Serendipitous Detection of Orbital Debris by the International Liquid Mirror Telescope

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ABSTRACT

The International Liquid Mirror Telescope is a 4-m zenith-pointing optical telescope that employs a rotating liquid primary mirror. Located in the Indian Himalayas, it began operations in October 2022. The telescope is equipped with a CCD camera that has a 22 x 22 arcmin field of view and employs time-delay integration readout to compensate for the Earth’s rotation. While its primary purpose is to conduct astronomical survey observations using broad-band filters, the telescope is also sensitive to objects in Earth orbit that pass through its field of view, leaving detectable streaks. We have examined all images obtained during the first year of observations and determined the transit times, position angles, and estimated magnitudes for all detected objects. These were compared with publicly available two-line elements, propagated to the time of observation, in order to identify cataloged objects. A total of 301 streaks were found in 1838 images. Of these, 64% were identified with cataloged objects. Most of the identified objects are in low-Earth orbit, in the altitude range of 400–1600 km.

1. INTRODUCTION

Orbital debris poses an increasing risk to space assets. At present, more than 28,000 resident space objects (RSOs) are tracked by NORAD and appear in the public database available at Space-Track.org. These include satellites, rocket boosters and orbital debris. It is expected that there are many more undetected objects that pose a significant collision risk, particularly to satellites in low-Earth orbit (LEO) [1; 2]. The advent of constellations potentially containing tens of thousands of satellites will greatly increase the number of RSOs [3]. The astronomical impact of these objects has long been recognized, but contamination of astronomical images by satellite and debris tracks is now becoming increasingly problematic [4–10].

Last year, a new ground-based optical telescope began operation. The International Liquid Mirror Telescope (ILMT) is a 4-m zenith-pointing telescope located at a latitude of 29.36° N on Devasthal Peak in the Indian Himalayas [11]. The telescope is fixed, pointing at the zenith, and is used for astronomical surveys. RSOs passing near the zenith produce streaks in the images acquired by the telescope. This provides a unique opportunity to serendipitously monitor the orbital environment [12]. On average approximately 100 cataloged objects pass through the field of view of the ILMT each day. Typically about 6% of these transit during dark hours (when the Sun is more than 18° below the horizon) while also being illuminated by the Sun. These can potentially be detected by the telescope.
The ILMT observing season extends from October until June. No observations are conducted during the summer months due to the monsoon. The telescope began operation in October 2022, with time divided between science observations and engineering. This paper presents an analysis of the 64 nights of science observations obtained during the first observing season. This work extends initial results that were based on the first 10 nights of observations [13].

2. OBSERVATIONS AND ANALYSIS

The ILMT, shown in Fig. 1, utilizes the principle that the equilibrium surface of a liquid rotating at constant speed about a vertical axis in a uniform gravitational field is a paraboloid. The mirror consists of a carbon-fiber parabolic dish supporting a 3 mm film of liquid mercury. It is mounted on an air bearing, which facilitates smooth rotation, and is driven by a brushless DC motor integrated within the air bearing. A control system maintains a constant rotation period of 8.028 s with a variation that is typically less than one part per million. A mylar film of 2.5 \( \mu \text{m} \) thickness is placed above the mercury surface and rotates with the mirror. Its purpose is to protect the liquid from air disturbances that result from wind and mirror rotation.

The telescope is equipped with a refractive prime-focus corrector that provides a 40-arcmin diameter well-corrected field of view. Its novel five-element design compensates for star-trail curvature effects [14], resulting in sharp images with a quality limited primarily by atmospheric turbulence. The detector is a 16-MPixel CCD camera which images a 0.373° × 0.373° region of the sky centred on the zenith. In order to compensate for image motion due to the Earth's rotation, the CCD is operated in time-delay integration mode, in which it is scanned continuously. As a result, photoelectrons are moved along the CCD columns at the same rate as the star images. In this way sharp images of stars and celestial objects are obtained. Objects that move, with respect to the stars, are trailed, leaving streaks in the images. The intensity in a streak may vary periodically if the object is rotating.

The telescope employs three optical filters, corresponding to the Sloan Digital Sky Survey g', r' and i' wavelength bands [15]. The filter is normally selected at sunset and used throughout the night. Color information can be obtained for astronomical objects, and for RSOs that are observed on more than one night, by selecting a different filter each night.

The ILMT saw first light in April 2022 and began a period of commissioning in October during which both scientific and engineering images were obtained.

The data set used for the present study comprises 1838 images acquired between October 23, 2022 and June 15, 2023, inclusive. The effective integration time for celestial objects was 102.36 s, which is the time interval for their images to cross the CCD. The effective integration time for RSOs is usually much less as they generally move at high angular rates, crossing the detector in just a few seconds, or less.

Each image was pre-processed to remove sensitivity variations and dark current. Spatial variations in the background level were removed by high-pass median filtering. The images were astrometrically and photometrically calibrated using Gaia stars present in the image. After processing, the images were searched visually for linear tracks. Detected tracks were then measured to determine the length, width, orientation, integrated flux and signal-to-noise ratio (SNR).

A complete set of publicly-available two-line elements (TLEs) was downloaded from Space-Track.org, for the period extending from 30 days before to 30 days after the observations. A list of "current" TLEs was then generated for each night of observation by selecting, for every cataloged object, the TLE whose epoch was closest to the time of observation. This formed our comparison data set. Each TLE in this set was then propagated, using the SGP4/SDP4 algorithm [16; 17], and the times and orbital parameters for all objects passing near the zenith were determined. A calculation was performed to determine which objects were illuminated by the Sun at those times. The data analysis and TLE propagation were performed using the OCS software package [18].
Fig. 1. Side view of the ILMT taken with a fish-eye lens. The mirror can be seen in the center, supported by the air bearing. The optical corrector and camera are located in the cylinder at the top of the telescope structure.

A comparison was then made of the catalog lists and the detected streaks. A cataloged object was deemed to match an observed streak if all of the following conditions were met:

1. The object passed within 0.3 degrees of the zenith.
2. The time of passage was within ± 3 minutes of the time of observation.
3. The position angle of the object was within ± 3° of the measured position angle of the observed streak.

The 3 minute time limit is sufficiently large to accommodate errors in the time recorded by the image acquisition system, uncertainties in the exact position of the CCD, and uncertainties in the TLE. The 3°
position angle limit is twenty times the observed standard deviation of 0.16° in the position angle differences. One object had a position angle error of 1.96°, but it had a very short track that resulted in a large position-angle uncertainty.

3. RESULTS

Our results are summarized in Table 1. A total of 301 streaks were identified in the ILMT images. 64% of these were correlated with cataloged objects. Six examples of tracks produced by correlated objects are shown in Fig. 2.

![Fig. 2. Montage showing streaks produced by six correlated objects detected by the ILMT. Clockwise from top left are STARLINK 1450, FREJA, METEOR 2-15, SL-6 R/B, COSMOS 2063, SL-12 R/B. These have V magnitudes ranging from 3.6 to 15.1. The individual images cover 29 x 22 arcmin.](image)

Apparent magnitudes of the correlated objects were estimated from the measured integrated flux and the integration time, found by dividing the track length by the angular rate determined from the TLE. These were transformed to the V (visual) band assuming a solar spectrum, using color indices for a star of spectral type K2V and Gaia DR3 photometric transformations [19; 20]. Magnitudes cannot be determined for uncorrelated objects as the angular rates are unknown. Four examples of tracks produced by uncorrelated objects are shown in Fig. 3.
Fig. 3. Montage showing streaks produced by four uncorrelated objects detected by the ILMT. The individual images cover 29 x 22 arcmin.

The apparent magnitude distribution for the correlated objects is shown in Fig. 4. The faintest correlated object is a rocket body with an apparent V magnitude of 15.1, detected with a SNR of 110. The faintest uncorrelated object has a flux 6.3 times smaller and a SNR of 19. The median flux of the uncorrelated objects is seven times smaller than the median flux of the correlated objects.

The altitude distribution for the correlated objects is shown in Fig. 5. We find that 61% have altitudes below 2000 km. There is a significant bias towards high-altitude objects as these are more likely to be illuminated by the Sun, due to the geometry of the Earth’s shadow at the latitude of the ILMT. Because of this, the LEO objects can only be seen within a few hours of sunrise or sunset. The distribution of these objects has a significant peak in the 400–600 km altitude range, and a sharp drop above 1600 km. Higher altitude objects are found to nearly 27,000 km, with a mild concentration around 20,000 km. We did not see any objects in geosynchronous orbit, but that is to be expected due to the latitude of the observatory.

On average, 7.1 detectable objects per square degree per hour pass near the zenith at the latitude of the ILMT. Objects having orbital inclination less than the latitude never reach the zenith and are thus not counted. One therefore expects the rate to be higher at lower latitudes.
Table 1: Observations and results.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector area</td>
<td>0.139 sq. deg.</td>
</tr>
<tr>
<td>Pixel size</td>
<td>0.327×0.327 arcsec</td>
</tr>
<tr>
<td>Size of TDI images (pixels)</td>
<td>4096×4096 and 36864×4096</td>
</tr>
<tr>
<td>Number of images examined</td>
<td>1838</td>
</tr>
<tr>
<td>Total observing time</td>
<td>307.2 hr</td>
</tr>
<tr>
<td>Number of streaks detected</td>
<td>301</td>
</tr>
<tr>
<td>Number correlated with cataloged objects</td>
<td>192</td>
</tr>
<tr>
<td>Number of uncorrelated objects</td>
<td>109</td>
</tr>
<tr>
<td>Percent uncorrelated</td>
<td>36.2%</td>
</tr>
<tr>
<td>Apparent V magnitude range of correlated objects</td>
<td>3.6 - 15.1</td>
</tr>
<tr>
<td>Altitude range of correlated objects</td>
<td>484 - 26,894 km</td>
</tr>
<tr>
<td>Satellite fraction of correlated objects</td>
<td>64.1%</td>
</tr>
<tr>
<td>Rocket body fraction of correlated objects</td>
<td>20.3%</td>
</tr>
<tr>
<td>Debris fraction of correlated objects</td>
<td>15.6%</td>
</tr>
</tbody>
</table>

Fig. 4. Apparent V magnitude distribution of correlated RSOs.

4. DISCUSSION AND CONCLUSIONS

These results demonstrate the potential of the ILMT for the serendipitous detection of satellites and orbital debris. More than a third of the objects that we detected could not be matched to cataloged objects. Some of these are quite bright and are likely classified military satellites. Others may be previously-undetected orbital debris. In either case, this indicates either a significant level of incompleteness, or inaccuracy, of TLEs in the public database.
Streaks from bright objects are a concerning source of contamination for astronomical observations. Many of the streaks that we detected are as wide as 12 arcsec and far brighter than the faint stars and galaxies that they cross. Subtraction of the streaks is problematic due to the high levels of photon noise.
that they produce, and intrinsic variations in brightness as the objects rotate [21].

Of particular concern are satellites launched by Starlink and OneWeb, due to the very large numbers that are planned. Fig. 6 shows the observed apparent magnitude distribution of these satellites. The mean apparent magnitudes are 6.7 and 8.6 for Starlink and OneWeb respectively. The difference is largely due to the higher altitudes of the OneWeb satellites (the mean altitudes are 546 km and 1203 km for Starlink and OneWeb respectively). More than half of the Starlink satellites that we observed are brighter than the International Astronomical Union recommended minimum magnitude of 7 [22].

As satellite mega-constellations continue to expand, it becomes increasingly important to develop measures to mitigate their astronomical impact [23]. It will be necessary to find effective ways to reduce both the amount of sunlight that their satellites reflect and the infrared radiation that they emit. Astronomical observations will be essential to assess the success of these measures [24].

In full-time operation, the ILMT is expected to obtain on the order of 1500 clear dark hours of observations per year, which is roughly five times the present data set. This will provide a unique opportunity to monitor the increasingly-crowded space environment.

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