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Experiment on diffuse reflection laser ranging to space debris and data analysis *

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Abstract Space debris poses a serious threat to human space activities and needs to be measured and cataloged. As a new technology for space target surveillance, the measurement accuracy of diffuse reflection laser ranging (DRLR) is much higher than that of microwave radar and optoelectronic measurement. Based on the laser ranging data of space debris from the DRLR system at Shanghai Astronomical Observatory acquired in March-April, 2013, the characteristics and precision of the laser ranging data are analyzed and their applications in orbit determination of space debris are discussed, which is implemented for the first time in China. The experiment indicates that the precision of laser ranging data can reach 39 cm–228 cm. When the data are sufficient enough (four arcs measured over three days), the orbital accuracy of space debris can be up to 50 m.

Key words: space vehicles — astrometry — celestial mechanics — methods: data analysis

1 INTRODUCTION

Space debris, also known as space junk, is composed of artificial material trapped in orbit around the Earth and comes from discarded rocket bodies, the upper stages of rocket engines, retired and unused satellites, leftover equipment from space missions, remains from collisions between space objects, etc (Liu et al. 2004). In recent years, human spaceflight and space launch activities have become more and more frequent and the amount of objects in orbit has increased exponentially. The latest news on the Space-Track website shows that there are about 16 000 pieces of debris that are larger than 10 cm. Space debris threatens the safety of the spacecrafts that are currently in service, and poses a potential collision risk that is a serious constraint on future spacecraft launches, spacecraft testing and other space activities. With the development of spaceflight technology, there will be increasing space activities in the future. To ensure the safety of future space activities, sustainable development and utilization of space resources, new technologies for tracking and cataloging space debris should be developed.

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Currently, the measurement systems routinely used for monitoring space debris and cataloging threats are mainly the Space Fence program which uses optical and radar equipment. Limited by the precision of the current measurement equipment from several meters to tens of meters, which cannot satisfy the required precision for measuring some space objects, new technology for observation is needed. As one of the most precise technologies implemented for observation in space geodesy, single measurement precision of satellite laser ranging (SLR) used to locate cooperative targets with corner reflectors could reach the subcentimeter level, and in the future will be up to the millimeter level (Ye & Huang 2000). However, for measurement of non-cooperative targets without corner reflectors, such as space debris, most satellites and unused spacecraft require diffuse reflection laser ranging (DRLR) technology. The method of DRLR is similar to conventional laser ranging where the distance between a ground-based laser station and a space target is obtained by measuring the round-trip propagation time of the laser signal. The main difference is that the method used for laser pulse reflection with cooperative targets reflects the incoming laser pulse back to the ground station through corner reflectors, but diffuse reflection must be used to locate non-cooperative targets. The laser energy required for diffuse reflection is much larger than that needed for a cooperative target. In addition, compared with conventional laser observation, diffuse reflection laser ranging technology has a wider range of applications, and its measurement precision can reach to 50–250 cm (e.g. Greene et al. 2002; Kirchner et al. 2013; Li et al. 2011; Zhang et al. 2012), which is about 1–2 orders of magnitude better than that of other programs that use optical and radar systems. DRLR could provide high-precision observation and it is beneficial for monitoring space debris.

Based on a 60 cm aperture laser ranging system and DRLR technology, some experiments with DRLR for tracking space debris were carried out using a 200 Hz, 50 W laser system in March – April, 2013 at Shanghai Astronomical Observatory (SHAO). A large amount of valuable laser ranging data was obtained. The laser ranging data of the single station from some space debris are processed to realize orbit determination (OD) for space debris and evaluate the accuracy of the DRLR data. Moreover, the application of DRLR data in OD for space debris is discussed in this paper.

Because of the ubiquity of collision risk from space objects, accurate surveillance of a space target such as a satellite or related debris has become very important. Institutions have paid great attention to technology that uses laser ranging for tracking and monitoring space debris and non-cooperative targets. Starfire Optical Range, a facility with an aperture of 3.5 m operated by the United States Air Force in New Mexico, has been collecting data on this topic. In recent years, a new trend has been noticed that uses diffuse reflection laser ranging technology to monitor non-cooperative targets. In 2000, the Australian company EOS started laser measurement of space debris at the Mount Stromlo observatory outside of Canberra from 2000. Greene et al. (2002) produced a report entitled "Laser Tracking of Space Debris" from the thirteenth session of the international laser ranging workshop in Washington, D.C. This report described progress related to using defuse reflection laser ranging to measure positions of non-cooperative targets. According to that report, these researchers could detect space debris with a size of 15 cm up to a distance of 1250 km using a 76 cm aperture telescope and a high power laser system at Mount Stromlo observatory (Greene et al. 2002). In 2004, the aperture of the telescope used for space debris ranging was increased to 1.8 m. In addition, the Graz laser ranging station in Austria successfully tracked 85 arcs of 43 space debris targets on 2011 December 11 and 2012 May 10 (Kirchner et al. 2013). The measured distances were from 600 km to 2500 km. The radar cross sections (RCSs) ranged from 0.3 m^2 to 15 m^2. The average precision (root mean square (RMS)) was about 0.7 m.

SHAO started to develop DRLR technology in 2006. In cooperation with the Eleventh Institute of the China Electronics Technology Group Corporation, the first set of DRLR systems with a laser power of 40 W at 20 Hz and a wavelength of 532 nm was developed at SHAO. Since then, this project has began to track and measure non-cooperative targets. In July, 2008, the debris from two rockets was tracked, yielding three arcs of laser ranging data that had a precision (RMS) of 68–83 cm (SHAO 2008). This opened the field of development for DRLR technology in China. After upgrading the measurement system, 43 arcs were measured from 18 space targets (rocket debris and defunct satellites) in March and April, 2013. Yunnan Observatories, Chinese Academy of Sciences, also developed technology for DRLR based on the SLR system using a telescope with an aperture of 1.2 m. Laser ranging data were successfully obtained from dozens of arcs of space debris in 2010–2011 (Li et al. 2011).

In the following, Section 2 gives information about the DRLR system and laser ranging data. Sections 3 and 4 describe orbit determination by DRLR and evaluation of its precision respectively. Section 5 gives conclusions and discussion.

2 DRLR SYSTEM AND LASER RANGING DATA STATISTICS FOR SPACE DEBRIS

During the past several years, SHAO has built a space debris laser ranging system that uses a lamp pumped solid-state laser with a high pulse energy and low repetition rate. For the first time in China, our group has successfully applied a diode pumped solid-state laser system that uses 50 W of power at 200 Hz. The system combines this laser with a low dark noise avalanche photodiode (APD) detector to observe space debris. Many passes of laser data have been obtained with this system.

For laser ranging of space debris, a high power laser system with good beam quality, stability and pointing accuracy is very important, especially for observing small space objects at a long distance. The lamp pumped laser system has a low pulse repetition rate and was used during 2008–2012 at SHAO. For a high power laser system, the best way to satisfy the power requirements but not damage the housing of the laser module is to increase the working frequency and decrease the pulse energy. In order to test the measuring ability of a high power laser when a high repetition rate is applied, a set of semiconductor pumped laser systems with 50 W of power and an operating frequency of 200 Hz was installed at SHAO at the beginning of 2013.

The high power laser system helps to solve the problem of determining the number of laser returns from space debris. The next issue is to reduce the level of noise detection by making a large scale adjustment of the range gate and obtain laser returns with a high signal to noise ratio for farther and smaller pieces of space debris. A breadboard prototype of an APD detector has been developed by our group based on a Compass LTT detector in cooperation with a domestic university. By using the detector, the dark noise can be decreased; however, the noise from the sky and targets also has some influence on the laser detection. For that, a spectral filter with high efficiency and narrow bandwidth is adopted to reduce the level of background noise. The main characteristics of the filter are as follows: (1) center wavelength: 532 nm; (2) bandwidth: 1 nm; and (3) efficiency: $>$90%.

The event timer Model A033-ET is used for measuring time intervals and has a precision of 10 ps. This device is made by Riga University in Latvia. The control system for the laser measurement is the same as that used in a standard kHz SLR system. The tracking error of the associated 60 cm telescope is less than $1''$ which satisfies the requirement for tracing the path of space debris targets.

In March and April, 2013, the DRLR data acquired from 18 targets which have more than two arcs were obtained. Those targets mainly represent rocket bodies and unused satellites with an orbital altitude (perigee altitude) from 400 to 900 km. The minimum target size (in terms of RCS) is about 1 m^2. The maximum is about 12 m^2. Table 1 shows detailed information about these measured targets. The targets, which have more than three arcs, are written in bold italic print in the table.

Table 1 indicates that there are six targets having more than three arcs. These three sets of measurements were acquired between March 2 and March 7, between April 12 and April 16, and between April 26 and April 29 in 2013, respectively.

Table 2 shows detailed information about laser ranging data from the six targets. The longest time for a measured arc is about 4 minutes. The mean interval for sampling data (except 28222) is about 100 ms. In other words, about ten laser ranging data could be collected per second. The

Table 1 Detailed Information about Targets that were Measured with DLRL

NORAD ID	Perigee (km)	Eccentricity	Inclination (°)	Inter ID	RCS (m^2)	Name
20453	428.41	0.03465	35.628	1990008B	9.79	DELTA 2 R/B(1)
28222	514.65	0.00691	97.367	2004012C	12.25	CZ-2C R/B
23343	630.79	0.00133	98.203	1994074B	8.94	SL-16 R/B
20323	688.23	0.00611	97.070	1989089B	8.90	DELTA 1 R/B
11574	739.92	0.00228	74.072	1979089B	5.43	SL-8 R/B
24968	765.70	0.00125	86.394	1997056D	3.95	IRIDIUM 37
23705	827.30	0.00181	71.025	1995058B	9.96	SL-16 R/B
16182	835.66	0.00013	71.006	1985097B	12.21	SL-16 R/B
12138	395.94	0.07381	82.960	1981003A	2.98	COSMOS 1238
20362	437.42	0.01284	35.627	1989097B	9.58	DELTA 2 R/B(1)
12465	507.94	0.00463	81.225	1981046B	5.67	SL-3 R/B
16496	595.89	0.00294	82.526	1986006B	4.50	SL-14 R/B
14820	596.89	0.00301	82.542	1984027B	3.86	SL-14 R/B
19275	614.55	0.00089	82.514	1988056B	4.83	SL-14 R/B
18765	748.98	0.00064	66.583	1985042H	1.13	SL-12 DEB
17590	829.31	0.00077	71.005	1987027B	9.64	SL-16 R/B
24298	834.92	0.00194	70.868	1996051B	8.79	SL-16 R/B
20788	868.20	0.00196	99.013	1990081A	3.05	FENGYUN 1B

Table 2 Detailed Information about Laser Ranging Data from DRLR

NORAD ID	Start Time (UTC)	Len. of Arc (s)	Len.of sampling (s)	Echoes	Mean Sampling (per sec)	Range (km)
20453	03–04 11:49:08	77	72	669	9	777–1179
	03–05 10:38:06	209	197	1629	8	
	03–05 12:21:57	101	99	1443	15	
	03–06 11:12:27	131	105	557	5	
28222	03–02 21:06:44	98	89	6010	68	571–1287
	03–03 21:06:39	30	30	893	30	
	03–04 21:07:55	104	98	3583	37	
11574	03–02 21:22:30	96	81	312	4	855–1317
	03–03 20:40:30	221	198	652	3	
	03–05 21:02:01	177	170	1638	10	
12465	04–12 12:03:52	99	99	2805	28	642–886
	04–13 11:57:34	121	111	806	7	
	04–14 11:51:03	170	110	1639	15	
17590	04–12 12:06:53	85	82	887	11	960–1372
	04–14 11:33:24	49	49	392	8	
	04–15 11:18:03	112	106	2694	25	
20788	04–26 11:34:25	63	63	687	11	905–1455
	04–27 11:29:55	69	56	219	4	
	04–28 11:30:27	84	51	151	3	

minimum measured distance is 571 km and the maximum is 1455 km. Information about the targets and arcs is shown in Table 2.

Table 2 indicates that the measuring system at SHAO used for DRLR could continuously track and measure space debris or defunct satellites with a size (in terms of RCS) larger than 1 m^2 and orbital altitude less than 1000 km. The maximum distance is approximately 1600 km. The sampling rate for laser ranging data can be used to infer the external characteristics of space targets.

Table 3 Description of the Dynamic Model Adopted in OD

Perturbation Correction	Description
Earth gravity	GGM02C (150×150)
N-body perturbation	JPL DE 405 Ephemeris, including solar, lunar and planetary gravitations
Solid earth tides / Pole tides	recommended model/IERS 2003
Ocean tides	TOPEX3.0
Earth rotation parameter (ERP)	IERS EOP series
Atmospheric drag	DTM94
Radiation pressure	Solar radiation pressure, Earth radiation pressure
Relativistic perturbation	Recommended model/IERS 2003
Tropospheric correction	MARINI/MURRAY model
Others	Weighted least squares method (Gauss-Jackson multistep method)

3 OD AND RESIDUAL ANALYSIS BY DRLR

Because the laser ranging data from DRLR are collected at single stations, most targets only have one arc per day except 20453. To satisfy the requirements of OD, at least two or three arcs are needed. In terms of data processing, non-cooperative targets are regarded as a particle and the size and centroid correction for these targets are not considered (Huang et al. 2003). The dynamic models used for OD are shown in Table 3.

All forces acting on the satellite are regarded as perturbations except for the central gravitational force. Considering the un-modeled errors and observational errors, some dynamic parameters are regarded as unknown parameters and estimated together with the orbital parameters (Tapley 1989). Based on these considerations, residuals from the results of orbit calculations for the mentioned six targets are shown in Table 4. The results include the atmospheric drag parameter (Cd0) that is estimated over the whole arc.

Figures 1–6 show the residuals for the orbits of six targets. The RMS for the six targets is about 111 cm. The maximum value is about 228 cm and the minimum value is about 39 cm.

Due to the size, orbital attitude and other factors related to a non-cooperative space target, especially space debris from used rocket equipment, they generally fly with an irregular spin. The OD residuals of these targets range from 39 cm to 288 cm, with an accuracy that is a little worse than that of laser ranging data (68–83 cm) (SHAO 2008). The partial data of 20 453 (the starting time of the arc is 2013-03-05 10:38:06, UTC) shown in Figure 1 obviously exhibit periodic variation. When the high-frequency component (scattered points denote the original results, the solid line represents filtered results) is filtered, the residuals are computed and shown in Figure 7.

4 EVALUATION OF PRECISION FOR OD FROM DRLR

For non-cooperative targets and space debris, under normal circumstances, it is difficult to obtain accurate results for the orbit. Thus, a Two-Line Element (TLE) set provided by the Space-Track website is used to test the reliability of the orbit results estimated with laser ranging data from a single station. After that, the methods of orbit segmentation and orbital overlaps (Tapley et al. 2004) are applied to assess the accuracy of the results for orbits of the targets that have an adequate number of observations.

Target 20453 has four arcs that were recorded over three days so that a larger amount of data that can satisfy the requirement of assessing the quality of results when orbit segmentation and orbital overlaps can be applied (the same dynamic model and OD strategy are used). So, the results from this target are used for assessing the accuracy of orbit determination. The results are shown in Table 5 and a plot of the deviation shown by the orbit is illustrated in Figure 8. The results of deviation between the whole arc and a sub-arc are shown in Table 6.

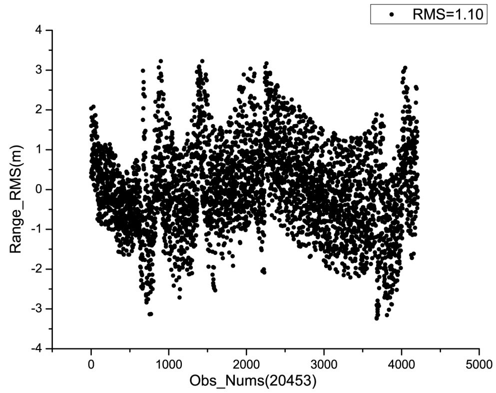

Fig. 1 Residuals of 20453.

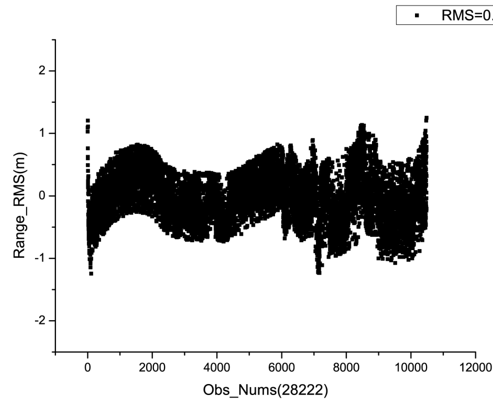

Fig. 2 Residuals of 28222.

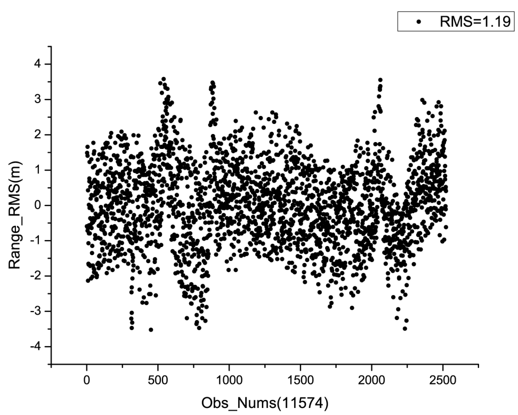

Fig. 3 Residuals of 11574.

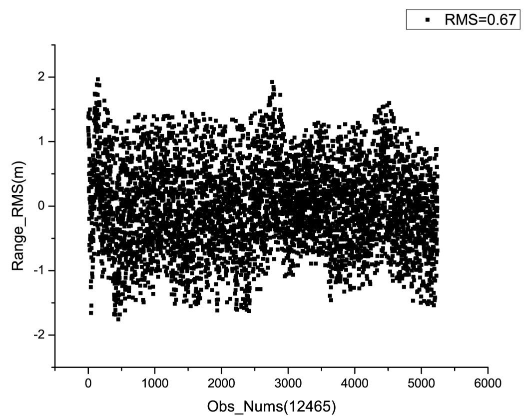

Fig. 4 Residuals of 12465.

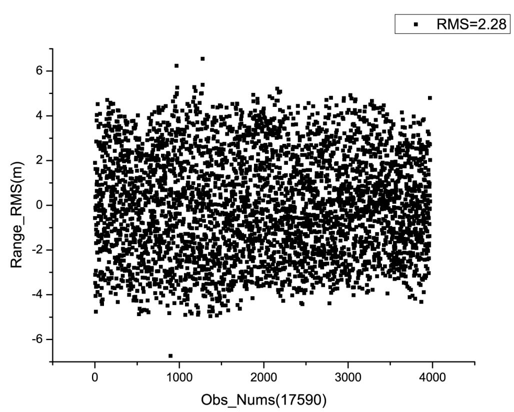

Fig. 5 Residuals of 17590.

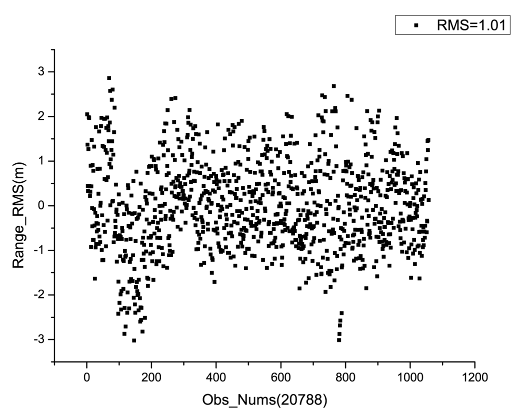

Fig. 6 Residuals of 20788.

Table 4 OD of Space Debris with Laser Ranging Data Collected from a Single Station (estimated Cd0)

NORAD ID	Start Time (UTC)	OD arc (d)	RMS (m)	Data Used (%)
20453	03–04 11:49:08 03–05 10:38:06 03–05 12:21:57 03–06 11:12:27	2.1	1.10	97.9
28222	03–02 21:06:44 03–03 21:06:39 03–04 21:07:55	2.1	0.39	100
11574	03–02 21:22:30 03–03 20:40:30 03–05 21:02:01	3.0	1.19	97.0
12465	04–12 12:03:52 04–13 11:57:34 04–14 11:51:03	2.1	0.67	99.8
17590	04–12 12:06:53 04–14 11:33:24 04–15 11:18:03	3.0	2.28	99.9
20788	04–26 11:34:25 04–27 11:29:55 04–28 11:30:27	2.1	1.01	100

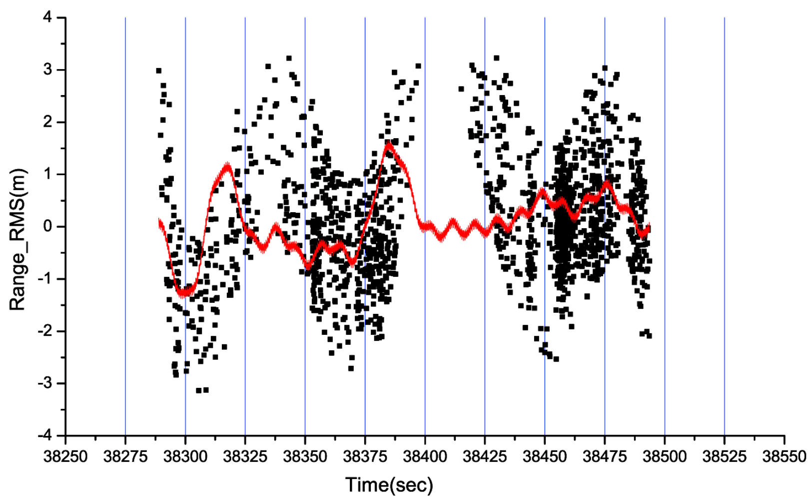

Fig. 7 Orbit residual of target 20453 after a low-pass filter is applied.

From the results in Tables 5 and 6, it can be seen that the accuracy of orbit determination for space debris is better than 50 m, when adequate laser ranging data from a single station are processed. This result is better than that of microwave radar or an optoelectronic measurement system under the same conditions.

Table 5 The Results of Orbital Overlaps

No.	Start Time (UTC)	Arcs	OD arc (d)	Overlaps arc (d)	Deviation RMS: m R	T	N	3D
1	03–04 11:49:08	3	1.5	1.0	7.13	31.16	17.41	36.41
2	03–05 10:38:06	3	1.5					

Table 6 The Deviation between the Whole Arc and Sub-arc

No.	Start Time (UTC)	Arc	OD arc (s)	Overlaps arc (d)	Deviation RMS: m R	T	N	3D
1	03–04 11:49:08	3	77+209+101	1.5	11.72	39.45	17.98	44.92
2	03–05 10:38:06	3	209+101+131	1.5	4.64	12.39	0.96	13.27

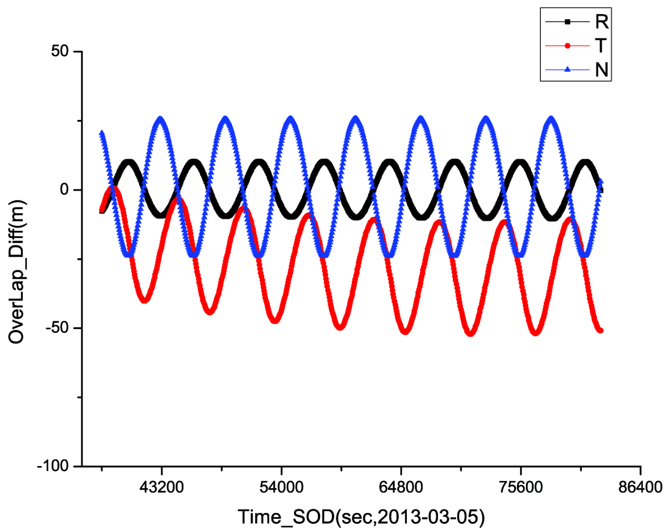

Fig. 8 The deviation of target 20453 through orbit segmentation and orbital overlaps.

5 CONCLUSIONS AND DISCUSSION

Based on the already existing technology of laser ranging, the laser measurement system at SHAO was upgraded. Some experiments on space debris tracking were carried out and some good results were obtained. In these experiments, the collected data from some debris were processed and analyzed. The conclusions are as follows:

(1) The residual of OD shows that the mean precision of an orbit is about 111 cm. The maximum is about 228 cm and the minimum is about 39 cm;
(2) The data from 18 targets and 43 effective arcs acquired from laser ranging are processed and analyzed. The DRLR system could continuously track a large (RCS$>$1 m^2) piece of space debris at an orbital altitude of less than 1000 km with a maximum range of approximately 1600 km.
(3) By using multiple arcs of laser ranging data that were taken from a single station, the orbit determination of space debris could be performed and the accuracy of orbit determination is better than 50 m (in terms of orbital overlaps) with an adequate amount of data.

As a new means of observing non-cooperative targets or space debris, DRLR technology has significantly improved precision to about 1 m, which is much higher than other space debris measurement systems, while keeping an accuracy of tens of meters. The DRLR system has the ability to take continuous measurements of targets, and DRLR technology is feasible to use in the measurement to space debris with a high success rate. With the development of technology related to high-precision measurement, the DRLR system can provide high-precision data for orbit determination and collision warning in the future.

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