Updates of BJFS station and SLR station Classification for GNSS Satellite Orbit Accuracy Validation

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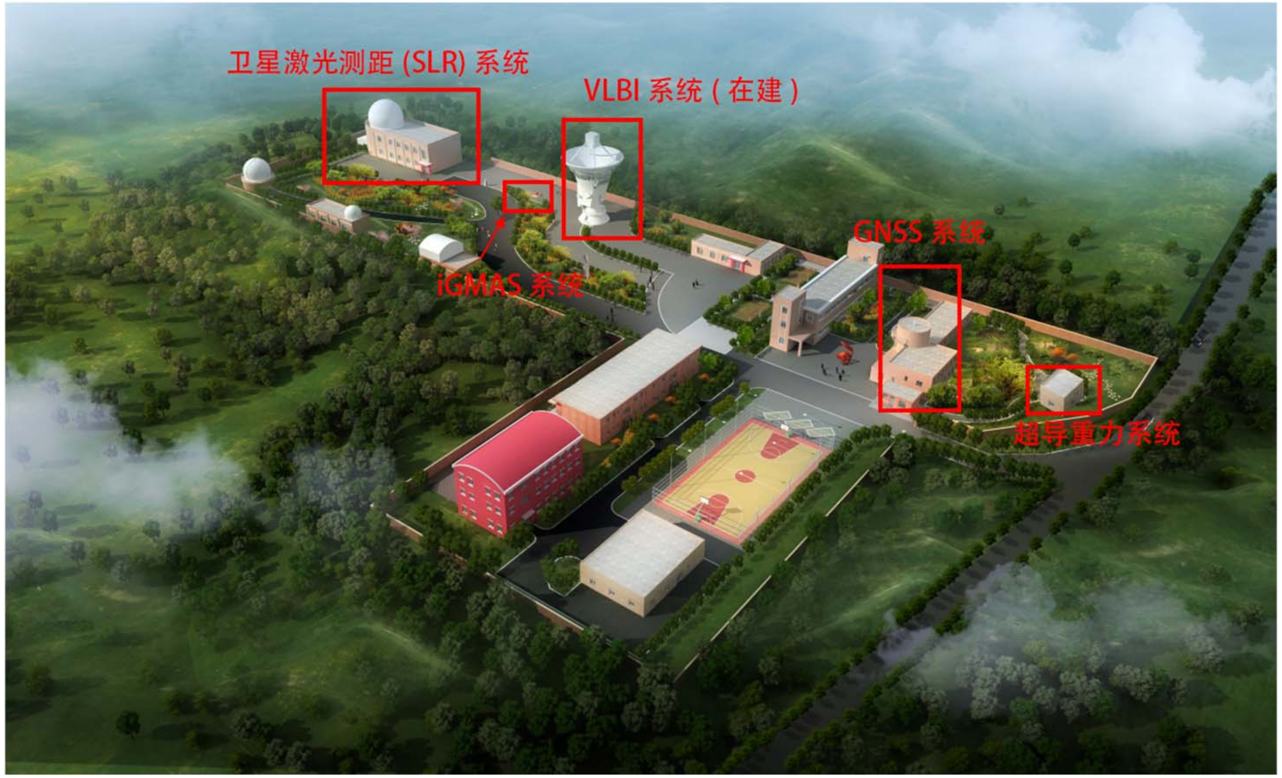
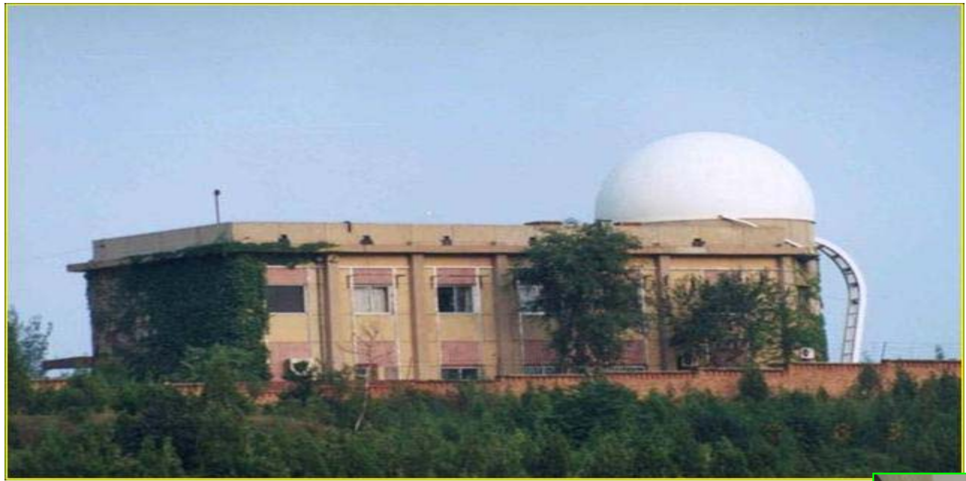
1 Brief introduction

- BJFS station was built in 1980, which is located in Fangshan district, Beijing, China
- There are Four kinds of geodetic observation techniques (GNSS, SLR, VLBI and gravity). It is a comprehensive observation research station of geodesy.



- There are 28 employees and nearly 50 graduate students for geodetic observation and research of BJFS station currently,



SLR

GNSS

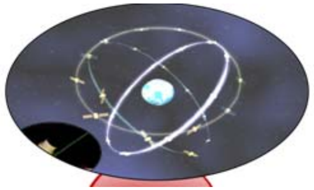
GNSS

gravity observation

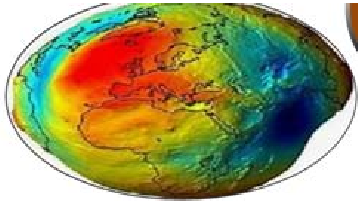
VLBI

- 13m geodesic VLBI
- Complete the the construction of antenna panel, receiver, observation and control system, mount and other subsystems
- Expect to complete the integration and test of subsystems early next year

Related research field

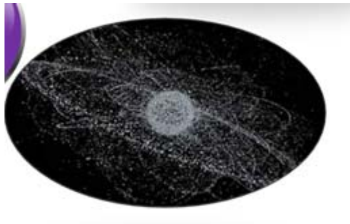


Geodetic data acquisition

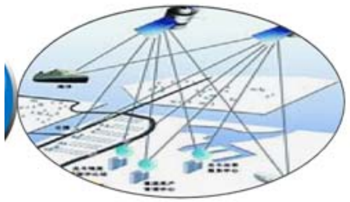


Earth gravity field and vertical datum

Geodetic datum and data processing



Orbit determination of space target



Navigation and positioning

Updates of SLR system

- Telescope servo system and its control software
- Laser and emission path
- Receiving terminal box and receiving optical path
- Ranging control and data acquisition and processing software system

Telescope servo system and its control software

Develop new telescope control software

Replace Absolute encoder

Replace the servo controller

- **Laser and emission path**

Replace laser

2000Hz/2mj

Upgrade Kuder light path

Remodel transmitting mirror tube

- **Receiving terminal box and receiving optical path**

Redesign and develop the receiving terminal box

the devices in the terminal box include:

- 2 CMOS cameras
- 1 PCO camera
- 1 C-SPAD detector

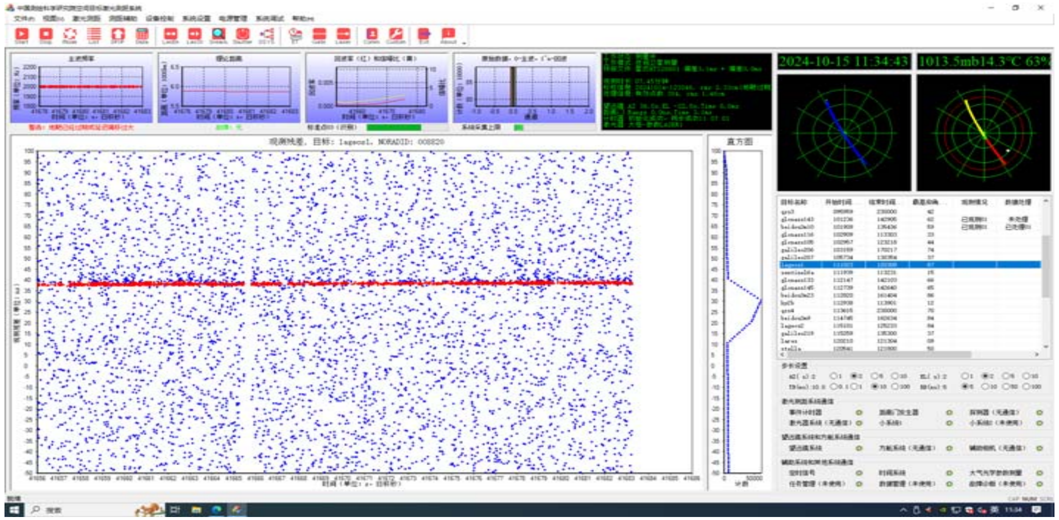
• Ranging control, data acquisition and processing software

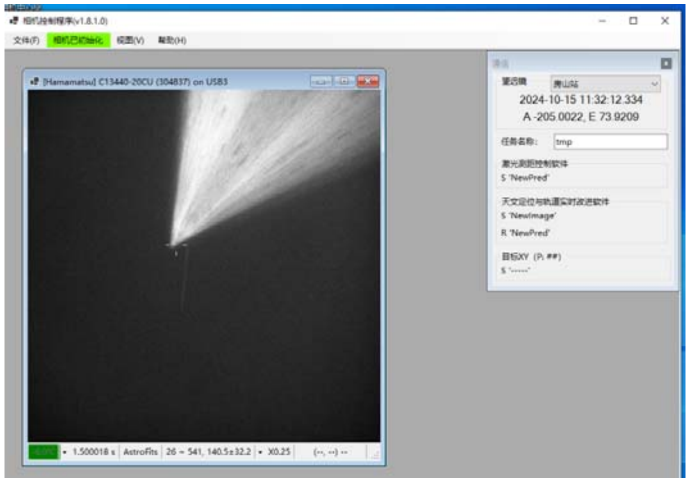
Replace the GPS Clock

Replace evet timer

Replace the ranging control system

Update ranging control, data acquisition and real-time processing software



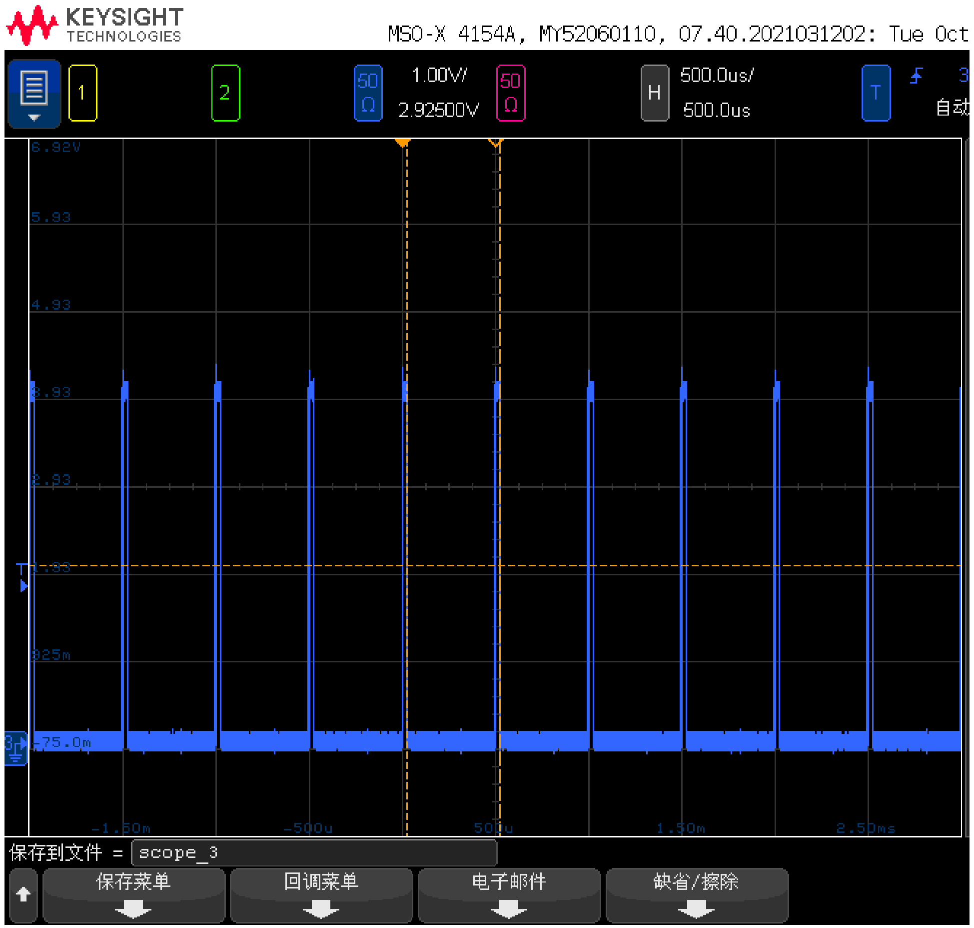


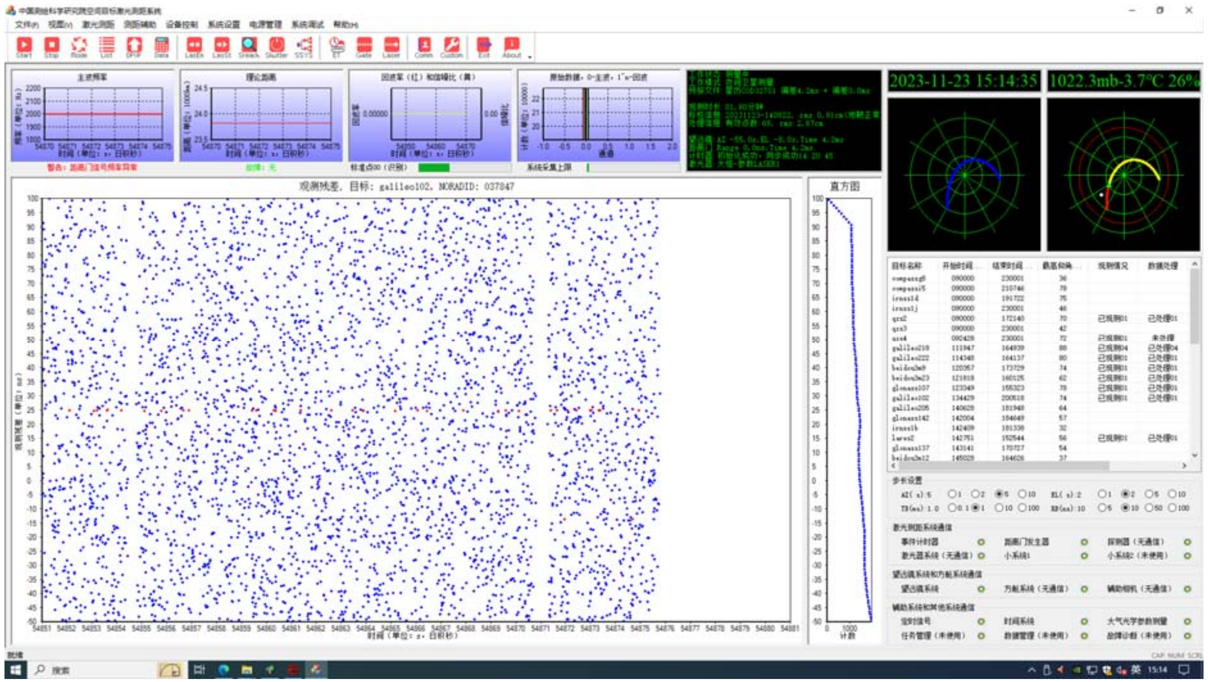
Update camera image capture and display software

☐ System performance (after updated)

- Detection frequency : 2000Hz
- The longest detection distance: 36000km
- Daytime laser ranging
- Ground target ranging accuracy: <10mm
- Normal point accuracy and system stability

• Detection frequency : 2000Hz



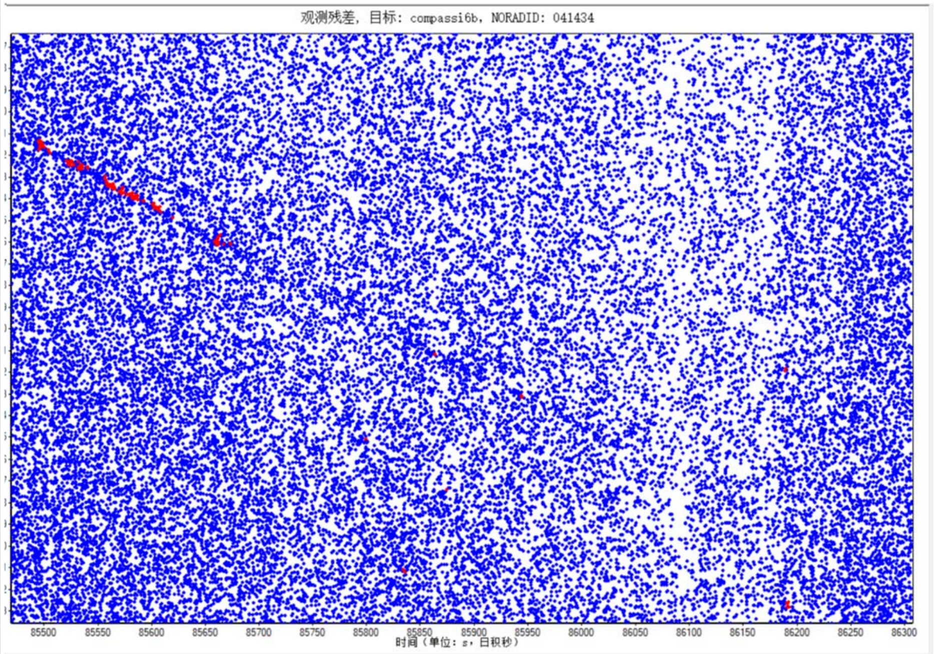


2kHz laser ranging interface screenshot

- The longest detection distance: 36000km

20231114	163635	164726	lares2	9513	5899
20231114	164803	165239	hy2c	7589	957
20231114	172011	172716	jason3	3045	1336
20231114	173709	174917	compassg8	321	35769
20231114	175014	175612	swarmb	8303	460
20231114	175714	180204	larets	60700	691
20231114	180326	183932	compassi3	547	35786
20231114	184056	185628	compassi5	465	35786
20231114	185948	190350	lageos1	353	5850
20231114	191252	191740	jason3	3142	1336
20231114	191844	193122	beidou3m21	1327	21500
20231114	193343	194036	compassi6b	415	35677
20231114	194211	195549	beidou3m20	960	21500
20231114	203327	204331	lares2	2547	5899
20231114	204426	204915	saral	902	814
20231114	205419	205714	lares	26770	1450
20231114	210752	211722	beidou3m14	1485	21500
20231114	211744	212300	kompsat5	6860	550
20231114	212419	212840	beaconc	37618	927

- daytime laser ranging



Daytime laser ranging interface for Beidou Satellite (compassi6b, ~36000km)

- Ground target ranging accuracy: <10mm

详细信息

校准编号	地靶日期	地靶时间	系统延迟...	延迟偏移...	数据点数	地靶RMS(cm)	激光器	观测员
1305	20240813	121527	105401.9...	137.200000	19626	0.890000	laser1	bjc
1306	20240813	121646	105413.8...	11.800000	20953	0.890000	laser1	bjc
1307	20240816	120850	105264.7...	-149.100000	6019	0.860000	laser1	cbh
1308	20240816	140321	105450.4...	185.700000	30789	0.820000	laser1	cbh
1309	20240818	115519	105184.1...	-266.300000	33656	0.860000	laser1	cbh
1310	20240818	115700	105231.0...	46.800000	1457	0.880000	laser1	cbh
1311	20240818	141013	105540.0...	309.000000	5321	0.850000	laser1	cbh
1312	20240827	113220	105295.8...	-244.100000	5037	0.860000	laser1	cbh
1313	20240827	134124	105374.0...	78.100000	5671	0.880000	laser1	cbh
1314	20240827	153027	105199.2...	-174.800000	34102	0.680000	laser1	cbh
1315	20240828	112752	105157.8...	-41.300000	394	0.860000	laser1	cbh
1316	20240828	112929	105205.6...	47.700000	2975	0.860000	laser1	cbh
1317	20240828	131344	105364.4...	158.700000	3746	0.890000	laser1	cbh
1318	20240828	152125	105347.0...	-17.400000	2974	0.850000	laser1	cbh
1319	20240829	112435	105210.5...	-136.400000	6506	0.830000	laser1	cbh
1320	20240829	131302	105368.2...	157.700000	3991	0.880000	laser1	cbh
1321	20240829	151802	105353.1...	-15.100000	2309	0.840000	laser1	cbh
1322	20240830	112639	105086.6...	-266.400000	8122	0.670000	laser1	bjc
1323	20240830	112710	105257.5...	170.900000	9813	0.880000	laser1	bjc
1324	20240830	112841	105280.4...	22.800000	10021	0.890000	laser1	bjc
1325	20240830	141452	105453.1...	172.700000	8443	0.890000	laser1	bjc
1326	20240901	91539	105092.2...	-360.900000	13197	0.680000	laser1	bjc
1327	20240901	135138	105117.0...	24.800000	10305	0.790000	laser1	bjc
1328	20240901	135218	105291.0...	174.000000	12242	0.870000	laser1	bjc
1329	20240901	135359	105302.8...	11.700000	8938	0.890000	laser1	bjc
1330	20240902	101037	105281.6...	-21.100000	516	0.890000	laser1	bjc
1331	20240902	114324	105301.0...	19.300000	9670	0.870000	laser1	bjc
1332	20240902	141753	105284.5...	-16.400000	11399	0.750000	laser1	bjc
1333	20240902	141832	105384.1...	99.600000	7063	0.840000	laser1	bjc
1334	20240902	162447	105357.6...	-26.400000	6460	0.880000	laser1	bjc
1335	20240905	112936	105276.9...	-80.700000	15059	0.890000	laser1	bjc
1336	20240911	150848	105372.0...	95.000000	29906	0.860000	laser1	bjc
1337	20240911	180511	105418.3...	46.300000	29414	0.840000	laser1	bjc

开始日期 2024/ 1/1 观测人员 所有人 统计 导出 目标名称（可不填）

结束日期 2024/ 9/19 目标类型 地靶目标 激光器（地靶有效） 所有激光器

- Normal point accuracy and system stability

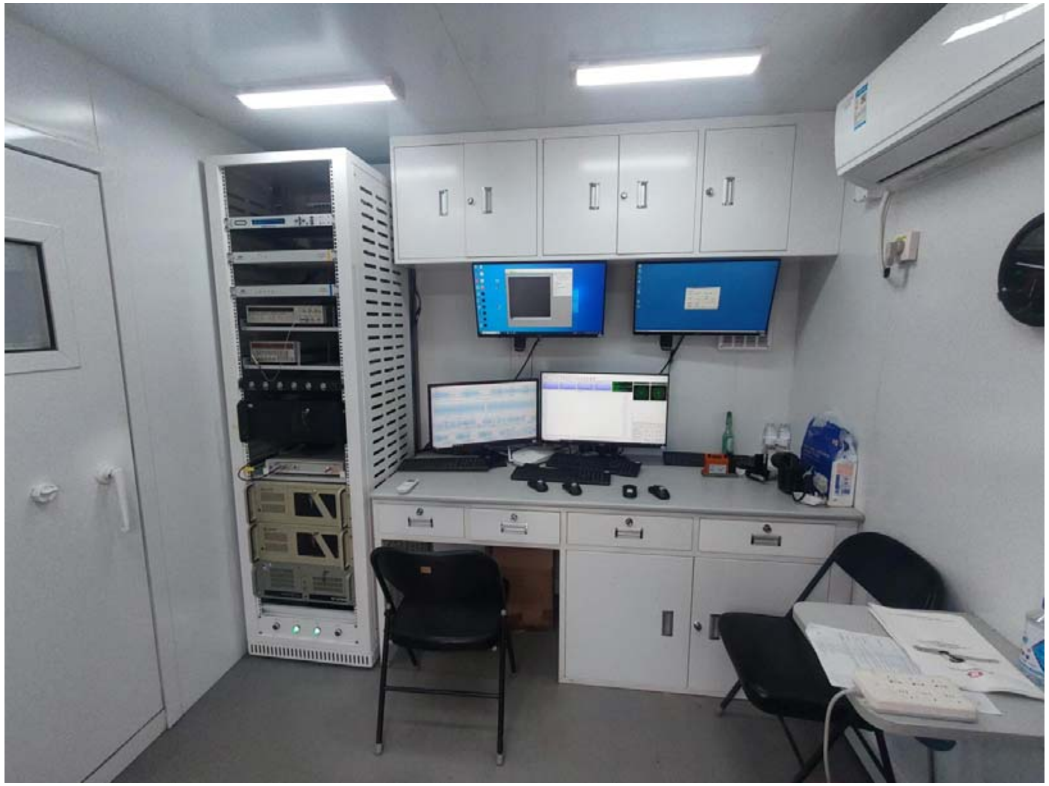
Site Information		DGFI Orbital Analysis				Hitotsubashi Univ. Orbital Analysis				JCET Orbital Analysis				MCC Orbital Analysis				SHAO Orbital Analysis			
Station Location	Station Number	LAG NP RMS (mm)	short term (mm)	long term (mm)	% good LAG. NP	LAG NP RMS (mm)	short term (mm)	long term (mm)	% good LAG. NP	LAG NP RMS (mm)	short term (mm)	long term (mm)	% good LAG. NP	LAG NP RMS (mm)	short term (mm)	long term (mm)	% good LAG. NP	LAG NP RMS (mm)	short term (mm)	long term (mm)	% good LAG. NP
Baseline		**10.0**	**20.0**	**10.0**	**95**	**10.0**	**20.0**	**10.0**	**95**	**10.0**	**20.0**	**10.0**	**95**	**10.0**	**20.0**	**10.0**	**95**	**10.0**	**20.0**	**10.0**	**95**
Kiev	1824					16.4	41.7	24.0	97	6.9	42.8	35.9	57					15.0		26.9	53
Simeiz	1873					22.6	45.9	19.3	96	5.4	51.6	20.3	54					11.3	29.3		
Mendeleevo	1874					3.5				4.5								3.0			
Riga	1884					7.9	18.1	42.8	100	4.4	16.5	17.4	96					1.5			
Svetloe	1888					1.8	10.4	3.6	100	2.1	9.5	3.1	99			9.2	99	1.1	12.3	6.8	96
Zelenchukskaya	1889					3.8	10.4	18.8	100	4.1	16.1	14.9	95			4.7	97	4.5	20.5	11.1	95
Badary	1890					2.0	6.6	6.7	100	2.4	10.5	11.1	96			6.3	97	1.2	22.9	11.2	96
Irkutsk	1891					4.6	12.3			4.4	16.8										
Katzively	1893					10.9	17.0	19.1	98	5.2	14.5	20.2	75					10.2	43.7	13.9	91
Yarragadee	7090					2.3	4.5	1.2	100	3.0	9.6	2.2	99			1.8	98	1.9	11.7	1.0	94
Greenbelt	7105					1.8	7.0	2.2	100	2.5	13.9	5.8	99			3.8	98	2.3	12.6	2.9	95
Monument_Peak	7110					2.4	5.9	4.0	99	2.2	10.0	4.6	98			3.2	98	1.6	16.7	2.3	94
Haleakala	7119					1.5	5.7	2.3	100	2.2	10.3	3.6	100			5.8	100	1.6	23.5	7.3	95
Tahiti	7124					1.9	4.9	2.2	100	2.8	11.8	10.8	99					1.2	15.9	21.3	93
Changchun	7237					1.9	16.9	18.0	100	2.1	19.1	19.1	98			5.0	97	1.2	22.7	7.7	96
Beijing	7249					1.2	11.9	10.9	100	1.7	14.3	13.3	99					0.6	22.5		

2

Updates of BJFS station (7249) and Mobile SLR system construction

- ☐ Developing one mobile SLR system

- Telescope (receiving) diameter: 1m
- Other technical index similar to the fixed system (7249)
- Laser ranging for satellite and space debris
- Size: 10.8*3*3m
- Plan to operate by 2025



The same ranging control software and hardware , laser, data acquisition software are used with the fixed station.

3

SLR station classification for satellite orbit validation

□ Background

- An independent observation technique for verifying the accuracy of GNSS satellite orbit products;

- Using all involved SLR stations or selecting some high-performance SLR stations based on experience may affect the reliability of orbit evaluation results;

- Effective station selection or weight determination to obtain more precise calculation results in some other applications, such as geocentric motion/ERP/station coordinate calculation and analysis.

□ Methods: fuzzy c-means algorithm (FCMA)

Step 1: Select SLR station quality evaluation index

- According to the requirements of ILRS, the evaluation criteria of station performance include three factors: data quantity, data quality and operation protocol compliance. All of these can be reflected by monthly and quarterly quality report cards for SLR stations published by ILRS regularly .
- Three parameters, the total number of observation cycles, the RMS value of LAGEOS standard point and the short-term deviation of system, were selected as the evaluation indexes of the station classification.

Why?

1) The performance evaluation of SLR station mainly includes three aspects: data acquisition ability, data accuracy and system stability.
2) Considering that there is a certain correlation between the data length and the total number of observations, the total number of observations and the RMS value of LAGEOS standard point are selected as the data quantity and quality indicators.
3) In terms of system stability, short-term deviation mainly affects the accuracy of satellite orbit determination and orbit correction, and long-term deviation affects the accuracy of reference frame solution.
4) The purpose of the research is to use SLR data for satellite orbit determination and calibration.

So, the total number of observation cycles, the RMS value of LAGEOS standard point and the short-term deviation of the system, as the classification evaluation index of the station.

Step 2: Normalize the evaluation Index

The linear normalization method is used to map the three types of index values to [0,1].

$$x_i^* = \frac{x_i - \mathrm{Min}(\boldsymbol{X})}{\mathrm{Max}(\boldsymbol{X}) - \mathrm{Min}(\boldsymbol{X})}$$

Where, *X* is the station evaluation index sequence, Max(*X*) and Min(*X*) is the maximum and minimum value of the sequence respectively, and, x_i、x_i^* is the index sample value before and after normalization respectively. After normalization, the station evaluation matrix is generated:

$$\mathbf{S} = \begin{pmatrix} \mathbf{s}_1 & \mathbf{s}_2 & \cdots & \mathbf{s}_n \end{pmatrix}^T = \begin{pmatrix} Num_1 & Rms_1 & Shs_1 \\ Num_2 & Rms_2 & Shs_2 \\ \cdots & \cdots & \cdots \\ Num_n & Rms_n & Shs_n \end{pmatrix}$$

Where, the row vector of the matrix is the station state vector, and the elements include the total number of observations, the RMS value of the LAGEOS standard point and the short-term stability of the system, which is the number of stations.

Step 3: Initialize of FCM clustering parameters

Initialize the parameters of the clustering algorithm, including cluster number, fuzzy weighting index, maximum number of iterations, standard error value and initial membership matrix, where the membership matrix must meet the constraint conditions:

$$\mathbf{U} = \begin{pmatrix} u_{11} & \cdots & u_{1j} \\ \vdots & \ddots & \vdots \\ u_{i1} & \cdots & u_{ij} \end{pmatrix}$$

$$\sum_{i=1}^{c} u_{ij} = 1,\ u_{ij} \in [0,1],\ j = 1, \cdots, n$$

Where, u_{ij} is the cluster i membership degree of the station j .

Step 4: Calculate or update of membership matrix and cluster center matrix

Corresponding to the station evaluation matrix, the cluster center matrix C is the normalized matrix, and the three elements of its row vector correspond to three evaluation indicators.

$$\mathbf{C}=\left(\mathbf{c}_1,\mathbf{c}_2,\cdots,\mathbf{c}_c\right)^T$$

where, $\mathbf{c}_i=\frac{\sum_{j=1}^{n}\left(\mathbf{s}_j\cdot u_{ij}^m\right)}{\sum_{j=1}^{n}\left(u_{ij}^m\right)}$, $u_{ij}^m=1\Big/\sum_{k=1}^{c}\left(\left\|\mathbf{s}_j-\mathbf{c}_i\right\|\Big/\left\|s_j-\mathbf{c}_k\right\|\right)^{2/m-1}$

where, u_{ij} is the cluster i membership degree of the station j .

Step 5: Calculate the distance difference before and after each update of the cluster center, and decide whether to proceed to the next step or repeat the step 4 according to the set standard error value and the maximum number of iteration.

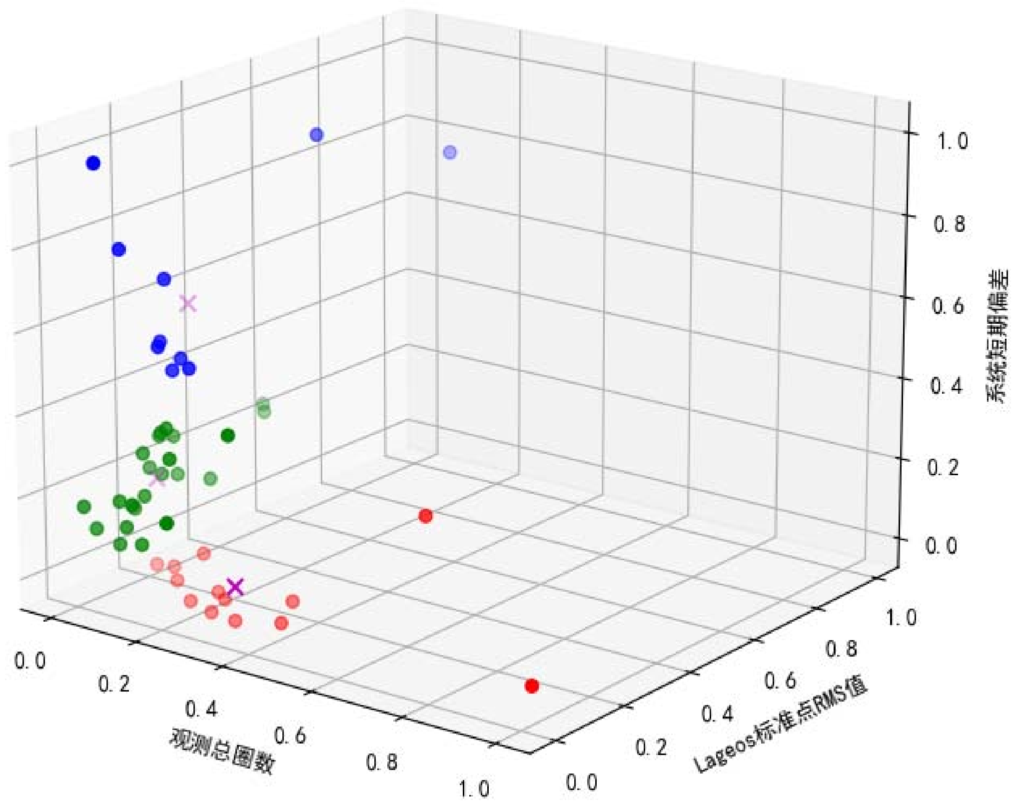
Step 6: After the iteration is stopped, the results of fuzzy classification are obtained, including fuzzy classes *c*, cluster centers v_k that can represent the properties of the corresponding categories, and membership degree u_{xk} that each station sample belongs to this class respectively.

The closer the membership degree u_{xk} is to 1, the more likely the station belongs to this fuzzy class. The closer to 0 the station is, the less likely it is to belong to this fuzzy class.

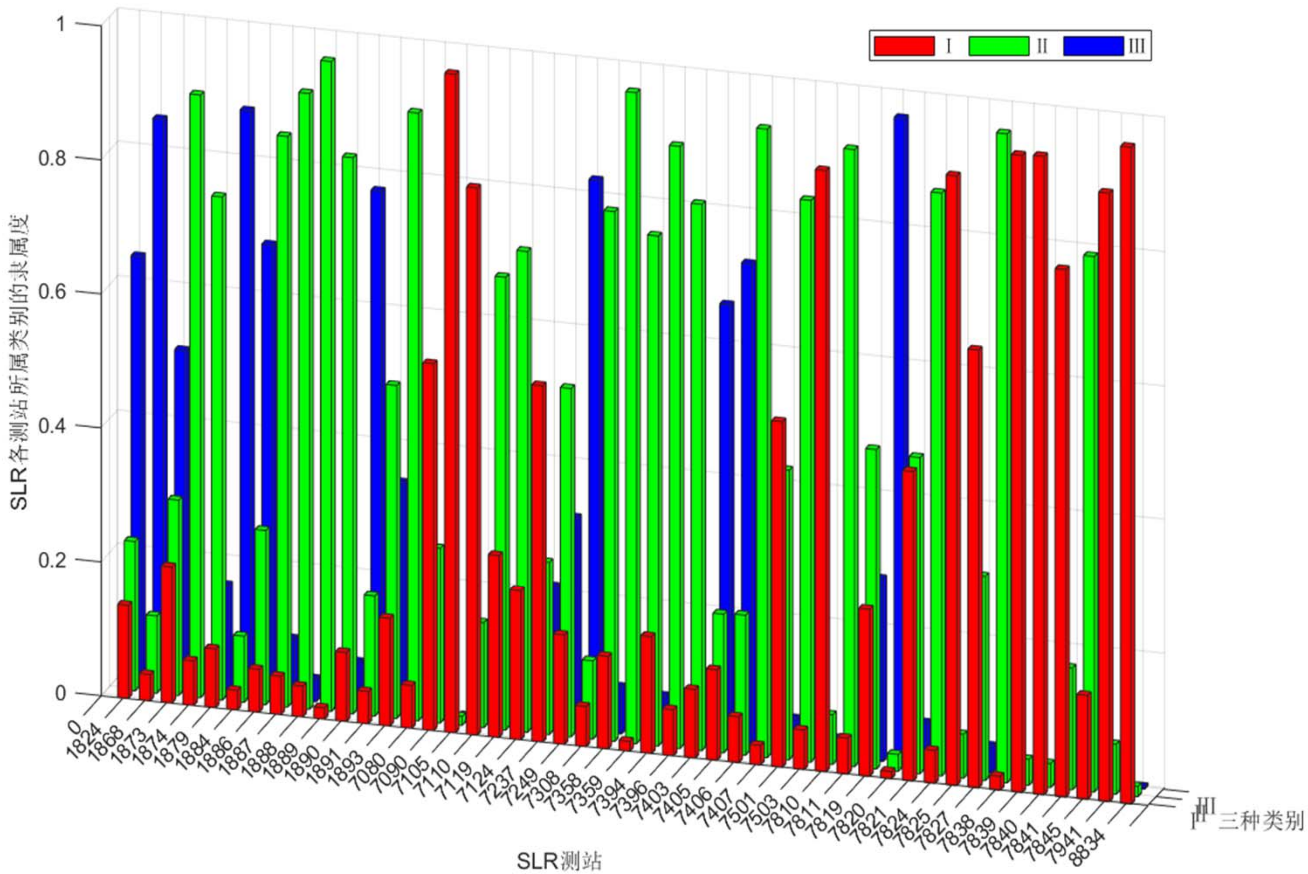
□ Classification result of SLR stations

A total of 96 months of quality report card data from ILRS (May 2013 to April 2021) were used to obtain the mean value of the classification evaluation index parameters;

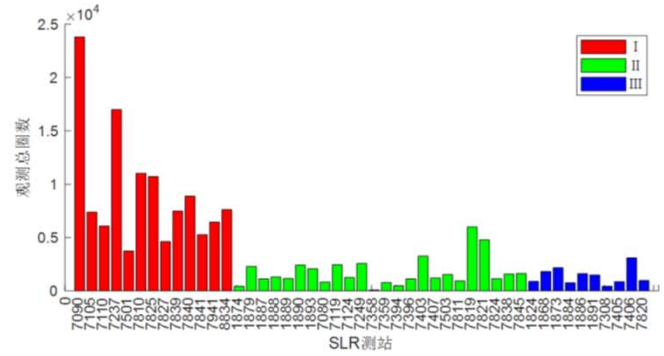
During the period, there were 49 stations in total, among which 7045 and 7125 stations were missing some indicators and were excluded, and the actual data stations were 47.

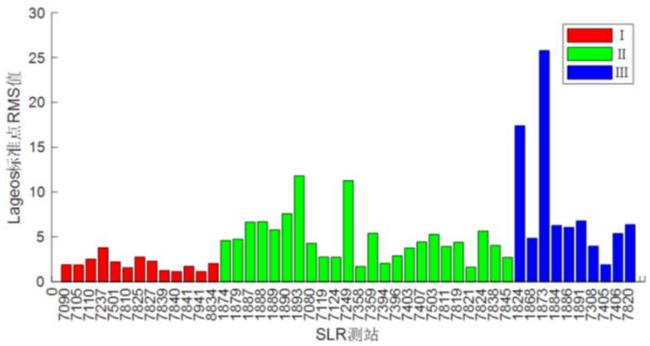


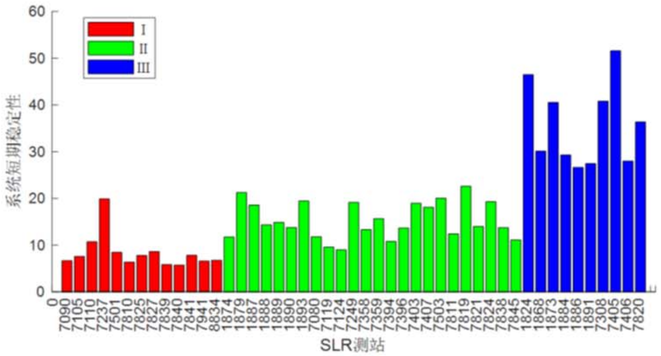
The distribution of the three evaluation indicators of the global SLR station is shown in figure above, in which the three colors of red, green and blue represent level Ⅰ, Ⅱ and Ⅲ respectively, and the purple "×" represents the location of the cluster center.



The horizontal coordinate is the SLR station number, and the vertical coordinate is the membership degree corresponding to different levels represented by different colors. The size of the membership degree represents the level to which the station belongs.







Level	Station ID
I	7090 7105 7110 7237 7501 7810 7825 7827 7839 7840 7841 7941 8834
II	1874 1879 1887 1888 1889 1890 1893 7080 7119 7124 7249 7358 7359 7394 7396 7403 7407 7503 7811 7819 7821 7824 7838 7845
III	1824 1868 1873 1884 1886 1891 7308 7405 7406 7820

Conclusion:

- Of the 47 SLR stations that participated in the evaluation, there were 13 level I stations, 24 level II stations and 10 level III stations, accounting for 28%, 51% and 21%, respectively.

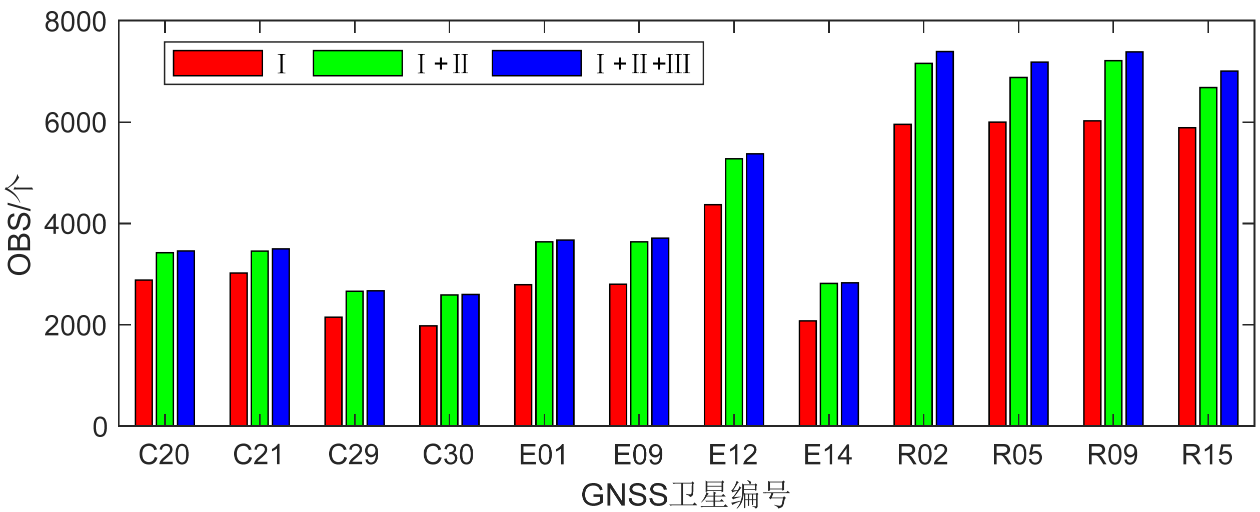
- Among them, the average number of annual observation cycles of the level I station is 9273, the average RMS of the LAGEOS satellite standard point is 2.007mm, and the average short-term deviation of the system is 8.368mm.

- Level I stations have more observation cycles, higher observation accuracy and better system stability, and should be used as the first choice for SLR data application.

☐ Orbit validation of GNSS satellites

•The GNSS satellite with high observation priority provided by the International Laser Ranging Network was selected in this research. The satellite orbit adopts the 2020 satellite orbit product released by Wuhan University; SLR observation data are derived from ILRS;

•In 2020, there are 12 GNSS satellites with high priority for SLR observation, including four BDS satellites (C20, C21, C29, C30), four Galileo satellites (E01, E09, E14), and four GLONASS satellites (R02, R05, R09, R15).



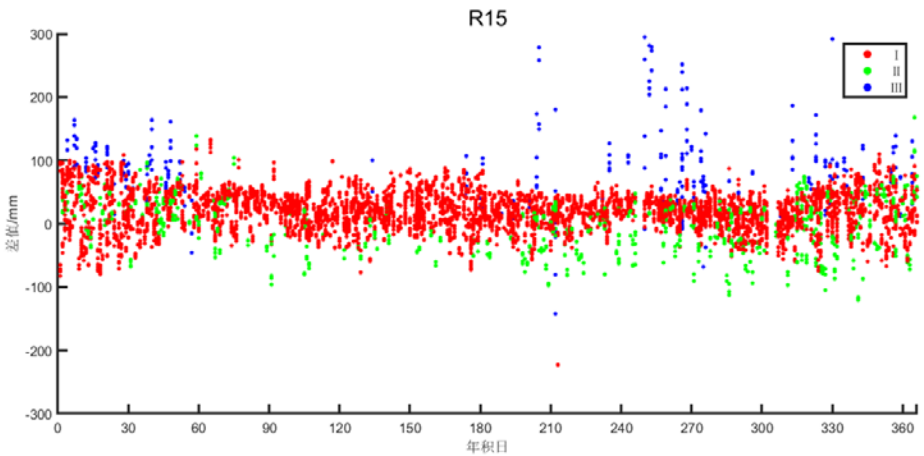
In 2020, the total observation amount (NP points) of GNSS satellites by SLR stations is 56,770, among which the NP points of Level I stations are 45,934, accounting for 80.9%; The number of NP in Level II stations is 9486, accounting for 16.7%; The number of NP in Level III stations is 1350, accounting for 2.4%.

Residual distribution of GNSS satellite orbits validation by SLR (mm)

GNSS	<20（%）			20-40（%）			40-60（%）			>60（%）		
	I	II	III	I	II	III	I	II	III	I	II	III
GLONASS	49.04	35.81	18.65	31.03	27.23	19.71	13.26	18.94	15.36	6.66	18.03	46.28
BDS	47.69	35.29	37.50	29.08	22.92	29.17	14.63	12.32	19.79	8.59	29.47	13.54
GALILEO	39.11	24.08	38.36	33.97	33.70	37.44	18.65	20.32	18.72	8.27	21.89	5.48

- For the residuals with small values (less than 20mm, 20-40mm interval), the proportion of level I stations is significantly larger than that of level II and III stations.

- the larger the residuals, the smaller the proportion.



Orbit accuracy validation results of R15

GNSS	MEAN/mm			STD/mm		
	I	II	III	I	II	III
GLONASS	2.692	-15.553	58.348	32.387	44.072	62.801
BDS	-6.236	-30.189	25.228	34.310	54.707	29.253
GALILEO	-25.401	-39.532	5.668	26.061	39.752	32.873

- Compared with BDS and Galileo satellites, the observation data of GLONASS satellite from level III stations was more. For the large (more than 60mm) orbit residual, level III stations accounted for 46.28%, while level I and II stations accounted for 6.66% and 18.03%, respectively.

- R15 satellite orbit residuals distribution: level I, II station residuals distribution is uniform, the change is stable, the absolute value of residuals is relatively small, level III station residuals are large, and there are obvious systematic deviations.

● According to the GLONASS, BDS and Galileo satellite orbits residuals checked by level Ⅰ station data, the statistical analysis of the residual components in the RTN coordinate system shows that the difference of the three GNSS satellites' orbit accuracy in all directions is not obvious, and the difference between the RMS values of the corresponding components is at mm level.

The residual components RMS of GNSS satellites orbits validation by classI SLR stations (mm)

GNSS	R	T	N	Res
GLONASS	31.752	4.760	5.026	32.498
BDS	34.199	5.147	4.462	34.871
GALILEO	35.714	5.119	4.762	36.392

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Next plan

- Carry out the trial operation and data processing of the mobile laser ranging system；
- Complete integration of VLBI subsystems;
- Carry out co-location surveying of multi-technology stations;
- Realize space debris tracking on fixed and mobile station;
- Establish multi-source geodetic data analysis center node of China;
- Strengthen SLR/GNSS/VLBI/gravity data application and related research

Thanks for your attention

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