中国科学院上海天文台天文地球动力学研究中心

Shanghai Astronomical Observatory, CAS

SLR global tracking of Beidou and its needs for SLR

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2015 ILRS Technical Workshop

Network Performance and Future Expectations for ILRS Support of GNSS, Time Transfer and Space Debris Tracking

ILRS

October 26 – 30, 2015, Matera, Italy

Outline

1、Motivation

2、BDS and SLR global tracking status

3、Evaluation of BDS orbits based on SLR

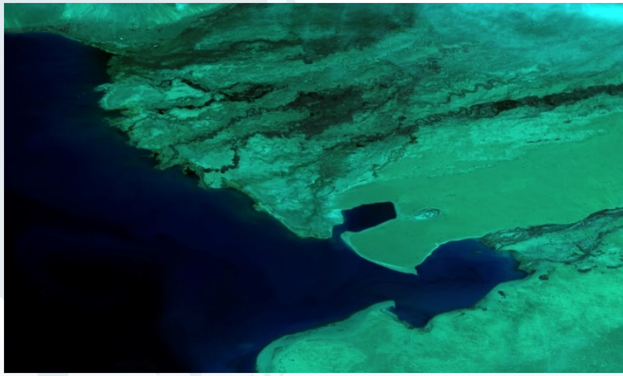
4、Role of SLR on TRF and EOP

5、System errors and orbit cross check

6、Conclusions，Problems and Future plans

1、Motivation

◆With the development of satellite technology and its wider applications, more and more satellites are launched. But what payloads should be loaded?



◆For example resources satellite ZY-3 designer asked if there was necessary to load laser reflectors.

◆ZY–3: launched in January 9, 2012

◆main task: They are used for the land and resources investigation and monitoring, disaster prevention and mitigation, agriculture and so on. They don’t require high accuracy orbits. So it needs to install laser reflector array?

1、Motivation

- In fact, it is difficult to answer. Because we hope SLR can have a wider applications. But there are 5 simple design satellites (**Lageos-1/2, Etalon-1/2 and LARES**) to be widely applied in geodesy due to their higher accuracy and more data. It is impossible for resources satellites to get more observation and higher accuracy orbits with complicated payloads；On the other hand the scientific aims of resources satellite don't require high accuracy orbits. So any other uses? We just try to deeply study SLR application in order to answer this question.

1、Motivation

- For high accuracy orbit requirement such as GNSS satellites and HY-2 SLR can be used as the tools of orbit accuracy evaluation and models choose.
- For high accuracy geodesy SLR can be used to determine TRF and EOP. High accuracy TRF and EOP are needed for space navigation of almost all space orbiters.
- SLR also can be used in system errors and orbit cross check between different techniques

Here we mainly focus on SLR applications on BDS.

2、BDS and SLR global tracking status

BeiDou Satellite Navigation System, BDS

- BDS is committed to the global customers with high quality PNT services, including open service and authorization service.
- Open service is provided free of charge with positioning accuracy of 10 meters, velocity accuracy of 0.2 m/s and timing accuracy of 10 nanoseconds.
- Authorization service provide PNT services, communication services and system integrity information to those users who demand higher precision, higher reliable satellite navigation.

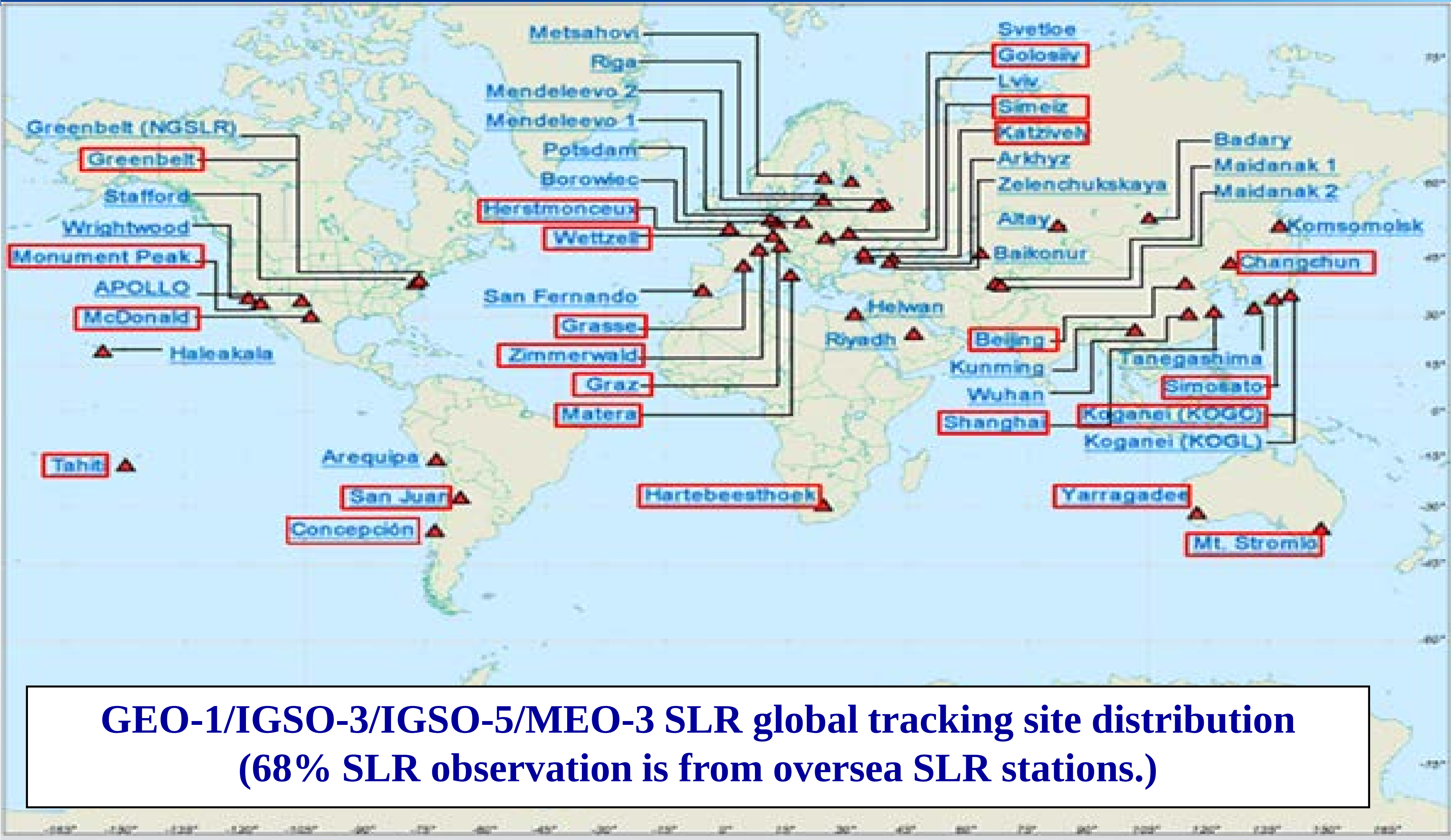
BDS Development Plans:

- Phase I: Before the end of 2012, BDS completed with PNT and Short message communication service ability over Asia-pacific region. This regional BDS includes 5 GEO + 5 IGSO + 4 MEO.
- Phase II: Before the end of 2020, the global BDS will be completed with 3GEO +3IGSO +24MEO(Maybe it will be 5GEO + 3IGSO + 27MEO). This year 2IGSO+2MEO experiment satellites have been launched.

2、BDS and SLR global tracking status

No.	Satellite/ID	Launch Date	Launch Site	Rocket	Orbit Type	Orbit Altitude（km）	Orbit Inclination	Status
1	BDS-M1/C30	2007.04.14	Xi Chang	CZ-3A	MEO	21559×21518	56.8°	Unused
2	BDS-G2	2009.04.15	Xi Chang	CZ-3C	GEO	36027×35539	2.2°	Uncontrolle
3	BDS-G1/C01	2010.01.17	Xi Chang	CZ-3C	GEO 140.0° E	35807×35782	1.6°	In service
4	BDS-G3/C03	2010.06.02	Xi Chang	CZ-3C	GEO 110.6° E	35809×35777	1.3°	In service
5	BDS-IGSO1/C06	2010.08.01	Xi Chang	CZ-3A	IGSO	35916×35669	54.6°	In service
6	BDS-G4/C04	2010.11.01	Xi Chang	CZ-3C	GEO 160.0° E	35815×35772	0.6°	In service
7	BDS-IGSO2/C07	2010.12.18	Xi Chang	CZ-3A	IGSO	35883×35691	54.8°	In service
8	BDS-IGSO3/C08	2011.04.10	Xi Chang	CZ-3A	IGSO	35911×35690	55.9°	In service
9	BDS-IGSO4/C09	2011.07.27	Xi Chang	CZ-3A	IGSO	35879×35709	54.9°	In service
10	BDS-IGSO5/C10	2011.12.02	Xi Chang	CZ-3A	IGSO	35880×35710	54.9°	In service
11	BDS-G5/C05	2012.02.25	Xi Chang	CZ-3C	GEO 58.7°	35801×35786	1.4°	In service
12	BDS-M3/C11	2012.04.30	Xi Chang	CZ-3B	MEO	21607×21463	55.3°	In service
13	BDS-M4/C12	2012.04.30	Xi Chang	CZ-3B	MEO	21617×21453	55.2°	In service
14	BDS-M5/C13	2012.09.19	Xi Chang	CZ-3B	MEO	21597×21473	55.0°	In service
15	BDS-M6/C14	2012.09.19	Xi Chang	CZ-3B	MEO	21576×21494	55.1°	In service
16	BDS-G6/C02	2012.10.25	Xi Chang	CZ-3C	GEO 80.2°	35803×35783	1.7°	In service
17	BDS-IS1/C31	2015.03.30	Xi Chang	CZ-3C	IGSO	35964×35601	54.9°	In commissio
18	BDS-MS1/C34	2015.07.25	Xi Chang	CZ-3B	MEO	21542×21519	55.1°	In commissio
19	BDS-MS2/C33	2015.07.25	Xi Chang	CZ-3B	MEO	21544×21516	55.1°	In commissio
20	BDS-IS2	2015.09.30	Xi Chang	CZ-3B	IGSO	35951×35606	54.9°	In commissio

2、BDS and SLR global tracking status



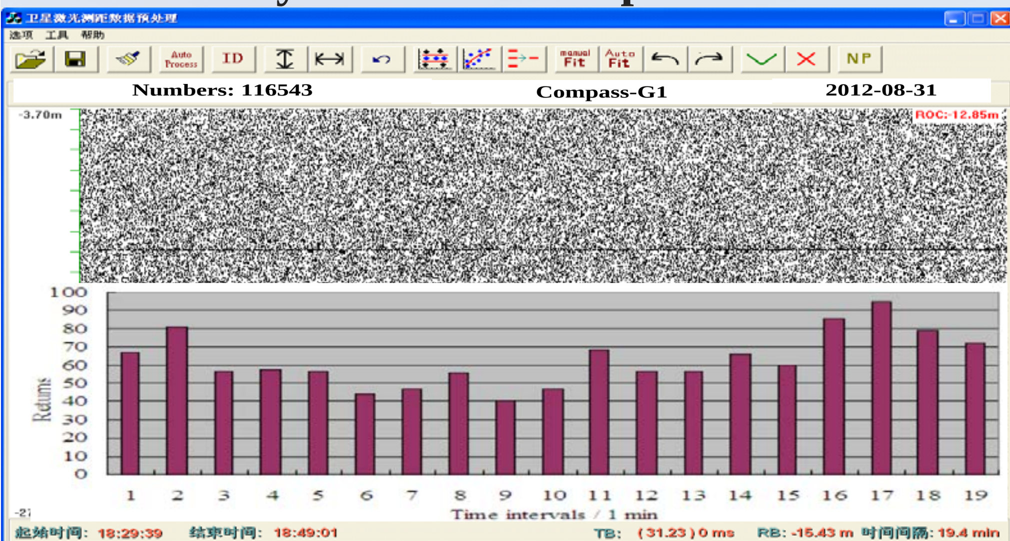
GEO-1/IGSO-3/IGSO-5/MEO-3 SLR global tracking site distribution
(68% SLR observation is from oversea SLR stations.)

2、BDS and SLR global tracking status

Satellite / Passes / Site	2012.04~2014.12 GEO-1	IGSO-3	IGSO-5	MEO-3	Sum	Country
Shanghai	92	99	108	51	350	China
Changchun	335	358	331	248	1272	China
Beijing	9	31	28	10	78	China
Yarragadee	359	483	505	297	1644	Australia
Mt Stromlo	32	102	48	150	332	Australia
Koganei	19	4	1	3	27	Japan
Komsomolsk	2	2	3	2	9	Russia
Grasse	0	26	115	113	254	France
Matera	0	0	160	229	389	Italy
Wettzell	0	36	117	143	296	Germany
Simeiz	0	0	2	0	2	Ukraine
Katzively	0	0	7	8	15	Ukraine
Greenbelt	0	0	0	92	92	USA
Monument Peak	0	0	0	110	110	USA
Tahiti	0	0	0	42	42	France
SanJuan	0	0	0	117	117	China/ Argentina
Hartebeesthoek	0	0	0	16	16	South Africa
Herstmonceux	0	0	56	114	170	England
Zimmerwald	0	1	140	204	345	Switzerland
Graz	0	25	111	140	276	Austria
McDonald	0	0	0	2	2	USA
Simosato	0	0	0	24	24	Japan
Golosiiv	0	0	0	3	3	Ukraine
Concepcion	0	0	0	3	3	Chile
Altay	0	6	7	2	15	Russia
Svetloe	0	0	2	2	4	Russia

2、BDS and SLR global tracking status

The maps give the observations and the statistic of laser returns for COMPASS satellites by 1 kHz SLR system with laser power of ~ 1W at Shanghai Station.

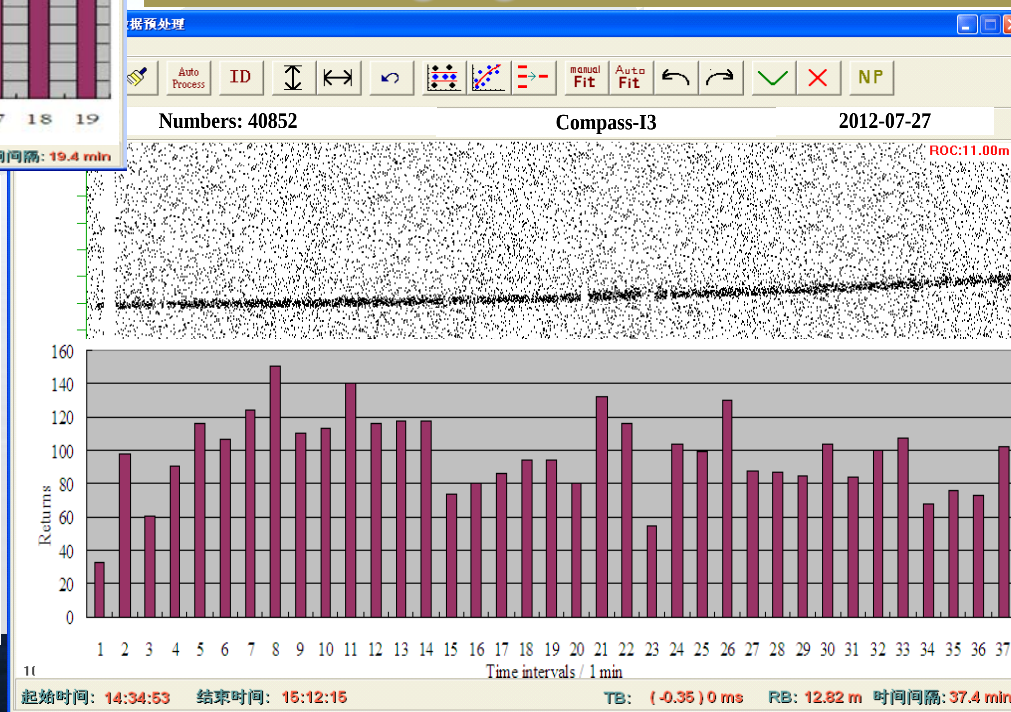


BDS-G1：

Altitude:~38,800km

Average return: ~62 photons/min

Ranging RMS: ~1.1cm



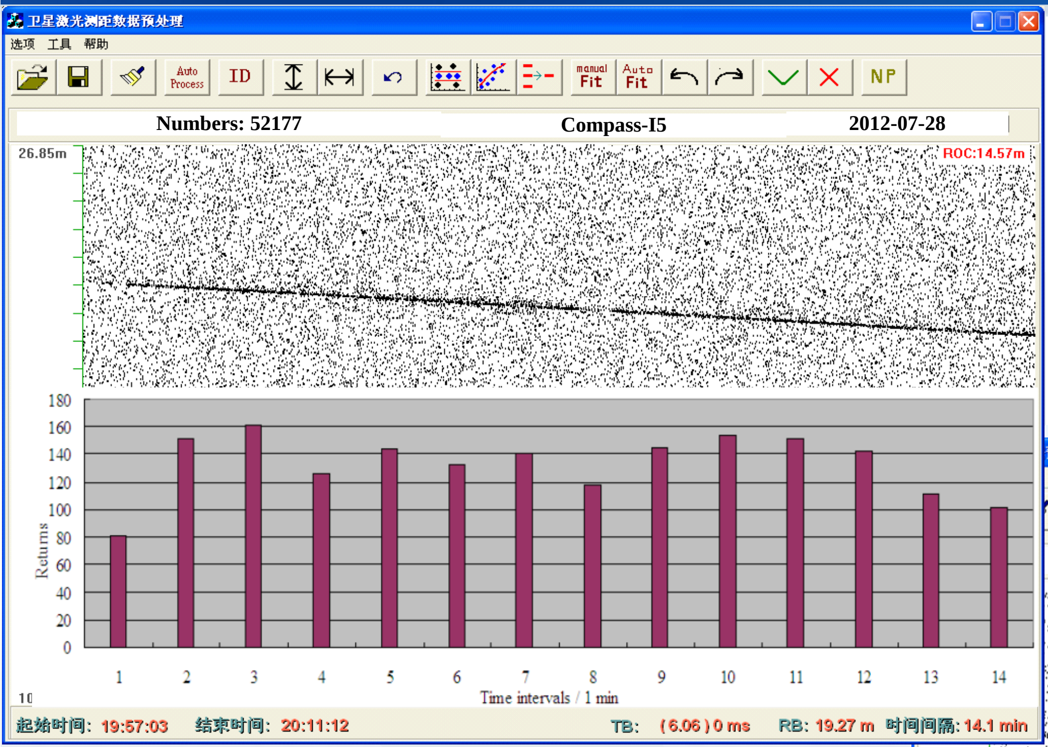
BDS-I3:

Altitude : ~36,000km

Average return: ~98 photons/min

Ranging RMS: ~1.4cm

2、BDS and SLR global tracking status

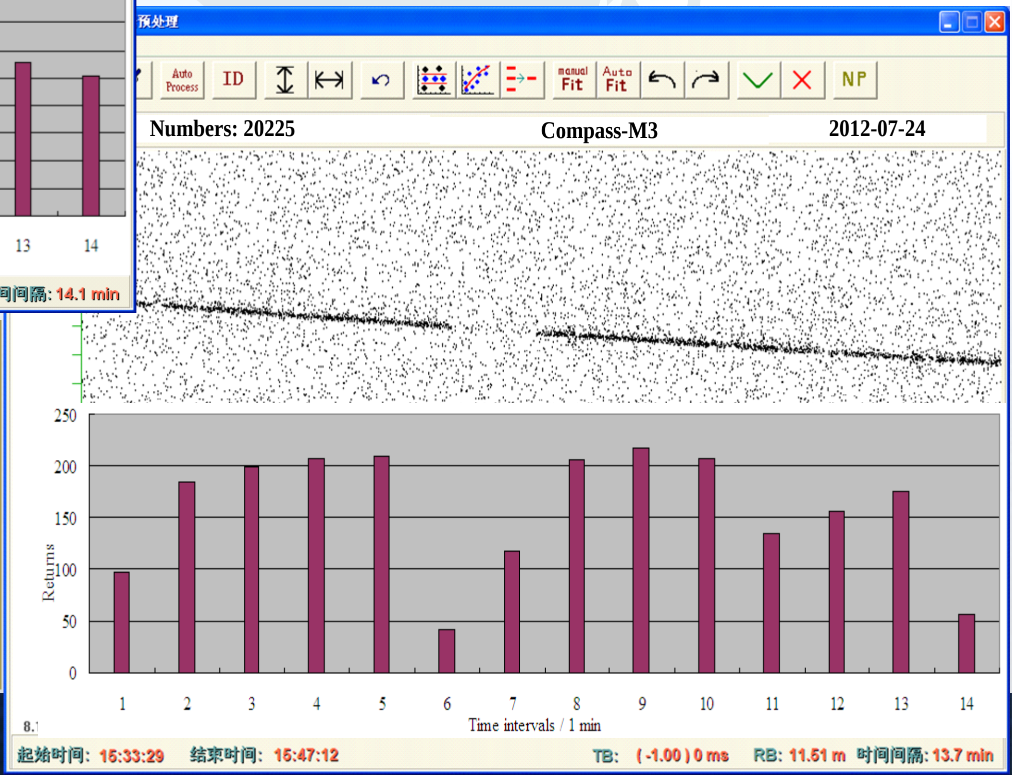


BDS-I5:

Altitude:~36,000km

Average return:~ 133 photons/min

Ranging RMS:~1.4cm



BDS-M3：

Altitude ：~22,000km

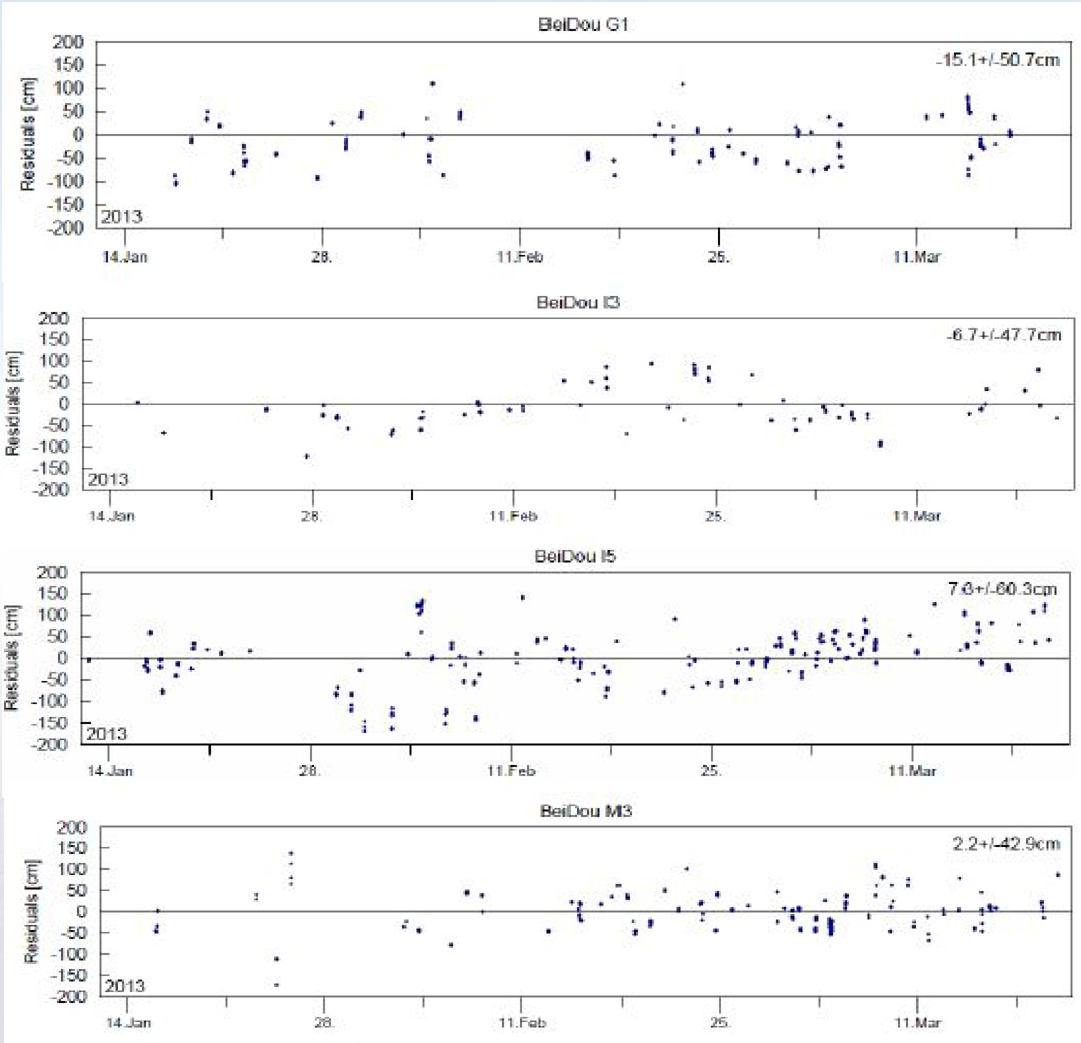
Average return: ~158 photons/min

Ranging RMS: ~1.3cm

3、Evaluation of BDS orbits based on SLR

By evaluation of BDS orbits based on SLR ,on the one hand we can know the GNSS orbit accuracy; on the other hand we can choose better orbit determination method and better models (e.g. solar radiation pressure SRP models).

3、Evaluation of BDS orbits based on SLR



◆BDS orbit accuracy evaluation by SLR observation

- By SLR observation the BDS broadcast ephemeris was evaluated. Its results are as the following(Oliver Montenbruck):

G1 ： -15.1 +/-50.7cm ；

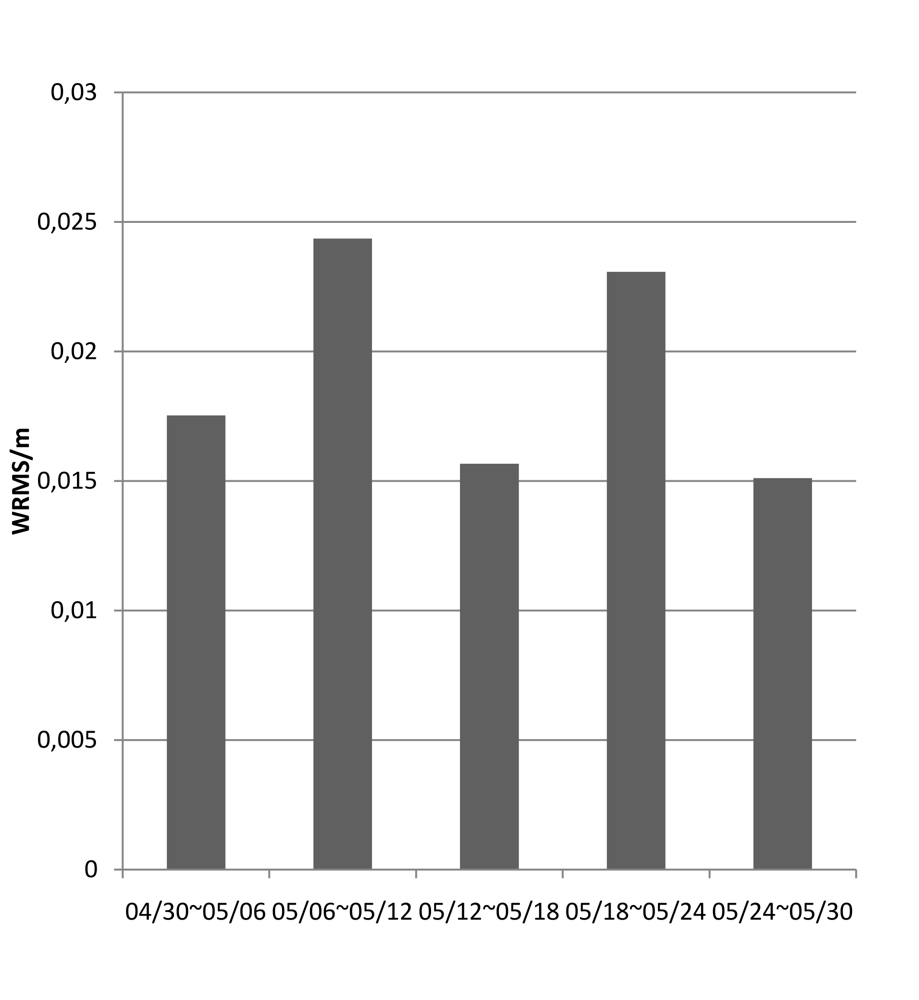
I3 ： -6.7 +/-47.7cm ；

I5 ： 7.0+/- 60.3cm ；

M3 ： 2.2+/- 42.9cm

- The BDS microwave orbit was also evaluated based on MGEX BDS data. It showed 1D overlap orbit error was 0.585m and 3D error was 1.002m.

3、Evaluation of BDS orbits based on SLR



Orbit errors using SLR data for BDS-M1 in May 2012

◆better model check (BDS CoM model)

- Reflector center in satellite fixed coordinate system by simulation method:(-0.4321 m,-0.5621 m,1.1338 m)
- CoM = -4.8mm in Z axis based on Probability Theory
- →(-0.4321 m,-0.5621 m,1.1125 m)
- Importing this CoM into data processing the BDS-M1 orbit residual WRMS is about 1.9 cm during May 2012.

$$CoM' = E(Z) = \int_{[z]} zP(z)dz$$

$$= \int_0^{i_{max}} Z(i)p(i)di$$

3、Evaluation of BDS orbits based on SLR

◆BDS solar pressure models evaluation

- solar radiation pressure（SRP） perturbation is difficult to be accurately modeled due to the complicated and changing satellite attitude and surface material characteristics. Therefore, it becomes the most important error source in the precise orbit determination POD and forecast of GNSS satellites.
- For BDS a SRP model is necessary for high precise applications especially with Global BDS establishment in future. The BDS accuracy for broadcast ephemeris need be improved. So, we adopted the radiation transfer theory and corresponding physical concept, simplified satellite body configuration and calculated SRP perturbation through the solar radiation intensity and flux. A box-wing theoretical SRP model with fine structure and adding conical shadow factor of earth and moon were established.

3、Evaluation of BDS orbits based on SLR

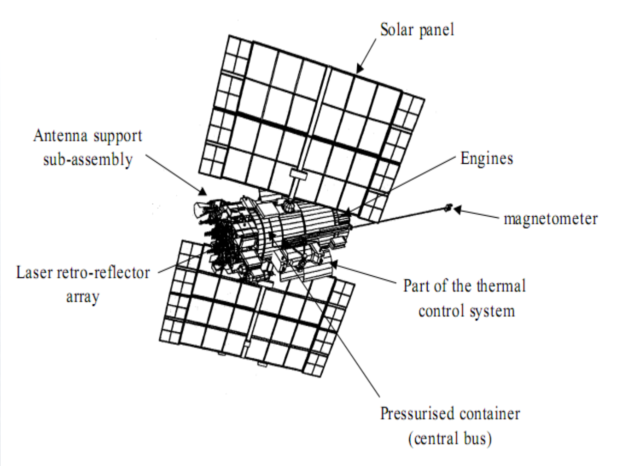
Adjusted Box-wing SRP (ADBOXW model) based on physical characters

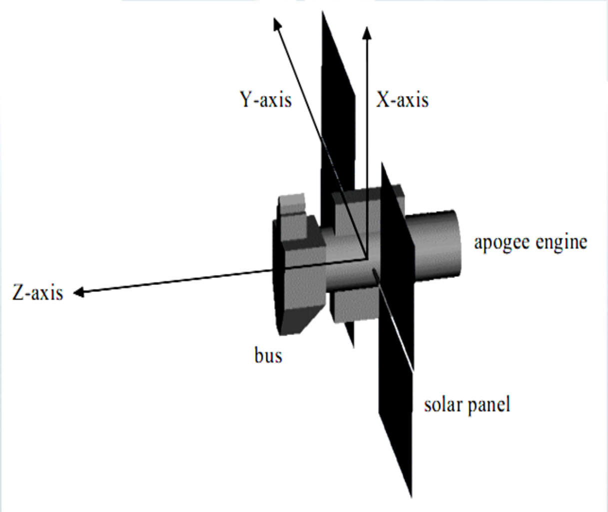
$$F_{SRP} = ma_{SRP} = \int d\vec{F}$$

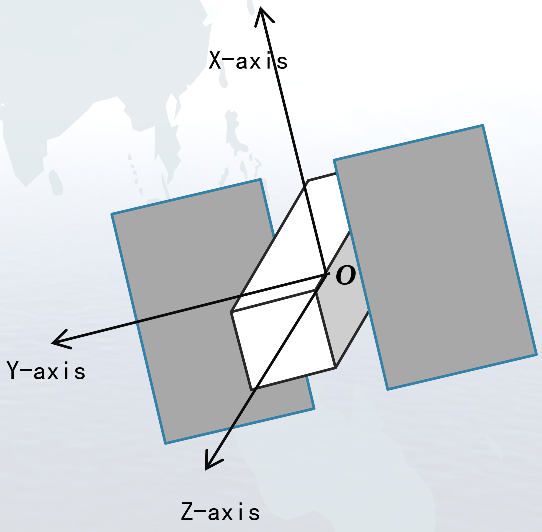
$$= -SRP\_scale * \lambda \frac{\Phi_0}{c}\left(\frac{AU}{r_{ss}}\right)^2 \cos\theta dA$$

$$\left\{2\beta\left[\delta\cos\theta + \frac{(1-\delta)}{3}\right]\hat{n} + (1-\delta\beta)\,\hat{p}\right\}$$

$$d\vec{F} = -\lambda\frac{\Phi_0}{c}\left(\frac{AU}{r_{ss}}\right)^2 \cos\theta dA\left\{2\beta\left[\delta\cos\theta + \frac{(1-\delta)}{3}\right]\hat{n} + (1-\delta\beta)\,\hat{p}\right\}$$







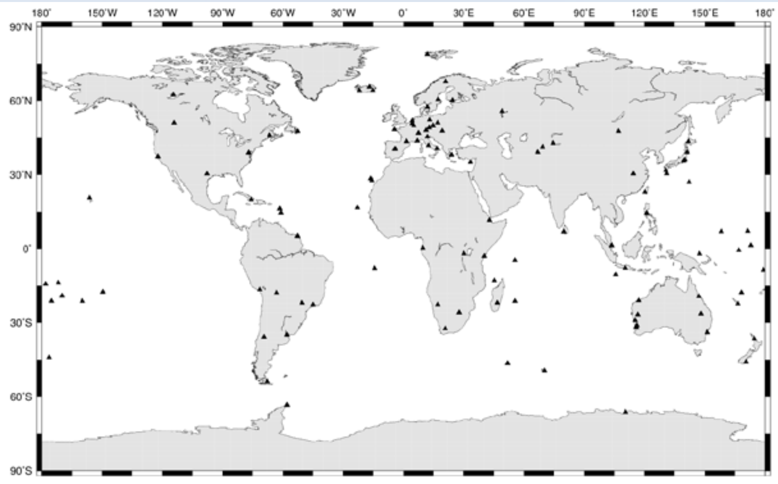
3、Evaluation of BDS orbits based on SLR

GPS orbit RMS comparison w.r.t. IGS precise orbits based on 100 or so IGS core sites data in 255~257 of 2015(unit: mm).

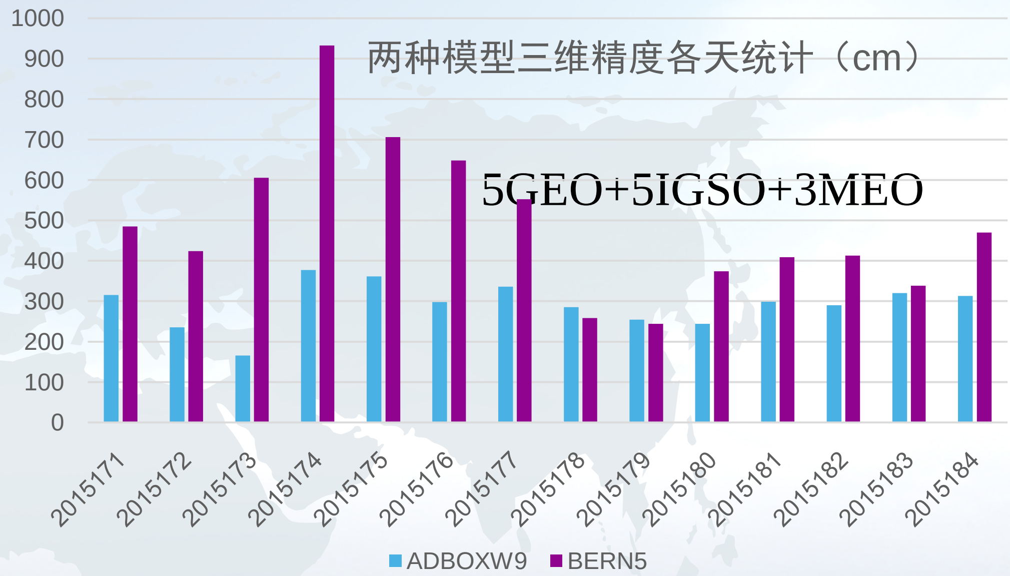
BlockType	BERN model	ADBOXW model
Block IIA	16	19
Block IIR-A	17	21
Block IIR-B	20	26
Block IIR-M	19	26
Block IIF	19	25
Avg of all satellites	18	24

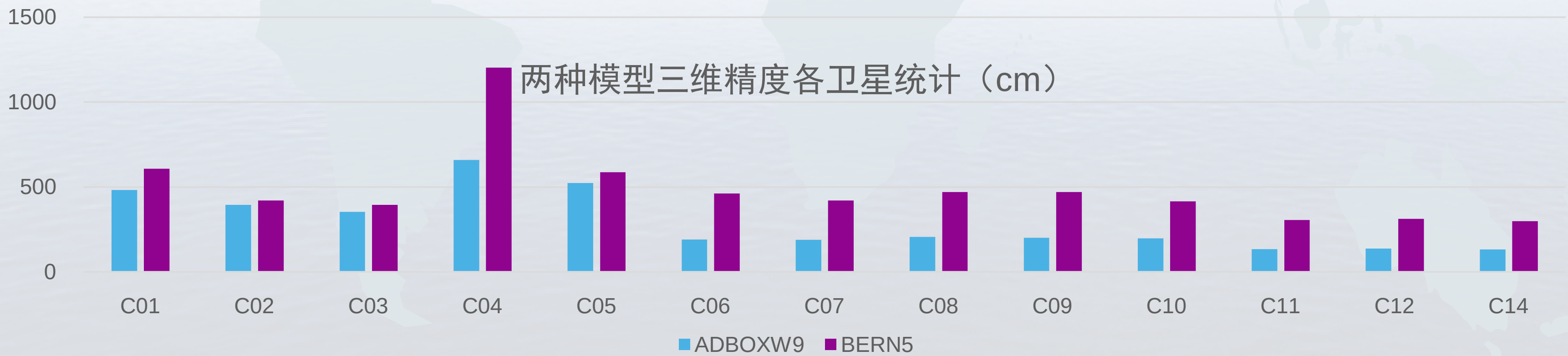
3、Evaluation of BDS orbits based on SLR

- Comparison between ADBOXW 9 parameters and BERN 5 parameters BDS SRP model



MGEX GNSS network:40~55 sites





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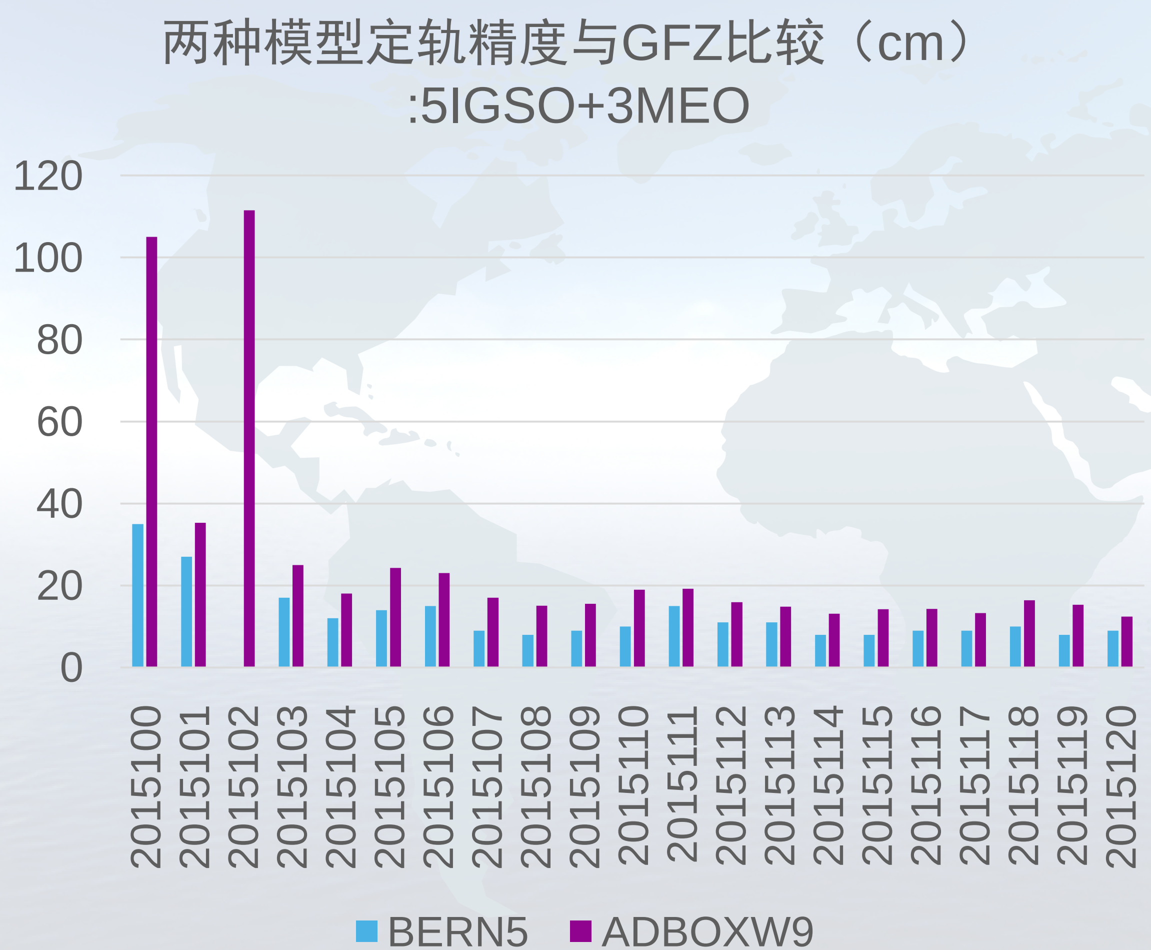

DATE	BERN5	ADBOXW9
2015100	35	105
2015101	27	35
2015102		112
2015103	17	25
2015104	12	18
2015105	14	24
2015106	15	23
2015107	9	17
2015108	8	15
2015109	9	16
2015110	10	19
2015111	15	19
2015112	11	16
2015113	11	15
2015114	8	13
2015115	8	14
2015116	9	14
2015117	9	13
2015118	10	16

3、Evaluation of BDS orbits based on SLR

Date	Satellite	Num of slr obs	mean/cm	STD/cm
2015173	C01	6	57.6	45.0
2015174	C01	7	48.2	56.8
2015176	C01	6	18.7	3.8
2015177	C01	5	60.4	4.6
2015178	C01	6	92.6	0.6
2015179	C01	3	-60.7	0.8
2015184	C01	5	41.2	2.3
2015243	C01	10	65.1	10.8
2015244	C01	23	32.1	17.8
2015245	C01	15	33.4	27.7
2015246	C01	29	73.1	13.6
2015247	C01	13	79.7	7.9
2015248	C01	23	69.9	24.5
2015249	C01	9	67.2	3.2
2015250	C01	9	5.2	6.9
Avg			45.6	15.1

3d arc, ADBOXW9

3、Evaluation of BDS orbits based on SLR

2015177	C10	5	2.7	0.7
2015178	C10	6	-2.4	1.2
2015179	C10	4	-1.1	2.9
2015182	C10	3	-2.7	0.9
2015183	C10	8	-4.7	8.5
2015184	C10	9	-3.7	5.3
2015243	C10	26	17.5	9.0
2015244	C10	29	13.9	5.8
2015245	C10	23	14.2	7.4
2015246	C10	19	23.6	9.9
2015247	C10	29	-19.8	27.9
2015248	C10	50	-35.2	30.0
2015249	C10	48	-12.3	21.8
2015250	C10	37	-24.8	25.2
3d arc， ADBOXW9Avg.			-2.5	11.2

3、Evaluation of BDS orbits based on SLR

2015171	C11	40	-19.8	22.8
2015172	C11	26	-54.6	29.7
2015173	C11	8	-80.7	18.2
2015174	C11	11	-4.6	16.4
2015175	C11	16	-17.7	21.4
2015176	C11	13	-6.6	17.4
2015177	C11	17	-19.5	16.3
2015178	C11	29	-27.5	37.8
2015179	C11	32	-38.1	25.1
2015180	C11	21	-22.9	27.0
2015181	C11	5	-28.2	3.6
2015182	C11	3	35.3	1.2
2015183	C11	7	-4.5	3.7
2015184	C11	19	-1.2	6.7
2015243	C11	38	1.7	10.8
2015244	C11	34	6.6	11.3
2015245	C11	28	8.3	11.2
2015246	C11	22	20.6	12.7
2015247	C11	36	25.6	11.0
2015248	C11	42	15.4	14.3
2015249	C11	47	12.2	13.1
2015250	C11	30	13.0	19.9
Avg.			8.5	16.0

3d arc, ADBOXW9

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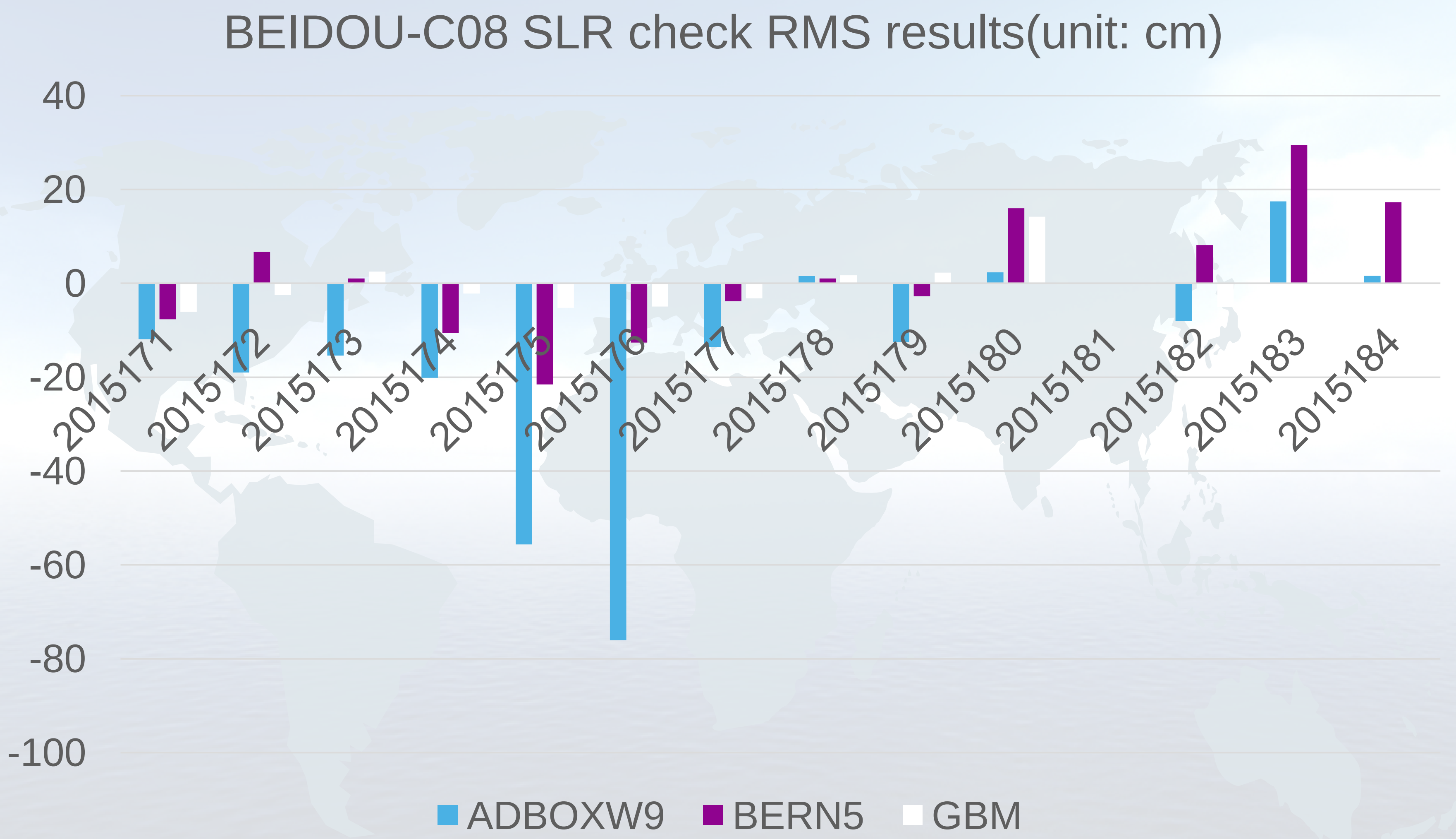

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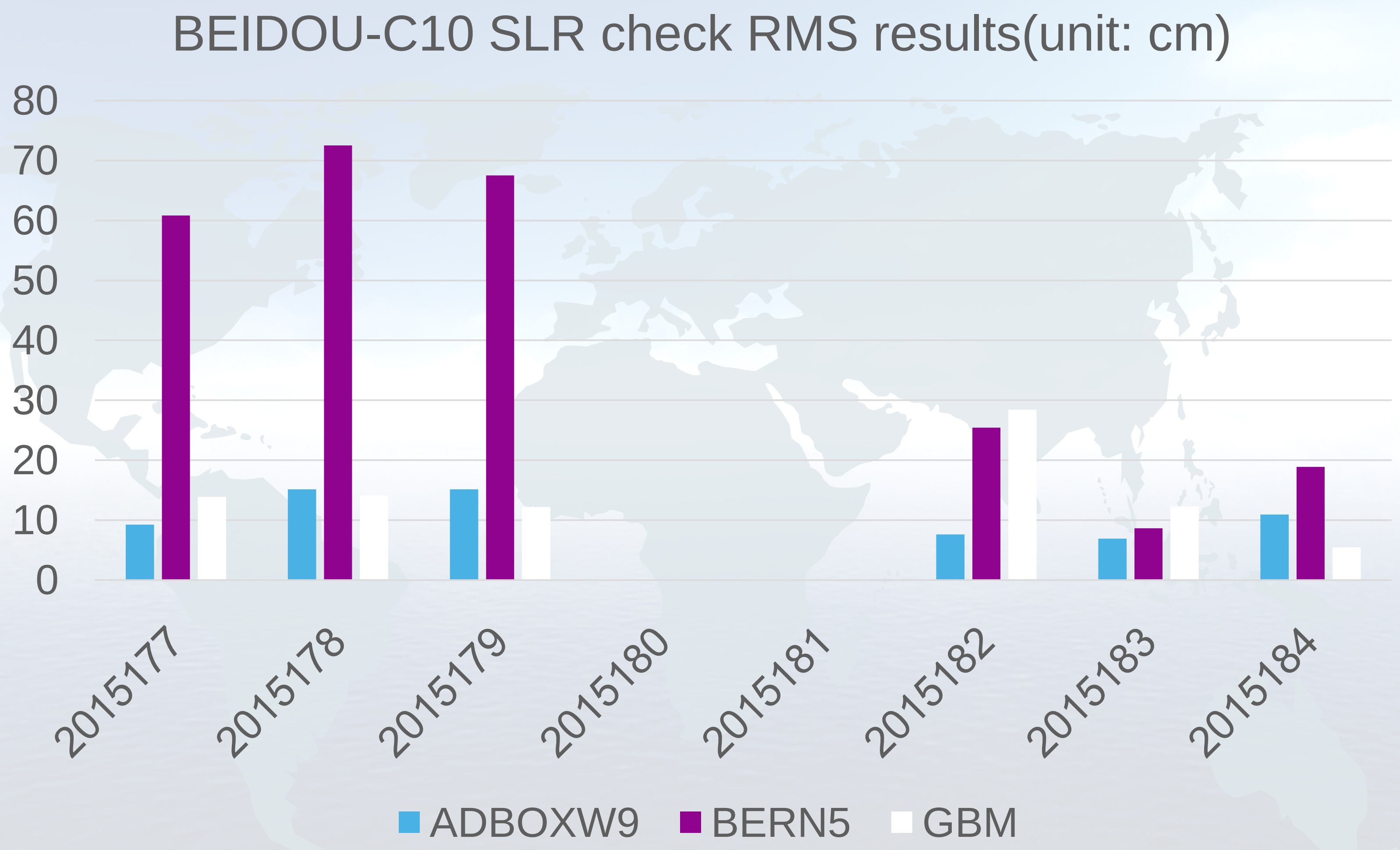

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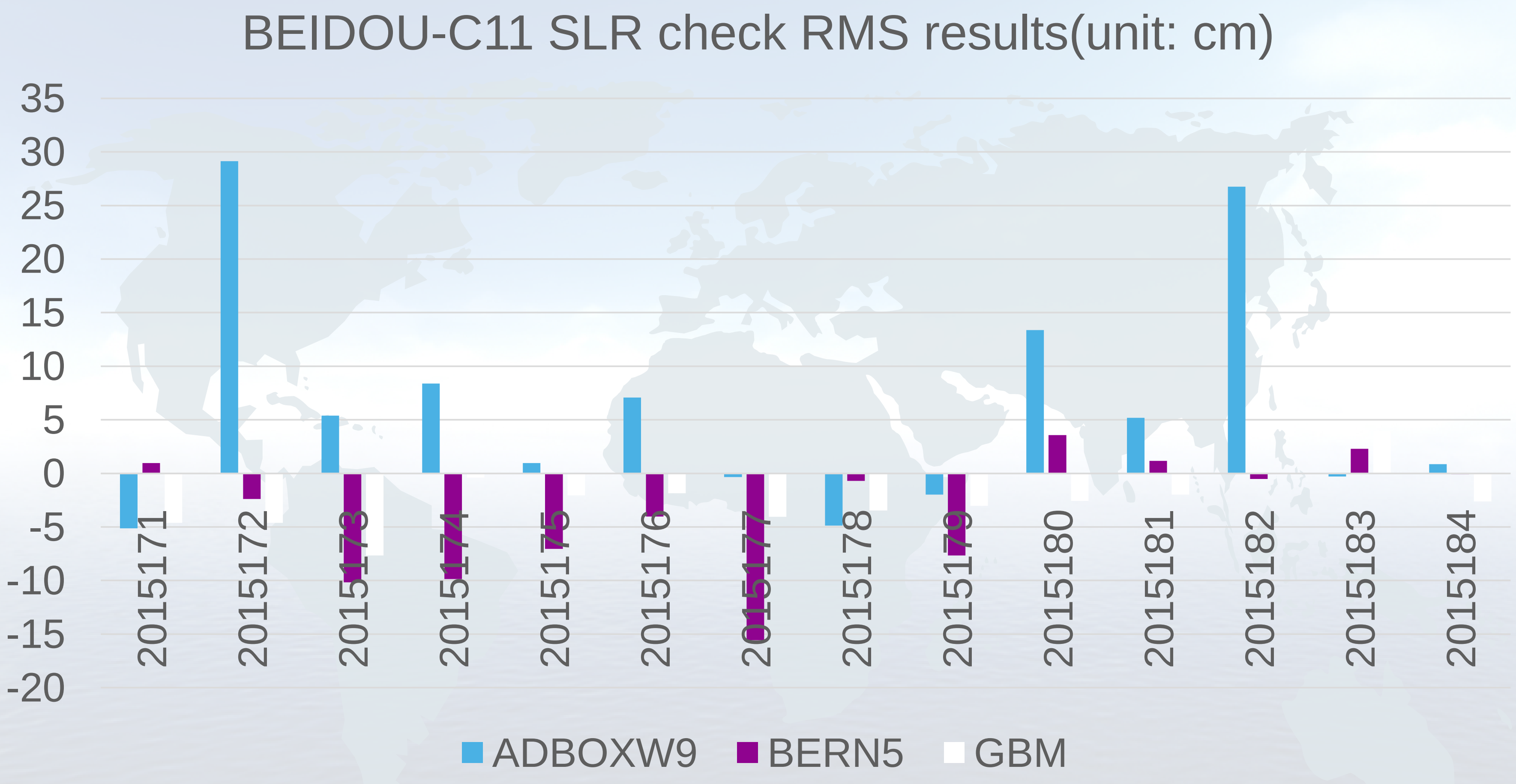
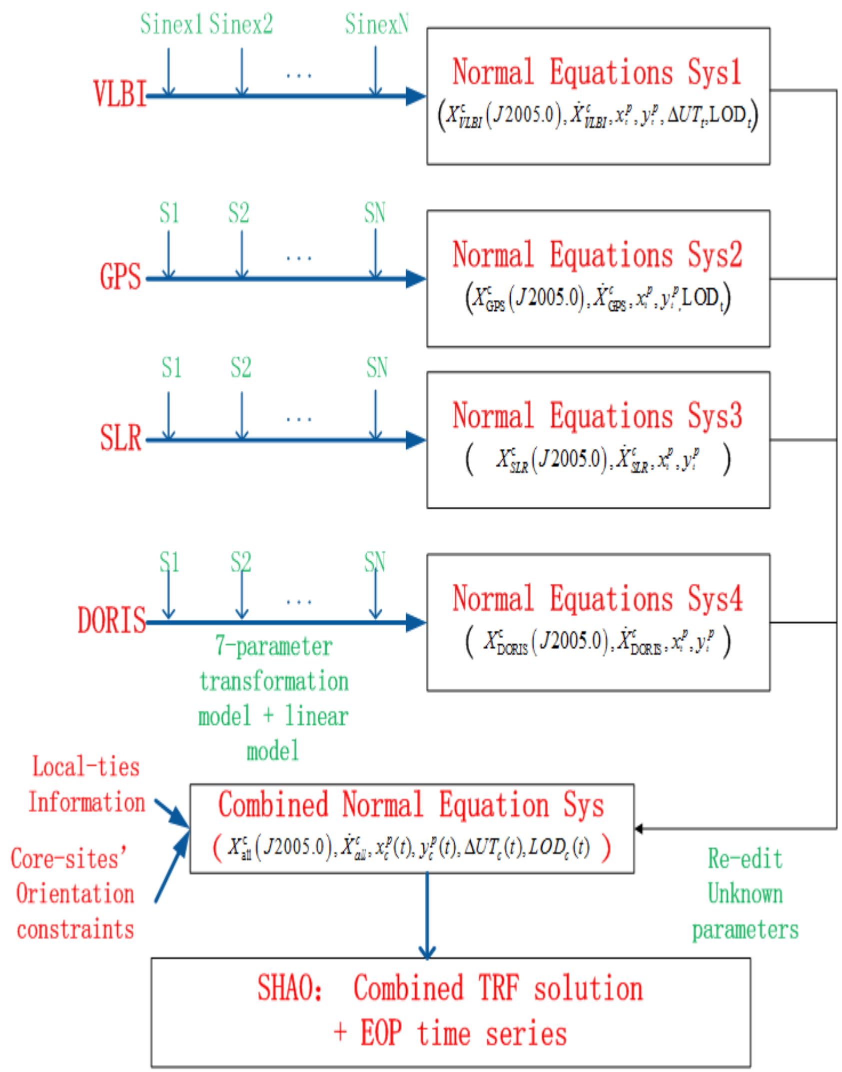


4、 Role of SLR on TRF and EOP



Datum definition	
Origin	CoM（defined by SLR）
Scale	Defined by VLBI and SLR
Orientation	align to ITRF2008's orientation（core sites） No. of core sites: SLR 23; GPS 89; VLBI 34; DORIS 26

Local-ties model: baseline vector

$$
\begin{cases}
\Delta x_s = x_s^i - x_s^j \\
\Delta y_s = y_s^i - y_s^j \\
\Delta z_s = z_s^i - z_s^j
\end{cases}
\qquad
D_{\Delta,s} = K \cdot D_{ij,s} \cdot K^T, K = \begin{bmatrix} 1 & 0 & 0 & -1 & 0 & 0 \\ 0 & 1 & 0 & 0 & -1 & 0 \\ 0 & 0 & 1 & 0 & 0 & -1 \end{bmatrix}
$$

4、 Role of SLR on TRF and EOP

- **Data span—STRF2014Jan----STRF2014Apr**

Month	SLR	GPS	VLBI	DORIS
Jan.2015	2015.1.14	2015.1.14	2015.1.13	2014.9.3
Feb.2015	2015.2.11	2015.2.11	2015.2.12	2014.9.3
Mar.2015	2015.3.13	2015.3.13	2015.3.12	2014.9.3
Apr.2015	2015.5.13	2015.4.29	2015.4.13	2014.9.3

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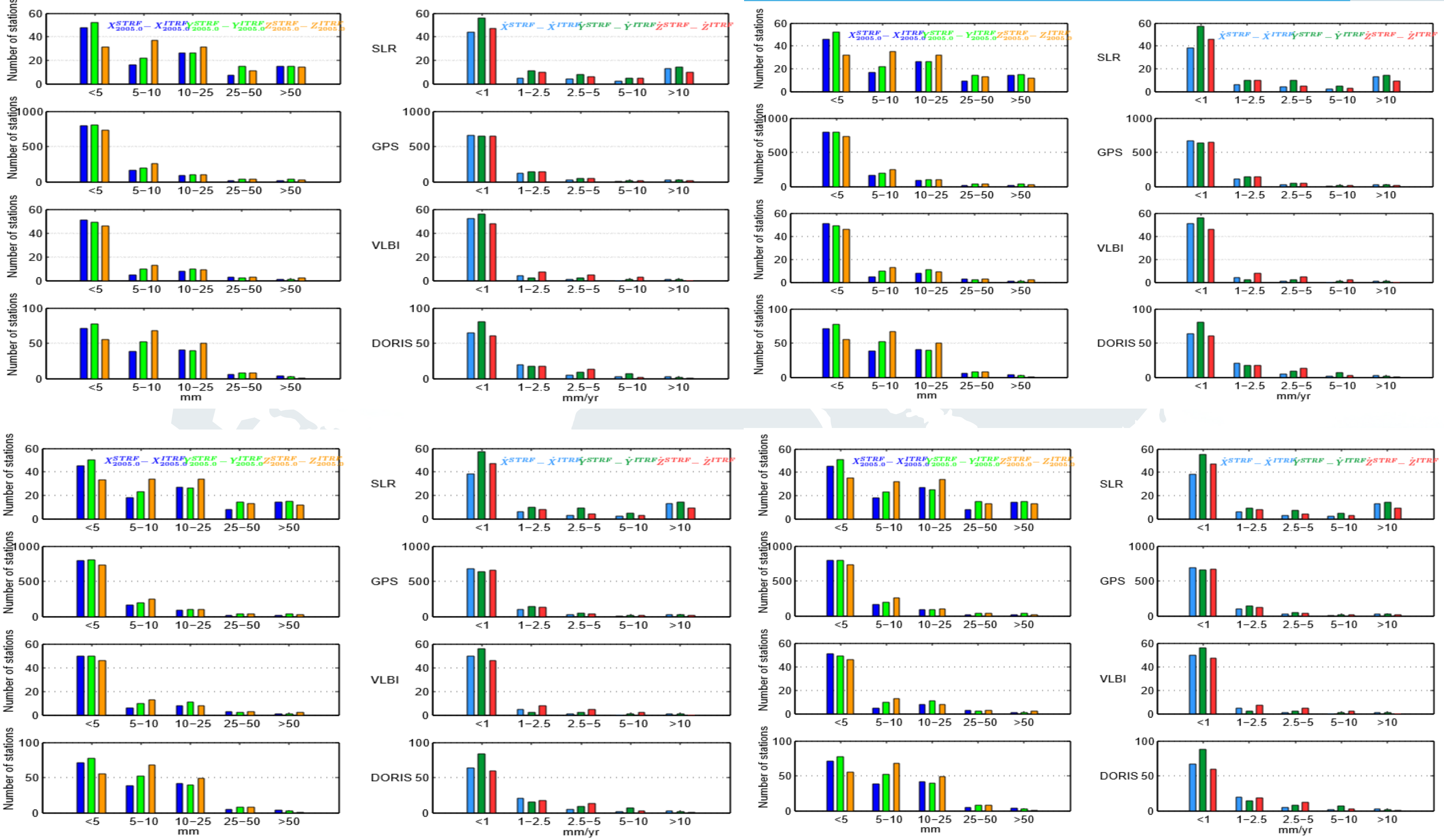
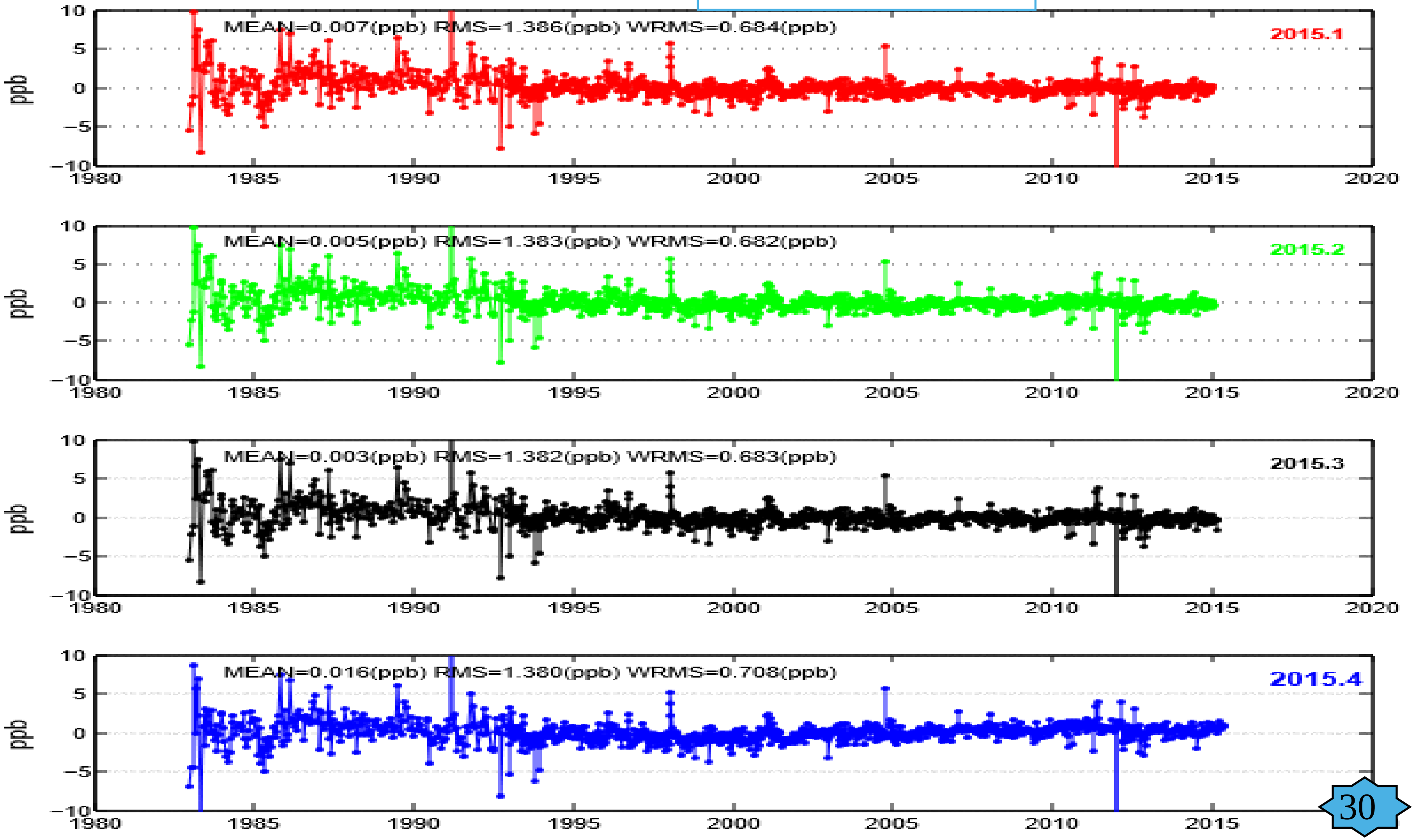


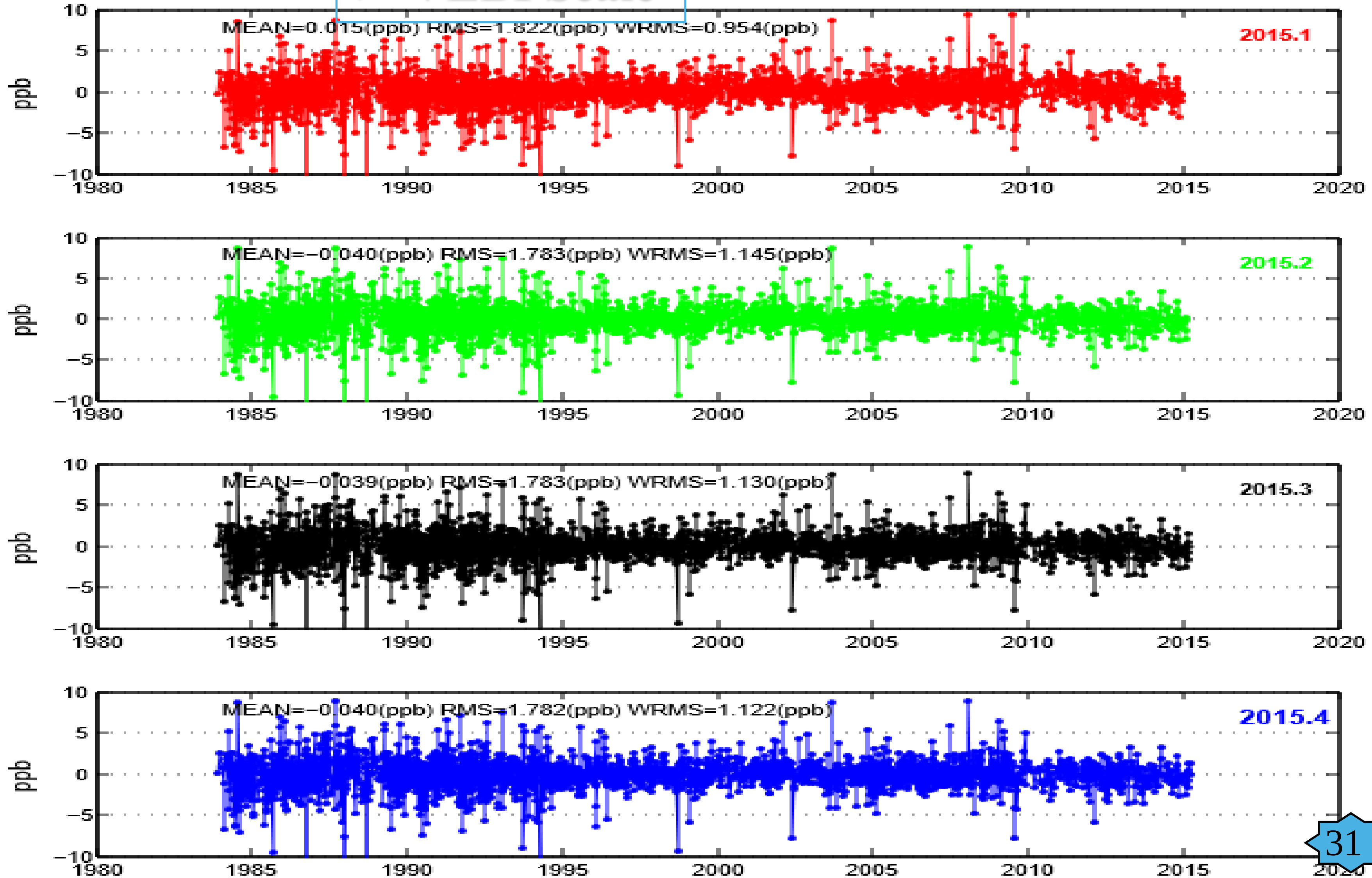
4、 Role of SLR on TRF and EOP

➤ SLR scale



4、 Role of SLR on TRF and EOP

➢ **VLBI Scale**



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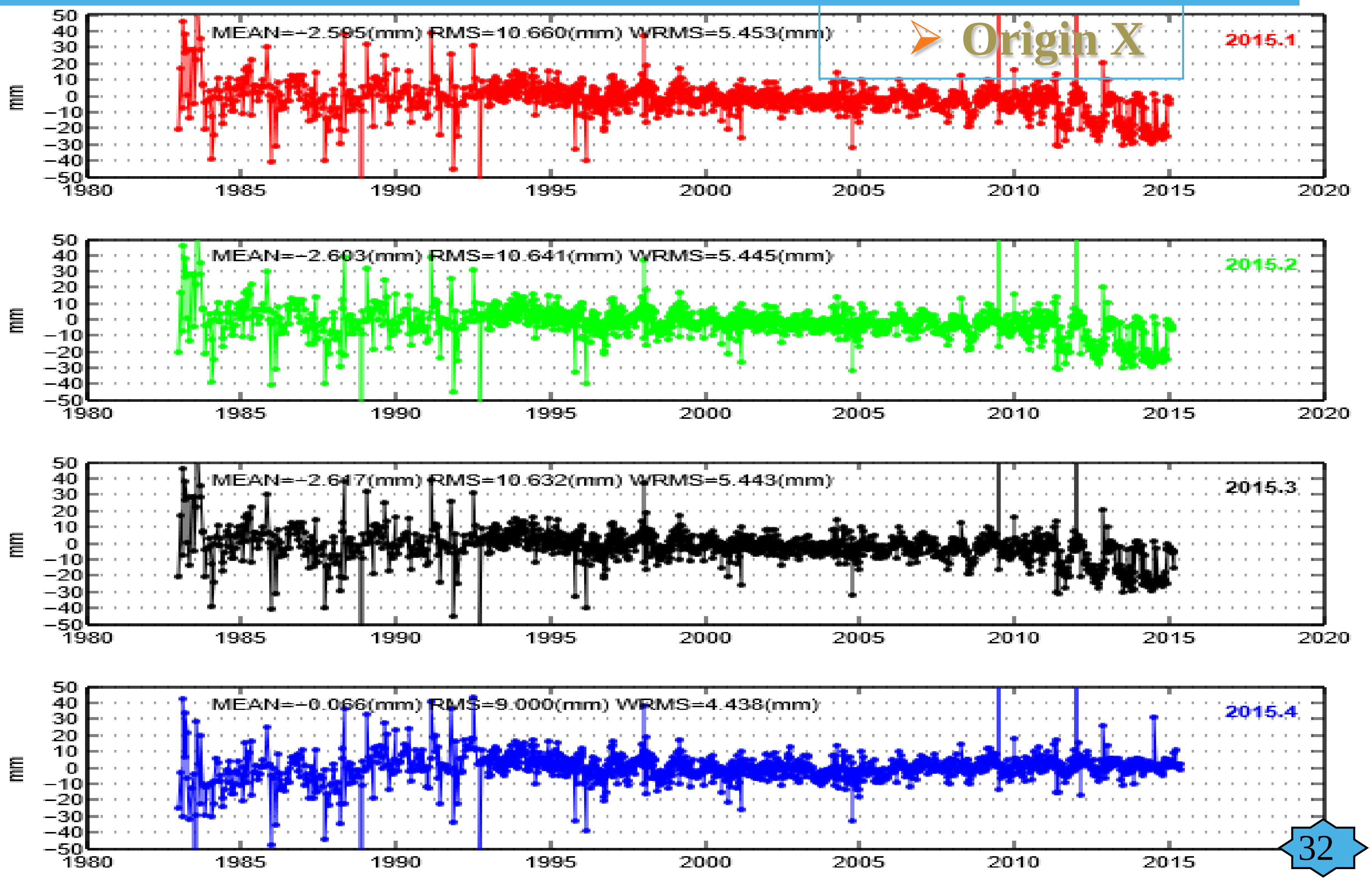

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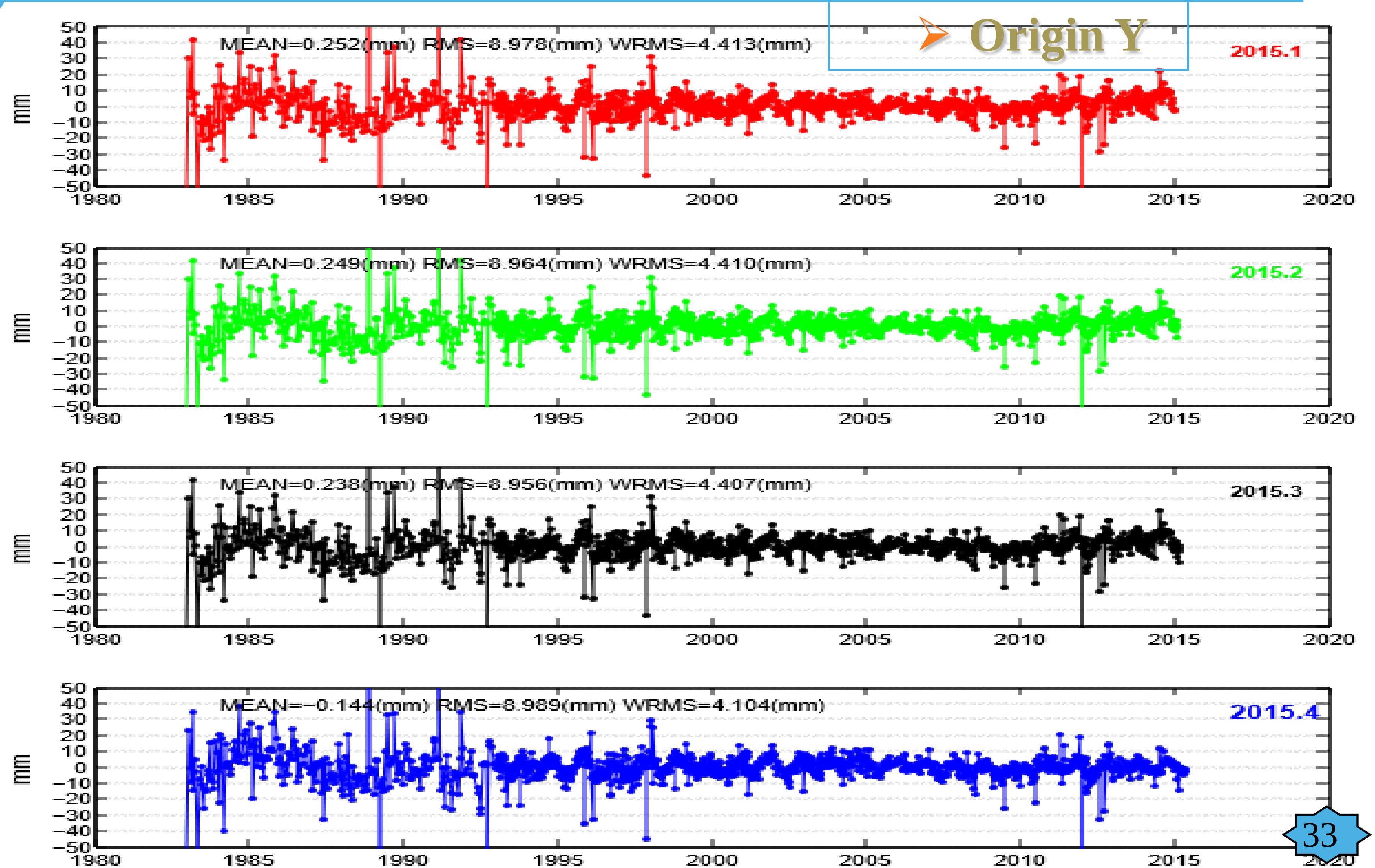

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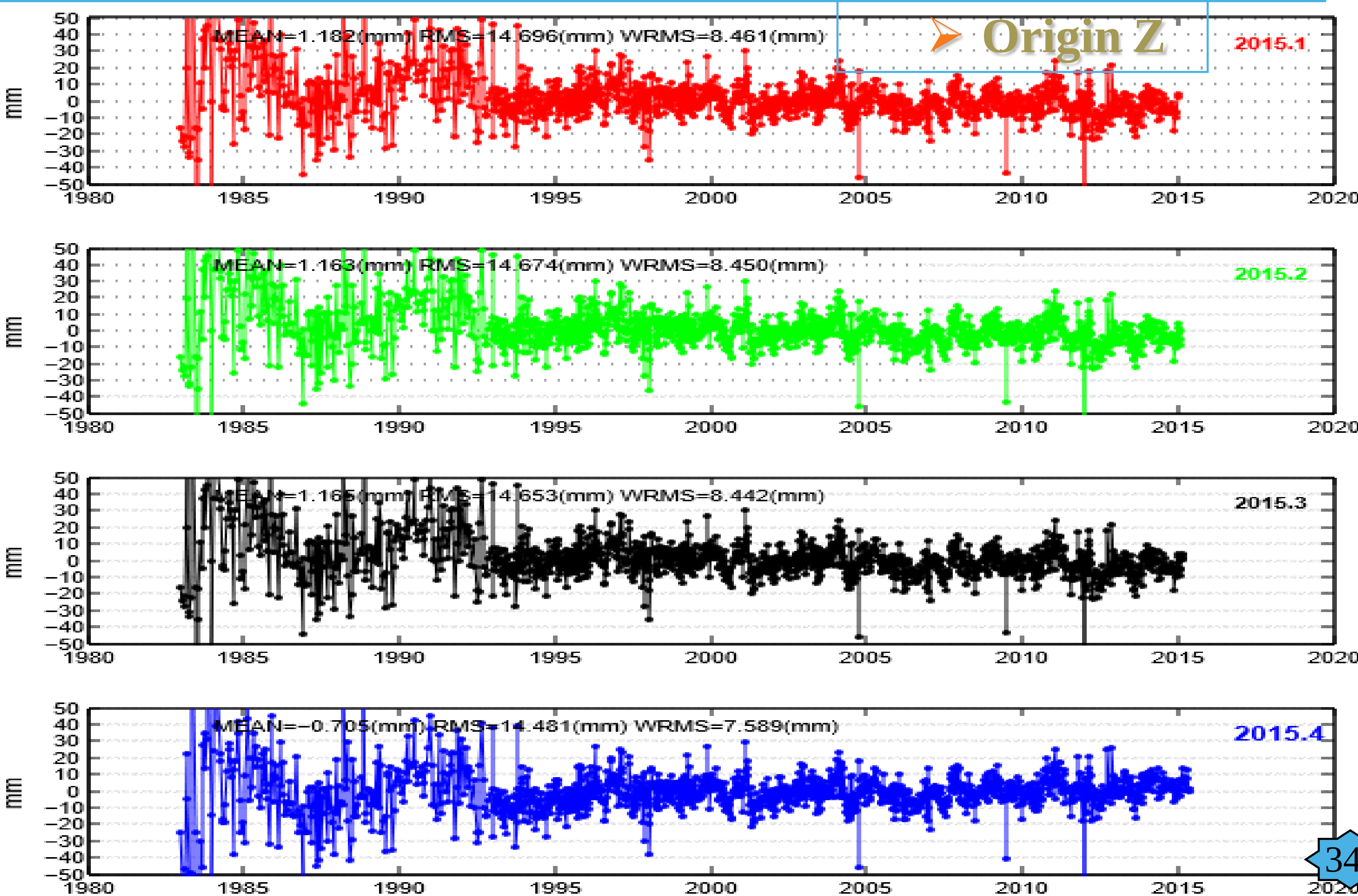
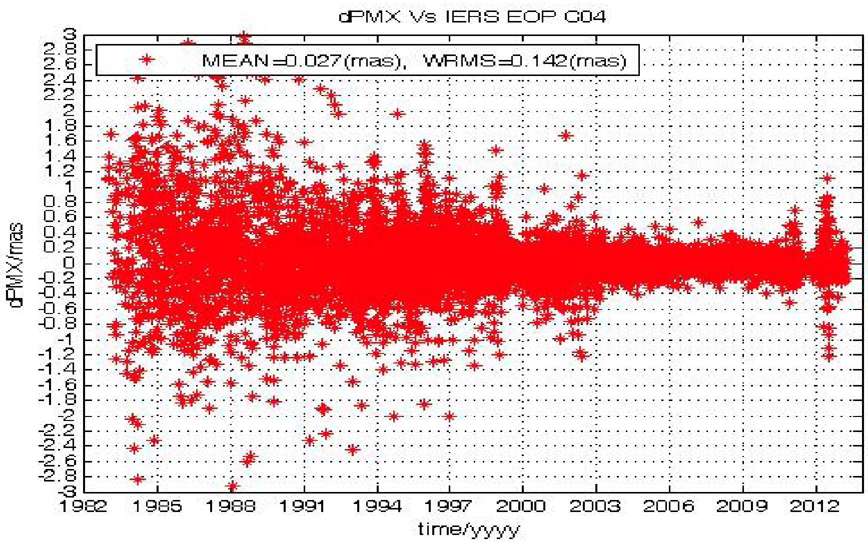
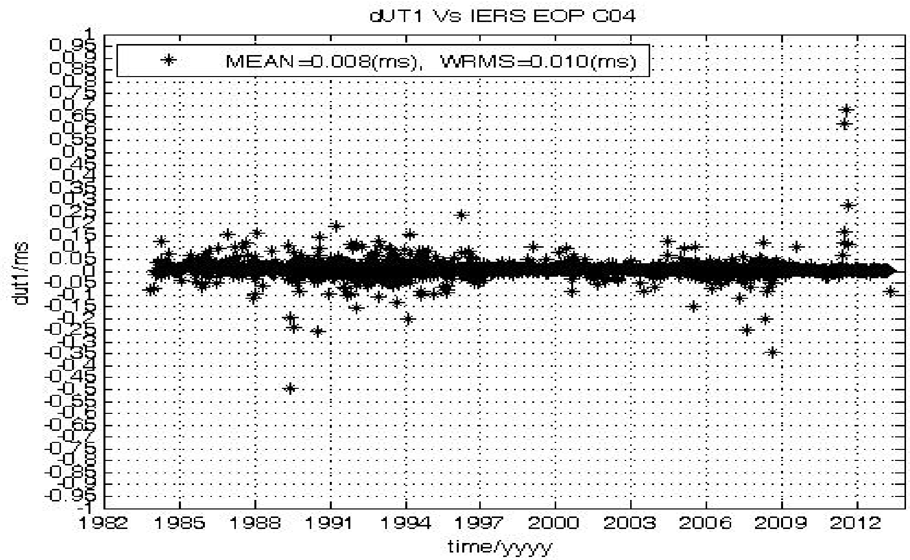
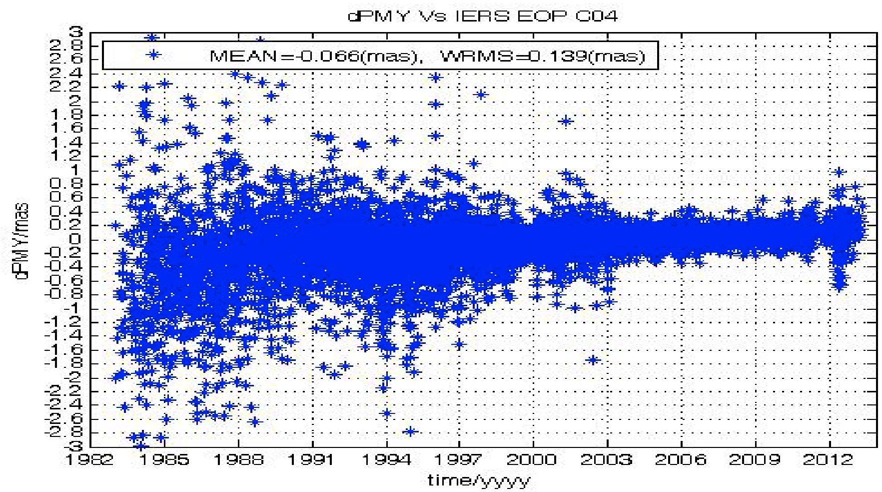
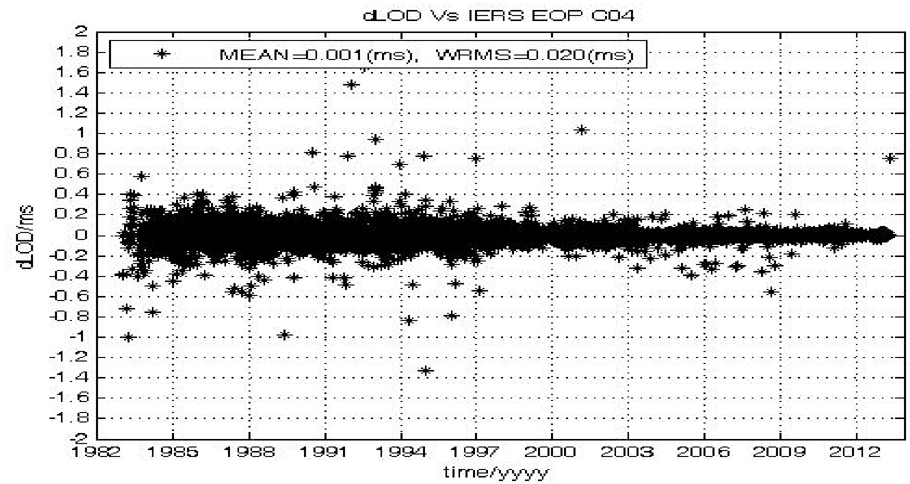


4、 Role of SLR on TRF and EOP

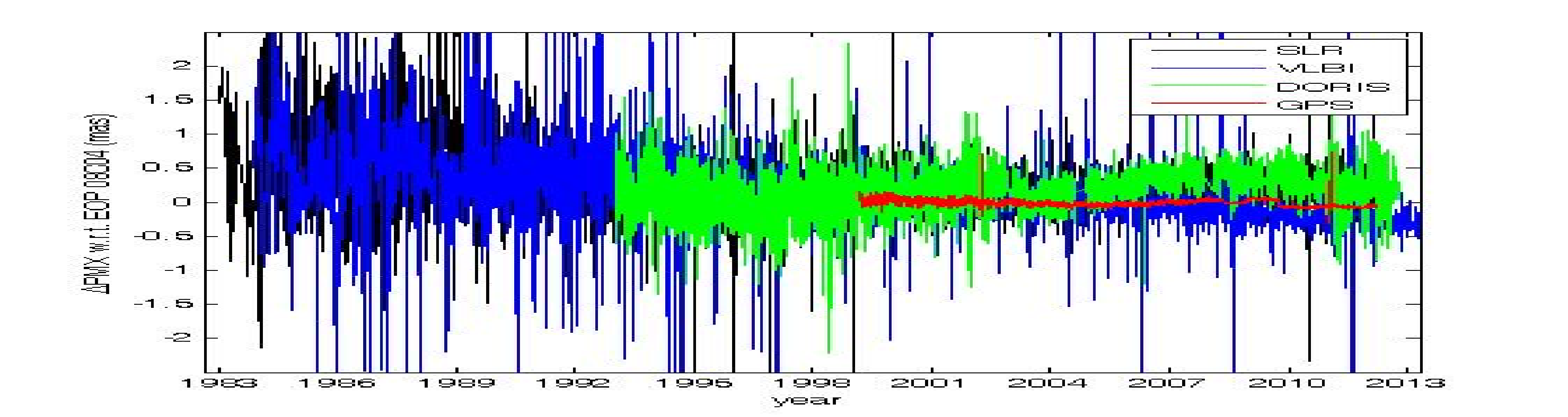


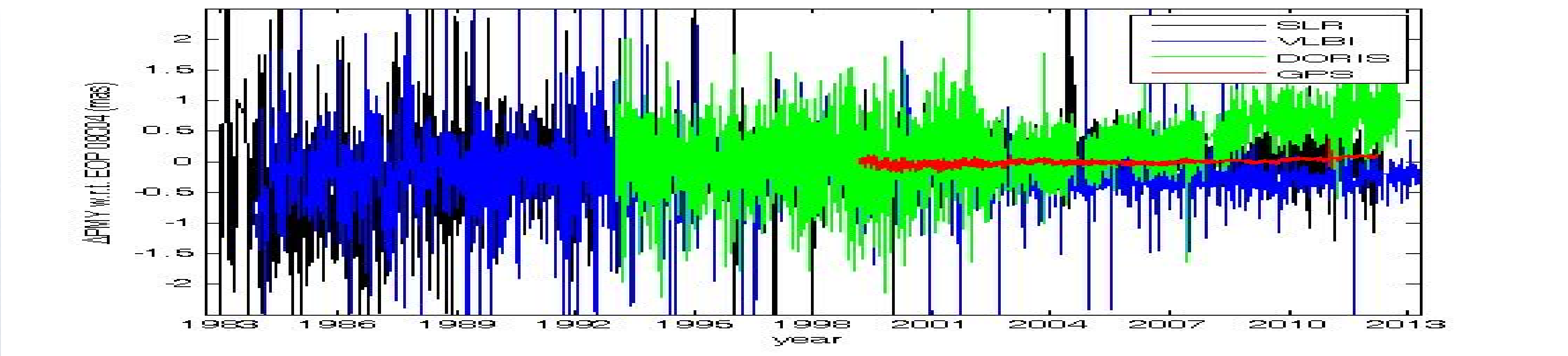






4、 Role of SLR on TRF and EOP





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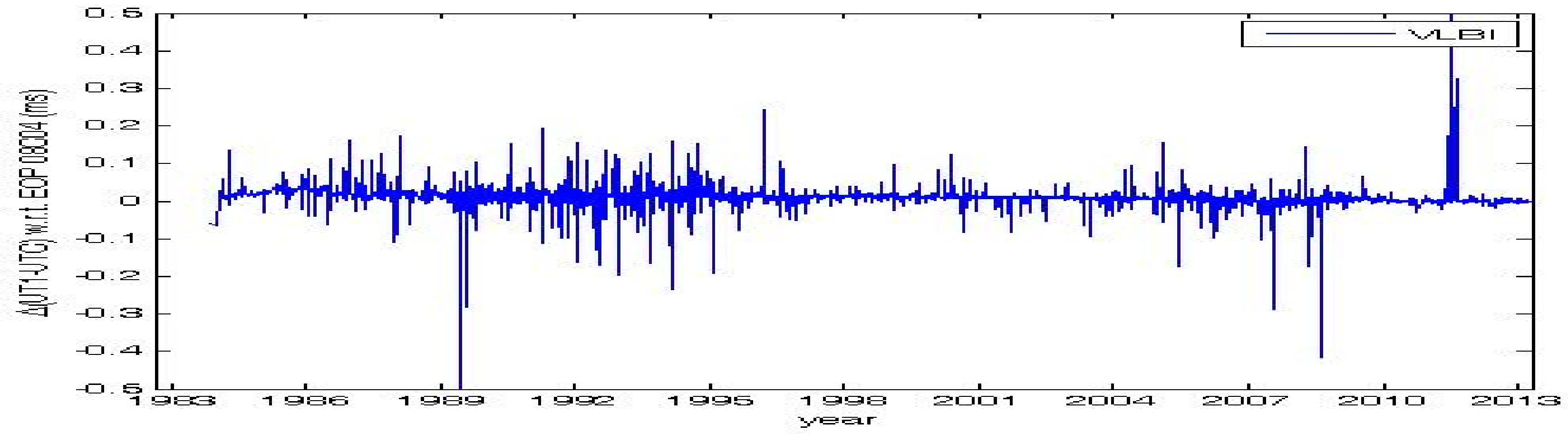
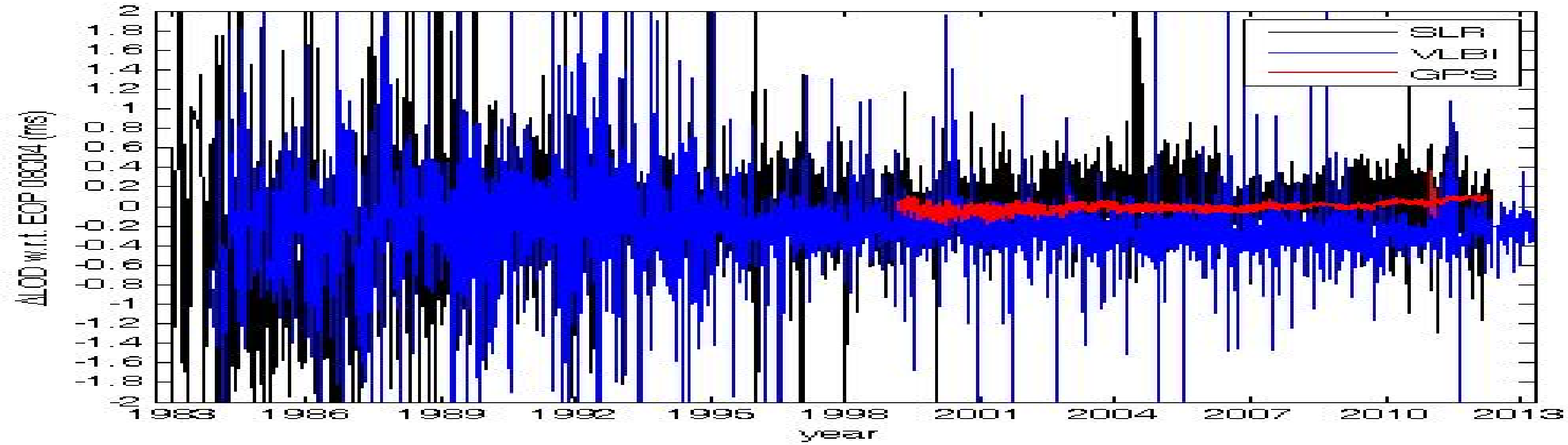




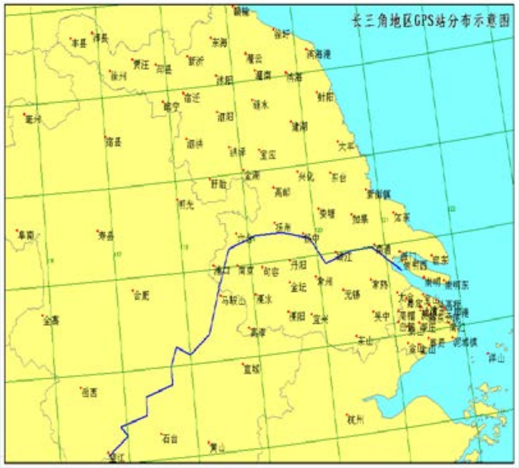
4、 Role of SLR on TRF and EOP

EOPs	SHAO	DGFI
PMX	0.142mas	0.123mas
PMY	0.139mas	0.122mas
LOD	0.020ms	0.022ms
UT1-UTC	0.010ms	0.012ms

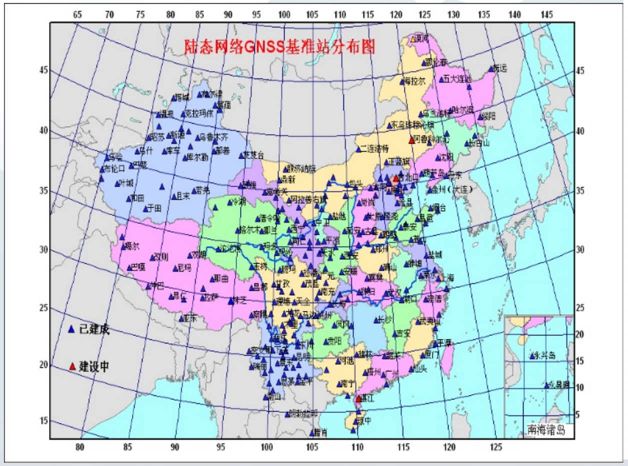
EOP	Techniqu	WRMS（DGFI）	WRMS（SHAO）
PMX（mas）	GPS	0.063	0.061
	VLBI	0.163	0.205
	SLR	**0.205**	**0.291**
	DORIS	0.234	0.850
PMY（mas）	GPS	0.055	0.071
	VLBI	0.232	0.184
	SLR	**0.204**	**0.242**
	DORIS	0.357	0.853
UT1-UTC（ms）	VLBI	0.013	0.017
LOD（ms）	VLBI	0.027	0.048
	GPS	0.022	0.007
	SLR	-----*	0.051

4、 Role of SLR on TRF and EOP

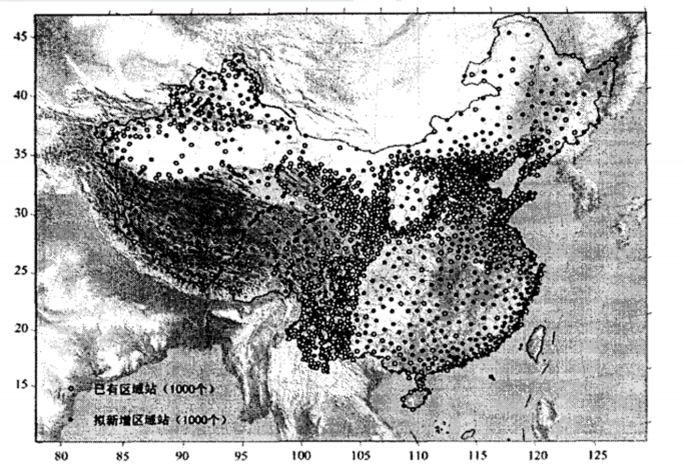
High accuracy China Geodetic coordinate system was needed by BDS. But present China Geodetic Coordinate System CGCS2000 published in 2008 mainly based on GPS. With more GPS,BDS, multi-GNSS sites, VLBI and SLR sites established in China CGCS should be updated and improved. It can be obtained with Global TRF and EOP. This work will be done.



150 GPS sites in Yanze Rive region(only 60 sites available)



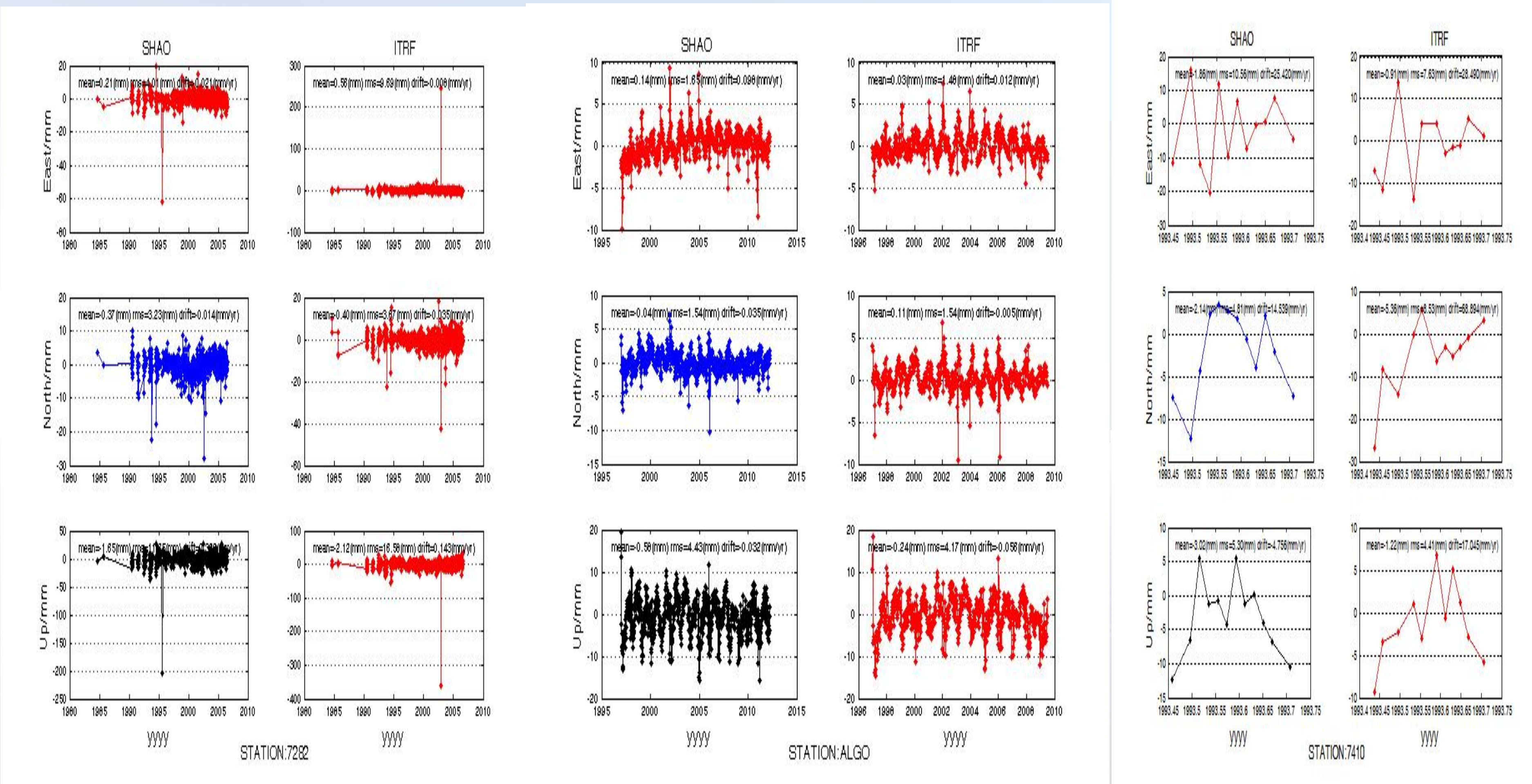
260 GPS sites



1000 regional campaign GPS sites
1000 GPS sites under consideration

5、 System errors and orbit cross check

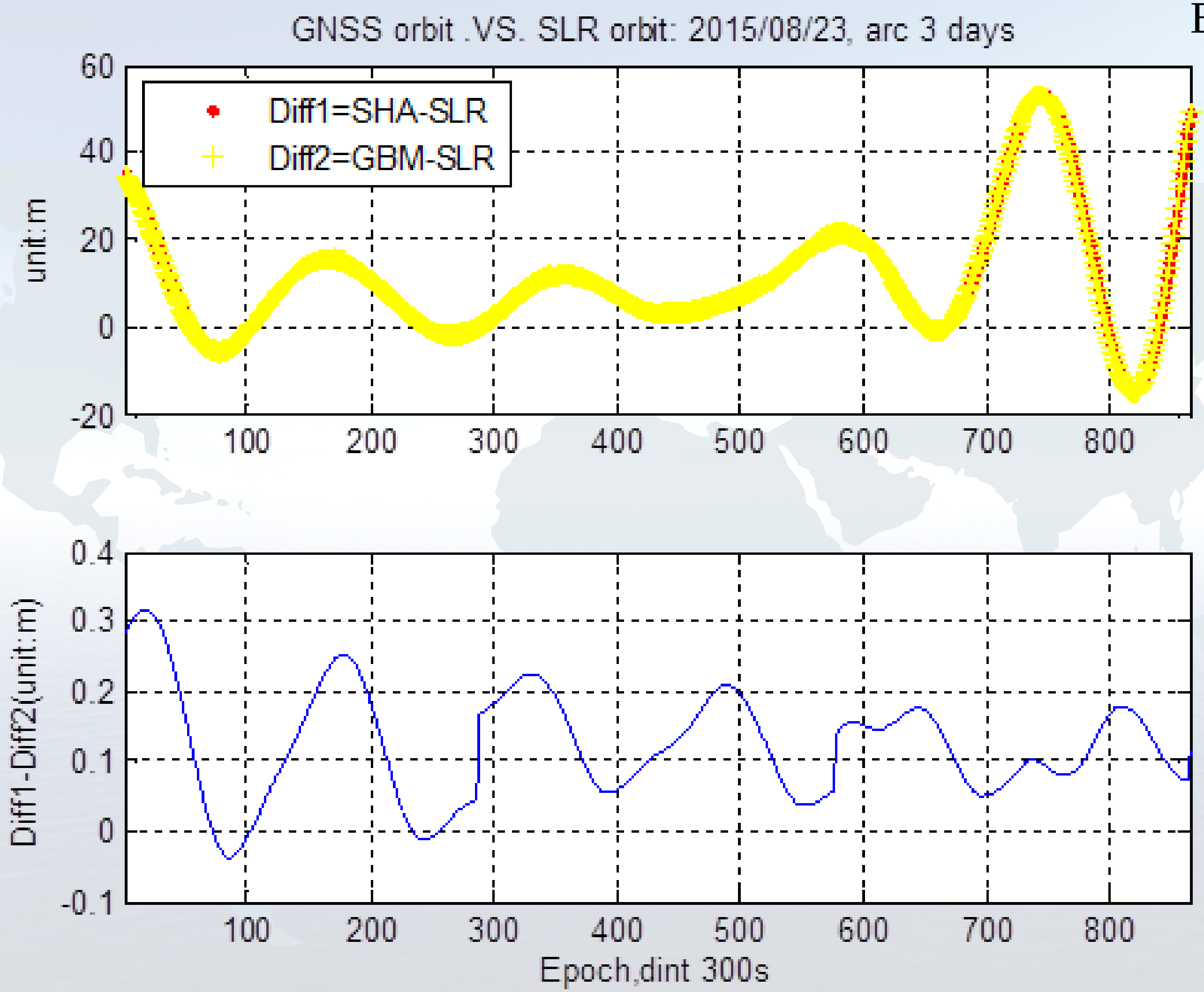
◆Residual series for co-location site coordinates



VLBI GPS SLR

5、 System errors and orbit cross check

BDS-M3



6、 Conclusions, Problems and Future plans

- **There are 16 satellites in service since the first Beidou experimental satellite launched in 2007. BDS can provide the PNT service now. All BDS satellites are installed by laser reflector array. SLR can provide an evaluation of Beidou orbits. It makes a important evaluation for better CoM, SRP model and orbit determination methods. But most of them are not tracked by SLR. So the problem similar to ZY-3's is emerging. What uses can SLR make of these satellites without more observation? It is worthy to be considered if SLR wants to be widely applied.**

6、 Conclusions, Problems and Future plans

- **SLR can make an important role on TRF and EOP. It determines the origin of TRF and contributes to the scale and EOP. To improve the accuracy of TRF and EOPs it needs do better SLR data processing including annual signal, semi-annual signal, jump and PSD analysis. The monthly epoch TRF is initially checked. But these work still needs further study.**

6、 Conclusions, Problems and Future plans

- **Regional TRF also needs SLR if high accuracy and consistence are required. For consistence regional GNSS data should be imported in the 4-technique combined processing and give a better results. This work will be done.**
- **SLR can also be used to check system errors between different techniques. For co-location sites there are some different residuals which show we maybe miss some errors in some data analysis. This is more important for new GNSS systems,e.g. BDS. It is useful for orbit cross check with GNSS microwave orbits.**

6、 Conclusions, Problems and Future plans

- **Certainly, SLR could provide more products such as satellite's orbits, gravity information and so on. We will provide BDS orbits besides Lageos-1/2, Etalon-1/2 and LARES based on SLR observation. Maybe we can also provide a low order gravity field based on more SLR LEO observations in future.**

Acknowledgments

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Thank you for your attention！