PPP with Ambiguity Resolution (AR) using RTCM-SSR

Gerhard Wübbena, Martin Schmitz, Andreas Bagge

Geo++® GmbH
30827 Garbsen Germany
www.geopp.de
PPP with Ambiguity Resolution (AR) using RTCM-SSR

Abstract

The RTCM SC104 is developing a standard format to disseminate GNSS state space information. The RTCM-SSR (State Space Representation) format will support a variety of applications at different accuracy levels. Different SSR messages are evolved in basically three stages.

Stage 1 enables code-based PPP applications and consists of messages to transport satellite orbit corrections, satellite clock corrections and satellite signal code biases.

The next milestone (stage 2) is approaching standardization and consists of messages for vertical ionospheric total electron contents (VTEC) to enable single frequency code based PPP as well as messages for satellite signal phase biases to enable phase based PPP and ambiguity resolution.

Stage 3 shall concentrate on the development of slant ionospheric total electron content messages (STEC) as well as tropospheric delay messages to allow PPP-RTK, i.e. centimeter accuracy through ambiguity resolution within seconds of observation time.

The presentation discusses the overall RTCM-SSR concepts and development strategies as well as the current status and schedule.

Special focus will be on the consistency of SSR parameters and processing with respect to satellite signal code and phase biases and its relation to ambiguity resolution.
Outline

- RTCM SC104 SSR Working Group
- Strategy / Concepts for RTCM-SSR Development
- Satellite Code and Phase Biases
- Carrier Phase Ambiguity Resolution
- RTCM SSR Working Group - Status
- Summary/Outlook
• RTCM SC104 SSR Working Group
  • Strategy / Concepts for RTCM-SSR Development
  • Satellite Code and Phase Biases
  • Carrier Phase Ambiguity Resolution
  • RTCM SSR Working Group - Status
  • Summary/Outlook
RTCM SC104 – SSR Working Group

- RTCM SC104 – SSR Working Group established in 2007
  - about 10+ active members
  - about 30+ members in total

- primary goal
  - development of RTCM-SSR messages to exchange information about GNSS error states (SSR State Space Representation) up to precise positioning applications including RTK

Synthesis of PPP and RTK Networking*

Major GNSS Error Sources & RTCM State Parameters

- Satellite signal delay+bias
- Satellite clock error
- Satellite orbit error
- Satellite antenna (PCV)
- Ionosphere
- Troposphere
- Multipath
- Antenna (PCV)
- Rcvr clock error
- Rcvr signal delay+bias

WGS84
RTCM SSR Working Group

The proposed work plan consists of development of RTCM-SSR Messages in three major stages/steps:

- **Stage 1**
  satellite orbit, satellite clock and satellite code bias messages to enable **code-based real-time PPP for dual frequency** receivers: DF-RT-PPP

- **Stage 2**
  vertical TEC (VTEC) ionospheric message to enable **code-based RT-PPP for single frequency** receivers: SF-RT-PPP, satellite phase bias messages to enable **phase-based RT-PPP**.

- **Stage 3**
  ionospheric slant TEC (STEC) and tropospheric messages to enable **RTK-PPP**.
• RTCM SC104 SSR Working Group

• **Strategy / Concepts for RTCM-SSR Development**

• Satellite Code and Phase Biases

• Carrier Phase Ambiguity Resolution

• RTCM SSR Working Group - Status

• Summary/Outlook
Strategy / Concepts for RTCM-SSR Development

- RTCM-SSR shall be a **self-contained** format as far as possible

  i.e. all necessary information for consistent processing shall be contained in the RTCM-SSR stream or shall be specified in the standard document; the need for external information should be avoided
  - counter example: satellite PCV (tbd)

- the definition of RTCM-SSR contents **shall not limit/restrict** the generation of SSR streams; **no use of particular generation models or approaches**
  - example: conventional approaches with dynamic orbit modeling (IGS) as well as approaches with kinematic orbit modeling shall be supported

- **international conventions for** observation **modeling and/or corrections** shall be applied **as far as necessary** and as long as they are well defined and documented and freely usable
  - example: IERS convention

- do not prevent new ideas, models or approaches!
Strategy / Concepts for RTCM-SSR Development

- the standard shall allow in a flexible way **different update rates for different state parameters**

  Different error states possess different variability with time. Slowly changing states need lower update rates as highly variable states. This is the key characteristic that allows minimization of stream bandwidth.

- **self-consistency** of RTSM-SSR streams must be achieved

- **consistent processing** of SSR stream contents must be ensured

  Consistency is one of the major requirements in order to achieve the desired performance. Consistency of algorithms and computations for reference models must be assured as well as consistency of state parameter sets.

- the RTCM-SSR standard shall support **scalable global, continental, regional and/or local applications**
State Space Representation – GNSS Error States

- satellite signal bias
- satellite clock error
- satellite orbit error
- ionosphere
- troposphere
- multipath
- antenna (PCV)
- rcvr clock error
- rcvr signal bias

separation and representation of individual error components
Strategy / Concepts for RTCM-SSR Development

- **multiple stage models**
  - different messages for same state constituent
  - different *messages are added*
  - added messages add accuracy
  - required for RTCM-SSR development
    (e.g. spatial variation of atmospheric parameters)
  - allows for different applications/accuracies

- **examples**
  - satellite clock
    - initial component clock polynomial
    - optional component high rate clock
  - ionosphere
    - initial model Vertical TEC spherical harmonics
    - additional component slant TEC
SSR – Spatial Variations of GNSS Atmospheric States

- Satellite signal biases – per frequency/signal
- Satellite clock error
- Satellite orbit error
- Per SV ionosphere
- Ionosphere
- Troposphere
- Multipath
- Antenna (PCV)
- Receiver clock error
- Receiver signal bias

Common and individual error components for different signals, satellites, and ground positions.
• RTCM SC104 SSR Working Group
• Strategy / Concepts for RTCM-SSR Development

• **Satellite Code and Phase Biases**
• Carrier Phase Ambiguity Resolution
• RTCM SSR Working Group - Status
• Summary/Outlook
Satellite Code and Phase Biases

- **every transmitted GNSS signal** component experiences a *specific signal delay* (bias) in satellite HW/SW
- applies to satellite *code and phase signals*

- example:
  - GPS dual frequency observations: *code* (P1, P2) and *carrier* (L1, L2)
  - error components: satellite clock error $dt$ and *code biases* $BP_i$ and *phase biases* $BL_i$
  - combined clock and signal signal delay error at satellite antenna:

$$
\begin{align*}
    dP1 &= dt + BP1 \\
    dP2 &= dt + BP2 \\
    dL1 &= dt + BL1 \\
    dL2 &= dt + BL2
\end{align*}
$$

linear dependency between clock and bias terms

$\Rightarrow$ *only* 4 $(n_{signal} - 1)$ independent parameters
Satellite Code and Phase Biases

- **no specific reference bias/signal used** in RTCM-SSR, which allows **maximum flexibility** for service providers

- example
  - complete support of **reference bias/signal** like ionospheric free linear combination of P1, P2 (GPS/IGS)
  - **BR** defined to be bias-free gives biased clock and “differential” signal biases:

\[
\begin{align*}
\text{dP1} &= (dt + BR) + (BP1-BR) \\
\text{dP2} &= (dt + BR) + (BP2-BR) \\
\text{dL1} &= (dt + BR) + (BL1-BR) \\
\text{dL2} &= (dt + BR) + (BL2-BR)
\end{align*}
\]

or

\[
\begin{align*}
\text{dP1} &= dt' + BP1' \\
\text{dP2} &= dt' + BP2' \\
\text{dL1} &= dt' + BL1' \\
\text{dL2} &= dt' + BL2'
\end{align*}
\]

- **individual signal** component (code or carrier) can be utilized, if corresponding and **consistent bias** is transmitted
• RTCM SC104 SSR Working Group
• Strategy / Concepts for RTCM-SSR Development
• Satellite Code and Phase Biases

• **Carrier Phase Ambiguity Resolution**
• RTCM SSR Working Group - Status
• Summary/Outlook
Ambiguity Resolution

- **RTK** ("centimeters in seconds") requires resolution of carrier phase ambiguities
- different techniques have been developed in the past
  - **GFAR** – Geometry Free AR
    - linear combinations of different code and carrier signals are used to determine ambiguities
    - often used: **Melbourne-Wübbena - MW**
      - combines carrier wide lane and code "narrow lane" to resolve wide lane ambiguity
  - **GBAR** – Geometry Based AR
    - utilizes redundant satellites to find the optimal integer ambiguity vector
    - often used: **Lambda** method (Teunissen (1993) Technical University of Delft)
  - combinations of **GFAR and GBAR**
First Order Ionospheric Effect on Signal Components

- signal components received at the same time have different "apparent" transmission times
  - higher order ionospheric and multipath effects ignored
  - satellite code and phase biases are important

**apparent GPS Signal transmission times (first order iono effect):**

- codes delayed
  - C5, C2, C1
  - L1, L2, L5
  - C0, L0 – ionospheric free (first order) linear combination for code (C0) and carrier (L0)

\[ R = t_r - t_t \]

- \( t_r \) codes delayed
- \( t_t \) carriers advanced

- RTK requires ambiguity free L0 or elimination of ionospheric effect
Ambiguity Resolution - Narrow and Wide Lanes

apparent signal transmission times:

low noise

code Narrow Lanes

C0,1,1
C1,0,1
C5,1,0

carrier Narrow Lanes

L0,1,0
L1,1,0
L1,0,1

low noise
wavelength ~ 11 cm

carrier Wide Lanes

L0,1,1
L1,0,1
L0,1,0

original wavelength
~ 19 … 25 cm

code Wide Lanes with
big noise + MP amplification
not shown

high noise
big wavelength L1/L2 ~ 86 cm
Ambiguity Resolution

- ambiguity resolution
  - requires consistent satellite phase and code biases
  - increasing complexity with variety of signals and GNSS

- RTCM-SSR biases support ambiguity resolution condition, furthermore
  - flexible, serves different approaches and strategies

- indication of partial services required in RTCM-SSR
- services may be based on
  - ionospheric free linear combination
  - on float/fixed ambiguities on reference stations
  - particular characteristic/consistency of RTCM-SSR
Ambiguity Resolution

- basic content of RTCM-SSR satellite phase signals and properties to indicate partial services
  - per GNSS
    - satellite bias-free ionospheric observable indicator (dispersive bias consistency indicator)
    - satellite bias free code/phase observable indicator (Melbourne-Wübbena - MW consistency indicator)
  - per satellite
    - yaw angle and yaw rate
  - per GNSS signal and tracking mode
    - satellite bias free phase with integer nature indicators (signal integer indicator, signal wide lane integer indicator and signal discontinuity counter)
    - phase bias
• RTCM SC104 SSR Working Group
• Strategy / Concepts for RTCM-SSR Development
• Satellite Code and Phase Biases
• Carrier Phase Ambiguity Resolution

**RTCM SSR Working Group - Status**
• Summary/Outlook
RTCM SSR Working Group - Status

- **Stage 1 DF-RT-PPP**
  
  **standardized** since Mai 2011: GPS GLONASS
  
  **proposed**/interoperability testing: Galileo QZSS SBAS BDS

- **Stage 2 SF-RT-PPP/RT-PPP**
  
  **proposed**/interoperability testing:
  
  satellite phase bias messages
  
  vertical TEC (VTEC) message
  
  (spherical harmonics)

- **Stage 3 RTK-PPP**
  
  **initial concepts**
  
  **under consideration**
  
  slant TEC (STEC) messages
  
  troposphere

  • availability of new proposed messages depends on some technical issues, interoperability tests and on progress in RTCM
  
  • need for an additional Stage 4 (“first define contents”)

- **Stage 4 Compression**
  
  compression of messages/reduce of bandwidth
SSR Application for GNSS Positioning

SSM  State Space Monitoring
OSR  observation space representation
SSR  state space representation
RS   reference station
GGA  NMEA position message

SSM/SSR concept operationally applied with Geo++ GNSMART
• RTCM SC104 SSR Working Group
• Strategy / Concepts for RTCM-SSR Development
• Satellite Code and Phase Biases
• Carrier Phase Ambiguity Resolution
• RTCM SSR Working Group - Status

• **Summary/Outlook**
Summary/Outlook

- SSR standardization is challenging

- RTCM-SSR messages shall
  - be self-contained, flexible and non-restricting
  - serve scalable applications and accuracy requirements

- ambiguity resolution for PPP supported by proposed satellite phase biases support ambiguity resolution

- SSR standardization requires time; next steps are
  - interoperability testing of proposed RTCM-SSR messages
  - start on Stage 3 RTCM-SSR development

- SSR can replace OSR techniques for all types of GNSS positioning applications with better performance and less costs

- need for demonstration of SSR performance to convince markets
Standardized RTCM SSR Messages

- Stage 1 for GPS and GLONASS

<table>
<thead>
<tr>
<th>Message Type</th>
<th>Message Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1057</td>
<td>SSR <strong>GPS</strong> Orbit Correction</td>
</tr>
<tr>
<td>1058</td>
<td>SSR <strong>GPS</strong> Clock Correction</td>
</tr>
<tr>
<td>1059</td>
<td>SSR <strong>GPS</strong> Code Bias</td>
</tr>
<tr>
<td>1060</td>
<td>SSR GPS Combined Orbit and Clock Corrections</td>
</tr>
<tr>
<td>1061</td>
<td>SSR GPS URA</td>
</tr>
<tr>
<td>1062</td>
<td>SSR GPS High Rate Clock Correction</td>
</tr>
<tr>
<td>1063</td>
<td>SSR <strong>GLONASS</strong> Orbit Correction</td>
</tr>
<tr>
<td>1064</td>
<td>SSR <strong>GLONASS</strong> Clock Correction</td>
</tr>
<tr>
<td>1065</td>
<td>SSR <strong>GLONASS</strong> Code Bias</td>
</tr>
<tr>
<td>1066</td>
<td>SSR GLONASS Combined Orbit and Clock Correction</td>
</tr>
<tr>
<td>1067</td>
<td>SSR GLONASS URA</td>
</tr>
<tr>
<td>1068</td>
<td>SSR GLONASS High Rate Clock Correction</td>
</tr>
</tbody>
</table>
Proposed RTCM SSR Messages (May 2012)

- Stage 1 RTCM SSR Galileo QZSS

<table>
<thead>
<tr>
<th>Message Type</th>
<th>Message Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1240</td>
<td>SSR Galileo Orbit Correction</td>
</tr>
<tr>
<td>1241</td>
<td>SSR Galileo Clock Correction</td>
</tr>
<tr>
<td>1242</td>
<td>SSR Galileo Code Bias</td>
</tr>
<tr>
<td>1243</td>
<td>SSR Galileo Combined Orbit and Clock Corrections</td>
</tr>
<tr>
<td>1244</td>
<td>SSR Galileo URA</td>
</tr>
<tr>
<td>1245</td>
<td>SSR Galileo High Rate Clock Correction</td>
</tr>
<tr>
<td>1246</td>
<td>SSR QZSS Orbit Correction</td>
</tr>
<tr>
<td>1247</td>
<td>SSR QZSS Clock Correction</td>
</tr>
<tr>
<td>1248</td>
<td>SSR QZSS Code Bias</td>
</tr>
<tr>
<td>1249</td>
<td>SSR QZSS Combined Orbit and Clock Correction</td>
</tr>
<tr>
<td>1250</td>
<td>SSR QZSS URA</td>
</tr>
<tr>
<td>1251</td>
<td>SSR QZSS High Rate Clock Correction</td>
</tr>
</tbody>
</table>
Proposed RTCM SSR Messages (May 2012)

- Stage 1 RTCM SSR SBAS BDS

<table>
<thead>
<tr>
<th>Message Type</th>
<th>Message Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1252</td>
<td>SSR SBAS Orbit Correction</td>
</tr>
<tr>
<td>1253</td>
<td>SSR SBAS Clock Correction</td>
</tr>
<tr>
<td>1254</td>
<td>SSR SBAS Code Bias</td>
</tr>
<tr>
<td>1255</td>
<td>SSR SBAS Combined Orbit and Clock Corrections</td>
</tr>
<tr>
<td>1256</td>
<td>SSR SBAS URA</td>
</tr>
<tr>
<td>1257</td>
<td>SSR SBAS High Rate Clock Correction</td>
</tr>
<tr>
<td>1258</td>
<td>SSR BDS Orbit Correction</td>
</tr>
<tr>
<td>1259</td>
<td>SSR BDS Clock Correction</td>
</tr>
<tr>
<td>1260</td>
<td>SSR BDS Code Bias</td>
</tr>
<tr>
<td>1261</td>
<td>SSR BDS Combined Orbit and Clock Corrections</td>
</tr>
<tr>
<td>1262</td>
<td>SSR BDS URA</td>
</tr>
<tr>
<td>1263</td>
<td>SSR BDS High Rate Clock Correction</td>
</tr>
</tbody>
</table>
Proposed RTCM SSR Messages (May 2012)

- Stage 2 RTCM SSR Satellite Phase Bias

<table>
<thead>
<tr>
<th>Message Type</th>
<th>Message Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1265</td>
<td>SSR Satellite GPS Phase Bias</td>
</tr>
<tr>
<td>1266</td>
<td>SSR Satellite GLONASS Phase Bias</td>
</tr>
<tr>
<td>1267</td>
<td>SSR Satellite Galileo Phase Bias</td>
</tr>
<tr>
<td>1268</td>
<td>SSR Satellite QZSS Phase Bias</td>
</tr>
<tr>
<td>1269</td>
<td>SSR Satellite SBAS Phase Bias</td>
</tr>
<tr>
<td>1270</td>
<td>SSR Satellite BDS Phase Bias</td>
</tr>
</tbody>
</table>
Proposed RTCM SSR Messages (May 2012)

- Stage 2 RTCM SSR VTEC

<table>
<thead>
<tr>
<th>Message Type</th>
<th>Message Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1264</td>
<td>SSR Ionosphere Spherical Harmonics</td>
</tr>
</tbody>
</table>