Research on GNSS Interoperable Parameters

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Beijing, China, Nov. 7, 2012
Interoperability refers to the ability of global and regional navigation satellite systems and augmentations and the services to be used together to provide better capabilities at the user level than would be achieved by relying solely on the open signals of one system.

Multi-GNSS is able to achieve interoperability.

BUT, existence of differences among GNSSs cause inconvenience to users.
Thus, we need:

- Define the differences among GNSSs
- Study the parameters to represent these differences
- Process and transmit the parameters to users
- Make sure the users can depend on the parameters to improve services
Differences among GNSSs:

— Constellation: Satellite number, Types of satellite orbit, etc.

— Signal: Modulation, Center frequency, Received power, etc.

— Message: Massage structure, Data content, Data format, etc.

— System time reference

— System coordinate reference

These differences effect users on:

— Position, Navigation and Timing
Positioning equation:

\[
\sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} - c \cdot v_{T_b} = \tilde{\rho}_i + (\delta\rho_i)_{\text{ion}} + (\delta\rho_i)_{\text{trop}} - c \cdot v_{t_i}^a
\]

- the elements:
  - can be obtained from signals or messages of different system;
  - have different format and precision.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Differences</th>
<th>Parameter</th>
<th>Differences</th>
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<tbody>
<tr>
<td>((x_i, y_i, z_i))</td>
<td>✓ ✓ ✓ ✓</td>
<td>(\tilde{\rho}_i)</td>
<td>✓ ✓ ✓ ✓ ✓</td>
</tr>
<tr>
<td>((\delta\rho_i)_{\text{ion}})</td>
<td>✓ ✓ ✓ ✓</td>
<td>(v_{t_i}^a)</td>
<td>✓ ✓ ✓ ✓ ✓</td>
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</tbody>
</table>
### GNSS interoperable parameters

<table>
<thead>
<tr>
<th>Differences</th>
<th>Items</th>
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<tr>
<td><strong>Signal</strong></td>
<td>User-Received Signal Level, Modulation Error, Correlation Characteristics, Phase Coherence, TGD</td>
</tr>
<tr>
<td><strong>Ephemeris</strong></td>
<td>Orbit offset, GNSS reference bias</td>
</tr>
<tr>
<td><strong>Onboard Clock</strong></td>
<td>Clock offset, GNSS Time Bias</td>
</tr>
<tr>
<td><strong>Propagation</strong></td>
<td>Ionosphere</td>
</tr>
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In order to provide better service for users:
— utilize specific method to monitor interoperable parameters;
— calculate parameters in a common time reference and coordinate reference frame;
— broadcast parameters to users;
— take parameters to eliminate adverse effect of the GNSS differences.
Without interoperable parameters

GLONASS Time
GLONASS Signal
GLONASS Ephemeris
GLONASS Ionosphere Model
GLONASS Coordinate Reference Frame
......

Beidou Time
Beidou Signal
Beidou Ephemeris
Beidou Ionosphere Model
Beidou Coordinate Reference Frame
......

Galileo Time
Galileo Signal
Galileo Ephemeris
Galileo Ionosphere Model
Galileo Coordinate Reference Frame
......

Too many dates!
Limited accuracy!
Divide these interoperable parameters into two sub-sets:

Interoperable Parameter Set

- Signal Parameters
  - User Received Signal Level
  - GNSS coordinate bias
  - GNSS time bias
  - TGD

- Message Parameters
  - Orbit
  - Correlation Characteristics
  - Phase Coherence
  - Clock offset
  - Ionosphere
  - Modulation

GNSS interoperable parameter Set
Signal Parameters

Provide users interoperable parameters in signal level:

— ability to chose a high quality signal in receiving process

— reduce the first positioning duration and decrease the complexity of receiver

Too many signals!
**User Received Signal Level**

**Definition:** The signal power when it arrives at the ground station.

**Detection:** Use ground monitoring receiver to monitor the signal power and its variation range.

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**Modulation**

**Definition:** The error which was produced in the modulation and transmission, including: phase modulation error and amplitude modulation error.

**Phase modulation error:** The differences between the real phase in each channel and the ideal phase of the signal.

**Amplitude modulation error:** The differences between the real amplitude in each branch and the ideal amplitude of the signal.

**Detection:** Compare the received signal to designed signal.
**Correlation Characteristics**

**Definition:** Outputs of correlation peak amplitude and correlation curve characteristics after the operation of signal correlation.

**Correlation loss:** Power difference between the actually received signal and the ideal signal in the designed bandwidth of the signal.

**Correlation curve:** The curve obtained through correlation calculation between recovered ranging code and the ideal ranging code of all signals.

**Detection:** The monitoring receiver acquire navigation signal, and then evaluate amplitude attenuation and curve distortion which is caused by wave distortion.
Calculation method:
Correlation function:

\[ CCF(\varepsilon) = \frac{\int_{0}^{T_p} S_{\text{BB-PreProc}}(t) \cdot S_{\text{Ref}}^*(t - \varepsilon) dt}{\sqrt{\left(\int_{0}^{T_p} |S_{\text{BB-PreProc}}(t)|^2 dt\right) \cdot \left(\int_{0}^{T_p} |S_{\text{Ref}}(t)|^2 dt\right)}} \]

\( S_{\text{BB-PreProc}} \) is the base-band signal been pretreated (down conversion, Doppler removal); reference signal \( S_{\text{Ref}} \) is ideal base-band signal generated by local receiver; integral time \( T_p \) is the main code period of reference signal.

Relative loss:
Power loss of available signal to all received signals:

\[ P_{CCF}[dB] = \max_{\varepsilon} \left(20 \cdot \log_{10}(|CCF(\varepsilon)|)\right) \]
**Phase Coherence**

**Definition:** The relative change of signal elements in the timeline.

**Code and carrier Coherence:** Relative jitter value between ranging code and carrier wave in the same signal branch.

**Codes Coherence:** Relative jitter value of time delay between ranging code and carrier wave; relative jitter value of ranging codes in different signal branch.

**Detection:** Monitor the navigation signal.

**Calculation:** Coherence between code and carrier & Coherence in ranging codes
Calculate method:

Code and carrier Coherence:
In interval of \([t, t+T]\), use carrier wave limited in \(L_j\) and \(L_k\) as radiation of code carrier wave in \(L_i\) frequency:

\[
\text{CCD}^{L_i}_{L_j,L_k}(t, t+T) = PR^{L_i}_{L_i}(t+T) - PR^{L_i}_{L_i}(t) - [CR^{L_i}_{L_i}(t+T) - CR^{L_i}_{L_i}(t)]
\]

\[
-2 \left( \frac{f_{L_1}}{f_{L_i}} \right)^2 \Delta I^{L_i,L_j,L_k}(t, t+T)
\]

\(\Delta I^{L_i,L_j,L_k}(t, t+T)\) denotes the ionospheric delay differences in \(L_1\) frequency on interval \([t, t+T]\), these differences calculated from D-value of \(L_j\) and \(L_k\) frequency amplitude. If \(\text{CCD}^{L_i}_{L_j,L_k}(t, t+T)\) neets:

\[100 \leq T \leq 7200, \ t_1 \leq t \leq t_2 - T\]

\[\text{CCD}^{L_i}_{L_j,L_k}(t, t+T) > 6.1 \text{ m}\]

Thus, code and carrier wave are consistence at \(t+T\).
Calculate method:

Coherence in ranging codes:

$$\rho'_i = \rho_i + \lambda_i^2 \frac{\Phi_j - \Phi_i}{\lambda_j^2 - \lambda_i^2}, \quad \rho'_j = \rho_j + \lambda_j^2 \frac{\Phi_i - \Phi_j}{\lambda_i^2 - \lambda_j^2}, \quad \Delta \rho = \rho_i - \rho_j - \Delta \rho_{i,j}$$

$$\rho'_i, \rho'_j, \rho_i, \rho_j$$ represent pseudo-range when exist ionospheric error and no ionospheric error respectively, $$j$$ represent frequency which is different from $$i$$. $$\Phi_i$$ and $$\Phi_j$$ are observation value of carrier phase (the unit is distance), wavelength are $$\lambda_i$$ and $$\lambda_j$$ respectively; $$\lambda_i^2 (\Phi_j - \Phi_i)/(\lambda_j^2 - \lambda_i^2)$$ is amended value of dual-frequency ionosphere; $$\Delta \rho$$ represent time delay between receiver channels.
**Definition:** GNSS precise orbit calculated based on same monitor station, same orbit determination algorithm, same space-time reference.

**Detection:** Utilize observation value of multi-mode receiver and precise orbit algorithm to calculate GNSS precise orbit.

**Calculation:**

a) Detect the coarse error of observation value and cycle slip;

b) Using the processed data to the precision of satellite orbit, station location and ERP parameter estimation;

c) Obtained by compare to the correction information of broadcast ephemeris orbit.
**Definition:** Calculate GNSS precise clock error based on same monitor station, same orbit determination algorithm, same space-time reference.

**Detection:** Utilize Observation data of Laser, radio, dual-frequency carrier wave and precise clock error algorithm to get precise clock error of GNSS.
Calculation:

a) Detect the coarse difference and cycle slip of the observation data;

b) Take real-time precise satellite orbit, the position of observation station, and EPR parameters as known parameters to real-time precise satellite clock error processor;

c) Use preprocessed real-time observation data by means of Square Root Filter to evaluate clock error;

d) Compare the evaluated clock error with the broadcasted clock error, and then get amended clock error information.
**Ionosphere**

**Definition:** Total electron content of global ionospheric grid based on the calculation of dual-frequency observations.

**Detection:** By monitoring of ionospheric grid model.

**Calculation:**

a) Total electron content (TEC) in the path from monitoring station to satellite:

\[ \tilde{P}^k_{1,i} - \tilde{P}^k_{2,i} = (1 - \xi) \frac{40.28 \cdot TEC}{f_1^2} + \Delta b^k + \Delta b_i \]

b) Work out total electron content of global ionospheric grid by geomagnetic model:

\[
TEC(\phi, \lambda) = \sum_{n=0}^{n_{d_{\text{max}}}} \sum_{m=0}^{n} \tilde{P}_{nm} (\sin \phi) \cdot (\tilde{A}_{nm} \cos(m\lambda) + \tilde{B}_{nm} \sin(m\lambda))
\]
**Definition:** The time differences between each satellite navigation system and UTC.

**Detection:** Monitor each system time and compare with UTC.

**Calculation:**
1) Calculate the differences $\Delta_{sys}$ between each system time and UTC(K),

$$\Delta_{sys} = T_{sys} - UTC(K);$$

2) Worked out the difference $\Delta k$ between UTC(K) and UTC,

$$\Delta k = UTC(K) - UTC;$$

3) Normalized each system time to UTC,

$$\Delta = \Delta_{sys} + \Delta k.$$
**GNSS interoperable parameters**

**Definition:** Differences between coordinate reference frame and ITRF.

**Detection:** Measure the coordinate of given points in different coordinate reference frame, then calculate their difference.

**Calculation:**

\[
\Delta P_{n,(ITRF,i)} = \begin{bmatrix} X_n \\ Y_n \\ Z_n \end{bmatrix}_{ITRF} - \begin{bmatrix} X_n \\ Y_n \\ Z_n \end{bmatrix}_i = \begin{bmatrix} dX_n \\ dY_n \\ dZ_n \end{bmatrix} + \begin{bmatrix} dm & \varepsilon_3 & -\varepsilon_2 \\ -\varepsilon_3 & dm & \varepsilon_1 \\ \varepsilon_2 & -\varepsilon_3 & dm \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_i
\]

\[
\Delta_{ITRF,i} = E(\Delta P_{(ITRF,i)}) \pm k \times \sqrt{D(\Delta P_{(ITRF,i)})^2}, \quad k = 1, 2, 3
\]
**Definition:** GNSS signal group time delay

**Detection:** Monitor and compare the signal time delay

**Calculation:**

\[
TGD(f_i, f_j) = \frac{PR(f_i) - PR(f_j)}{1 - (f_i/f_j)^2}
\]

Where, \(f_i\) and \(f_j\) are carrier wave frequency of two GNSS signals, \(PR(f_i)\) and \(PR(f_j)\) are the corresponded signal group time delay.
Two forms can represent the parameters:
The precision data point the assessment result.
The tolerance data point the difference between the monitoring result and the assessment result.
## Form of interoperable parameters

### Comparison of the two forms:

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<th>Advantages</th>
<th>Disadvantages</th>
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<tr>
<td><strong>Precision data</strong></td>
<td>Less computational complexity of user receiver</td>
<td>Need high data rate</td>
</tr>
<tr>
<td></td>
<td>Less computational complexity of the third monitoring station</td>
<td>Increased the time of receiving complete information</td>
</tr>
<tr>
<td><strong>Tolerance data</strong></td>
<td>Low requirements of data rate</td>
<td>Additional process at user receiver</td>
</tr>
<tr>
<td></td>
<td>Receive complete information in short time</td>
<td>Increased the amount of computation in the third monitoring station</td>
</tr>
<tr>
<td></td>
<td>Can still use original GNSS to realize PVT when the parameters of the third party are unavailable</td>
<td></td>
</tr>
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Except the providers own links, interoperable parameters can be broadcasted to users in different ways.

— internet/mobile communication/commercial satellite

Broadcasting interoperable parameters
Other issues about GNSS interoperability:

<table>
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<th>DOP amelioration of multi-GNSS</th>
<th>The third frequency for interoperability</th>
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<tr>
<td>DOP saturation value</td>
<td>Frequency diversity</td>
</tr>
<tr>
<td>Utilize existing or planned spare capacity in civil/open service navigation messages to increase multi-GNSS interoperability</td>
<td>Definition, model and calculation of interoperable parameters</td>
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<tr>
<td>Utilize existing or planned spare capacity SBAS navigation messages in order to increase multi-GNSS interoperability</td>
<td>Monitoring method in interoperable parameters (include system time difference monitoring)</td>
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<tr>
<td>Patent of MBOC signal</td>
<td>System time difference monitoring</td>
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<td>Receive multi-system observation data</td>
<td>interoperable parameters broadcasting</td>
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<tr>
<td>Technology on receiving interoperable signal and receiver</td>
<td>Correction model of ionosphere and atmospheric delay in multi-GNSS</td>
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<tr>
<td>interoperable parameter model and algorithm taken by users</td>
<td>Correction model of solar radiation pressure in multi-GNSS</td>
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<tr>
<td>Data type consistency and transferability</td>
<td>Other methods to enhance interoperability</td>
</tr>
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Conclusion

WG-B and WG-D have paying more attention to overlaps between their work and in-depth interoperability research.

A platform is required to attracts more academic, experts and industry specialists to research on interoperability and to provide better services for users.
Conclusion

Under this platform, we can discuss the following topics:

- Interoperable signal
- Interoperable parameter
- Interoperability in user level
- Methods to enhance interoperability
- Interoperable algorithm

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Thank You for Your Attention!

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