it passes over a ground site at a culmination angle of 20 degrees off zenith.

In Table 1, as an example of the satellite retroreflector system efficiency, the effective cross-section of the system is shown vs. the elevation angle for a pass with a culmination point elevation angle of 60°. The maximum value of cross-section is here about 1 km², providing return signal strength comparable with the one obtained from low-orbit satellites specially designed for SLR measurements (e.g. STELLA, STARLETTE).

Table 1

Effective cross-section of the REFLECTOR satellite retroreflector system vs. the line-of-sight elevation angle (for a pass with a culmination at an elevation angle of 60°)

Line-of-sight elevation angle, deg.	20	30	40	50	60
Effective cross-section, km ²	0.983	0.986	0.694	0.113	0

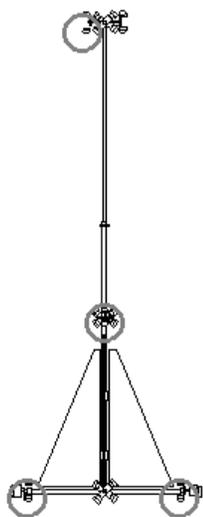


Figure 6. One group of four retroreflectors, indicated with circles, that would return light when REFLECTOR is illuminated from the side

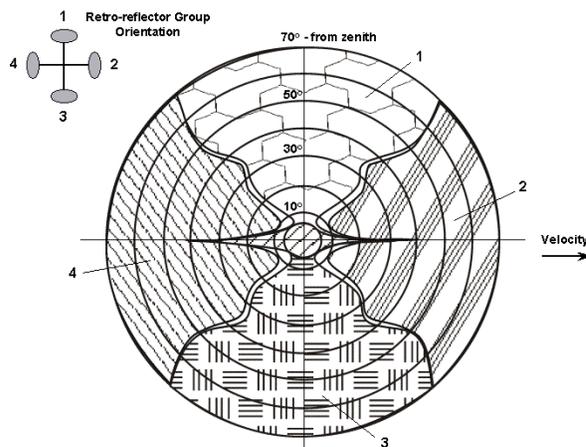


Figure 7. Ground map showing retroreflector group observation zones

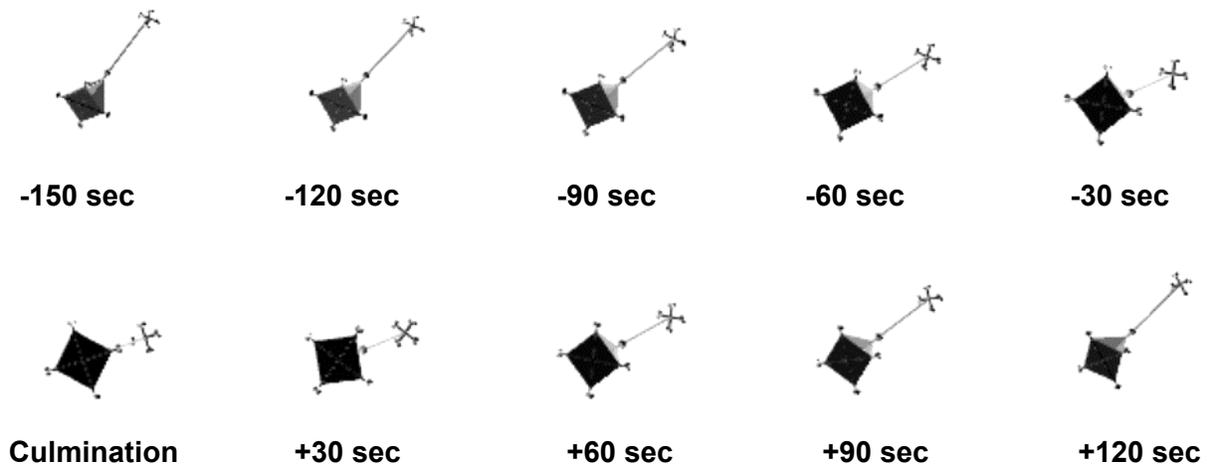


Figure 8. Simulation showing visualization sequence of REFLECTOR satellite for a pass at 1 Mm range, 99 degree inclination and a culmination angle of 20 degrees off zenith

5. SUMMARY AND FUTURE WORK

The REFLECTOR micro-satellite, built through a joint program between U.S. and Russian scientists will provide laser sensing experimenters with a unique low-earth orbit target of retroreflectors. The retros are separated spatially and one set of reflectors imparts a polarization signature to the return light. To provide a known target for the experimenter, the orientation of the vehicle will be maintained in orbit to a few degrees of oscillation by passive means. After launch, currently scheduled for the fall of 2000, a more detailed model of the expected return signal and ground patterns will be pursued to allow better experimental calibration and prediction capability when using REFLECTOR.

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7. REFERENCES

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