

# Laser Tracking of Space Debris

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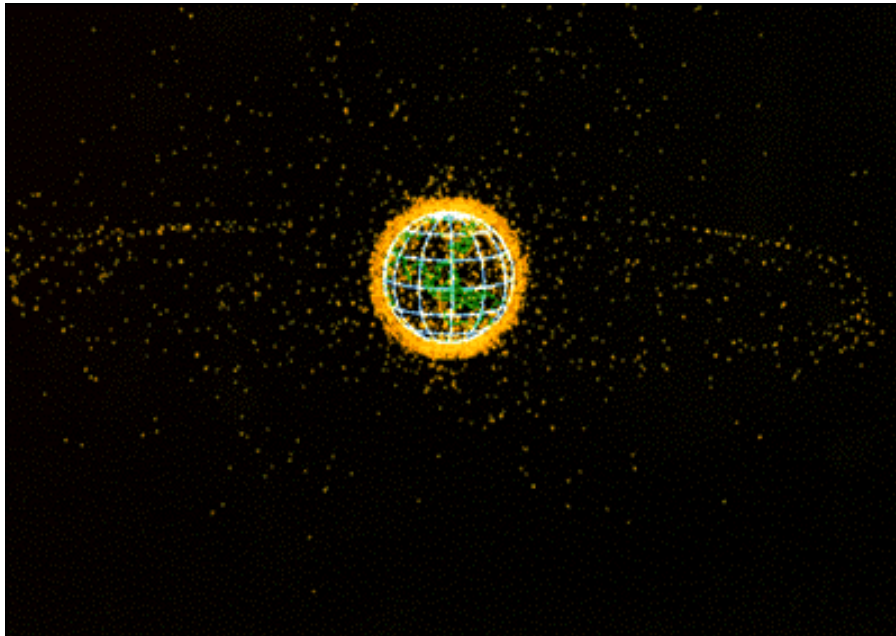
## Abstract

Space debris is a major problem for all space-faring nations. A reliable and accurate catalogue of space debris is a fundamental requirement for any effort towards debris collision avoidance. This is presently not achievable because of the small size and large number of debris objects, combined with the orbital instability for small and low objects.

Laser tracking is inherently accurate, and laser link equations allow scaling of laser tracking systems to track small space debris. Results are presented for a massively up-scaled laser tracking system that has successfully tracked small space debris. The project also verified the high accuracy of the real-time laser-determined orbital elements, and explored a wide range of ancillary, but essential, technology developments.

It is inferred from the data that debris as small as 1 cm can be accurately tracked with lasers. The amount of tracking time required is consistent with supporting a large number of LEO objects from a single operational site. Future work is indicated.

## 1. THE REQUIREMENT



**Figure 1:** Image of space debris distribution around earth. [NASA image].

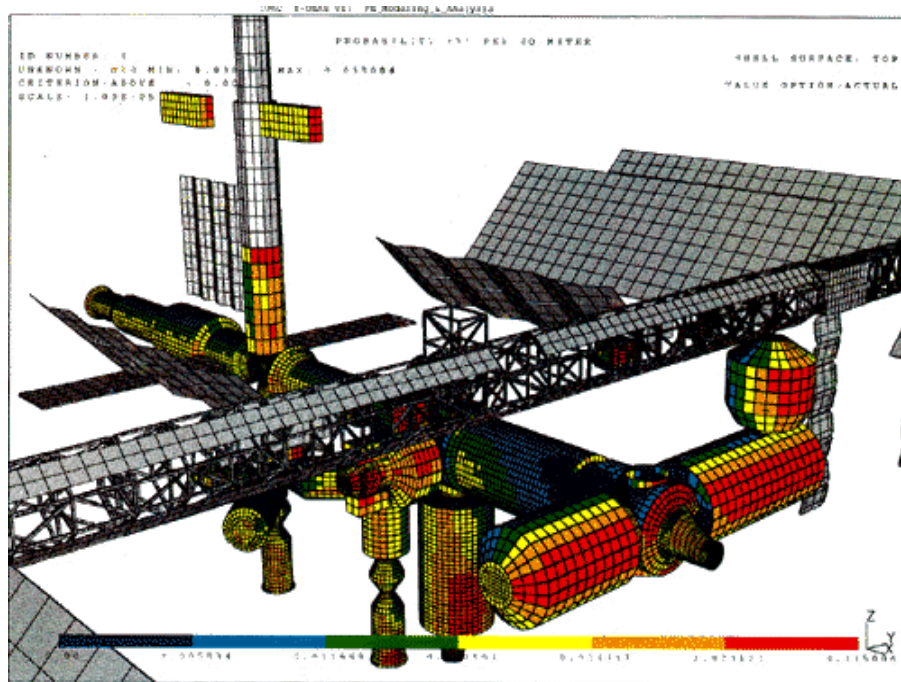
Current estimates of space debris with a mean dimension of 1 cm or more exceed 120,000 objects. Since the distribution of debris is naturally consistent with popular orbits and altitudes

for satellite missions, this is an increasing concern for the safe use of space for commercial or scientific purposes.

Space debris presents near-intractable problems for tracking since it is extremely difficult to track objects smaller than 10 cm, due to both their small cross section, and also their reduced orbital stability. A third negative factor is the [almost] exponential increase in population size as the size threshold of debris is reduced.

Debris as small as 1 cm will cause significant damage to spacecraft. Modern spacecraft often employ cladding to protect against debris collision, but this is effective only up to 5-10 mm debris. Since space catalogues include almost no objects smaller than 10 cm, and since there are over 100,000 objects between 1 and 10 cm, the problem is evident.

The image below shows the debris cladding used by ISS to mitigate damage due to debris collision. The manned sections of ISS have the thickest cladding.



**Figure 2:** ISS schematic showing cladding [red] for space debris protection. [NASA image].

Even if debris can be tracked for collision avoidance, the orbital data for debris would have to be accurate to better than 700 m at all times. Simulation shows that it would be impractical to maneuver spacecraft to avoid collisions predicted with lower accuracy for 150,000 objects. This implies an at-epoch accuracy of a few metres.

Space debris is relatively easy to find. Both radar and optical detectors can find debris, although determining an orbit with sufficient accuracy to allow reliable re-acquisition is presently problematic for more than a few hundred objects of special interest. The task can be summarised as a requirement to track:

- **1 cm debris.** This is 10 times smaller than current technology allows.

- **150,000+ objects.** This is 10 times more than current technology can provide.
- **with 1m accuracy.** This is  $\gg$  10 times better than current radar technology.

*This appears to present a very significant challenge. However with appropriate technology extensions, laser ranging can meet this requirement.*

## 2. TECHNOLOGY

The laser ranging equations are well documented in the literature. These clearly show that ranging to space debris is possible if the following parameters are scaled upwards sufficiently:

- **Laser irradiance** [at the target plane]. This can be increased by increasing laser power, reducing beam divergence, and optimising transmission losses.
- **Receiving aperture size.** Laser ranging systems typically employ 75 cm telescopes. Debris object size sensitivity will scale [inversely] linearly with receiver aperture.
- **Receiver sensitivity.** This is controlled by such parameters as detector quantum efficiency and optical path efficiency.



**Figure 3:** 2m tracking telescope specifically developed for debris tracking. It has diffraction-limited optics and servo systems with similar limits [EOS image].

The link equations indicate that the link to 10 cm space debris will be around 6 orders of magnitude lower than to LAGEOS. This does not simply mean that a system which can range to LAGEOS with  $ND = 6$  in the receive path will be able to track space debris.

In practice it has been found that the debris predictions are low quality, and the orbits are unstable, compared to LAGEOS. A significant SNR margin is required to ensure lock-on for tracking real debris.

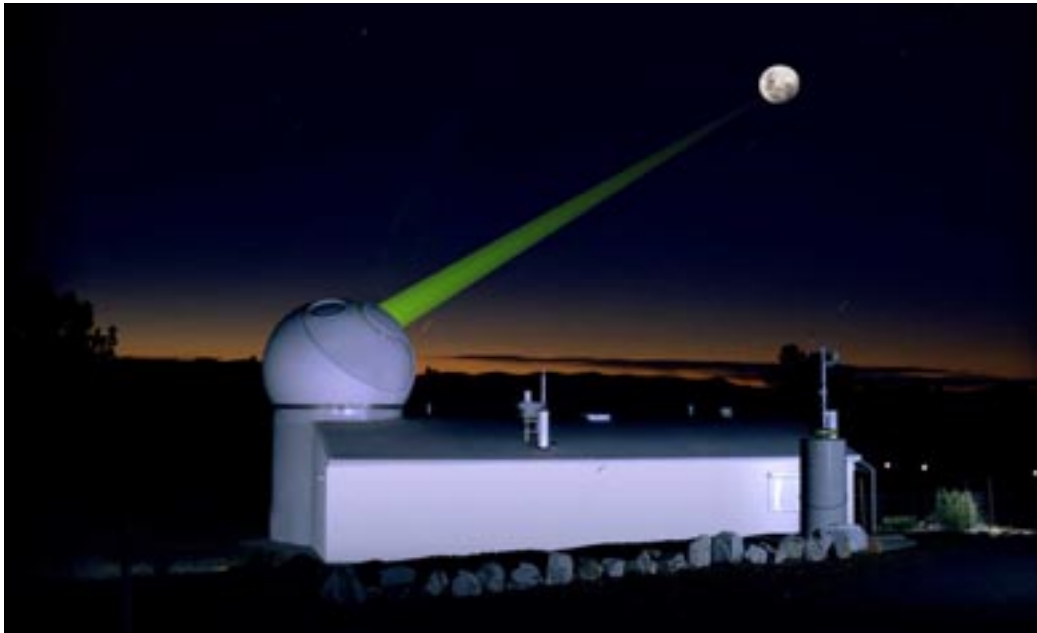
Current laser tracking systems are designed to track satellites fitted with retro-reflectors, and it is practical to use these SLR systems as a baseline for discussion of the technology requirements for 7 orders of magnitude of SNR improvement. Relative to a state-of-the-art SLR system, the following upgrades will allow debris tracking.

- **Laser power.** Typically 3 orders of magnitude power increase are possible with current technology, although the cost of such large lasers may be high.
- **Laser irradiance.** This can be improved for 2 orders of magnitude improvement in SNR by reducing the laser beam divergence from 25 urad to 2.5 urad. This requires near-diffraction-limited performance with 1m optics, and places constraints on pointing and tracking systems to hold this stability.
- **Efficiency.** By designing specifically for this application, receiver, coatings, and detector improvements yield around 2 orders of magnitude SNR improvement over current SLR technology.

Once these elements had been addressed it was found that a broader range of improvements was required to achieve the requirements. For example:

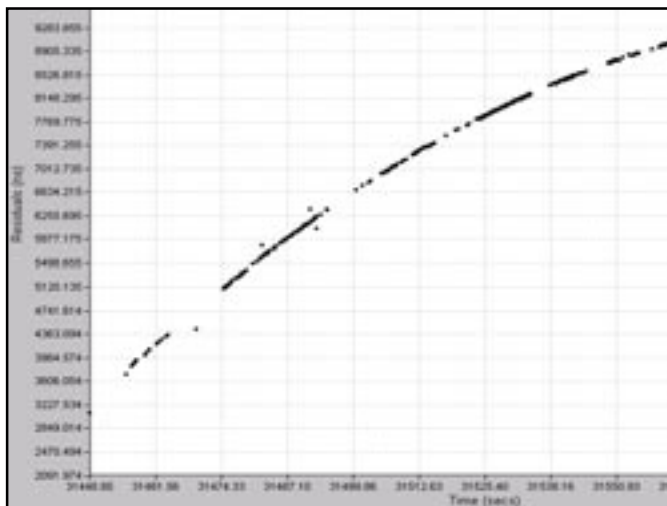
- **Dome.** Dome vibration is a serious problem for tracking telescopes seeking to maintain 1-2 urad pointing and tracking stability. Entirely new domes were designed and built for this application.
- **Wind.** Buffeting by wind, even in semi-enclosed domes, is a major inhibitor of tracking performance at 1-2 urad levels. Wind control and air management in general are required.
- **Thermal contamination.** Thermal gradients around the telescope and its major optics become a significant performance factor at 1-2 urad. These must be controlled.
- **Safety.** SLR systems are normally a hazard to human eyesight. This problem is significantly compounded by the large power increases required for reliable debris tracking. An increase in system safety is required, especially if the vastly increased duty cycle of a debris tracking mission is considered.
- **Reliability.** The system must employ an architecture that is reliable enough to permit 24-hour operation for long periods without maintenance or repair time.
- **Automation.** Because any debris tracking system would operate with higher duty cycle, higher complexity, and with very demanding response times [low orbits], it is not feasible to consider manned operation. An unmanned technology platform is required.

### 3. RESULTS

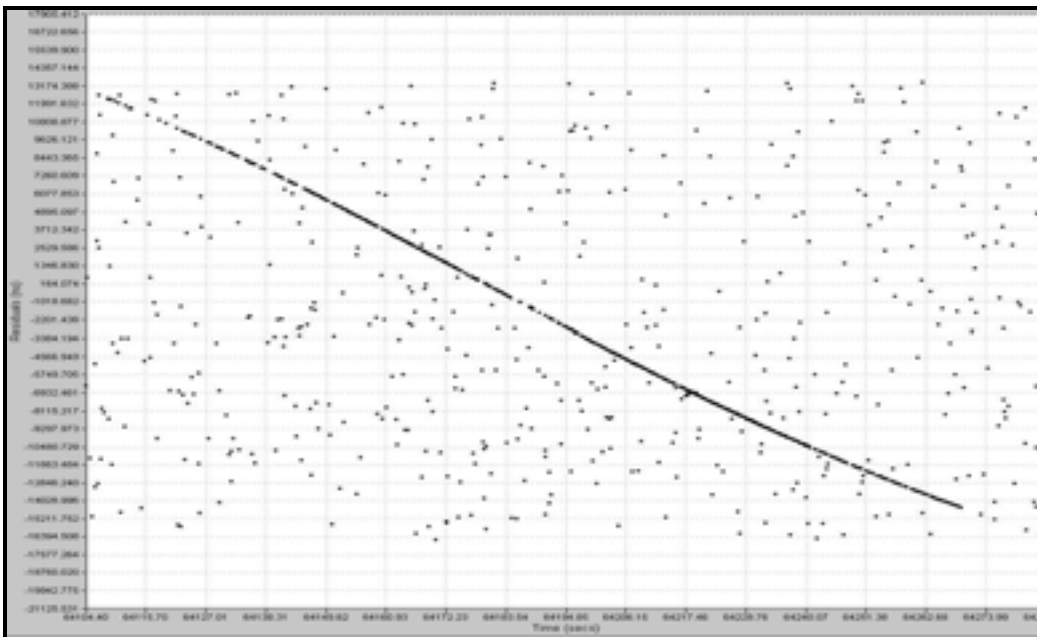


**Figure 4:** The Stromlo facility used for debris tracking tests in 2002 [Geoscience Australia image].

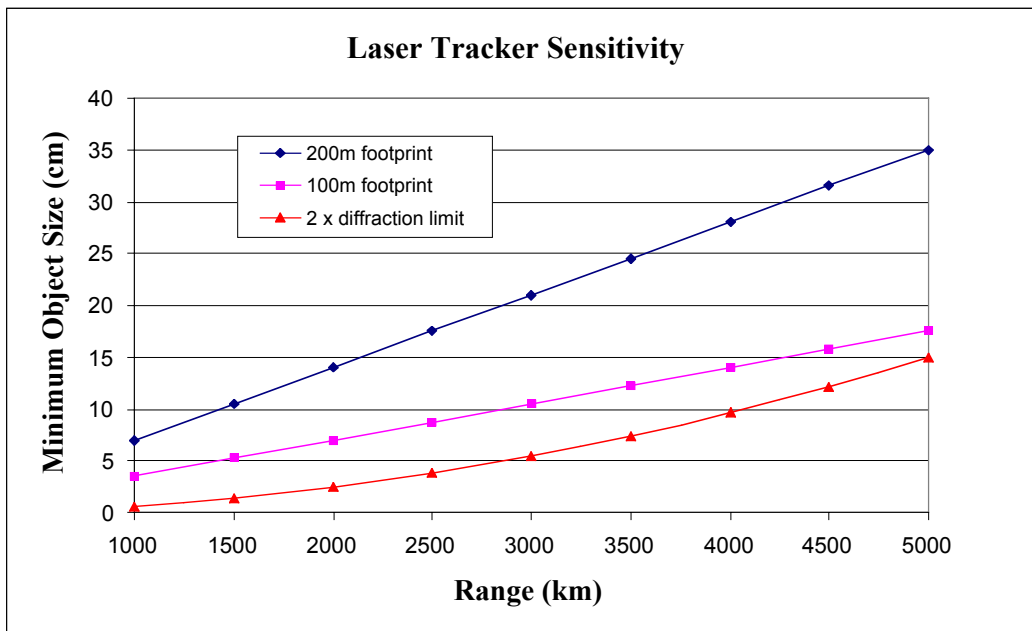
The Stromlo SLR system was upgraded for debris tracking during 2001/2002. Results were obtained for space debris objects down to 10 cm in size.



**Figure 5:** Laser track of 15 cm object at 1,100 km. Dark noise has been stripped by data filters. [X = elapsed time. Y = range residual].



**Figure 6:** Laser track of 15 cm object at 1,250 km. Data filters inhibited. [X = elapsed time. Y = range residual].



**Figure 7:** Real and implied tracking sensitivity for the Stromlo space debris tracker. The upper curve represents the current configuration and actual data. The lower curves show alternative beam propagation strategies to be tested in 2003.

The results shown in Figures 5 and 6 appear very similar to normal SLR residual plots, except the residual scale here is much larger. This difference is very significant, since it conveys a sense of the poor quality of *a priori* orbital elements available for debris objects.

Although the orbital elements obtained by the Stromlo laser tracking system *after* acquisition were excellent, a significant problem in acquiring and tracking debris is the poor initial quality of the debris elements.

A purported benefit of the laser technique is the rapid determination of accurate orbits and elements. This was verified. With only 10 seconds of laser data, orbits could be generated in real time, with an accuracy suitable for down-range re-acquisition.

The smallest tracked object was estimated by multi-spectral cross-section analysis to be 10 cm. The theoretical sensitivity plot is shown in Figure 7. It can be seen that the system performed as expected, in the deployed mode [200m footprint at target plane].

During 2003 the operating mode will be varied to allow <5 cm objects to be tracked.

#### **4. CONCLUSIONS**

Laser tracking systems can almost certainly meet the sensitivity and accuracy requirements of the space debris catalogue task. Further experiments are required to demonstrate 1 cm sensitivity, but this seems routine given the reliability of performance projections so far.

The cost-effectiveness of a laser-maintained debris catalogue must now be determined.

The orbits obtained from this work were sufficiently accurate to allow re-acquisition down-range, but the optimisation of the real-time orbit quality and down-range tracking network configuration require further analysis and experimentation.

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