Micro-satellite for calibration of active ground-based optical collectors

1. DESCRIPTION

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 retro-reflectors. 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 8 and 13 visual magnitude.

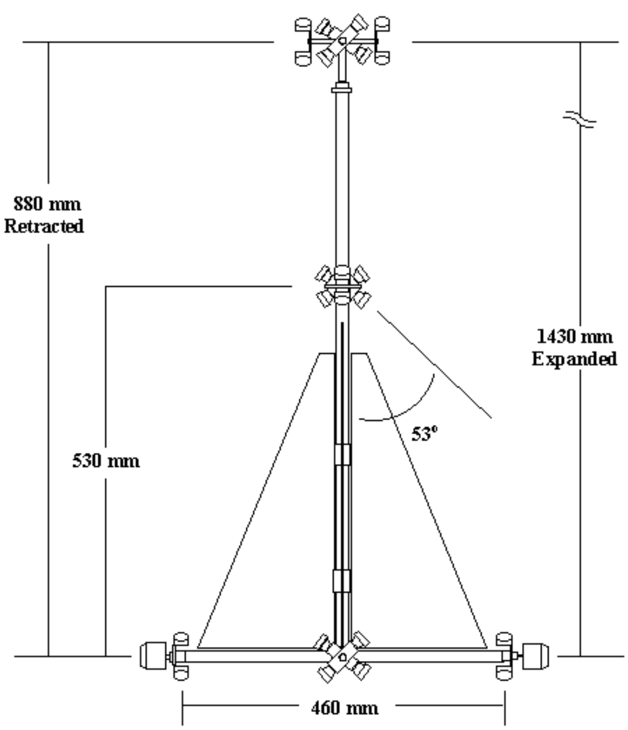


Figure 1. Diagram of the REFLECTOR micro-satellite.

Figure 2. Photograph of REFLECTOR with boom extended

A close-up of the retro-reflector assembly on the top of the boom is shown in Fig. 3.

Figure 3. Photograph of top retro-reflector assembly.

The specifications of the retro-reflectors carried on REFLECTOR are:

- Fused silica prism, 1.4607 index of refraction at λ =532 nm
- Aluminum reflective coating on side facets
- Reflection coefficient at λ =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 $\pm$ 36 degrees (half-max reflected power)

The basic retro-reflector provided by IPIE 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 retro. 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 retro. 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, retro-reflectors have little effect on the polarization of the incident light. We are not aware of any retro-reflectors currently in orbit that provide a specific polarization signature to the returning light. For REFLECTOR, ¼ wave plates were placed the over entrance apertures of the 4 center retros. The fast axis of the ¼ wave plate was aligned with the vehicle's central body tube. Light returned from these retros will pass through the ¼ wave plate twice, once on the way in to the retro 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 ¼ wave plates in front of a test retro showed no significant effects on the divergence of the return beam.

2. 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.

3. RETRO-REFLECTOR 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 retro 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.

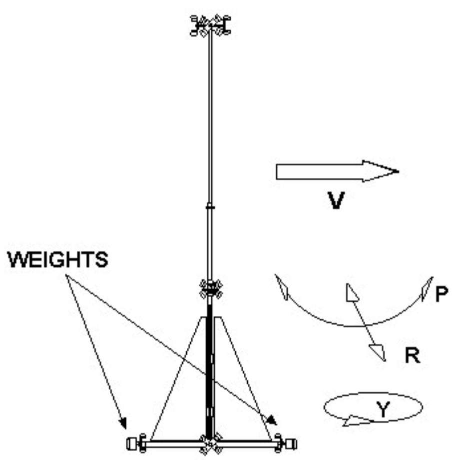


Figure 4. Orientation is maintained by gravity boom and weights. Pitch (P), roll (R), and yaw (Y) motions are shown schematically.

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 retro 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 retro 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 retro 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 km^2, 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**

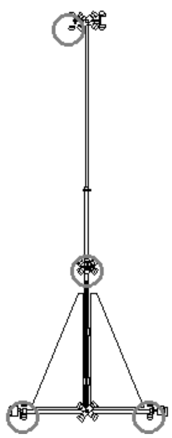


Figure 6. One group of four retros, indicated with circles, that would return light when REFLECTOR is illuminated from the side.

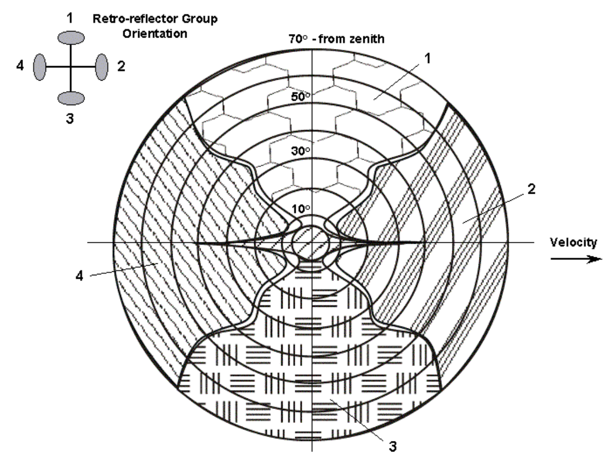
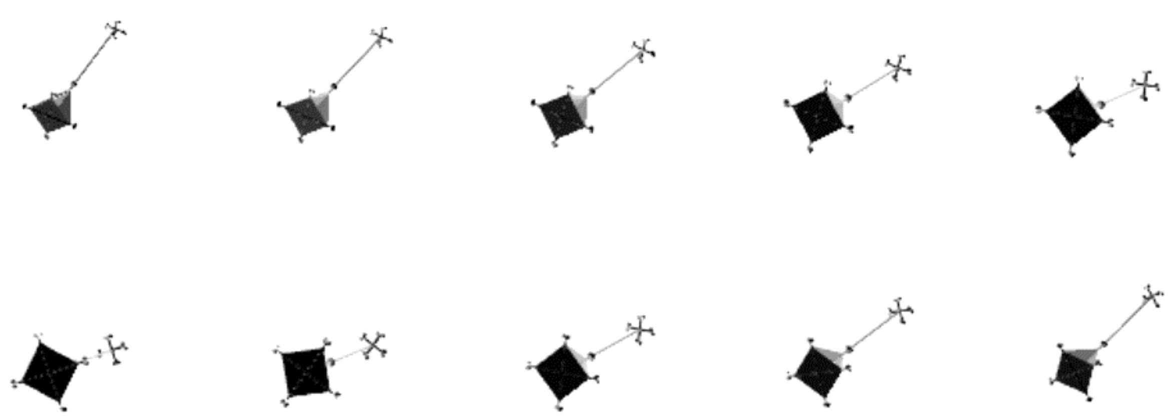


Figure 7. Ground map showing retro-reflector group observation zones.



-150 sec -120 sec -90 sec -60 sec -30 sec

Culmination +30 sec +60 sec +90 sec +120 sec

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.