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Tour de l'IGS 4th Stop: BDS Constellation Spotlight

Beidou Coordinate System: Its Realization and Maintenance

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2022-9-27

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Introduction

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Background

- Since July, 2020, Beidou Satellite Navigation System (BDS) has provided various PNT services.
- Both BDS services and the compatibility and interoperability with other navigation systems require high accuracy realization and maintenance of BDS coordinate system(BDCS).
- To meet the accuracy requirements, satellite geodesy techniques are used for coordinate estimation of BDS monitoring stations, and alignment to the International Terrestrial Reference Frame (ITRF).

1.1 First Realization of BDCS

- Four joint campaigns with IGS stations. Coordinates of BDS monitor stations are aligned to ITRF2014 with a set of IGS stations.
  - ✓ 1st , 2007 ~2009, station-wise surveying.
  - ✓ 2nd, December 2011, campaign mode for 15 days.
  - ✓ 3rd, April 2014, campaign mode for15 days.
  - ✓ 4th, 2016, regional joint surveying.

- **Result**: The first realization of BDCS is aligned to ITRF2014 with accuracy better than 1 cm.

Ref: F. Wu, BeiDou Coordinate System And Its First Realization , ICG-13, 2018

1.2 BDCS Update and Maintenance

➢ **Strategy:**

✓ Daily network solutions with loose constrain obtained by estimating GNSS satellite orbital parameters and stations coordinates and then aligned to ITRF.

✓ Updating station coordinates when difference between estimated values and current values exceeding threshold (3 cm, currently)

✓ Annual maintenance

	Accuracy	Alignment to ITRF
WGS84（G1762）	< 1 cm	ITRF2008
GTRF	< 1 cm	ITRF2014
PZ-90	< 2 cm	ITRF2014
BDCS（2019V01）	< 1 cm	ITRF2014

BDCS(2019V01)

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2.1 Data Processing

- **Strategy:**
  - ✓ Continuous GNSS tracking data.
  - ✓ Daily network solutions with loose constrained obtained by estimating GNSS satellite orbital parameters and stations coordinates.
  - ✓ Aligning to ITRF by minimum constrain IGS station coordinates in ITRF2014.
- **Data：**
  - ✓ pseudo-range and carrier phase ionospheric-free combinations , from 2019.01.01 to 2019.03.31 of more than 120 stations distributed globally (IGS stations and regional stations)

BDCS(2019V01)

BeiDou Coordinate System

Responsible Organization: China Satellite Navigation Office(CSNO)
Abbreviated Name: BDCS
Associated TRS: ITRS
Coverage of Frame: Global
Type of Frame: 3-Dimensional
Latest Version: 2019V01

Brief Description

BDCS is an Earth-centered, Earth-fixed terrestrial reference system. The definition of BDCS is in accordance with the specifications of the International Earth Rotation and Reference System Service(IERS), and its realization is aligned to the latest International Terrestrial Reference System(ITRF). The BDCS(2019V01) is the current solution obtained by adopting more than 100 stations.

Definition of Frame

Origin: Earth's center of mass.

Axes:

Z-Axis: The direction of the IERS Reference Pole(IRP)

X-Axis: the intersection of the IERS Reference Meridian (IRM) and the plane passing through the origin and normal to the Z-Axis.

Y-Axis: together with Z-Axis and X-Axis, constitutes a right-handed orthogonal coordinate system.

Scale: The length unit is the international system of units(SI) meter.

Orientation: Given by the Bureau International de l'Heure (BIH) orientation of 1984.0

Time Evolution: Its time evolution in orientation will create no residual global rotation with regards to the crust.

Coordinate System: Cartesian Coordinates(X, Y, Z)

Defining Parameters: The geometric center of the BDCS Ellipsoid coincides with the Earth's center of mass, and the rotation axis of the BDCS Ellipsoid is the Z-Axis. The parameters of the BDCS Ellipsoid are shown as follows:

Semi-major axis	a= 6378137.0 m
Geocentric gravitational constant(including the atmosphere)	$\mu=3.986004418\times10^{14}$m3/s2
Flattening	f=1/298.257222101
Earth's rotation rate	$\dot{\Omega}_e = 7.2921150 \times 10^{-5}$rad/s

Transformation Parameters:

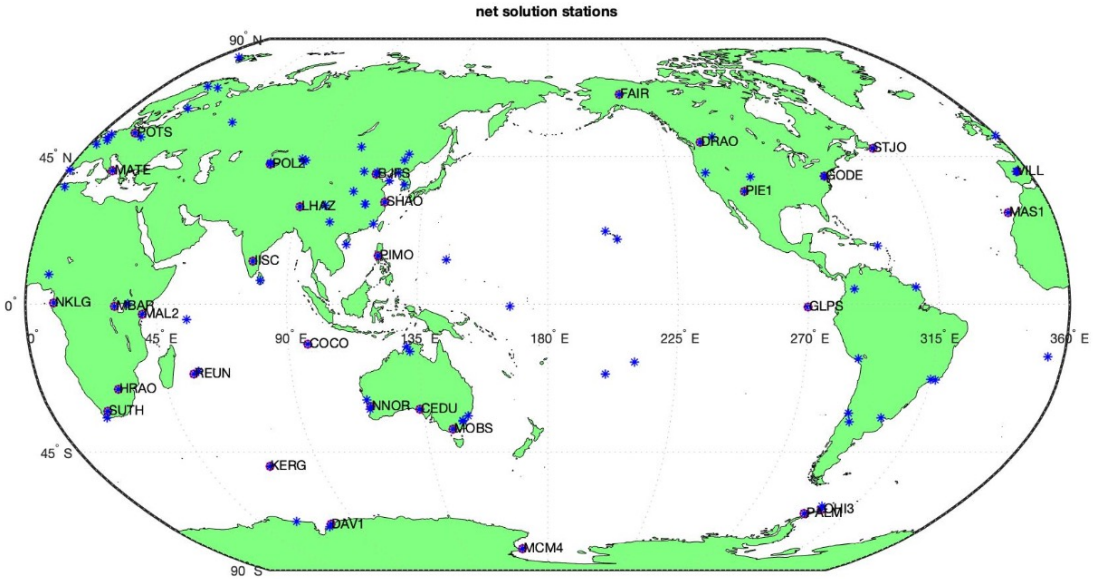
Transformation parameters from BDCS(2019V01) to ITRF2014.

	Tx (mm)	Ty (mm)	Tz (mm)	Rx (mas)	Ry (mas)	Rz (mas)	Scal (ppb)
Estimation	-0.37	1.12	-0.55	0.01	-0.02	0.05	0.011
STD	0.74	0.74	0.74	0.03	0.03	0.04	0.012

www.beidou.gov.cn

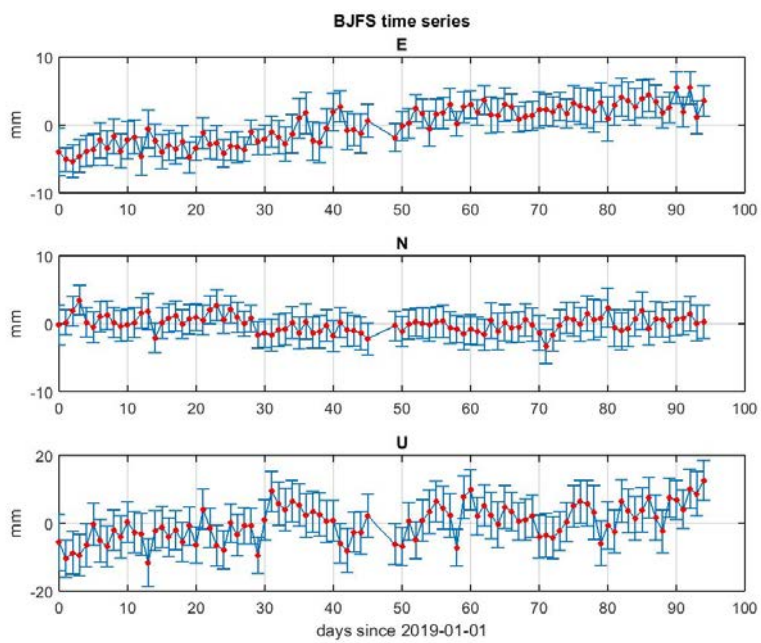
2.1 Data Processing

- Data: 2019.0-2019.25 pseudo-range and phase LC from 120+ global stations.
- Processing: precise orbit determination
- Estimation:
  - satellite orbital parameters
  - ECOM-9 SRP
  - station coordinates
  - ZTD
  - phase ambiguity
  - satellite and station clock offsets
- Satellite Antenna PCO/PCV: IGS14.atx
- Alignment: minimum constrained IGS core station coordinate in ITRF2014

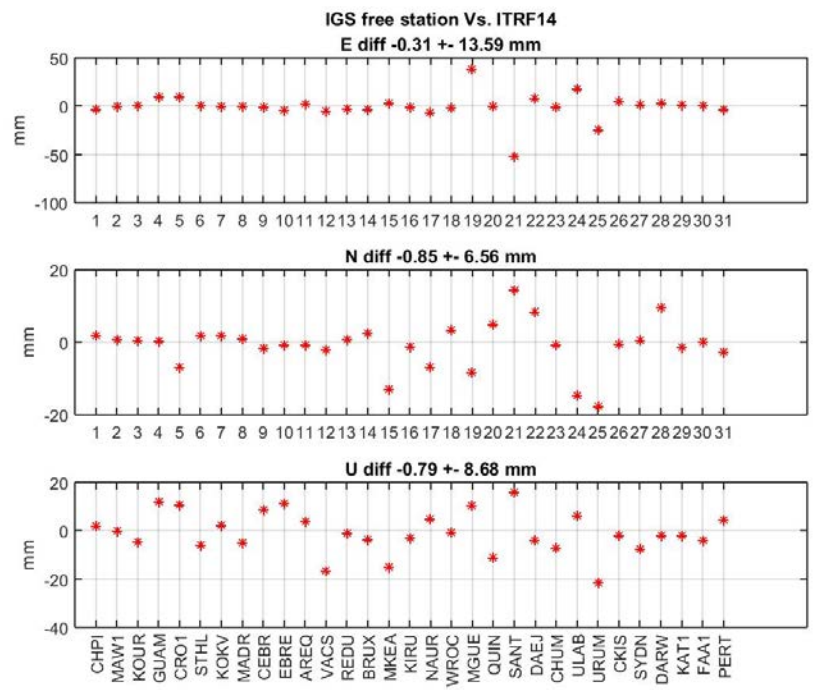


2.2 Accuracy

Coordinates time series



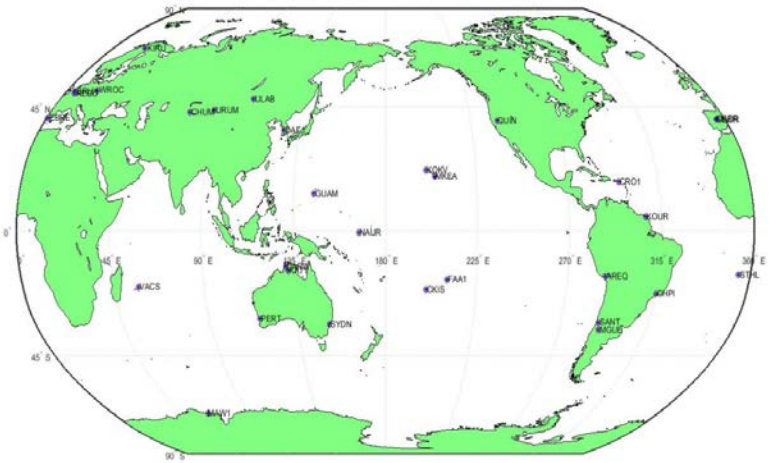
Coordinates differences
between BDCS(2019v01) and ITRF2014 solutions



The difference is better than 1cm.

2.2 Accuracy

Selected stations to assess alignment accuracy



Station list

CHPI	VACS	DAEJ
MAW1	REDU	CHUM
KOUR	BRUX	ULAB
GUAM	MKEA	URUM
CRO1	KIRU	CKIS
STHL	NAUR	SYDN
KOKV	WROC	DARW
MADR	MGUE	KAT1
CEBR	QUIN	FAA1
EBRE	SANT	PERT
AREQ		

Transformation parameters from BDCS(2019v01) to ITRF2014

	Trans_x mm	Trans_y mm	Trans_z mm	Rotate_x mas	Rotate_y mas	Rotate_y mas	Scal ppb
Estimation	-0.37	1.12	-0.55	0.01	-0.02	0.05	0.011
Sigma	0.74	0.74	0.74	0.03	0.03	0.04	0.012
3*Sigma	2.22	2.22	2.22	0.09	0.09	0.11	0.037

Alignment accuracy: 2 mm

BDCS Accuracy Assessments

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Methods

- **Several methods are adopted to assess the accuracy of BDCS maintenance**

✓ 1. Consistency comparison of co-located station coordinates time series

✓ 2. Station coordinates repeatability

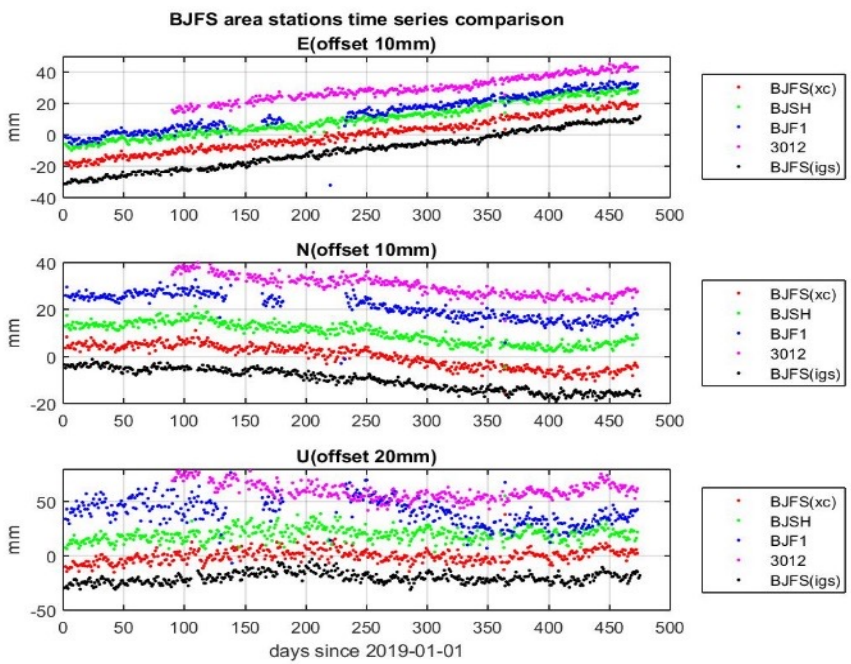
✓ 3. Station velocity comparisons

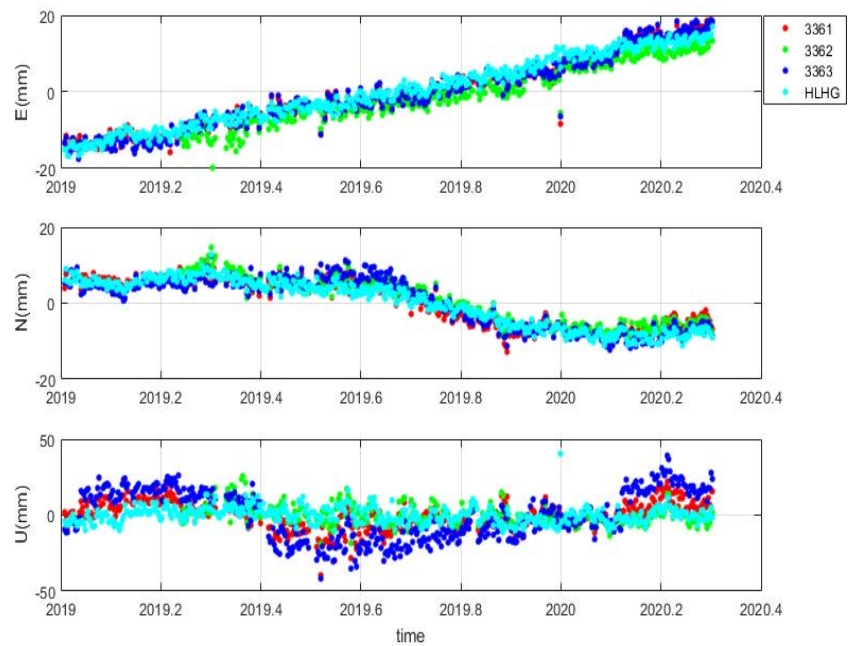
✓ 4. Transformation parameters between BDCS and ITRF2014

✓ 5. Broadcast ephemerides and precise orbit comparisons

3.1 Co-located stations

➢ **Co-located stations coordinates time series**

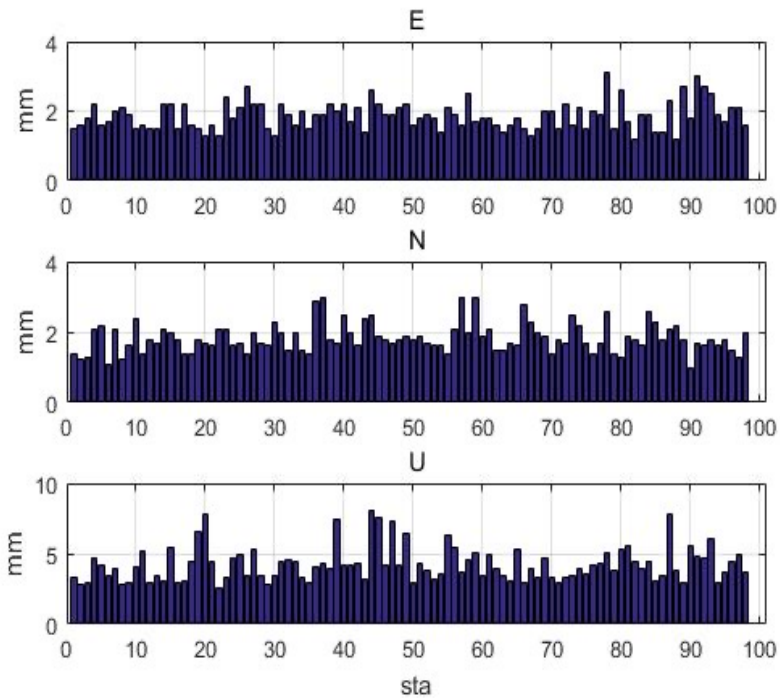




✓ **Apparent trend changes in horizontal and vertical components.**

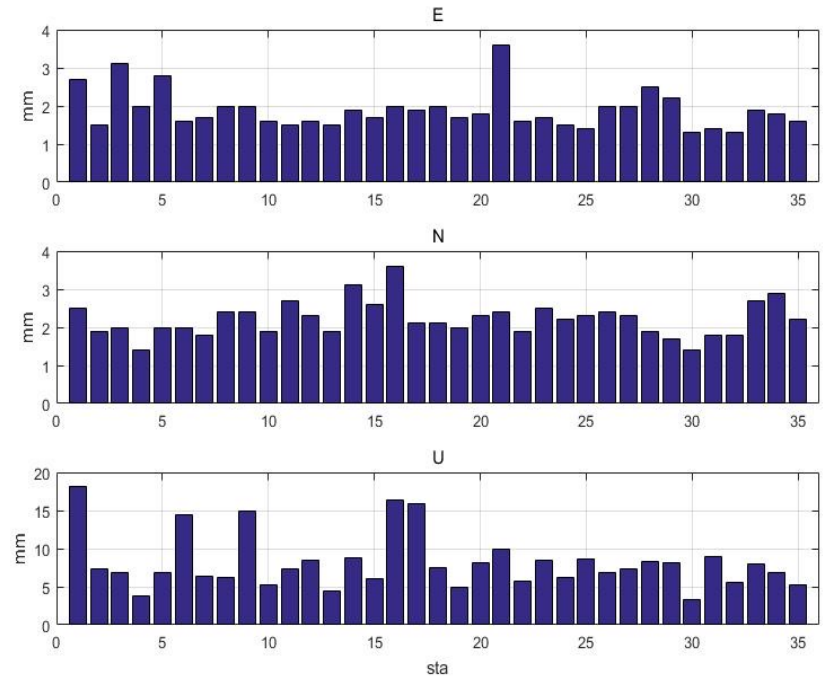
✓ **Co-located sites coordinate variations show good consistency.**

3.2 Station coordinates repeatability



IGS stations

E:1.8mm; N: 1.8mm; U: 4.3mm



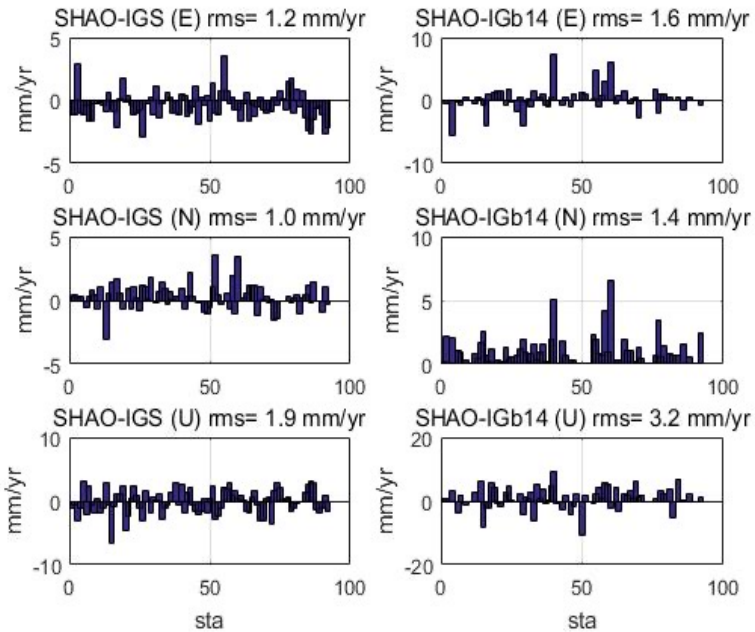
BDS stations

E: 1.9mm; N: 2.2mm; U: 8.2mm

Repeatability better than 1 cm

3.3 Station velocity

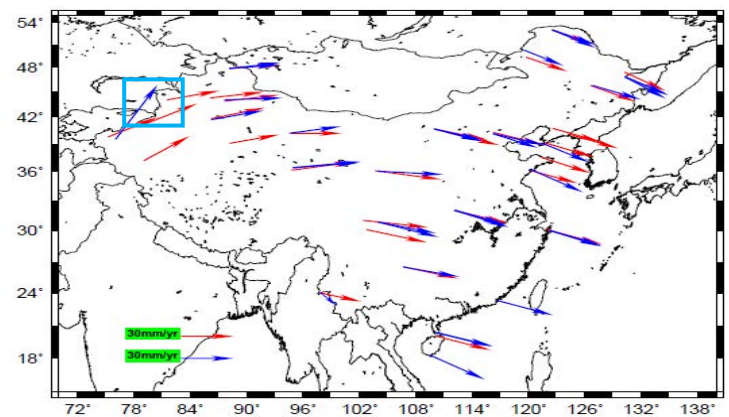
Station velocity difference statistics



BJFS velocity comparisons

	N(mm/yr)	E(mm/yr)	U(mm/yr)
BJSH (shao)	-10.3	28.4	3.1
BJFS (shao)	-11.8	29.3	4.4
BJFS (igs)	-11.6	31.7	1.9
BJFS (ITRF14)	-10.6	30.6	2.2
BJFS(IGb14)	-10.5	30.7	2.2

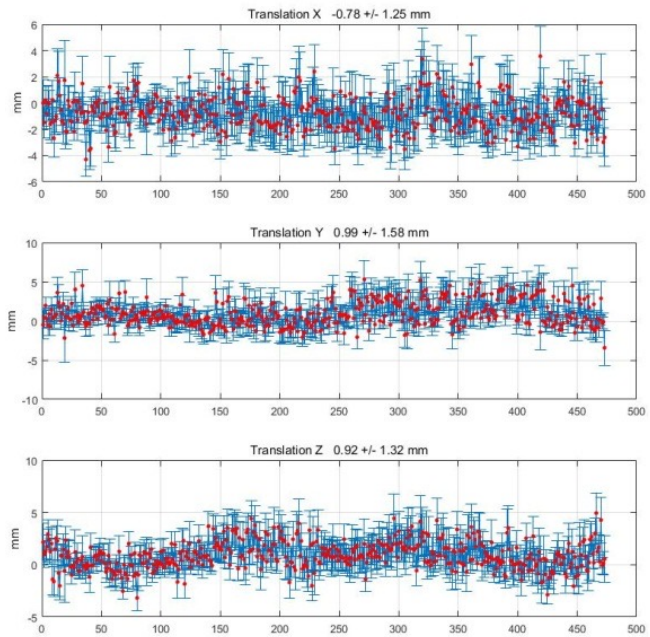
Velocity field comparisons

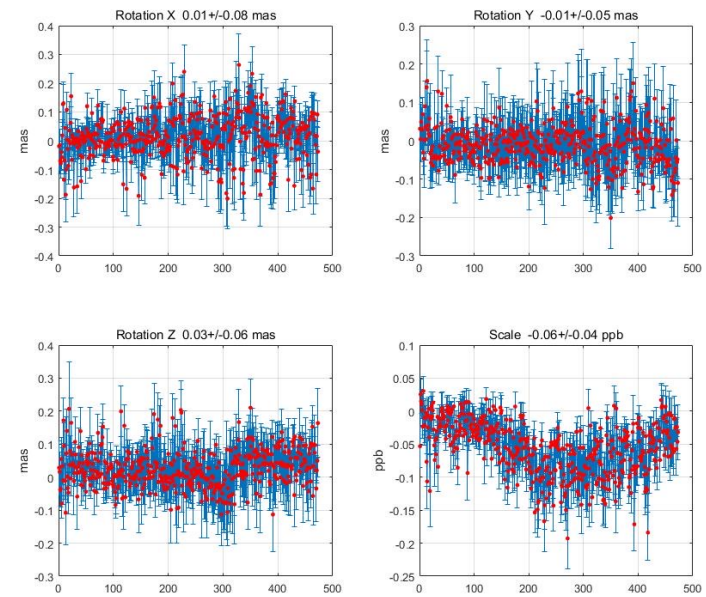


Velocity difference 2mm/yr (horizontal) and 3mm/yr (vertical)

3.4 Transformation between BDCS and ITRF2014

Daily solution transformation parameters time series





	Tx/mm	Ty/mm	Tz/mm	Rx/mas	Ry/mas	Rz/mas	Scal/ppb
Mean	-0.78	0.99	0.92	0.01	-0.01	0.03	-0.06
Std	1.25	1.58	1.32	0.08	0.05	0.06	0.04

Accuracy consistent with BDCS(2019V01)

Maintenance of the BDCS continuous and stabilization

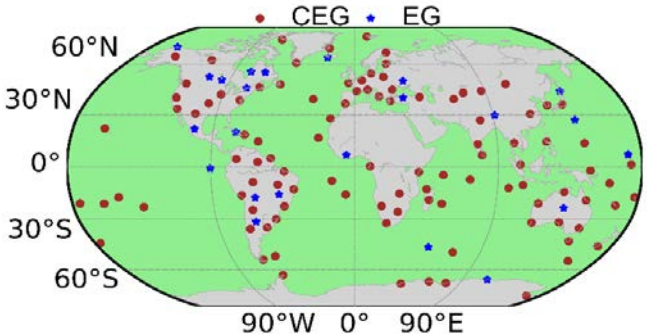
3.5 Broadcast Ephemerides and Precise Orbits

- **Orbit comparison:** transformations between broadcast and precise orbits
- **Station coordinates comparison:** transformations between station coordinates of PPP using broadcast and precise products

➢ **Data:**

- BDS-3/GPS/GAL precise orbits of GFZ and broadcast ephemerides
- 130 globally distributed MGEX stations for PPP processing
- Time span from 2020.1 to 2020.12
- **PCO values :**

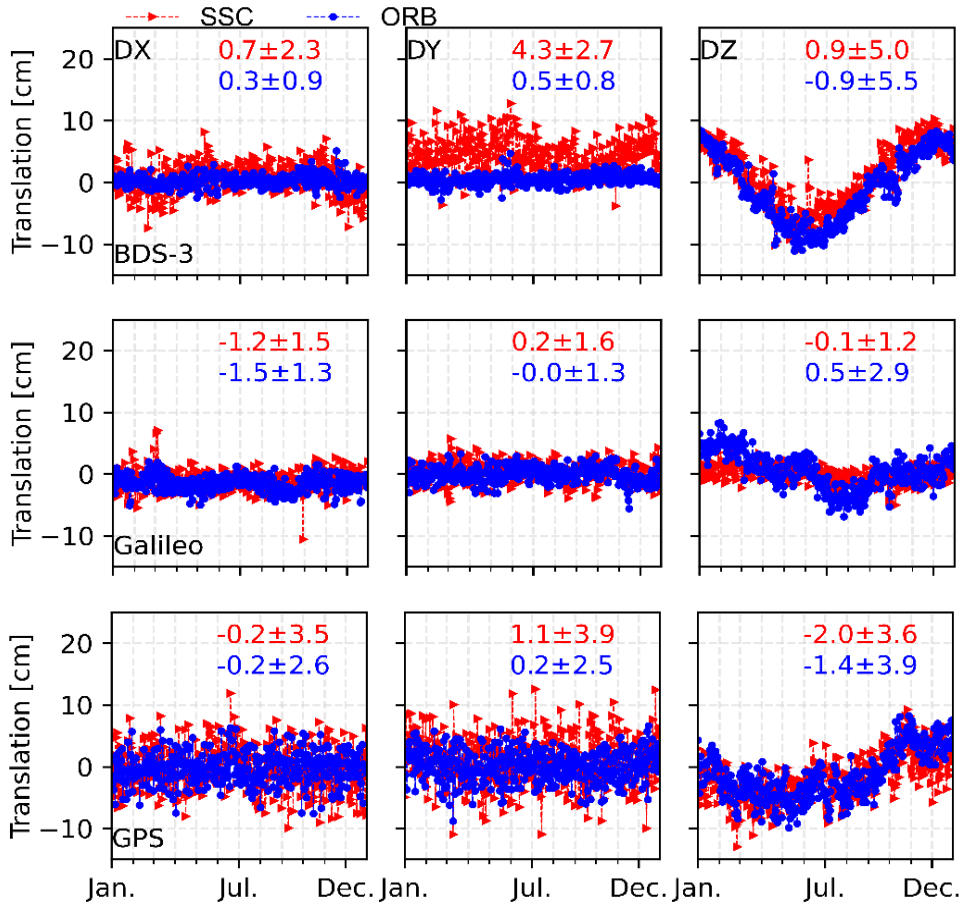
BDS3: http://www.beidou.gov.cn;
GPS:NGA(2018); GAL:GSC,(2019)



Site distribution **(C/91, G/118,E/113)**

3.5 Broadcast Ephemerides and Precise Orbits

➢ Translations



Blue/Red: orbit/coordinates comparison

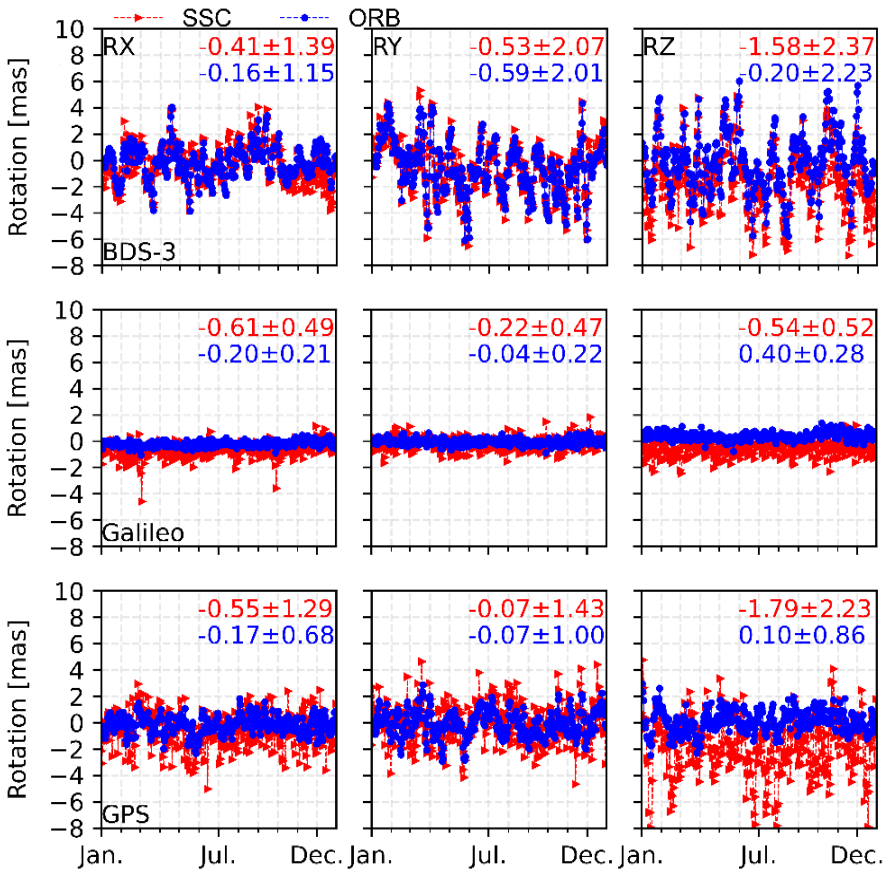
Correlations between orbit/coor. comparisons

	DX	DY	DZ
BDS-3	0.14	0.10	0.93
Galileo	0.10	0.20	0.50
GPS	0.28	0.33	0.68

- ➢ Annual systematic errors found in z-translation for BDS-3, showing manufacturer- and orbit-plane-dependent characteristics
- ➢ Random errors dominating GPS/GAL
- ➢ Results from orbit and coordinate comparisons are at the same level

3.5 Broadcast Ephemerides and Precise Orbits

➢ Rotations



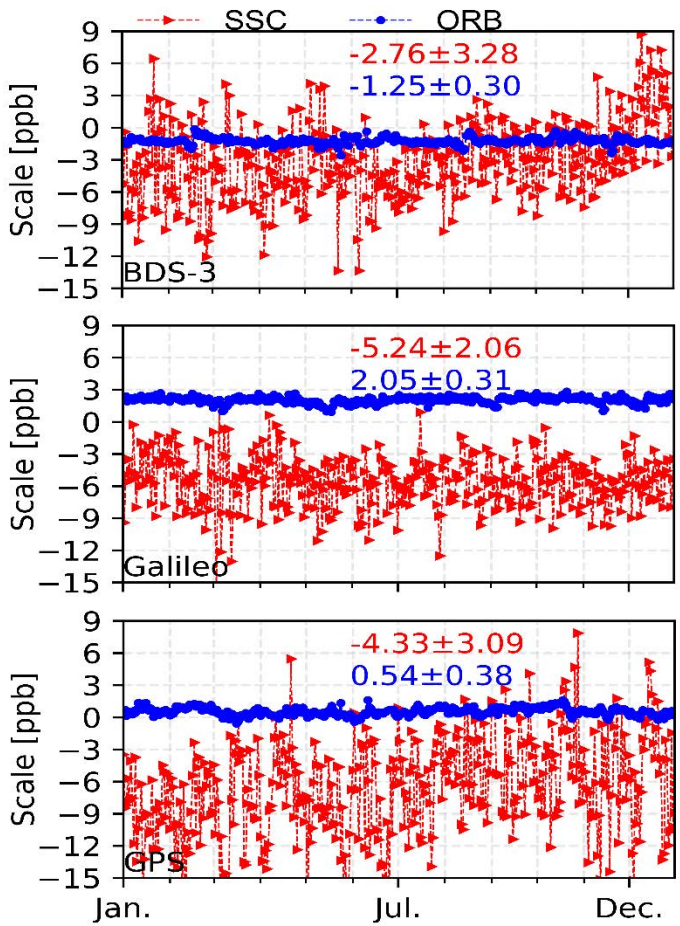
Correlations between orbit/Coor. comparisons

	RX	RY	RZ
BDS-3	0.79	0.94	0.91
Galileo	0.55	0.28	0.20
GPS	0.57	0.65	0.54

- ➢ Systematic errors in rotations also found in BDS-3 due to increasing errors of EOP predictions within one week, resulting in positioning errors up to 25 cm
- ➢ Rotations of GPS/GAL are stable within one week
- ➢ Results from orbit and SSC comparisons are also at the same level

3.5 Broadcast Ephemerides and Precise Orbits

➢ **Scale**



Correlations between orbit/coor. comparisons

	SCL
BDS-3	0.02
Galileo	0.11
GPS	0.05

- ➢ No systematic errors in scale found in three systems
- ➢ But, negative biases found between orbits and SSC comparisons due to highly correlation between clock offsets and scale factor during PPP

BDCS Maintenance Using BDS Data

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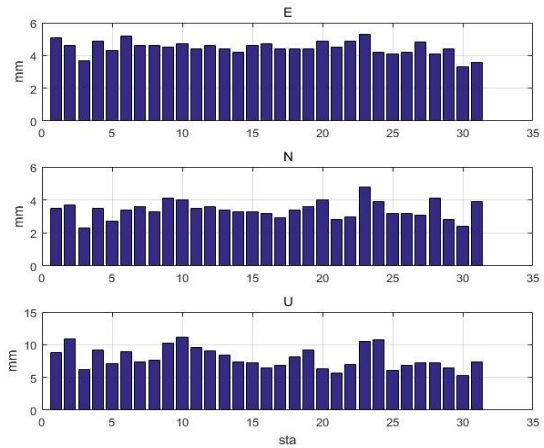
4.1 Data Processing

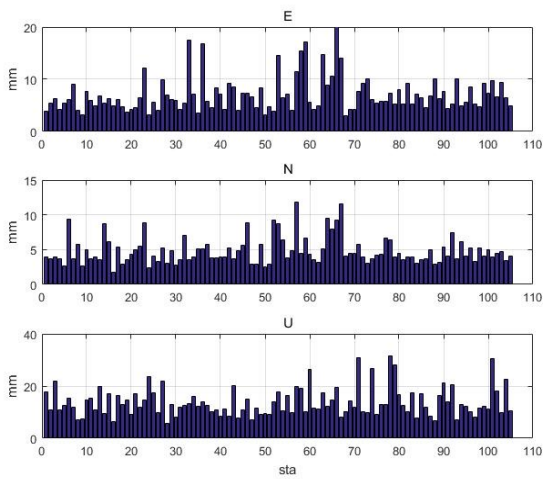
- **Strategy:**
  - ✓ Continuous BDS data.
  - ✓ Daily network solutions with loose constrained obtained by estimating BDS satellite orbital parameters and stations coordinates.
  - ✓ Aligning to ITRF by minimum constrain IGS station coordinates in ITRF2014.
- **Data:**
  - ✓ 2019.10.01-2020.03.19, more than 200 global stations, including IGS stations and BDS stations.
- **Accuracy evaluation**
  - ✓ Consistency analysis of BDS station coordinate
  - ✓ Transformation parameters

4.2 Coordinates Repeatability and Comparisons



BDS stations

E: 4.4mm
N: 3.4mm
U: 7.9mm

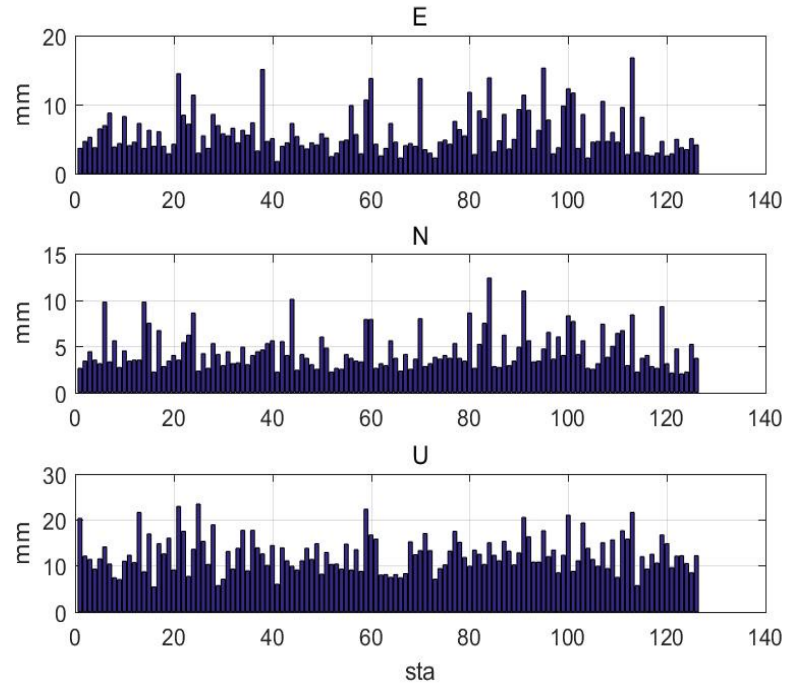


IGS stations

E: 5.9mm
N: 4.5mm
U: 12.5mm

Coordinate differences between BDS and GPS

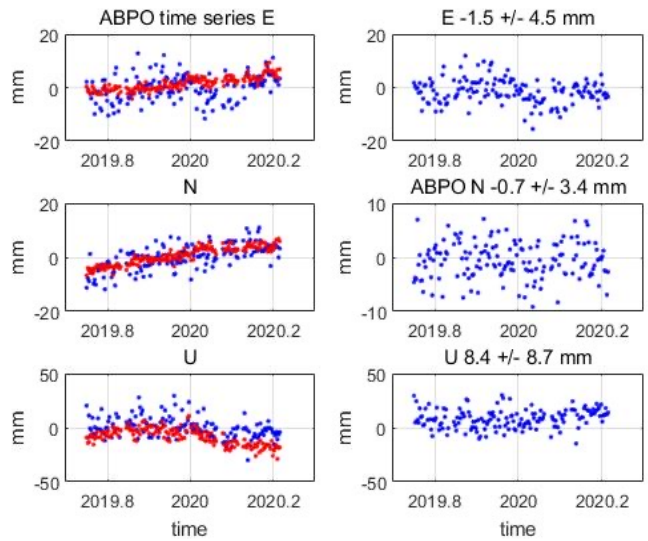
E: 7.0mm N: 4.8mm U:13.8mm



Accuracy of site coordinates using BDS data about 1 cm

4.3 Coordinates Time Series

Time series comparison between BDCS(BDS only) and IGS solutions



- **Apparent trend changes in horizontal and vertical components.**
- **Scatter of site coordinate time series larger when using BDS data!**

	Tx/mm	Ty/mm	Tz/mm	Rx/mas	Ry/mas	Rz/mas	Scal/ppb
Mean	**0.62**	**0.16**	**-0.61**	**0.02**	**0.00**	**-0.05**	**-0.01**
Sigma	**1.41**	**1.38**	**1.23**	**0.06**	**0.06**	**0.05**	**0.02**

Accuracy of BDCS(BDS only) at millimeter level

Summary

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Summary

- BDCS in high accuracy alignment with ITRF2014. Although BDS-3 broadcast orbits are constrained only by several regional stations, TRF accessible via BDS-3 broadcast orbits still coincides with ITRF2014 at cm level.
- Nonlinear characteristic evident in BDS station coordinate time series need further modeling.
- Only using BDS data from global tracking stations, coordinates can be estimated accurately and BDCS can be aligned to ITRF at mm level.
- Joint forces from GNSS community are mostly welcome to improve BDCS.


THANKS !