Beidou Satellites Prediction from Navigation Messages

Xue DONG[1], Zhipeng LIANG[1], Junping CHEN[2], Chao YU[2],
1. Changchun Observatory, NAOC, CAS
2. Shanghai Astronomical Observatory (SHAO)

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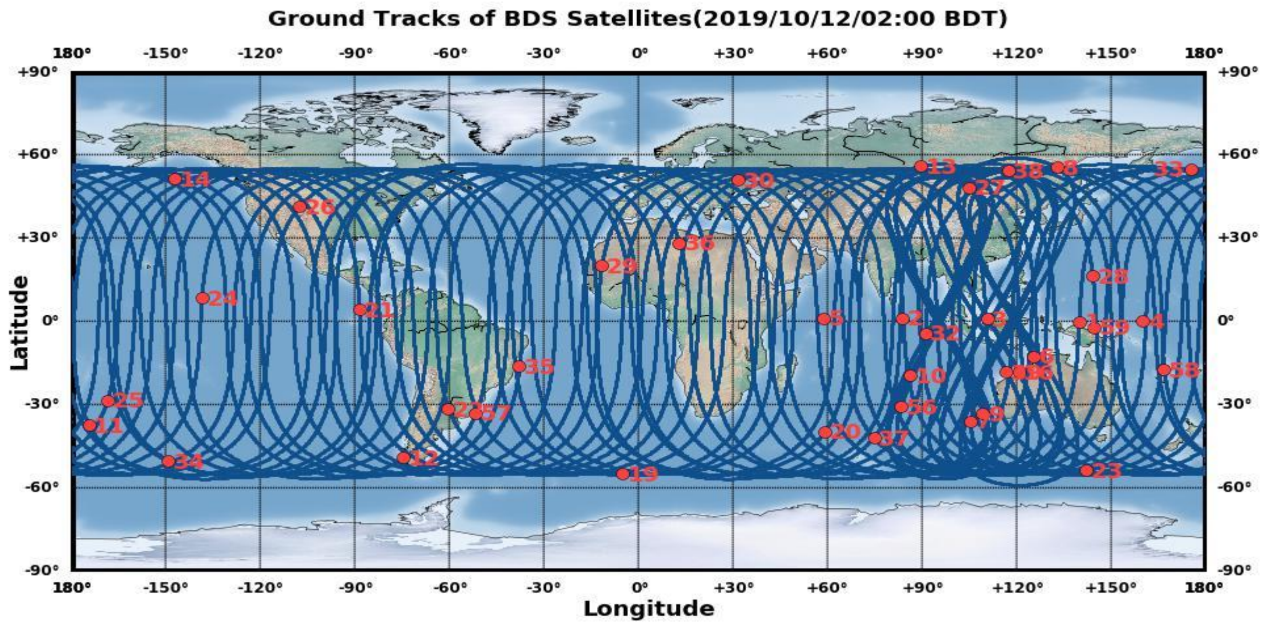
Contents

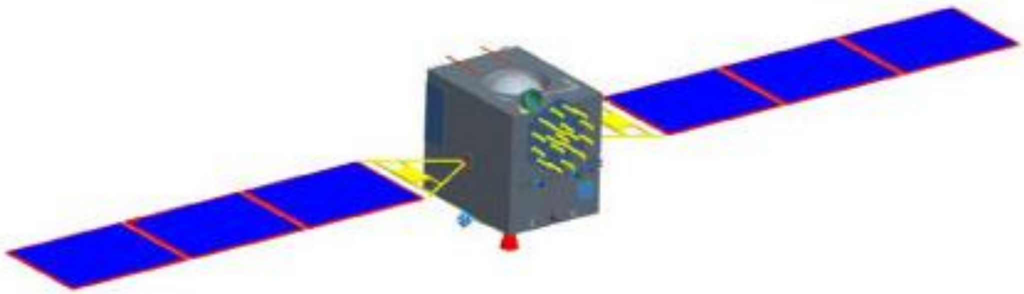
1 Beidou Navigation System

The BeiDou Navigation Satellite System (BDS) is constructed and operated by China. It was once known as “Compass” system. The BDS space segment is a hybrid navigation constellation consisting of GEO, IGSO and MEO satellites.



1 Beidou Navigation System

The BDS satellites all carry retro-reflectors, and their predictions are provided by SHAO.



COMPASS (Courtesy of Shanghai Astronomical Observatory)

The shape of Beidou satellite

Courtesy of Chinese Academy of Sciences

Beidou retro-reflector

2 BDS Navigation Message

The BDS Open Service broadcast navigation message is similar in content to the GPS navigation message. The Rinex file which contain observe data, broadcast, other useful message was acquired from BDS receiver.

The file was in Rinex V3.03d format

Details: https://kb.igs.org/hc/en-us/articles/206482558-RINEX-3-03-Release-Notes

2 BDS Navigation Message

BDS Navigation Message Example

```
    3.03d           N                   C                   RINEX VERSION / TYPE
MergeRinexNav       NUDT                20181104 010103 UTC PGM / RUN BY / DATE
BDS1    1.3500E+01 -2.5000E+00  4.8750E+00  0.0000E+00 c C30 IONOSPHERIC CORR
BDS2    3.1250E+00  4.3750E+00 -1.2500E-01  0.0000E+00 c C30 IONOSPHERIC CORR
BDS3   -6.2500E-01  1.0000E+00  6.2500E-01  0.0000E+00 c C30 IONOSPHERIC CORR
```

```
     4     4    61     6                                    LEAP SECONDS
                                                            END OF HEADER
C01 2018 11 04 01 00 00-1.578773371875e-04 4.812061860093e-11 0.000000000000e+00
     1.000000000000e+00 5.774062500000e+02 2.382242087088e-09 2.413152406855e-01
     1.900270581245e-05 4.734520334750e-04-2.195825800300e-05 6.493362161636e+03
     3.600000000000e+03-1.471489667892e-07-2.616879573778e+00-2.980232238770e-08
     7.228413403290e-02 6.797500000000e+02-1.201101365642e+00-1.590066232641e-09
    -8.214627886510e-12 0.000000000000e+00 6.700000000000e+02 0.000000000000e+00
     0.000000000000e+00 0.000000000000e+00 1.420000028673e-08-1.039999997232e-08
     3.657000000000e+03 0.000000000000e+00 0.000000000000e+00 0.000000000000e+00
C01 2018 11 04 02 00 00-1.577038783580e-04 4.815703391614e-11 0.000000000000e+00
     1.000000000000e+00 8.406250000000e+01 1.972225008231e-09 5.013996398676e-01
```

File header

Ionospheric parameters

UTC and 31 parameters

Data block

2 BDS Navigation Message

```
C01 2018 11 04 01 00 00-1.578773371875e-04 4.812061860093e-11 0.000000000000e+00
     1.000000000000e+00 5.774062500000e+02 2.382242087088e-09 2.413152406855e-01
     1.900270581245e-05 4.734520334750e-04-2.195825800300e-05 6.493362161636e+03
     3.600000000000e+03-1.471489667892e-07-2.616879573778e+00-2.980232238770e-08
     7.228413403290e-02 6.797500000000e+02-1.201101365642e+00-1.590066232641e-09
    -8.214627886510e-12 0.000000000000e+00 6.700000000000e+02 0.000000000000e+00
     0.000000000000e+00 0.000000000000e+00 1.420000028673e-08-1.039999997232e-08
     3.657000000000e+03 0.000000000000e+00 0.000000000000e+00 0.000000000000e+00
```

The navigation message provides broadcast ephemeris in the form of Keplerian orbit elements and additional correction parameters. The orbit ephemeris should be calculated via specified algorithm.

3 BDS Orbit calculation

BDS Specification:

BDS orbit calculation is Keplerian, similar to GPS algorithm, but coordinate system is BDCS (BeiDou coordinate system).

BDT (BeiDou Time) is 14 seconds behind GPS time.

$\mu = 3.986004418 \times 10^{14}\ \mathrm{m^3/s^2}$	Geocentric gravitational constant
$\dot{\Omega}_e = 7.2921150 \times 10^{-5}\ \mathrm{rad/s}$	Earth Rotation Rate
$\pi = 3.1415926535898$	Circumference Ratio

$A_{\mathrm{ref}} = 27906100\mathrm{m}$（MEO），$A_{\mathrm{ref}} = 42162200\mathrm{m}$（IGSO/GEO）

3 BDS Orbit calculation

The GPS Orbit Algorithm (Seeber,2003,Satellite Geodesy)

Keplerian Parameters to ECEF Coordinates

$$T = 2\pi / \sqrt{GM / A^3}$$ Satellite orbital period

$$n_0 = \sqrt{\frac{GM}{A^3}}$$ Computed mean motion

$$n = n_0 + \Delta n$$ Corrected mean motion

$$\overline{M}_k = \overline{M}_0 + nt_k$$ Mean anomaly

$$E_k = \overline{M}_k + e\sin E_k$$ Kepler's equation of eccentric anomaly is solved by iteration.

$$\cos \upsilon_k = \frac{\cos E_k - e}{1 - e\cos E_k}$$ True anomaly

$$\sin \upsilon_k = \frac{\sqrt{1-e^2}\sin E_k}{1 - e\cos E_k}$$ True anomaly

3 BDS Orbit calculation

$\Phi_k = \upsilon_k + \omega$	Argument of latitude
$\delta u_k = C_{uc} \cos 2\Phi_k + C_{us} \sin 2\Phi_k$	Argument of latitude correction
$\delta r_k = C_{rc} \cos 2\Phi_k + C_{rs} \sin 2\Phi_k$	Radius correction
$\delta i_k = C_{ic} \cos 2\Phi_k + C_{is} \sin 2\Phi_k$	Inclination correction
$u_k = \Phi_k + \delta u_k$	Corrected argument of latitude
$r_k = A(1 - e\cos E_k) + \delta r_k$	Corrected radius
$i_k + i_0 + \dot{i} t_k + \delta i_k$	Corrected inclination
$\mathrm{X}'_k = r_k \cos u_k$	Position in the orbital plane
$Y'_k = r_k \sin u_k$	Position in the orbital plane
$\Omega_k = \Omega_0 + (\dot{\Omega} - \omega_e) t_k - \omega_e t_{0e}$	Corrected longitude of ascending node
$X_k = X'_k \cos \Omega_k - Y'_k \sin \Omega_k \cos i_k$	Earth-fixed geocentric satellite coordinate
$Y_k = X'_k \sin \Omega_k + Y'_k \cos \Omega_k \cos i_k$	Earth-fixed geocentric satellite coordinate
$Z_k = Y'_k \sin i_k$	Earth-fixed geocentric satellite coordinate

The coordinates are in BDT/GPST.

4 Comparison with official (SHAO) CPF

- ✓ Calculate Navigation Message CPF

  Calculate ECEF (Earth Center Earth Fixed) coordinates on given epochs, in BDT or GPST. (Compensate leap seconds since year 2006.0).

  UTC = GPST - 18 @ Nov. 2018

  UTC = BDT - 4 @ Nov. 2018

  The coordinates are transformed in UTC.

- ✓ Write coordinates into CPF ‘10’ records. Set dummy header, data blocks and tail.

4 Comparison with official (SHAO) CPF

- ✓ Calculate Navigation Message CPF

  Calculate ECEF (Earth Center Earth Fixed) coordinates on given epochs, in BDT or GPST. (Compensate leap seconds since year 2006.0).

  UTC = GPST - 18 @ Nov. 2018

  UTC = BDT - 4 @ Nov. 2018

  The coordinates are transformed in UTC.

- ✓ Write coordinates into CPF '10' records. Set dummy

```
H1 CPF  1  CHA 2015 08 01 06  0000 CompassG1
H2  1000101 2002    36287 2018 11  4  0 14 42 2018 11 13 23 44 42   300 1 1  0 0 0
H5  0.0000
H9
10 0 58426    882.000000 0     -32277581.915     27095702.014         81334.833
10 0 58426   1782.000000 0     -32278981.454     27094344.038         10577.309
10 0 58426   2682.000000 0     -32280349.986     27092994.162        -60225.270
10 0 58426   3582.000000 0     -32281688.101     27091650.581       -130767.626
10 0 58426   4482.000000 0     -32282997.502     27090312.380       -200745.619
```

4 Comparison with official (SHAO) CPF

- ✓ Compare the two CPF files

Consider the meter level accuracy of our orbit, the differences between BDCS and ITRF could be ignored.

The SHAO CPF as host CPF. The NavMsg CPF as guest CPF. Interpolate the data in host for coordinates on guest epochs.

Host : ……X_{T1}, X_{T2}, …… X'_{t0}, X'_{t1} ……

Guest: X_{t0}, X_{t1}, X_{t2}, …… → X_{t0}, X_{t1}, ……

Also calculate derivatives while interpolation.

4 Comparison with official (SHAO) CPF

✓ Comparison Statistic

Calculate 3D-position difference:

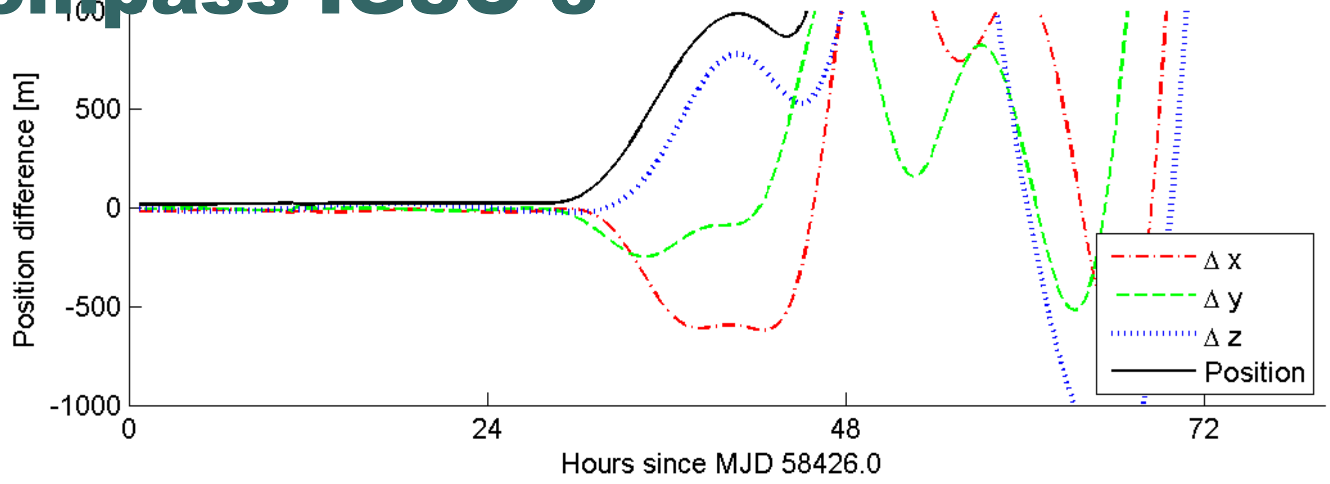
$$\Delta R = \sqrt{\Delta X^2 + \Delta Y^2 + \Delta Z^2}$$

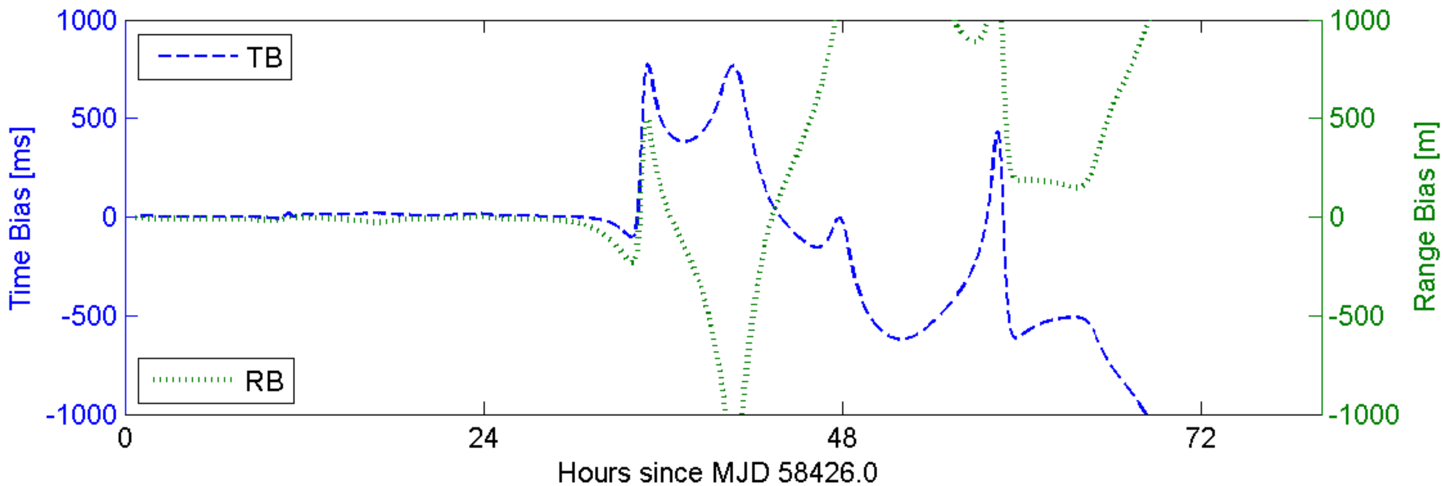
Solve Time Bias and Range Bias:

$$\rho = \dot{\rho} \cdot \mathrm{TB} + \mathrm{RB}$$

Note that TB\RB is unstable around geostatic points, where range derivative approaches zero.

Compass-IGSO-3

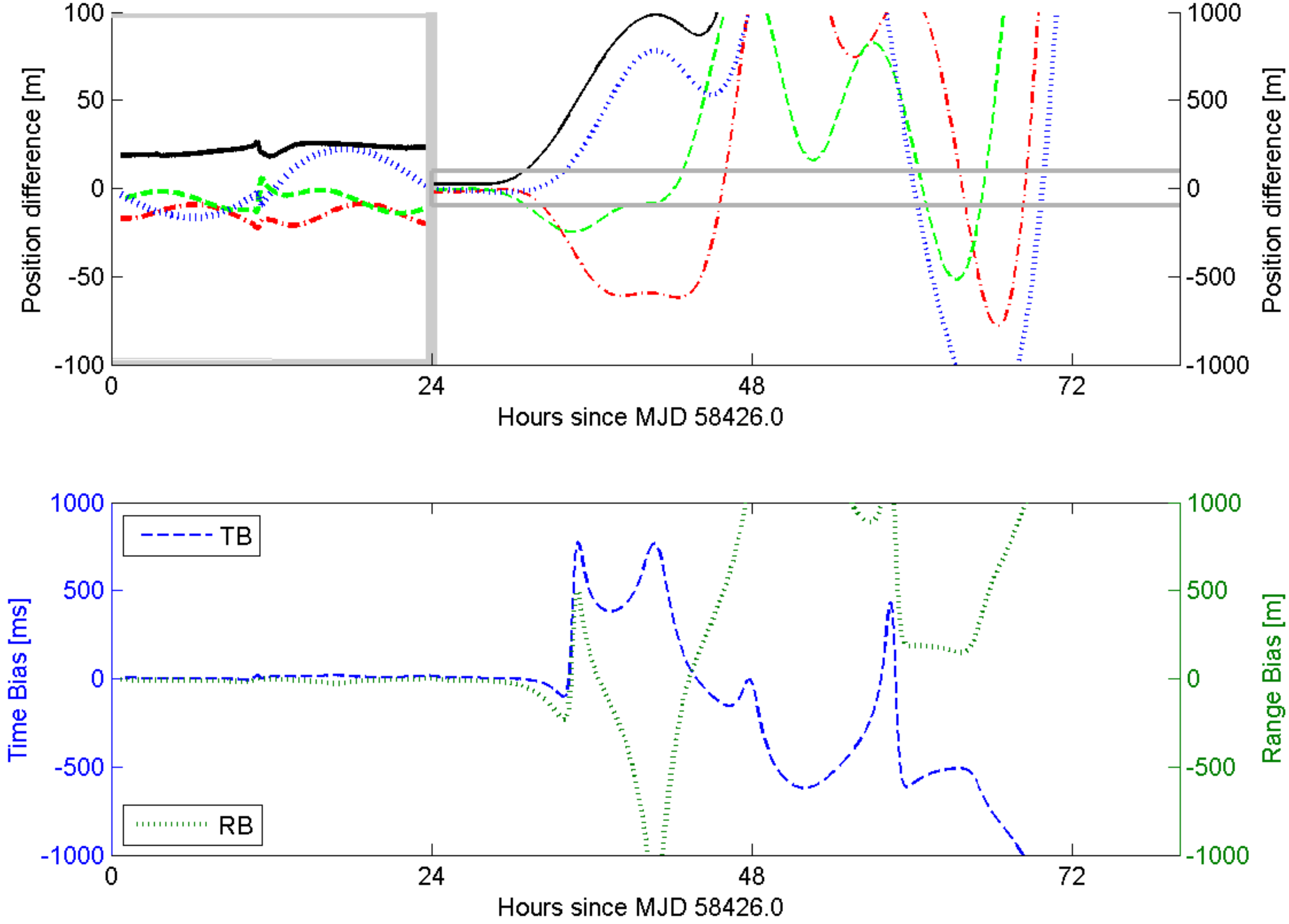




The upper plot shows differences in X,Y,Z coordinates within ±1 km.

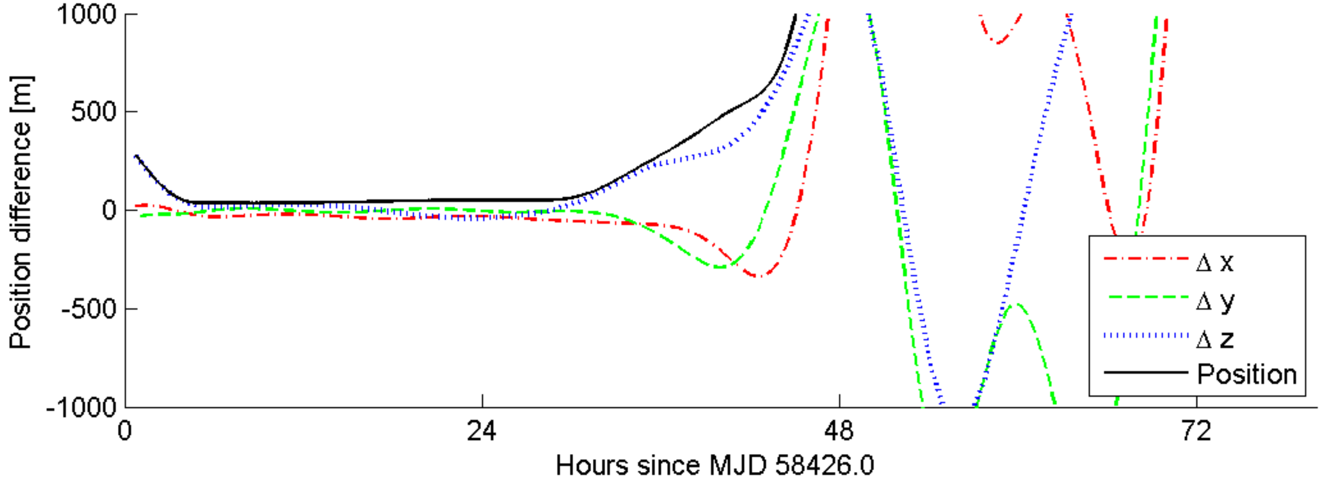
The lower plot shows Time Bias [ms] and Range Bias [m].

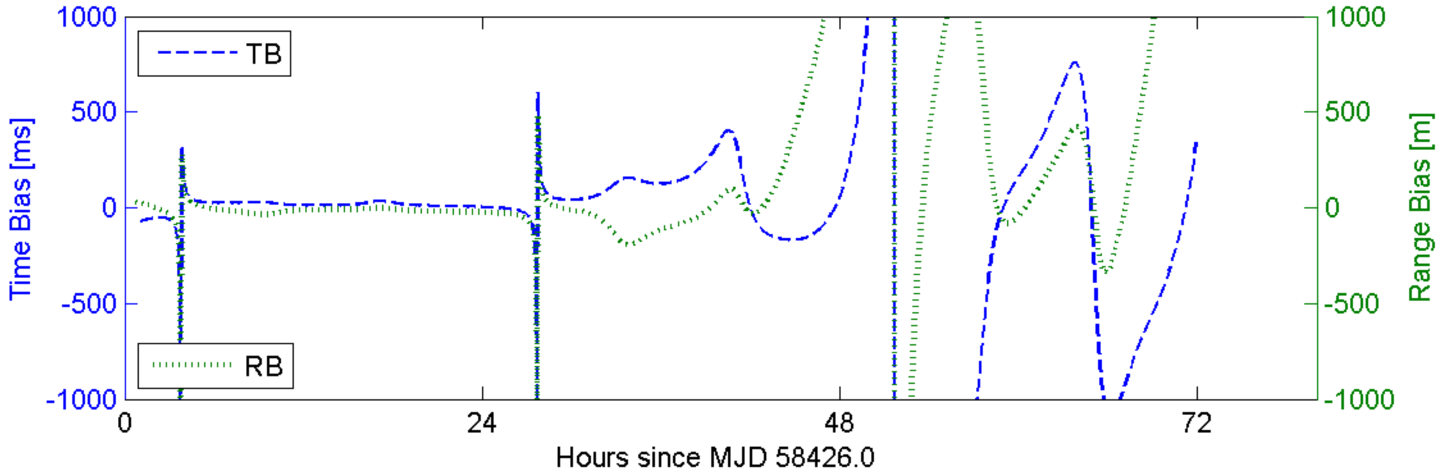
Compass-IGSO-3



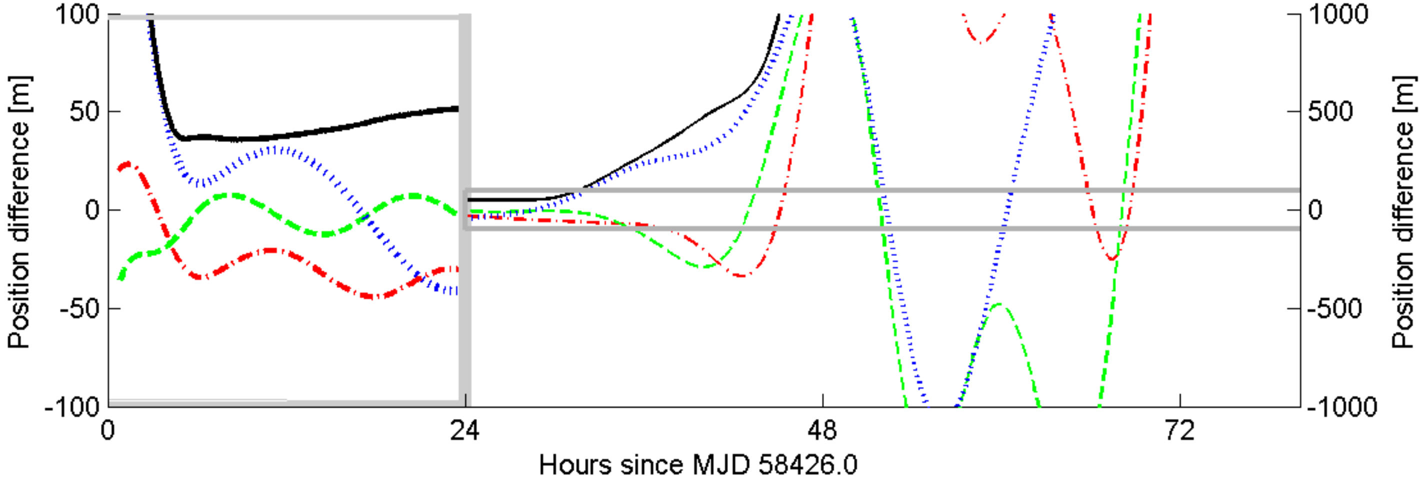
The X,Y,Z coordinates and position are less than 50m in 24h.

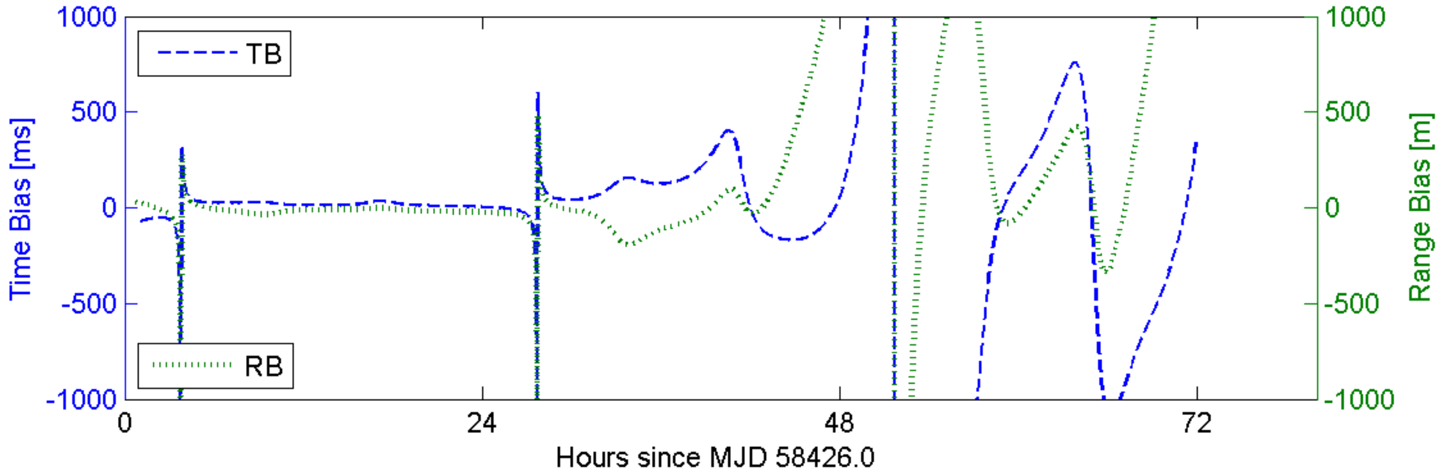
Compass-IGSO-5



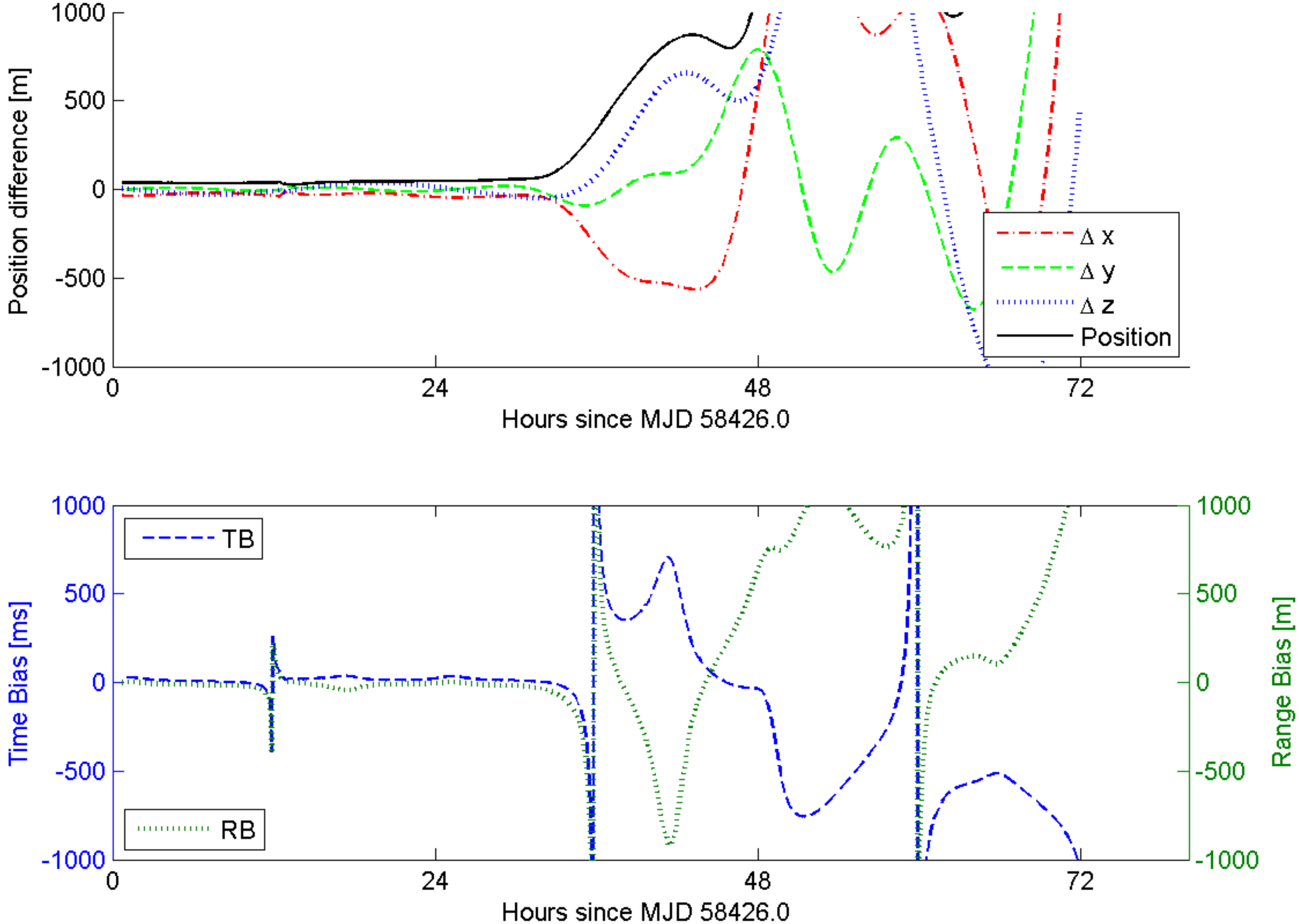


Compass-IGSO-5

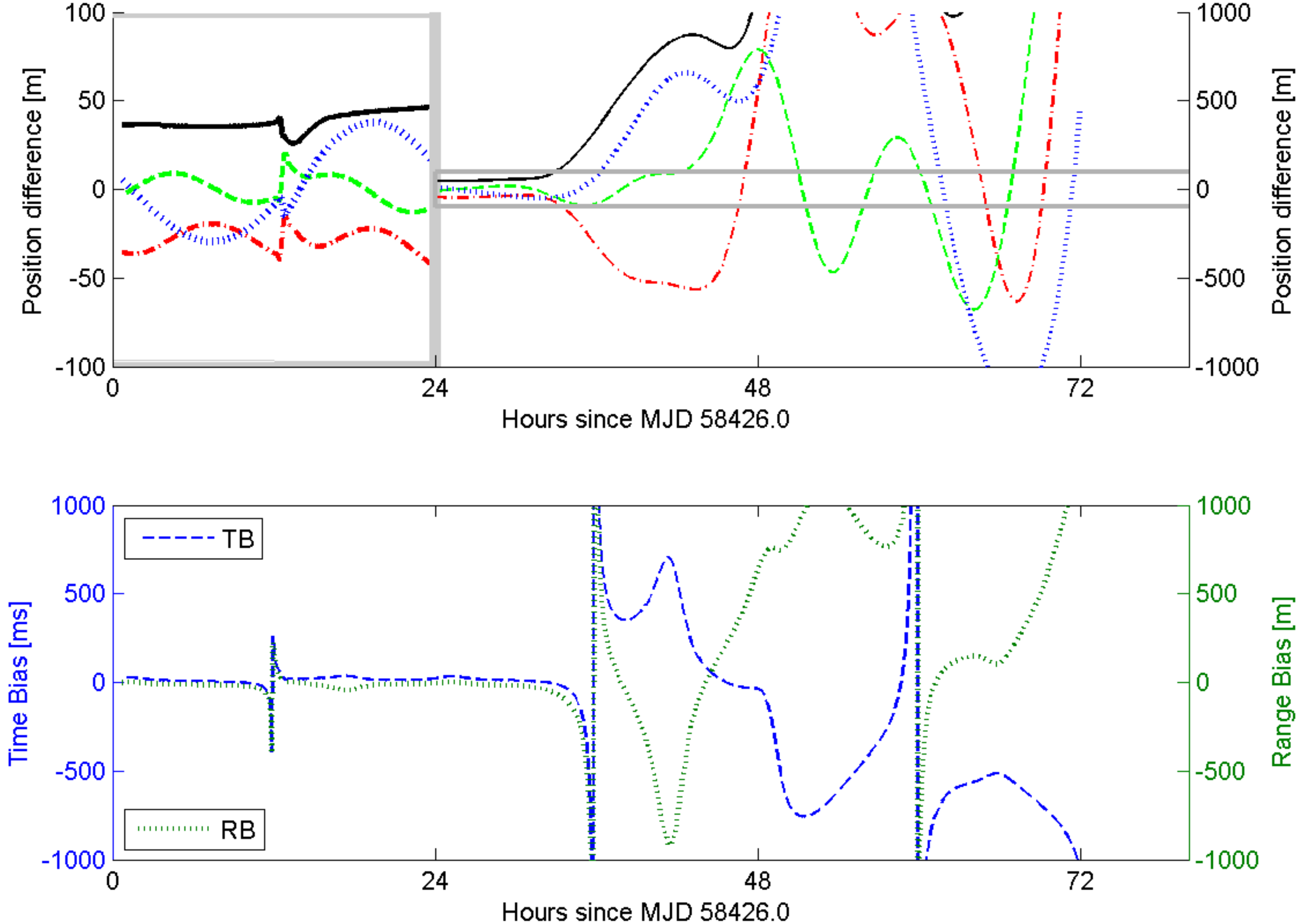




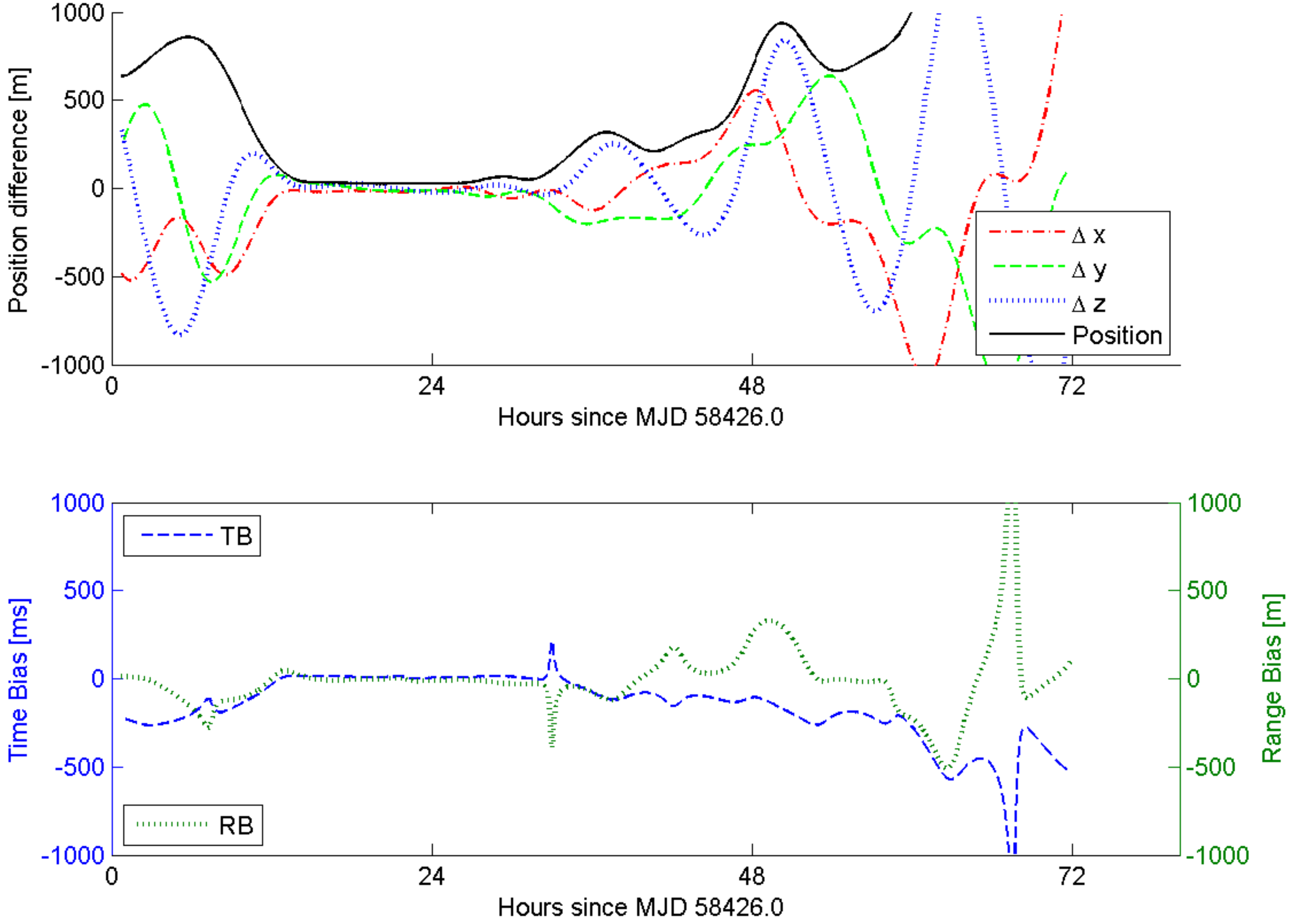
Compass-IGSO-6B



Compass-IGSO-6B



Compass-MEO-3



The coordinates for MEO are less than 1Km in 24h.

4 Comparison with official (SHAO) CPF

From the results showed above, we could see that:

- the plots shows much better consistency between the two predictions in first 24 hours.
- the observatory can always update navigation message whenever the satellite is visible.

5 Conclusion

1. Comparison between BDS broadcast orbit and official CPF orbit exhibits high consistency in first 24 hours.

2. BDS receiver-based navigation message can be alternative source for BDS CPF prediction.


Thank you!