SLR FOR SPACE DEBRIS MONITORING: AN ANALYSIS ON REQUIREMENTS AND ACHIEVABLE ORBIT IMPROVEMENT

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ABSTRACT

Global Satellite Laser Ranging (SLR) network has been supporting numerous high-profile geodetic missions for over three decades; high precision range measurements were possible with retroreflectors carried on-board by geodetic missions. New advances in SLR technologies enable to track and range non-cooperative objects, without retroreflectors, and of different sizes. This new development enables SLR as a cost-efficient alternative tracking system for the entire range of object sizes in the space object catalogue, and obtain precise and high frequency of observations to assist several space operation applications. By providing the orbit refinements prior to conjunctions, to a level that can reduce false alert rates, significantly improves the cost effectiveness of space operations. This paper evaluates the required characteristics and constrains for maintaining a laser only observed catalogue. In the end, we discuss possible laser based remediation for avoiding possible space objects collision.

Keywords: SLR; space objects catalogue; Space Debris Monitoring.

1. INTRODUCTION

Estimating the probability of collision for the Earth orbiting Space Objects (SO) should ensure sufficient accuracy to give meaningful results. If the associated positional uncertainty is very large, a Gaussian calculation will result in a low confidence conjunction probability. Also, an effective and optimal collision avoidance is possible only if an excellent orbital data is available for both the active satellite and the threatening space object(s) [6].

The existing Satellite Laser Ranging (SLR) network is promising for Space Debris Monitoring (SDM) with advantages of global coverage, high covering rate, and high repeatability in tracking. Technological advancements in SLR observation technique in terms of daylight tracking and high power laser systems have enabled ranging of uncooperative targets. Authors in [7] have successfully observed space debris using multi static laser ranging, by synchronizing the SLR stations at Zimmerwald, Wettzell, and Herstmonceux to the Graz laser firing times. The above three passive (receiving only) stations detected the laser pulses, diffused reflection from space debris targets, from Graz. This experiment showed the potential of ranging and receiver network.

All the above qualities could make SLR stations to be SST ready. Preliminary studies have shown that the a few number of SST ready, globally distributed, SLR stations are sufficient for maintaining precise ephemerides catalogue. On the other hand, the main challenge is to use short-arc range only measurements for orbit improvements. Precise range measurements increases the confidence of orbits in radial direction, while the along-track and cross track confidence remain not improved [1]. In order to support space operations and estimate high confidence in probability of collision, it will be of interest to maintain a precise ephemerides catalogue which is based solely on SLR observations. To maintain such a catalogue, here we term it as a “Laser range observations based Precise Space Object Catalogue” (LP-SOC), it is required to address the following questions:

- What are the required qualities of a SLR station for debris tracking, and what are the present technical limitations?
- What is the minimum observation arc length, and how frequently one need to observe the space objects in order to perform a subsequent blind tracking?
- Will it be possible to use SLRs for space debris surveying, or will it always be limited to tracking of SOs?
- How many stations are required, and what is the optimal geographical distribution to observe all possible orbiting objects?
- What are the efficient means to make use of range only observations in orbit determination (OD), and what are the additional observables could improve the performance of SLR based OD?

The present paper addresses the above questions from a system point of view. The system which is required to maintain the envisioned LP-SOC. Global laser ranging network system study carried out through proxy stations presented in [9] addresses the network requirements. Authors of the paper have emphasised the network optimisation through visibility conditions, while we address the optimality through achievable orbit refinement.

The question related to the use of SLR stations for debris surveying depends on future technical developments in the field. Mainly on fast and accurate positioning systems, which will enable SLRs to scan the sky faster. This in turn will enable laser ranging to shoot and expect for echoes from unknown objects. With the present state-of-the-art laser ranging methodology, SLRs can only be used in tracking mode. That is to refine orbits of known objects, or requires assistance from other means of tracking sensors to initialise a LP-SOC.

The following section 2 will analyses the required orbital accuracy to improve the support to space operations. Section 3 establishes the theoretical constrains and requirements raised from the above questions. Section 4 will point out the achievable orbital accuracy and foreseen strategies to make use of range only observations for maintaining a SO catalogue. Section 5 will provide a brief insight to ground based laser momentum transfer for avoiding possible collisions between operating satellites and SOs. The final section will summaries the established requirements and discusses the future work.

2. OPTIMAL ORBITAL ACCURACY FOR SPACE OPERATIONS

The main motivation of maintaining a LP-SOC is to bring in considerable improvements in orbital information compared to conventional catalogue. This in turn will support the routine space operations and reduce the cost burden from low confidence collision warnings. To understand the required accuracy for increasing the confidence in probability of collision ($\mathrm{P_c}$) estimations, the influence of orbital uncertainty in $\mathrm{P_c}$ computations, more specifically on number of probable events for given $\mathrm{P_c}$ threshold, is considered.

The key component for a successful LEO mission is the careful planning of resources required for collision avoidance. To facilitate the inclusion of possible encounters during the mission, tools such as: Assessment of Risk Event Statistics (ARES) within the Debris Risk Assessment and Mitigation Analysis (DRAMA) software suite is developed [3]. The tool allows mission planners to estimate the probable required number of collision avoidance manoeuvres based on the risk threshold. DRAMA/ARES is available worldwide through the Space Debris Offices web portal: `https://sdup.esoc.esa.int`

Manoeuvre decisions are based on defining a threshold through statistics related to the collision risks for a given mission. For example: To cover 90% of the risk induced by known objects, can be achieved by Accepted Collision Probability Level (ACPL) of $\mathrm{P_c} = 10^{-4}$ when accurate Collision Data Message (CDM)s are available. Krag et al. [8] presents details on the manoeuvre decision driving parameters in routine space operations using DRAMA/ARES tool. While the ACPL level stands at $\mathrm{P_c} = 10^{-6}$ for using TLE based computations. This shows the significance of accurate surveillance information in space operations. To understand positional information requirement by reducing the false alert rate by 90%, the annual collision probability is analysed in more detail as a function of quality of the orbital information of the target and chaser objects, which are involved in collision events. DRAM/ARES simulation was carried out for Sentinel-2A spacecraft using ESA-MASTER model and US Strategic Command TLE catalogue. Table 1 shows the comparison between two different assumed covariances associated with SOs.

Table 1. Implication of using accurate orbital information on space operations. Results comparison for Sentinel-2A satellite using DRAMA/ARES tool.

Covariance matrix with	
$20m \times 150m \times 30m$ at TCA	$10m \times 10m \times 10m$ at TCA
An action threshold of 10^{-4} would have to be applied to reduce the collision risk by $> 90\%$	For the same risk reduction of $> 90\%$ an action threshold of 10^{-2} will be sufficient
This leads to about 2 annual manoeuvres per spacecraft on average	This leads to 0.025 annual manoeuvres per spacecraft on average
The false alert rate is at 99.9%	The false alert rate is at 10%

Although, extensive simulations were carried out to find the optimal size of the covariance matrix, authors present the relevant information in table 1 to provide the understanding of the orbit associated covariance and $\mathrm{P_c}$. From the above study it is clear that to achieve the required cost benefit, from establishing LP-SOC, it is required to maintain a catalogue with the accuracy of 10 m in all coordinate directions, or orbits with better than c.a. 20 m of positional uncertainty.

With the above assumptions and information, we establish the LP-SOC should have orbital information with < 20m positional uncertainty. From analysing different laser ranging observation sets, it is understood the ranging accuracy is in the order of 0.1 m. Making the radial direction to be estimated with higher confidence. Also the normal direction will have positive correlation factor, which is influenced from the observation geometry. This allows one to set the following one sigma constrains on the uncertainties in three satellite centred reference coordinates Radial (R), Tangential (T), and Normal (N):

$$\begin{aligned}\sigma_{\mathrm{R}} &< 10\mathrm{m}\\ \sigma_{\mathrm{T}} &< 15\mathrm{m}\\ \sigma_{\mathrm{N}} &< 10\mathrm{m}\end{aligned}$$

3. "LP-SOC" A POSSIBILITY

To realise catalogued information with the established orbital accuracy requirement, and to address the questions posed earlier in the introduction section, the questions are categorised into three groups as: desired SLR station requirement, network requirements and observation requirements.

Currently SLR stations are able to track and observe satellites with retro-reflectors during dusk and dawn times regularly and efficiently. Also, when precise orbits are provided, through consolidated prediction formats (CPF), SLR station at Mt. Stromlo has performed blind acquisition and blind tracking based on precise orbit predictions [10]. But, there are technical constrains on performing: day light tracking, blind tracking (without optical visibility of the SO), and uncooperative tracking (tracking SO without retro reflectors). To effectively utilise the SLR resources for debris tracking it is required to over come all the above three limitations. Which is dictated by the nature and number of SOs. To establish concrete SLR station requirements for the purpose of LP-SOC, it takes dedicated study to be carried out for optimising different system parameters which are left out of the present study.

Before proceeding ahead with network requirements, it is required to understand the sufficient and/or optimal observations required from SLR data to maintain LP-SOC. The following subsection examines the observation requirement further in detail.

3.1. Observation requirements

Simulations are carried out to understand the observation requirements through the accuracy of estimated orbits. Designed simulations include generation of observations and performing orbit determinations (OD) for different observation arc lengths and station passes. Table 2 shows the set up for the study. Although the observation noise level for existing data shows that measured ranges consists noises on the order of 0.01m, the one sigma noise value of 0.1m (an order of magnitude higher) is assumed within the simulation. The level of uncertainty takes atmospheric noise, instrument noise, and mainly the uncooperative targets reflectivity characteristics into account. Also, it is important to be noted that the missing attitude information for debris contribute towards and SO's laser ranging accuracy. This leads to higher level of noises in the actual observations, which requires further investigation and left as part of the future work.

Table 2. Stations and their coordinates used in simulation test cases.

Test satellite	Sentinel 2A
Period of analysis	18/05/2017 to 25/05/2017
Precise orbit data	GNSS based SP3 precise orbital solution
Simulated observations	Range observations + noise with 0.1m one sigma value

For LEO satellites, for semi-major axis < 7500km, the longest station pass is in the order of five to ten minutes. Considering all the passes for a given station, OD was performed on arc lengths ranging from 0.5 to 10 minutes, at the time steps of 0.5 minutes. This experimental set up show cased the improvements in orbit estimation using different observation arc length on each station pass. It was observed from the ODs that the accuracy of the estimated orbit does not improve significantly beyond one minute of observations for a given station and maximum observing length of one day. This allowed us to set tracking arc length of one minute to be considered for simulations, while including multiple passes occurring during one day.

For the simulation study hypothetical ESA operated optical station locations are used. Table 3 provides the list of selected stations. Selection of stations were driven by their long baselines and low, mid, and high latitudes. This gives representative perspective of geometrical influence of the station location with respective to orbit determination. Steps presented below describes the simulation methodology employed for testing the observation requirements for range only observations:

Table 3. Stations and their coordinates used in simulation test cases.

Station	Code	Coordinates	
Teplice	TOSS	50.6 N	13.8 E
Arequip	KABS	16.4 S	71.5 W
San Fernando	ROAA	36.5 N	6.2 W

1. Generate synthetic observations using SP3 orbit for the test satellite
2. Post filter the number of station passes
3. Perform orbit determination using TLE as a-priori, and with large initial sigma value of 50 km in all directions.
4. Propagate the orbit for selected arc length
5. Compare the propagated orbit with precise orbit and evaluate the RMS differences

Figure 1 shows the results from the above test procedure. It reaffirms the established knowledge on performing Least Squares orbit determination requires at least two passes to be able to estimate the orbit with sufficient confidence. The required positional accuracy of 20m is reached after minimum of four station passes.

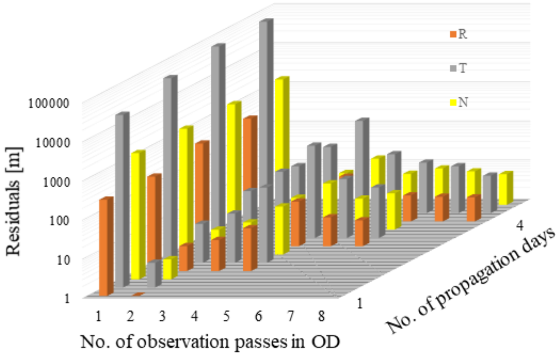

Figure 1. Mean position errors for observational arc for different number of station passes and for increasing propagation arc lengths, including the orbit determination fit time arc.

Table 4 presents the accuracy of estimated orbits after different passes by using observations from single stations. Due to the examination time period, orbit and station geometry different stations produce moderately different orbits.

Table 4. Position RMS differences (in meters) computed for four days of orbit propagation, from the orbits estimated using observations from TOSS, KABS, and ROAA SLR stations individually. All the estimated orbits assumed fixed C_d values.

	No. passes	SLR Station		
		TOSS	KABS	ROAA
Radial	1	383.4	313.8	368.3
Tangential		1727.6	1029.2	6069.4
Normal		1884.6	1705.5	367.2
Radial	2	39.8	9.6	146.2
Tangential		280.1	220.9	1285.8
Normal		57.0	97.4	1356.5
Radial	3	5.1	5.2	8.3
Tangential		20.2	11.1	43.7
Normal		4.2	23.4	7.1
Radial	4	5.1	4.8	6.5
Tangential		20.1	11.9	18.4
Normal		4.9	6.9	6.2

Previous simulation was carried out using single observing station. To examine the network requirement multiple stations, combination of different stations, mentioned in table 3 are further examined. Table 5 gives the orbital accuracy for the observations produced for three different station pairs. It is clearly observed that the using two stations, in place of multiple passes from single station, greatly improves the accuracy of estimated orbit. Also, as an added advantage, when using range only observations from SLR stations, four passes, one one minute observation lengths, within one day is sufficient to achieve the required positional accuracy of < 20m.

Table 5. Position RMS differences (in meters) computed for four days of orbit propagation, from the orbits estimated using observations from different SLR stations combinations.

	No. passes	SLR Station combinations		
		TOSS/ KABS	KABS/ ROAA	ROAA/ TOSS
Radial	2	26.2	6.1	6.7
Tangential		31.2	13.2	14.7
Normal		11.0	7.5	7.4
Radial	4	6.9	4.8	6.7
Tangential		20.8	10.7	10.7
Normal		5.9	6.1	5.6

Using these information, further network requirements are further analysed.

3.2. Network requirements

To understand the required stations and optimal geographical locations for observing most possible space objects, and to maintain a precise ephemerides "laser" catalogue, we defined a quantity Cumulative Visibility Time (CVT) for all the known space objects. CVT is computed by adding all the SOs passes within the given time period and the length of each pass. If $\mathrm{t_{vis}}$ is the visibility of a space object for a given station, then the CVT for the station is given by the summation of all the N space objects passing over the station

$$\mathrm{CVT_{sta}} = \sum_{i=1}^{N} \mathrm{t}^{i}_{\mathrm{vis}} \ ; \ N : \text{Number of satellites} \tag{1}$$

The quantity CVT describes the observable quality of the given geographical location for all the known objects.

Using the above definition for cumulative visibility times, CVTs at all possible geographical location are computed. Figure 2 shows the computed cumulative ground visibility times for one day and for all the objects in TLE catalogue on a latitude and longitude grid. For the simulation 5° latitude and longitude grids are used, and the satellite passes with the elevation cut-off angle of 15° are considered to be visible. The visibility computations are carried

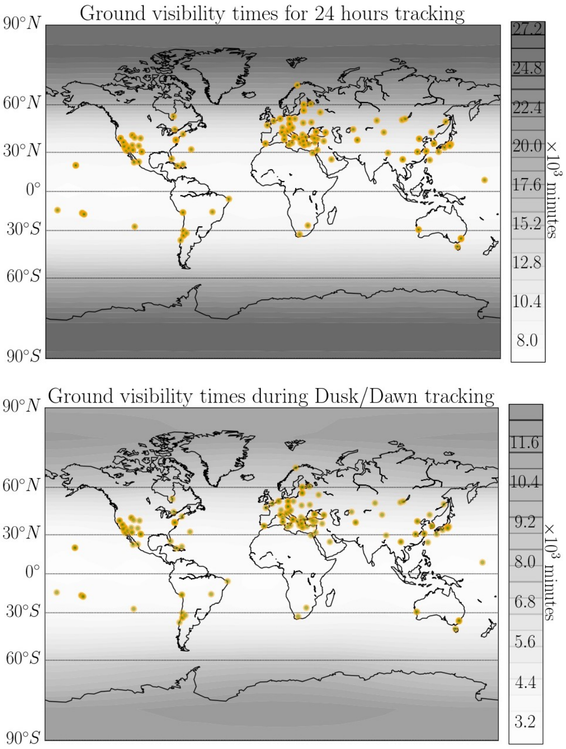

Figure 2. Cumulative visibility times for SOs in TLE catalogue at different geographical locations (top) assuming 24 hours tracking capability, and (bottom) with conventional tracking during dusk and dawn. The circular markers provides the location of active Satellite Laser Ranging stations as per [4]

out for both 24 hours tracking which assumes day and night tracking capabilities of SLR stations, and conventional dusk and dawn time tracking. As it is observed, and as one can extrapolate the information from the inclination distribution of the TLE catalogue, higher latitudes have larger visibility of objects than at lower latitudes. Also, from observing the right ascension distribution of the TLE catalogue, it can be seen that the there is no much of longitudinal variation in visibility times.

A network which is distributed in higher (in both hemispheres) latitudes requires lesser number of stations than the network which are in mid-latitudes. A station in ±60° latitude will have approximately CVT = 25,000 minutes for the available TLE catalogued objects. Assuming it is required to perform one minute of tracking for each object at given station, and each object requires minimum of four passes, either in single station or from combination of stations. That is to say that, for given c.a. 20,000 objects, it is required to have 80,000 minutes of observation time. Which translates to 4 stations located in mid to high latitudes. By observing the distribution of ILRS station network, it can be seen that enabling a few selected existing infrastructure for debris tracking will be sufficient initiating the maintenance of LP-SOC. ESA is supporting optical and SLR stations through its Expert Centre for bringing existing infrastructure for the application of SDM [11].

4. ORBIT IMPROVEMENT ANALYSIS

Performing orbit determination using single station pass and range only measurements, does not provide enough information to reduce the uncertainty in an orbit. Figure 3 shows a schematic representation of range only measurements and all possible orbits which could produce similar residuals while performing a non-linear least squares.

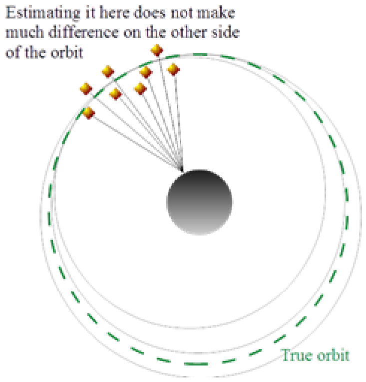

Figure 3. Schematic representation of possible orbits, which produces similar fit RMS using a single station pass range measurements

Multiple orbits with different eccentricities can pass through the same set of range measurements. In order to increase accuracy in the estimated orbit, it either require to process observations from multiple passes to constrain the uncertainty in tangential direction, or to include angular measurements.

To evaluate the improvement that could be achieved through inclusion of coarse angular measurements with SLR ranging observations, another simulation was carried out presented in the following subsection.

4.1. Benefits from including coarse angular measurements in OD

In this section, we check the benefits from including the angular measurements with large noise and precise range measurements to see how different the orbits are estimated in comparison with orbits by range only measurements.

From previous test cases presented in section 2, it is understood that single station pass is not sufficient to improve orbital knowledge on an object. Hence, we considered two station passes with range measurements, and generated elevation and azimuth observations from given station with noise of 0.1° one sigma noise levels. Figure 4 shows the comparison between two estimates of same orbit with and without angular measurements.

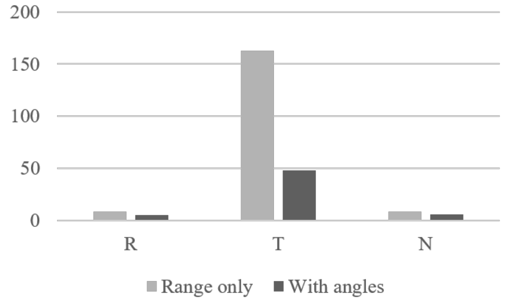

Figure 4. Comparison of estimated orbit quality from range only measurements and coarse angular and range measurements

As it can be see from the simulated test case, inclusion of coarse angular measurement constrains the velocity parameter while estimating states, or mean motion while estimating elements. Thus providing larger improvements in estimated orbits compared to range only orbit determinations. The test case was carried out on a single representative altitude. By the nature of the orbit, one could assume that the above behaviour is valid for different altitudes, but it requires either intense testing with large simulations or validation with real observation campaigns.

Hence we propose that the future SLR stations consider the possibility of providing angular measurements, which are already recorded from the mount encoders for guiding the pointing system. This will enable < 5 laser ranging stations, with day time operational capability, to maintain the envisioned LP-SOC.

5. FUTURE LASER BASED MANOEUVRING

Laser based manoeuvring is the mitigation strategy based on medium-powered ground-based laser combined with a telescope to prevent collisions between debris objects in Low Earth Orbits (LEOs). The laser system is designed to exert photon pressure on the surface of selected targets to perturb their orbits. This system is termed as Laser Momentum Transfer (LMT) systems.

Although photons lack mass, they carry momentum. Shining light upon the surface of a space object will result in transfer of these photons-momentum. Radiation pressure models are regularly used in evaluating the orbital forces for modelling the effect of radiation pressure impinged on the satellites. The models are employed in estimating the orbital accelerations due solar radiation pressure and Earths albedo effects. The well-established radiation-surface interactions shows that the absorption of photons results in the transfer of momentum in a direction parallel to the incoming/incident light; photon pressure due to surface reflection will results in the transfer of momentum in the opposite direction of the incident light. The schematic representation of the surface -photons interaction is shown in 5

Author in [2] have analysed the required technical tools to carry out and implement a laser momentum transfer system. Space Research Centre in Australia have already scheduled a demonstrative mission to test the feasibility to use lasers for collision avoidance [5].

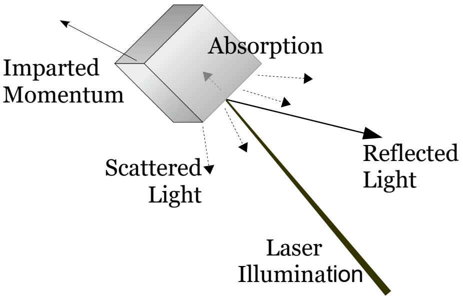

Figure 5. Photon momentum due to laser illumination

Due to the generally high accuracy in the laser catalogue a radial position uncertainties can be maintained well under 10m for both objects. This would mean that the achievable collision avoidance manoeuvre sizes of approximately 20m is sufficient for a risk reduction of 1 to 2 orders of magnitude. Also for operated satellites, the small covariances are not only helpful to reduce the false alert rate but also to reduce the manoeuvre size.

For the entirety of objects contained in the operation zone of the system, about 600 engagements will become necessary in a year (i.e. about 2 per day). This seems to be compatible with the manageable workload of 4 dedicated ranging stations and 2 momentum transfer stations being available.

Given the high cost burden of operational collision avoidance effort and of active removal missions, the proposed concept provides a very interesting approach to space traffic management and long-term environmental stability, ensuring space safety.

To bring LMT to operational stage it requires to address several technical challenges, few main issues are listed below:

- to accurately model the photon pressure from a beam to an object, its area, mass and material properties need to be known
- to accurately model the attitude of the debris to be known
- to understand the photon-surface interaction and establish the resulting forces imparted on SO due to laser illumination
- to model atmospheric aberrations in laser beam propagation
- to develop technical means to minimise the beam propagation divergence

6. SUMMARY

In this paper we have proposed to maintain a high precision space objects catalogue, Laser range observation based Precision Space Object Catalogue (LP-SOC), and the benefits that could bring in space operations. Maintaining a catalogue with positional uncertainty of less than 20 meters will bring in reduction of 90% in false collision warnings. We have also briefly addressed the accuracy requirement, and subsequent network requirement for the distribution of satellite laser ranging stations to maintain a LP-SOC. When using range only observations from SLR stations, four passes of one minute observation lengths, within one day are sufficient to achieve the required positional accuracy of < 20m. This translated to the requirement of having a network of minimum four stations for tracking will suffice for maintaining a high precision LP-SOC of track-able objects.

Using lasers for remote manoeuvring and bringing reduction in probable collision events will reduce the growth of debris population, and at the same time brings value addition to the space operations by reducing the operational costs. The laser momentum transfer (LMT), requires further investigation to study the feasibility of such a system. In the running Space Situational Awareness and intended Space Safety programmes, European Space Agency (ESA) is carrying out studies to evaluate the feasibility and bring the technology readiness level of future LMT system to operational state.

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