Effects of Interoperability of GNSS Coordinate System

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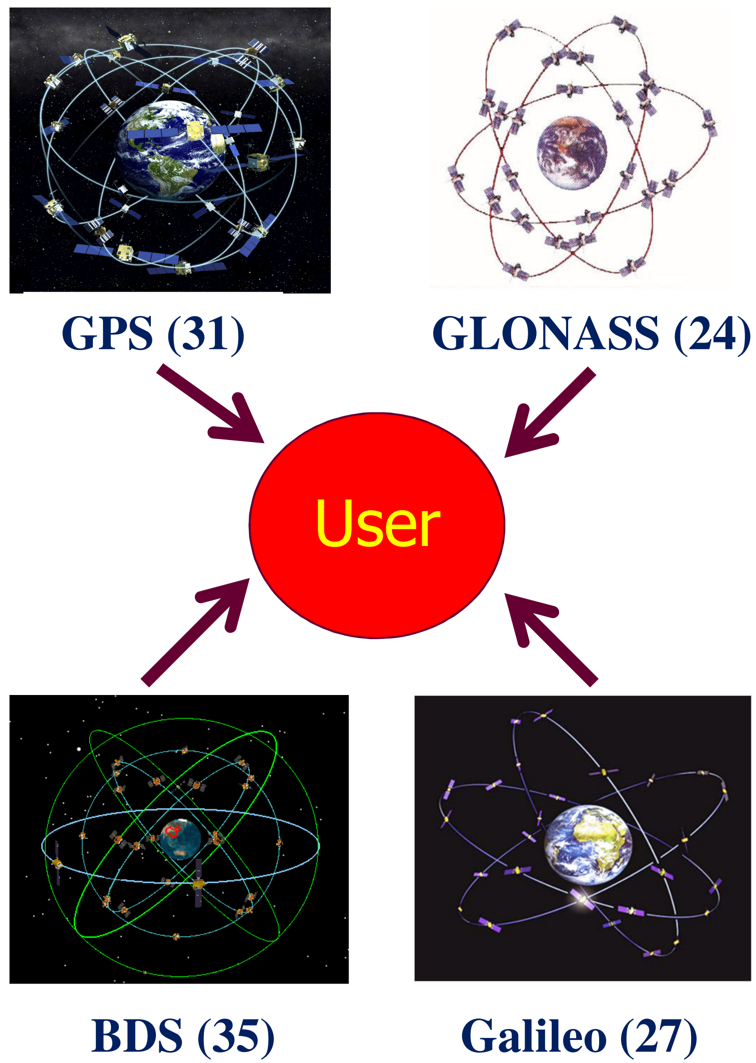
1. Introduction

■ Background

- ➢ **Multi GNSSs using together should provide better PNT performance than relying solely on one system if the systems compatible and interoperable**



1. Introduction

Background

- ➢ Interoperable open signals can
- ✓ improve the observed geometry
- ✓ increase reference fame stations
- ✓ increase time keeping clocks
- ✓ compensate systematic errors
- ✓ compensate random errors

The requirements are compatibility and interoperability!

1. Introduction

The status of GNSS coordinate references

- **GPS---WGS 84**
- **GLONASS---PZ-90**
- **BDS---CGCS 2000 or BDC 2000**
- **Different geometrical reference ellipsoids**
- **Different gravitational constants**
- **Different rotation velocity**
- **Different reference frame**
- **Different updating period**

2. Effects of Grav Cons on ephemeris

Broadcast ephemeris

↑

Fitting of orbit parameters

↑

Orbit & its prediction

↑

Ground control system

↑ ↑

Tracking stations | **Monitoring stations**

↑ ↑

Reference ellipsoid constants, reference frame, gravitational constant and earth' rotation velocity

2. Effects of Grav Cons on ephemeris

■ Change of GPS gravitational constant

Original gravitational constant of GPS	Since 1994, the gravitational constant of GPS
↓	↓
$GM = 3.986005 \times 10^{-14}$	$GM = 3.986004418 \times 10^{-14}$
↓	↓
Existing receivers use the original GM	Reduces about 1.2m orbit radial error

Receivers **?** **Orbits**

2. Effects of Grav Cons on ephemeris

- **Gravitational constant and earth rotation rate of GNSS**

	Gravitational cons GM （m^3/s^2）	Rotation rate $\omega_\oplus$ （rad/s）
GPS	3.986005×10^{-14}	7.2921150×10^{-5}
GLONASS	$3.986004418 \times 10^{-14}$	7.2921150×10^{-5}
Galileo	$3.986004415 \times 10^{-14}$	$7.2921151467 \times 10^{-5}$
BDS	$3.986004418 \times 10^{-14}$	7.2921150×10^{-5}
IERS	$3.986004418 \times 10^{-14}$	7.2921150×10^{-5}

2. Effects of Grav Cons on ephemeris

Effect of ΔGM on orbit

$$\Delta\vec{r} = \frac{1}{2GM} \cdot t_k \cdot \left(\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} + \omega_{\oplus} \cdot \begin{bmatrix} -y \\ x \\ 0 \end{bmatrix} \right) \cdot \Delta GM$$

$\dot{\vec{r}} = [\dot{x} \quad \dot{y} \quad \dot{z}]^T$ (satellite velocity vector)

$t_k = t - t_{oe}$ (time starting from reference epoch)

Effects of ΔGM changes with →

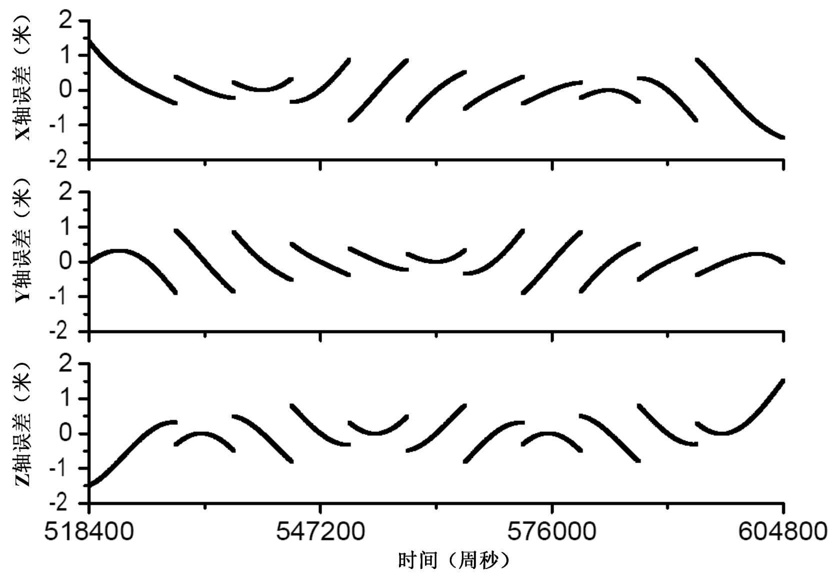
- Observation time t_k
- Satellite position
- Satellite velocity

2. Effects of Grav Cons on ephemeris

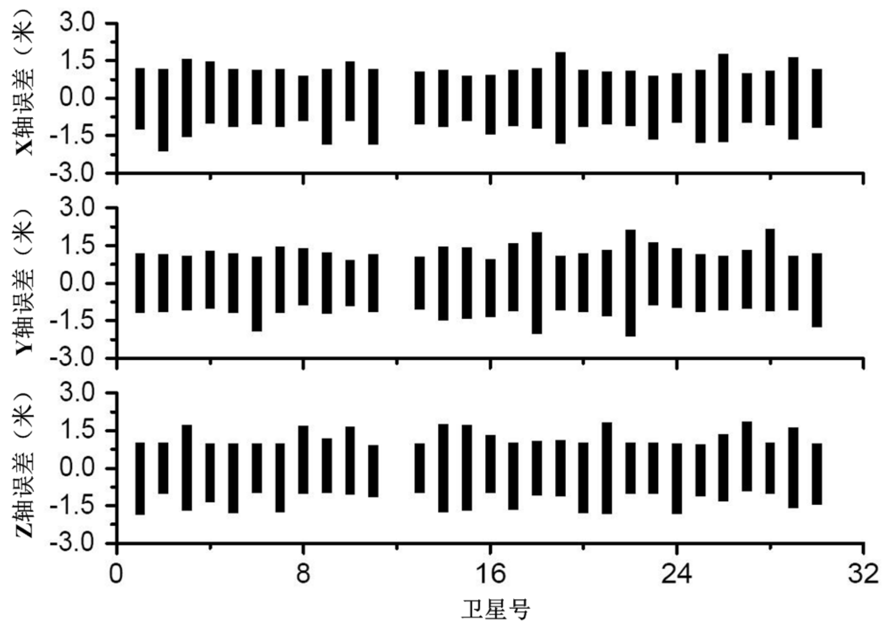
Effect of ΔGM on orbit

- $\Delta GM = GM_{GPS} - GM_{IERS}$

$$\Delta GM = (3.986005 - 3.986004418) \times 10^{14} = 5.82 \times 10^{6}$$



Effect of GM on Orbit of GPS03

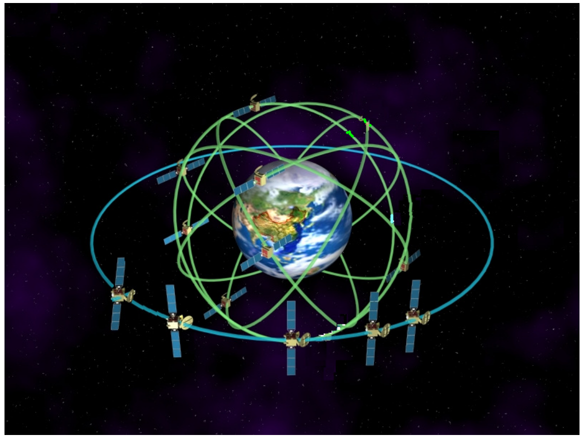


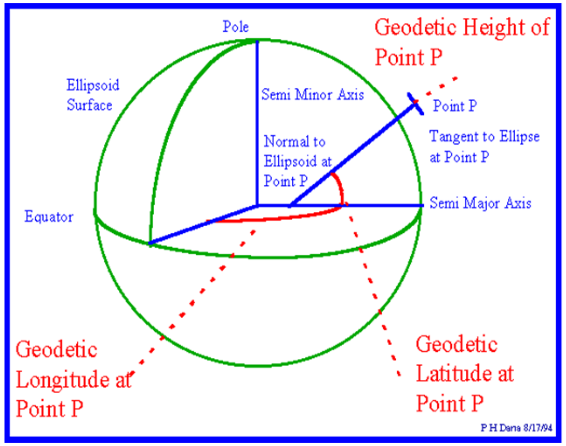
Effect of GM on all GPS orbits

2. Effects of Grav Cons on ephemeris

Analysis of Effect ΔGM on orbit

- **Different GM will result in orbit error to 2m**
- **The effects of ΔGM on the satellite orbits are different for different epochs**
- **The effects of ΔGM on different satellite orbits are different**





3. Effects of rotation velocity on orbits

■ Effects of rotational velocity $\Delta\omega_{\oplus}$ on orbit

$$\Delta\vec{r} = \begin{bmatrix} y \\ -x \\ 0 \end{bmatrix} \cdot t_k \cdot \Delta\omega_{\oplus}$$

Effects of rotation rate changes $\Delta\omega_{\oplus}$ →

- Observation time t_k
- Satellite position

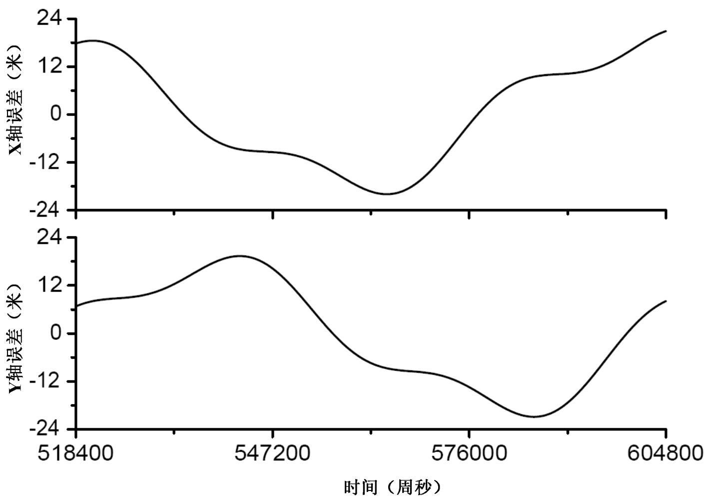
✓ GPS starts its broadcast ephemeris according to the second of GPS week, thus the biggest effect of the rotation rate on the orbit appears at the last day of the GPS week

3. Effects of rotation rate on ephemeris

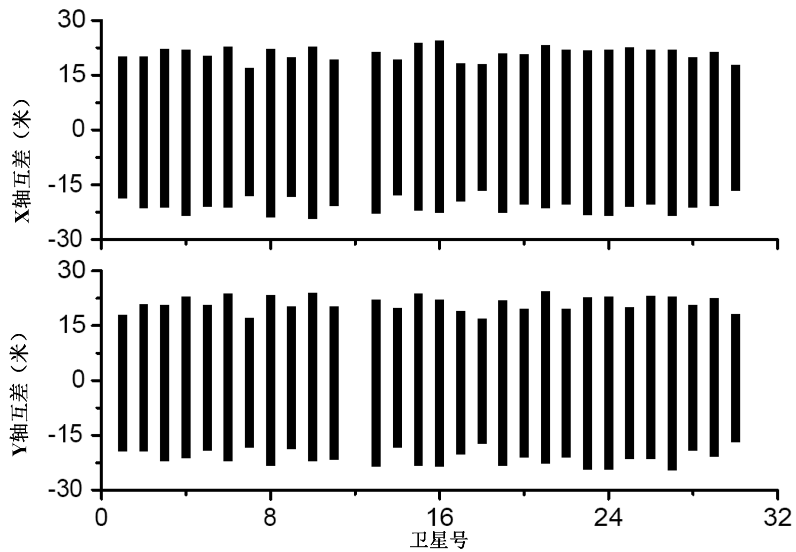
- **Effects of rotational rate $\Delta\omega_{\oplus}$ on orbit**

$$\omega_{Galileo} - \omega_{IERS} = \Delta\omega_{\oplus}$$

$$\Delta\omega_{\oplus} = (7.2921151467 - 7.2921150)\times 10^{-5} = 1.467\times 10^{-12}$$



Effects of Δω on GPS03



Effects of Δω on all GPS sats

3. Effects of rotation rate on ephemeris

- Effect analysis of $\Delta\omega_{\oplus}$ on orbit

➢ If substitute Galileo's rotational rate into GPS orbit determination software , then $\Delta\omega_{\oplus}$ will produce error more than 10m on the GPS orbit

➢ It should be noted that Galileo system uses a different earth rotation velocity from those of other GNSS, or from IERS recommended value

4. Effects of reference ellipsoid constants

■ Ellipsoid geometrical constants of GNSS

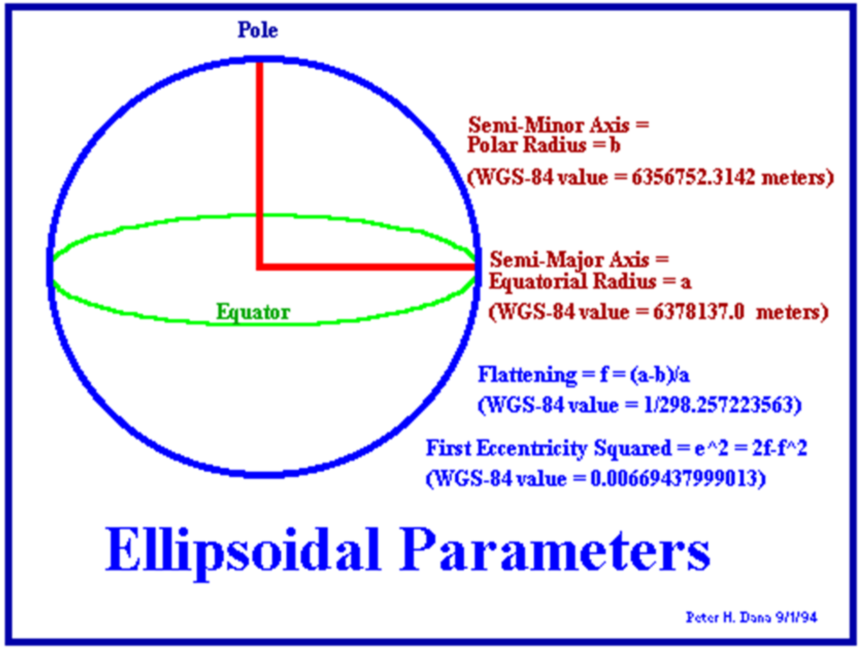
	Semi-major axis (m)	Flatting
GPS	6378137.0	298.257223563
GLONASS	6378136.0	298.25784
Galileo	6378136.5	298.25769
BDS	6378137.0	298.257222101
IERS	6378137.0	298.2572221008827

(Cheng P et al 2009)

4. Effects of reference ellipsoid constants

Effect of ellipsoid constants on GNSS positioning

- **The semi-major axis of GPS (WGS 84) and BDS (CGCS 2000) ellipsoids are the same, only the flatting is different**
- **Different GNSS uses different flatting of ellipsoid**



- **Difference of semi-major axis of the reference ellipsoid will only affect the height and the latitude, not the longitude**

4. Effects of reference ellipsoid constants

- **Effects of Δa, Δf, $[x_0, y_0, z_0]$, $(\varepsilon_x, \varepsilon_y, \varepsilon_z)$ as well as the scale m on positions**

$$
\begin{bmatrix} dB \\ dL \\ dH \end{bmatrix} = \begin{bmatrix} -\frac{\sin B\cos L}{M+H} & -\frac{\sin B\sin L}{M+H} & \frac{\cos B}{M+H} \\ -\frac{\sin L}{(N+H)\cos B} & \frac{\cos L}{(N+H)\cos B} & 0 \\ \cos B\cos L & \cos B\sin L & \sin B \end{bmatrix} \cdot \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix}
$$

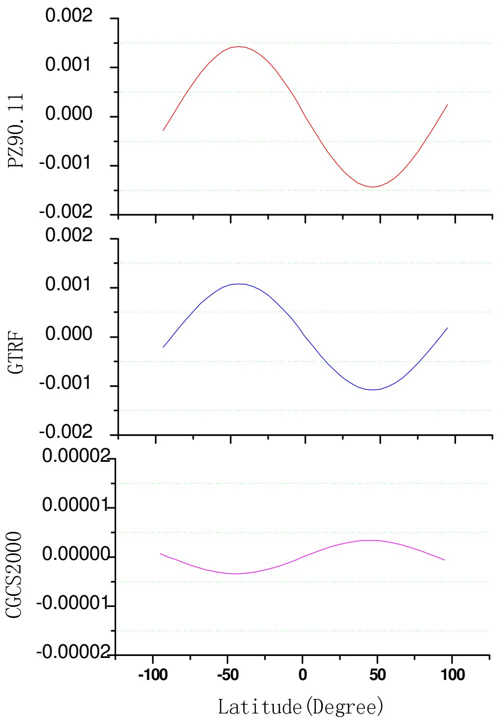
$$
+ \begin{bmatrix} -\frac{(N+H)-Ne^2\sin^2 B}{M+H}\sin L & -\frac{(N+H)-Ne^2\sin^2 B}{M+H}\cos L & 0 \\ \frac{N(1-e^2)+H}{N+H}\mathrm{tg}B\cos L & \frac{N(1-e^2)+H}{N+H}\mathrm{tg}B\sin L & -1 \\ Ne^2\sin B\cos B\sin L & Ne^2\sin B\cos B\cos L & 0 \end{bmatrix} \cdot \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \end{bmatrix}
$$

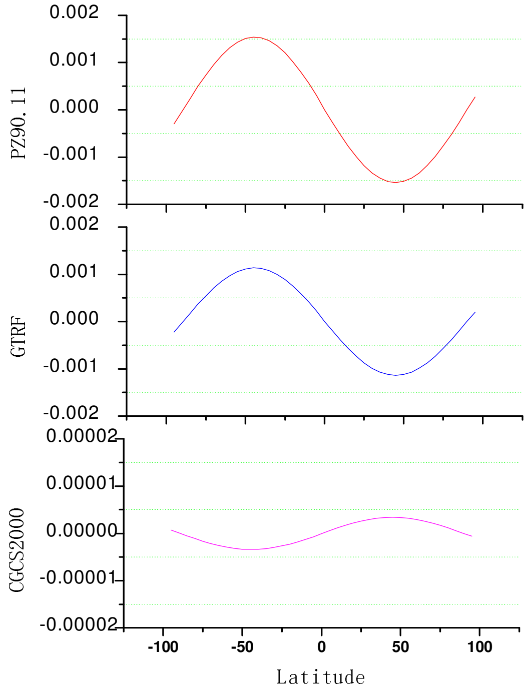
$$
+ \begin{bmatrix} -\frac{Ne^2\sin B\cos B}{M+H} \\ 0 \\ (N+H)-Ne^2\sin^2 B \end{bmatrix} \cdot m
$$

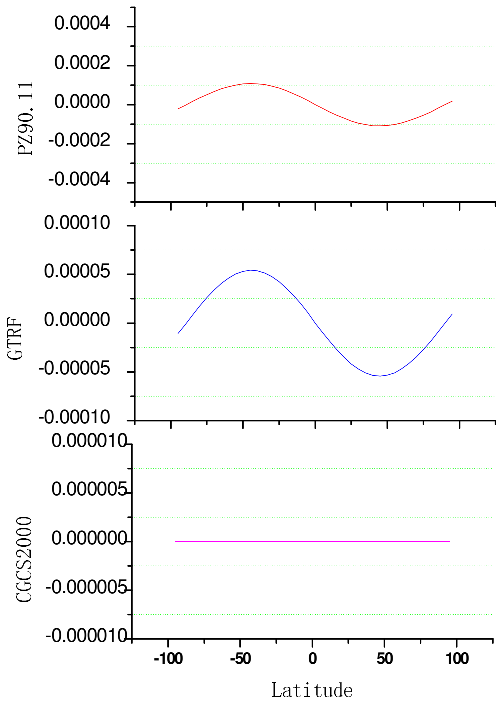
$$
+ \begin{bmatrix} \frac{Ne^2\sin B\cos B}{(M+H)a} & \frac{M(2-e^2\sin^2 B)\sin B\cos B}{(M+H)(1-f)} \\ 0 & 0 \\ -\frac{N}{a}(1-e^2\sin^2 B) & \frac{M(1-e^2\sin^2 B)\sin B\sin B}{1-f} \end{bmatrix} \cdot \begin{bmatrix} da \\ df \end{bmatrix}
$$

4. Effects of reference ellipsoid constants

■ Latitude effects of diff ellipsoids



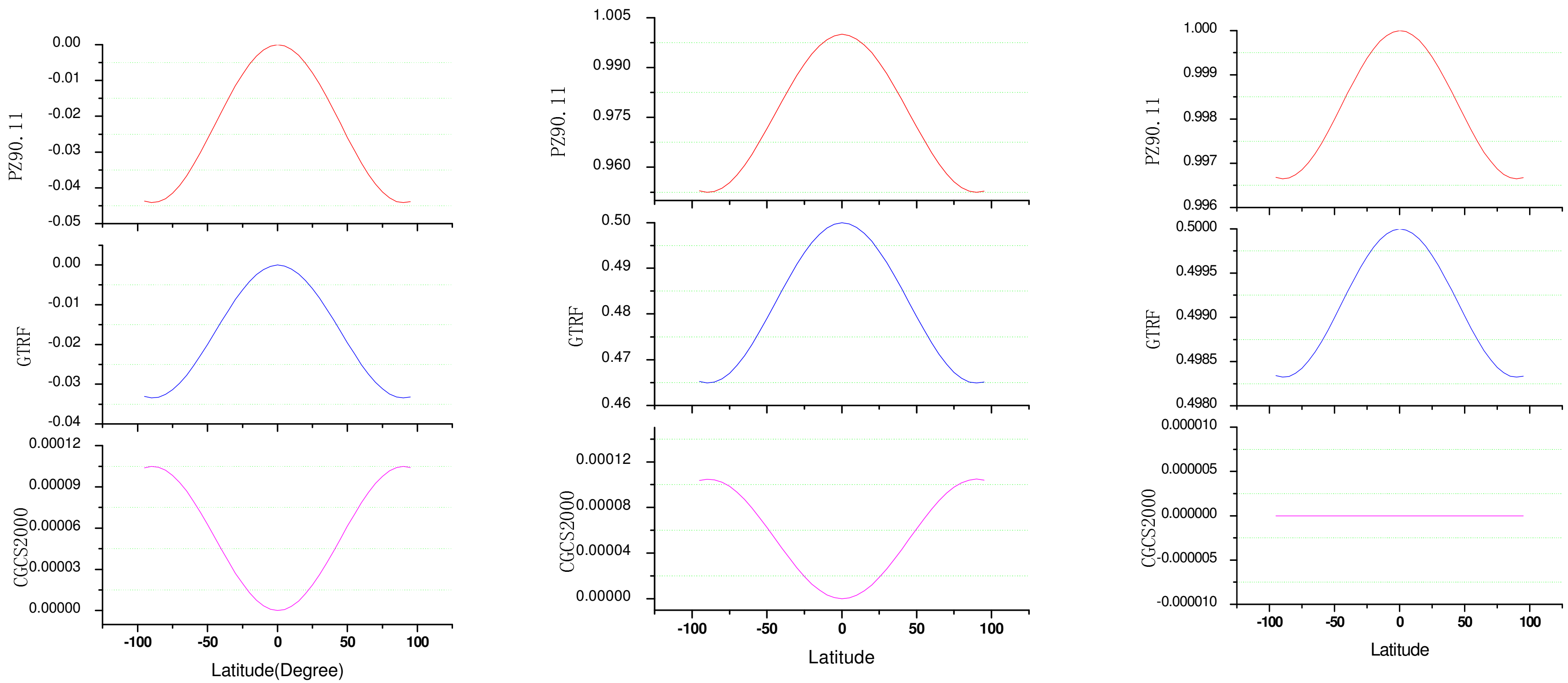




Effect btw GPS & BDS Effect btw GPS & Glo Effect btw GPS & Gal

4. Effects of reference ellipsoid constants

■ Height effects of diff ellipsoids



Effect btw GPS & BDS   **Effect btw GPS & Glo**   **Effect btw GPS & Gal**

4. Effects of reference ellipsoid constants

■ Effect analysis of ellipsoid constants

- Effects of GPS & BDS ellipsoids on both of the latitude and Height are about 10^{-6}s (or 0.1mm) . It may be neglected
- However, different *a* btw GPS (or BDS) and Galileo (GRTF) as well as GLONASS (PZ90) will result in error of 0.001s (or 3cm) and 0.0015s (or 4.5cm) in latitude respectively
- Height effects arrives at 0.5m and 1m respectively

5. Effects of diff reference frames

■ Effects of reference frames

- **Differences of coordinate frames are usually reflected in satellite orbits**
- **If CGCS2000 is selected as positioning system, the corrections of the linearized GPS observation equations will contain the effects of reference frames and systematic orbit errors**
- **If single differencing positioning method is employed, only the remain errors of reference frames affects the positioning results**

5. Effects of diff reference frames

Effects of reference frames

Frame errors ➡ orbit errors ➡ positioning errors

$$\left|U_{ij}^{T}\Delta r_{ij}\right| \le \frac{\left\|r_{ij}\right\|}{\left\|r_{j}^{s}\right\|}\left\|\Delta r^{s}\right\|$$

Influence function

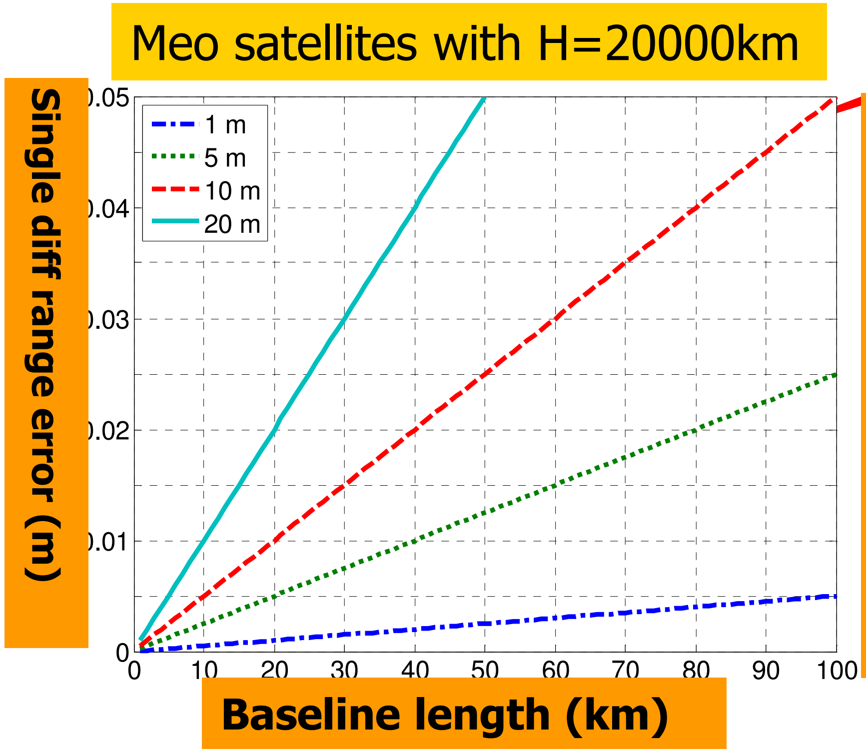
$\left\|U_{ij}^{T}\Delta r_{ij}\right\|$	Errors of baseline vector
Δr^{s}	Error of satellite orbit
$\left\|r_{ij}\right\| / \left\|r_{j}^{s}\right\|$	Ratio of Ranging btw stations and btw satellite and stations

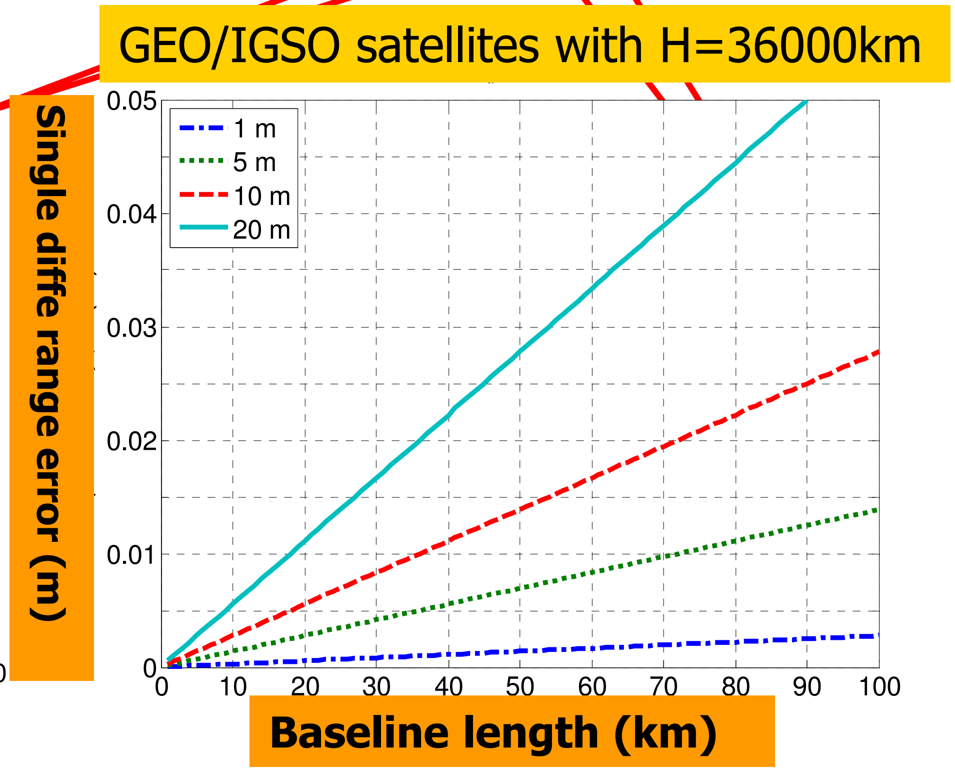
- Coordinate system errors will be reduced by differentiating the observations of near stations

5. Effects of diff reference frames

- **Effects of coordinate system offsets on single differential positioning**

<5cm





Influences of single differentiation positioning by the coordinate offsets are 1m, 5m, 10m, 20m respectively

5. Summary

1. As broadcast ephemeris is related to the gravitational constant GM and the rotation velocity ω of the earth, they should be consistent to those of ephemeris
2. Original GM of GPS and present one are different, the orbit error more than 1m will be introduced (Receiver and broadcast ephemeris still use the original one for consistency)
3. Different rotational velocity affects satellite orbits. The biggest error will arrive at several ten meters
4. Broadcast ephemeris is not related to semi-axis *a*, thus different *a* does not affect user positioning

5. Summary

5. If GNSS positioning results need to be transformed to geodetic ones, the parameters of different ellipsoids should be used for different countries

6. The different frames of GNSS will result in satellite orbit errors with several cm or dm, then systematically affect the single point positioning results

7. The interoperability parameters should be introduced into functional models; or using differential positioning to reduce the effects

8. BDS coordinates connected to CGCS2000 by GPS observations, thus additional errors are included

5. Summary

9. Coordinates updating strategies of BDS and GPS are different. GPS updates them to every June 30, which reduces deformation effects

10. Multi GNSS receivers should be used for tracking stations. The plate moving information from the ITRF and IGS should be used for generating the interoperability parameters

The idealized reference coordinate system of GNSS should be Interchangeable!

Thank you!