- Industry Perspective 2 -

SSR Technology for Scalable Real-Time GNSS Applications

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Abstract

SSR Technology for scalable Real-Time GNSS Applications

The use of State Space Representation (SSR) is the most convincing and acknowledged GNSS augmentation technology to cope with the increase of new signals and new constellations in the future.

The synergy of Precise Point Positioning and SSR for RTK networking has been widely addressed. Scalable SSR applications have the goal to support both, global but also regional or local applications.

Concepts are presented working out the benefits of SSR and the consequential splitting of GNSS error components over messages. An essential task is the handling of signal biases in multi-signal multi-constellation GNSS applications.

The general approach proposed for SSR is summarized. International standardization efforts are addressed and examples of SSR applications presented.

Outline

- GNSS Augmentation in SSR and OSR Domain
- Scalable Services with SSR
- SSR Standardization
- SSR Application Examples
- Summary/Outlook

- **GNSS Augmentation in SSR and OSR Domain**
- Scalable Services with SSR
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GNSS Augmentation in the OSR Domain

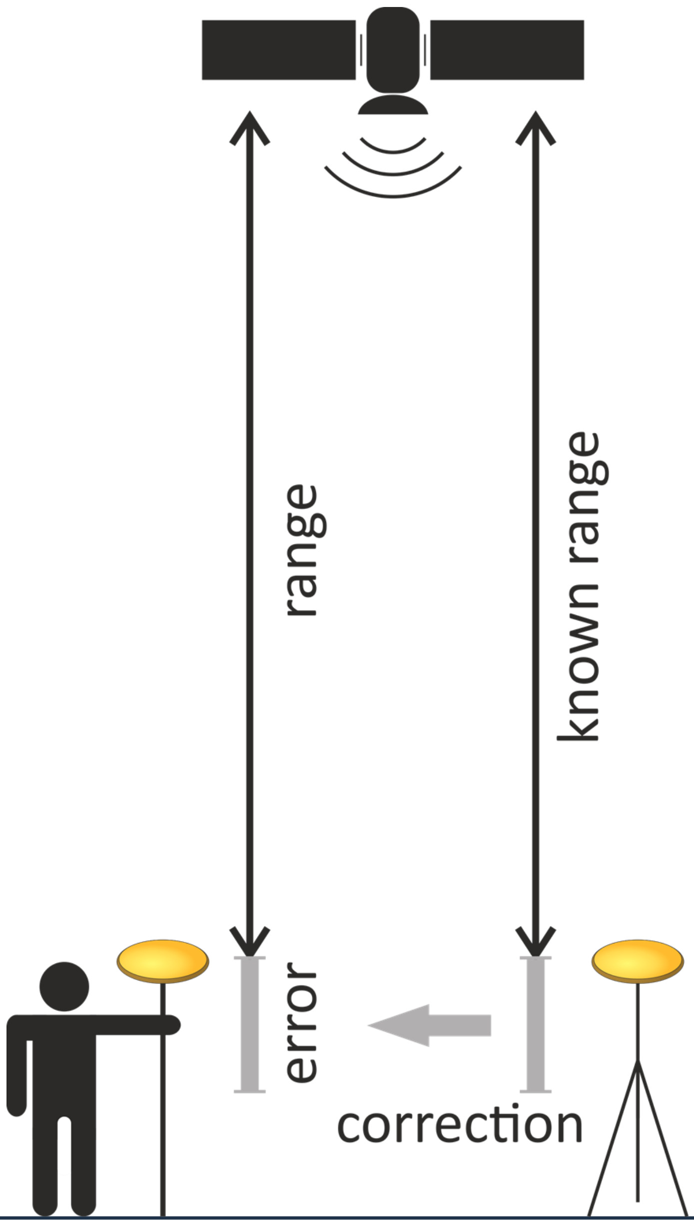
Recall, the simple case of real-time differential GNSS corrections assuming high correlation of **GNSS error components:**

- use known reference station coordinates
- determine lump-sum of GNSS errors

The range measurements of a user's GNSS positioning are improved by applying **GNSS range correction** as measured by a nearby reference station.

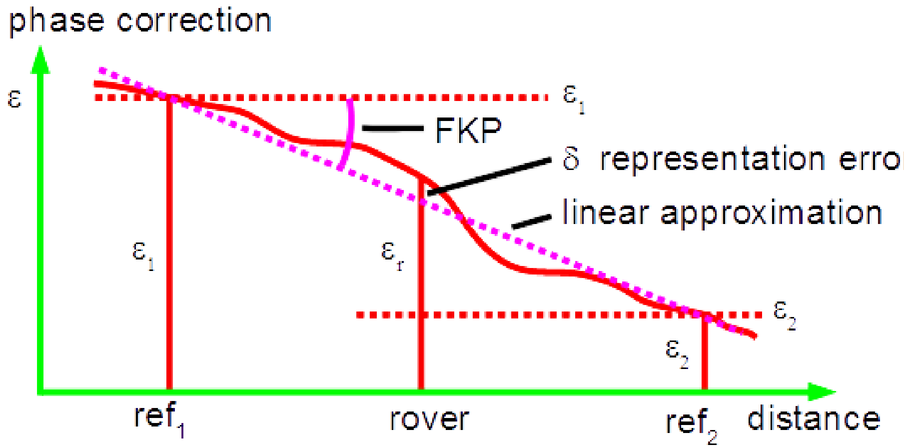
Since the observations of the reference stations are used directly, this approach is classified as an **observation space representation (OSR)** technique.

Examples include (network)-RTK and DGPS.



GNSS Augmentation in the OSR Domain

- **OSR** is the currently used method in **network RTK** applications to provide correction or corrected data to a user. The following major terms based on the **correction parametrization***
  are in use:
  - observation data + network correction
    - **RS** (Reference Station) **+ FKP**
    - range correction gradients
  - network-corrected (individualized) observation data, non-physical data
    - **PRS** (Pseudo Reference Station)
    - **VRS** (Virtual Reference Station)
  - observation data of multiple reference stations
    - **MAC** (Master-Auxiliary-Concept)
    - range correction differences



simple sketch of
linear correction model of distance dependent errors, applicable to all network correction

VRS	Virtual Reference Station
PRS	Pseudo Reference Station
MAC	Master Auxiliary Concept
FKP	Flächenkorrekturparameter
SSR	State Space Representation

* remark: combination of techniques and/or combination with SSR are possible

GNSS Augmentation in the SSR Domain

A network of reference stations is used to decorrelate the different **GNSS error components:**

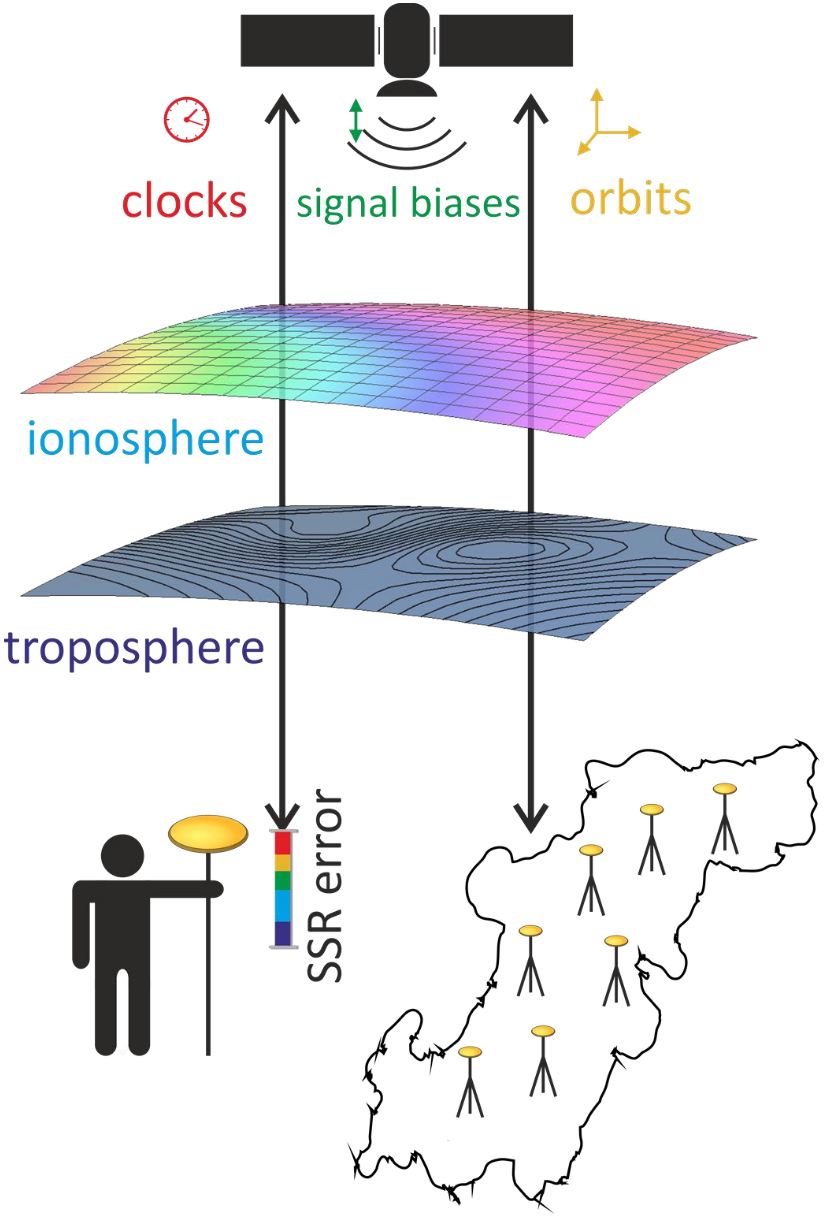
- satellite clocks
- satellite orbits
- satellite signal biases
- ionospheric delay/advance
- tropospheric delay

With this, users can **generate GNSS corrections** valid for their own position.

Additionally, statistical **accuracy information** can be provided to support the user's GNSS positioning algorithm.

Since the state of the GNSS error components is determined, this approach is termed as a **state space representation (SSR)** technique.

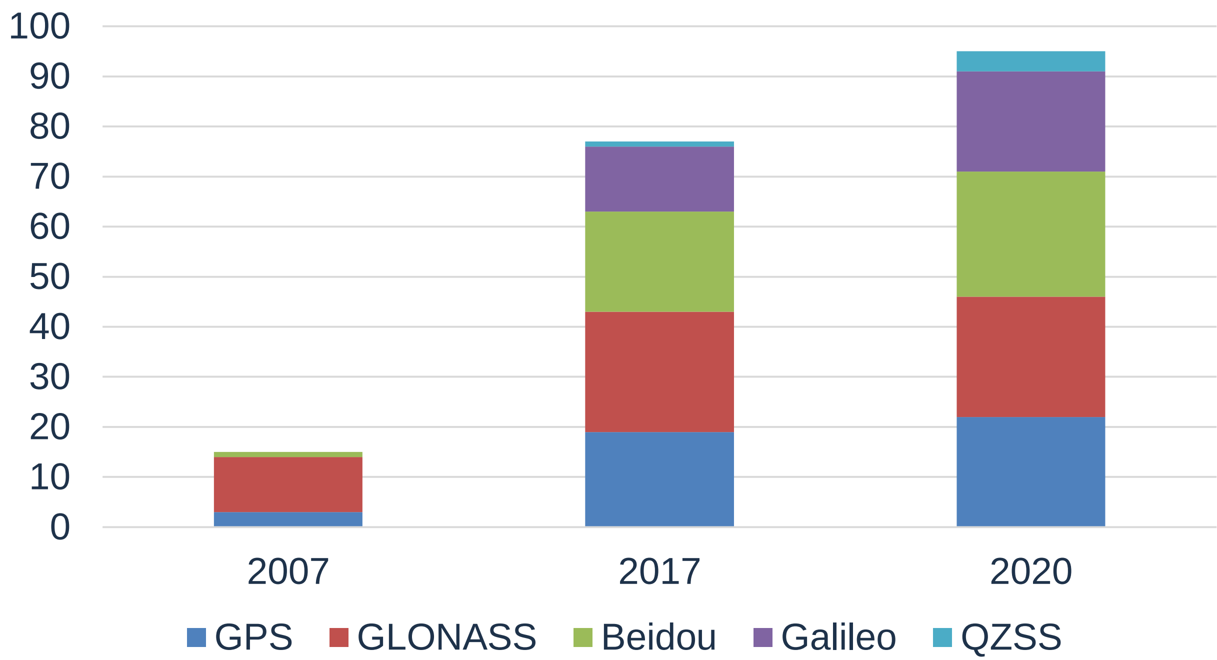
Examples include SBAS, PPP and PPP-RTK.

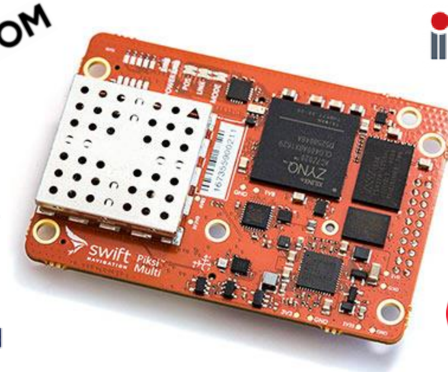


SSR – Why?

- The **demand for GNSS correction** to be used for worldwide positioning application will significantly increase in the near future, due e.g. to
  - novel applications
  - low-cost 2-frequency receiver
  - more usable satellites
  - …

Number of satellites
with 2 civilian frequencies





SSR – SSR Today

- different SSR services are in operation, examples are
  - IGS **Precise Point Positioning** (PPP)
    - main state parameters (IGS products)
      orbits, clocks, (VTEC)
  - **SBAS**
    - main state parameters
      orbits, clocks, VTEC
  - **Proprietary Systems** with satellite communication
    - Omnistar, Starfire, Veripos/Terrastar,
      CenterPoint RTX, ...
  - **Network RTK** services
    - monitoring of complete state parameters
    - conversion to OSR
  - **combinations** of above showing up …

- GNSS Augmentation in SSR and OSR Domain
- **Scalable Services with SSR**
- SSR Standardization
- SSR Application Examples
- Summary/Outlook

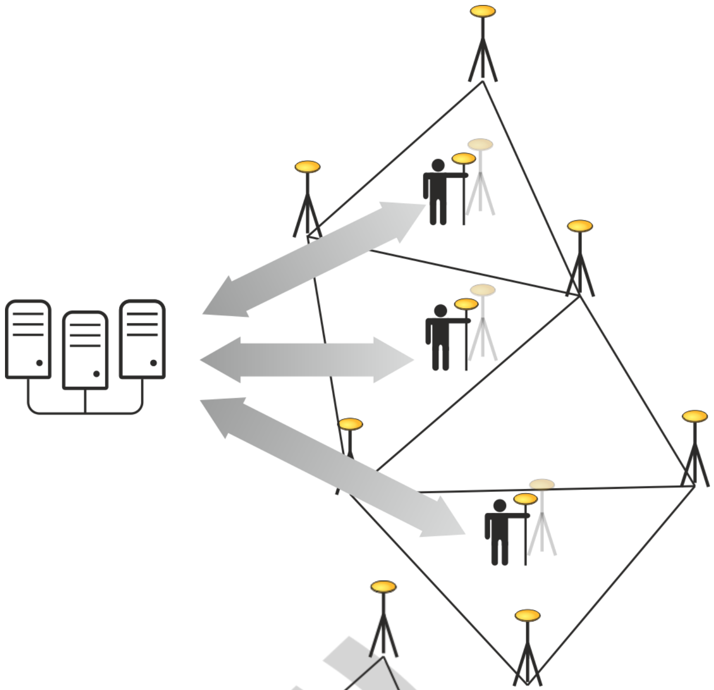
Scalable Services – Communication Link

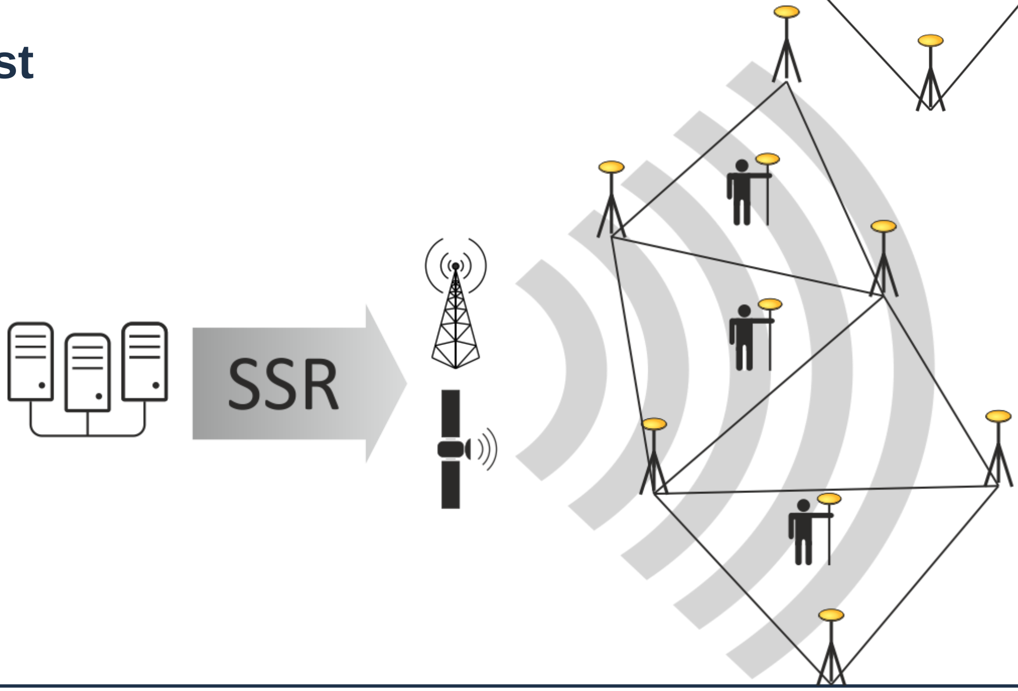
With **OSR**,

- the GNSS corrections are often realized with a so-called pseudo (PRS) or **virtual reference stations** (VRS).
- This requires **one duplex data channel per user**.

With **SSR**,

- the GNSS corrections are **broadcast** with **one data stream** for **all users**.
- This enables the use of **simplex communication** media (satellites, digital radio, ...) alternatively to the Internet.

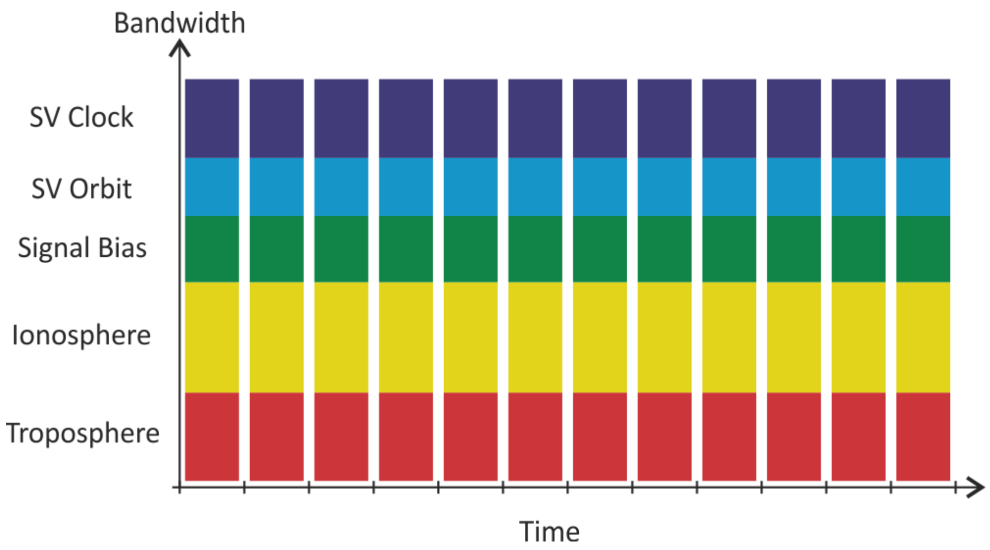


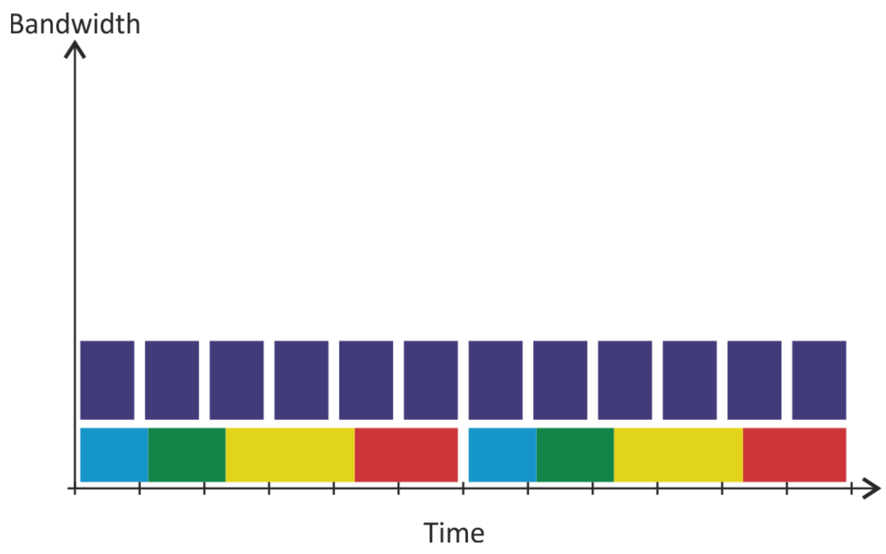


Minimizing Bandwidth – Scaling SSR in Time Domain

Analyzing the **individual characteristics** of the GNSS error components **reveals**:

- Due to **short-term fluctuations** of **satellite clocks**, cm level positioning requires correction data updates approximately every 10 seconds.
- **Other GNSS errors** components change at **lower rates**.
- **Adjusting individual update rates** of SSR components can drastically **reduce the bandwidth requirement** while keeping the **quality the same**.

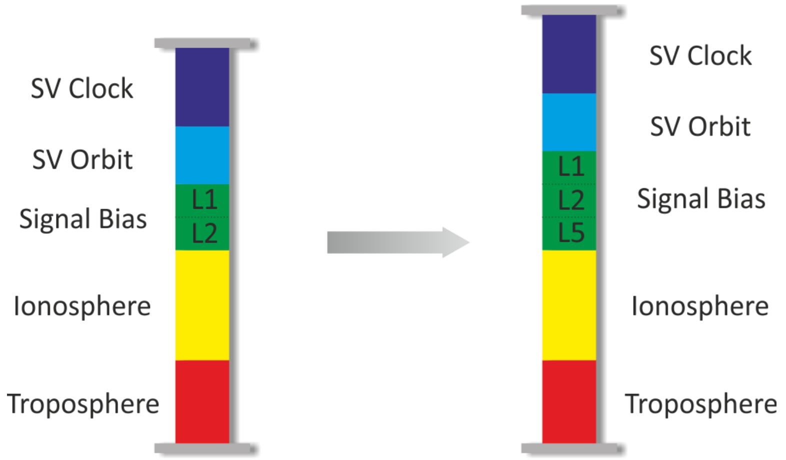


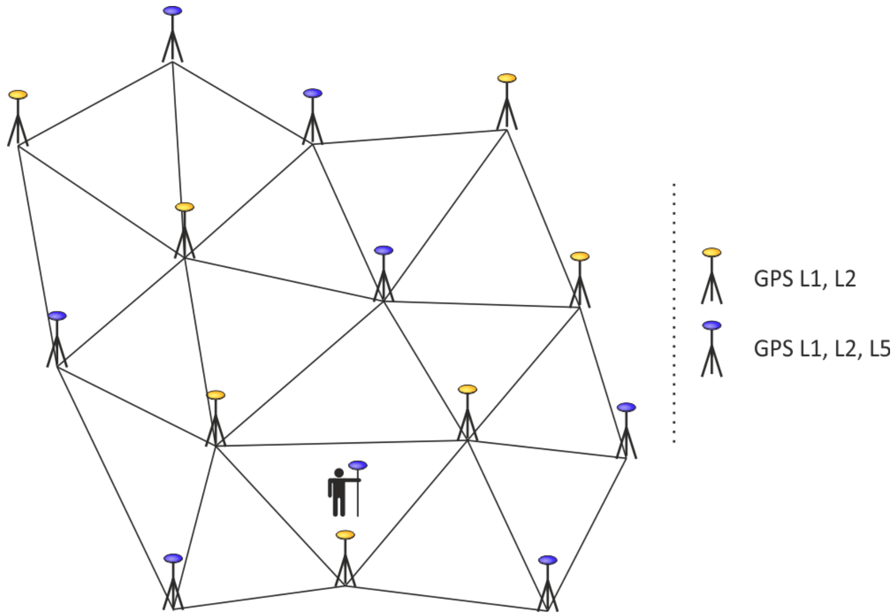


Scalable Services – Scaling Signals

SSR inherently supports the **variety** of **GNSS, frequencies and signals**:

- **Additional GNSS or signals** can be **added** to existing services **seamlessly.**
- There is **no need for the same** reference **station hardware** to support all GNSS and signals.
- The **same SSR service** can be used by
  - mass market **single frequency users**
  - and **high precision** multi-GNSS multi-frequency **users**.

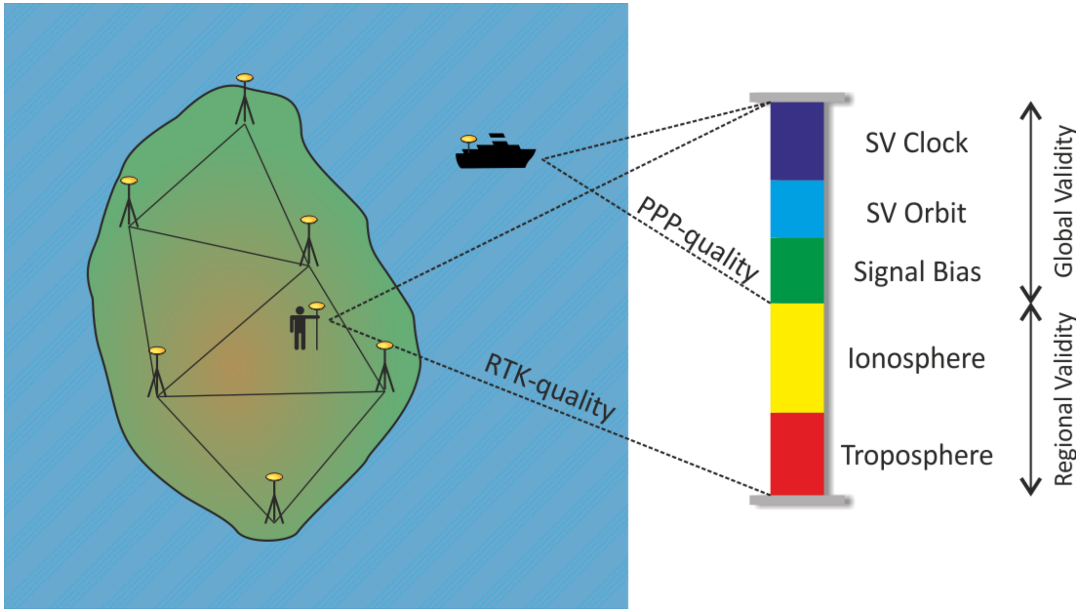




Scalable Services – Scaling Service Areas

With SSR,

- **various quality levels** of GNSS positioning
- **for different regions**
- can be represented with a **single data stream**.



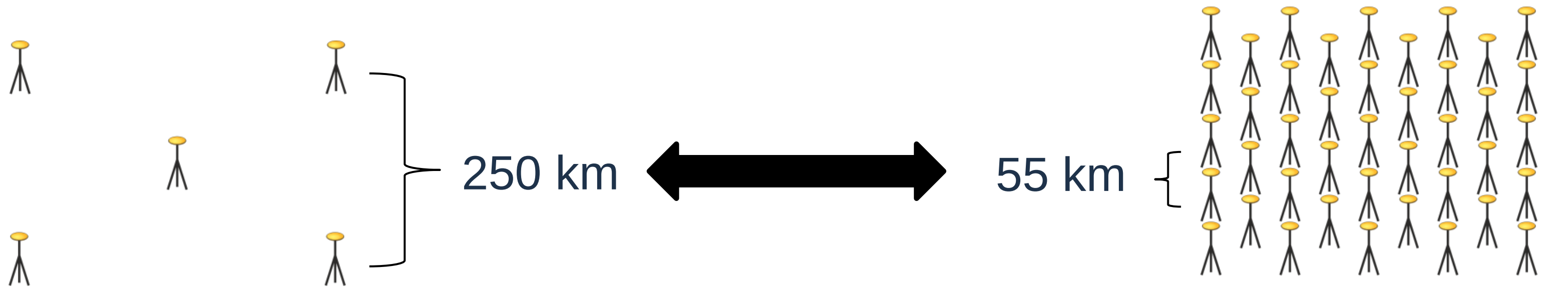
For example, a GNSS correction service

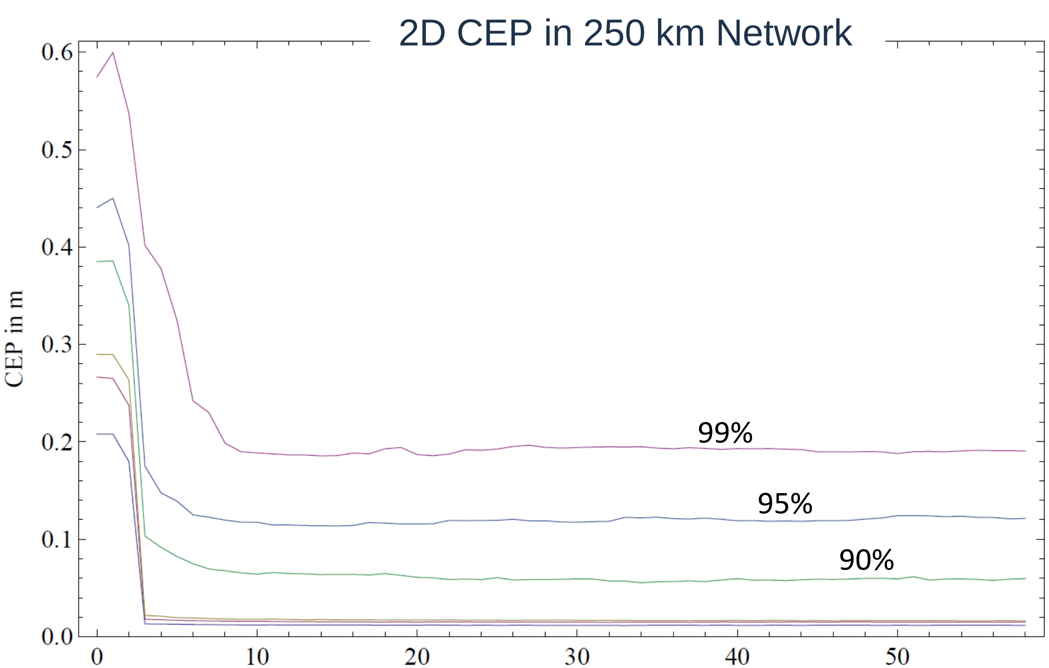
- could supply a **region with high** reference **station density** with an **RTK quality** service,
- while **all adjacent regions** are provided with **PPP quality**.

Scalable Services – Scaling Performance

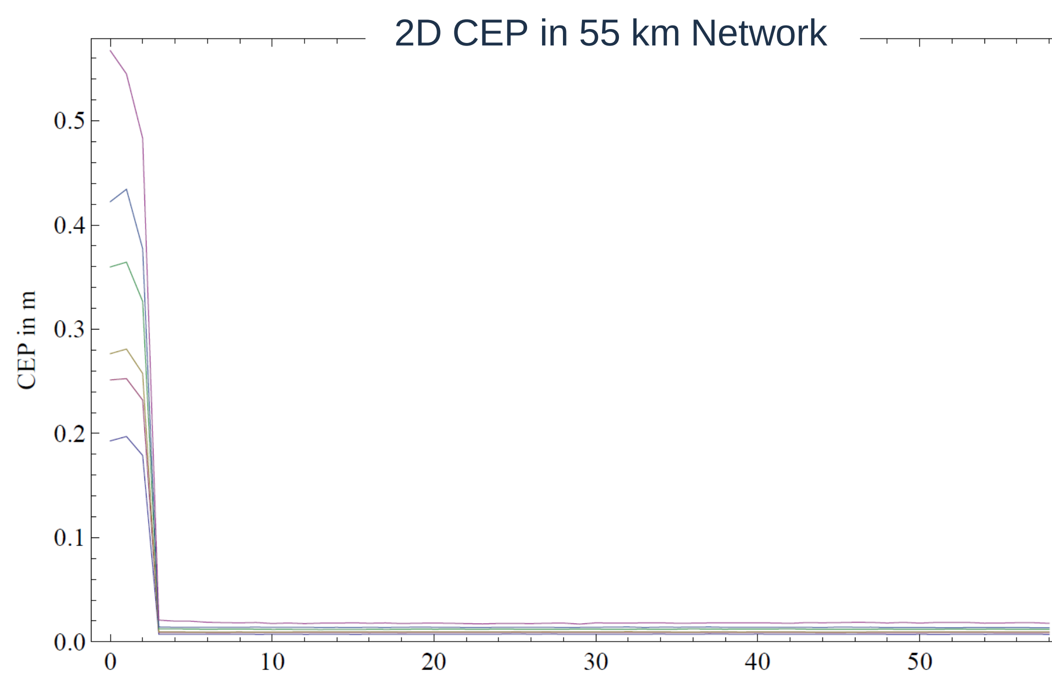
The GNSS network **station density** can be scaled to meet **different positioning** or monitoring **requirements**.

CEP Circular Error Probable



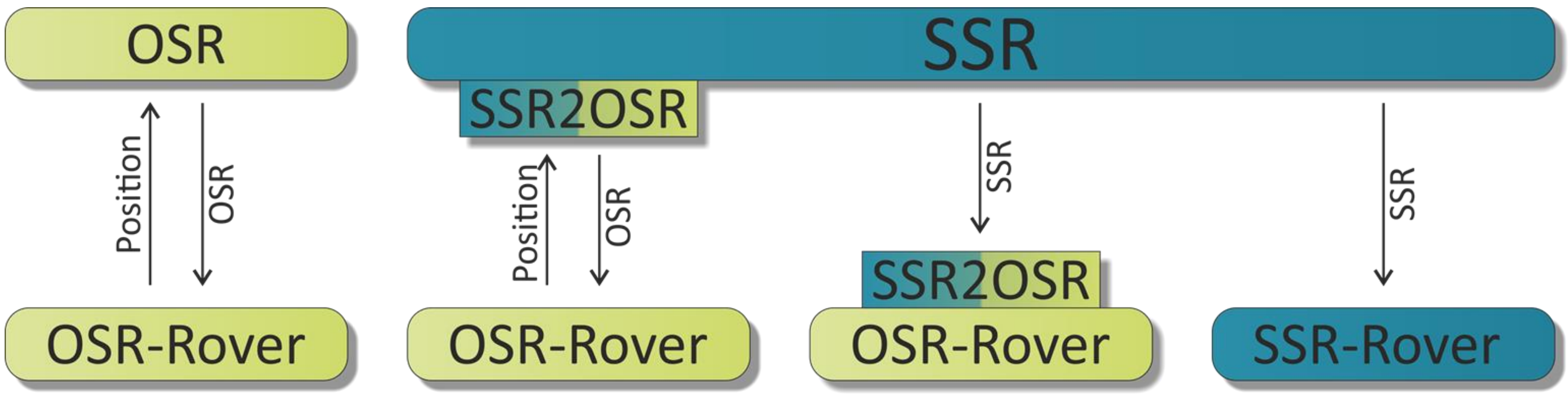


Time after reset in seconds



Time after reset in seconds

Scalable Services – Backward Compatibility



- **Legacy GNSS positioning** can be supported **via SSR2OSR conversion** either on the server or rover side.
- **Optimal performance** will be reached once the **SSR corrections** with accompanying accuracy information are **directly incorporated** in the positioning engine.

- GNSS Augmentation in SSR and OSR Domain
- Scalable Services with SSR
- **SSR Standardization**
- SSR Application Examples
- Summary/Outlook

Standardization – RTCM-SSR

Since 2007 the SSR working group of the Radio Technical Commission for Maritime Services (**RTCM**) **S**pecial **C**ommittee **104** is developing a standard message format for SSR messages.

Goals of RTCM-SSR development are

- that messages are self-contained, flexible and non restricting
- and serve scalable GNSS applications with different accuracy requirements.

Status of standardization

- is slowed down, because of missing agreement on interoperability testing (new WG established).
- Consensus is expected after testing of a complete set of SSR messages.

Standardized (2011)+	Proposed (since 2013)	In Preparation (since 2016)
Orbits*	Phase Biases	Slant TEC (STEC)
Clocks*	Vertical TEC (VTEC)	Troposphere
Code Biases*		Compressed Messages
User Range Accuracy		

+: RTCM-SSR first published in „RTCM STANDARD 10403.1 with Amendments 1-5“, July 1, 2011
*: for GPS and GLONASS only, messages are proposed for Galileo, QZSS, BDS & SBAS

SSR Standardization - Satellite Biases

Every transmitted GNSS signal component experiences **a specific signal delay** (bias) **in every satellite** hardware/software.

Satellite Biases are **defined**

- as "**absolute biases**" (may contain remaining/average/reference receiver biases),
- for satellite **code and phase signals,**
- which inherently supports relative biases.

It is expected, that **all** software dependent **bias concepts can be mapped to the RTCM-SSR** approach.

example

- error components:
  satellite clock error dt and
  code biases B*i and **phase biases B*i**
- combined clock and signal signal delay error at satellite antenna:

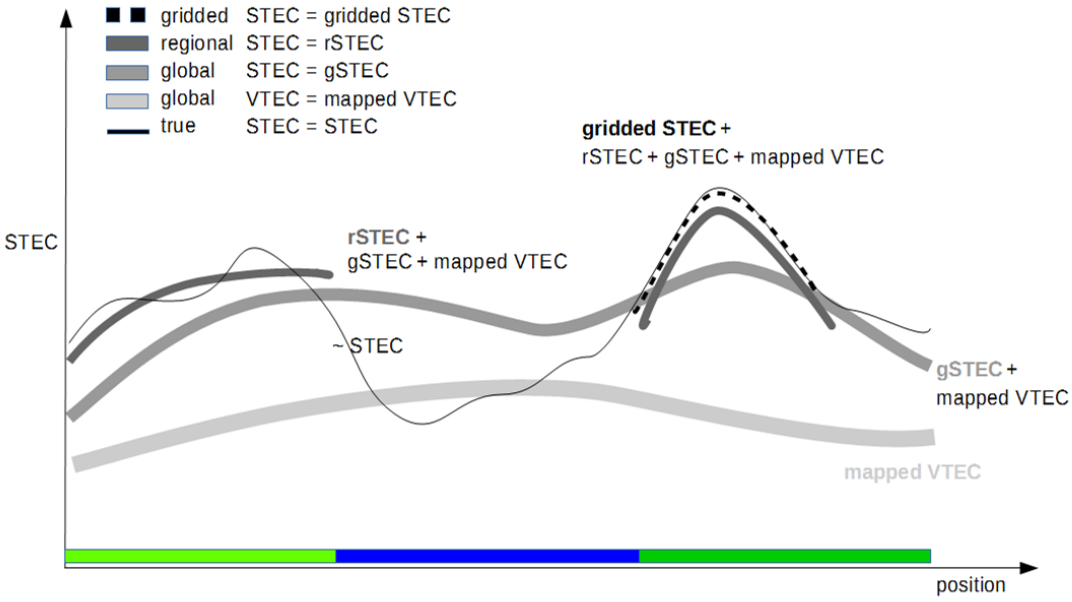
dC1C	=	dt + BC1C							
dC2W	=	dt	+ BC2W						
dC2C	=	dt	+ BC2C						
dC5I	=	dt		+ BC5I					
dL1W	=	dt			+ BL1W				
dL2W	=	dt				+ BL2W			
dL2C	=	dt				+ BL2C			
dL5I	=	dt					+ BL5I		

linear dependency between clock and bias terms
==> **only** 7 (**n_signal -1**) **independent parameters**

SSR Standardization - Proposed Multi-Stage Concept

The **multi-stage model**

- utilizes **different messages** for the same GNSS error component.
- **constituents** from different messages **are added**, which **adds accuracy**.
- is **required** for e.g. **spatial variation** of atmospheric parameters or optimal **data compression**
- and allows different service applications/accuracies.



An example is the ionosphere, which consists of one or more constituents provided as

- an initial Vertical TEC spherical harmonics model
- and/or slant TEC components
- and/or a gridded TEC component.

SSR Standardization – Additional Corrections

- **additional correction** to be considered for **SSR positioning**
  - satellite-receiver **phase wind-up** effect (satellite attitude)
  - (absolute) **satellite antenna** phase and group delay variations (PCV, GDV)
  - **site displacement** effects (plate motion, solid earth tide, pole tide, ocean loading, atmospheric loading, local displacement)
  - **relativistic** effects
  - **higher order ionosphere**
  - (absolute) **receiver antenna** phase and group delay variations (PCV, GDV)

- requires
  - **SSR Standardization** or
  - **definition for specific services**

Standardization - International Formats

- **Different Hardware and Software**
  on Client and Server side is requesting for
  standardized data exchange formats.

- **RTCM** for **real-time** applications
  - Radio Technical Commission for Maritime Services (RTCM)
  - RTCM **SC-104 Differential GNSS Services**
  - Since 1985, currently RTCM 10403.3, i.e. Version 3.3 (2016)

- for comleteness
  RINEX for **post-processing** applications
  - **Receiver Independent Exchange Format**
  - Developed by IGS, maintained by IGS/RTCM
  - RINEX 3.03 (2015)

Remark – Variety of GNSS Signals

- **satellite view**
  - variety of GNSS **signals in space** according to GNSS Interface Control Document (**ICD**), respectively
- **receiver view**
  - variety of **tracked signals** by GNSS receivers

- every **phase and code** signal has inherently a **signal biases**
- consequences
  - **complex** task **for GNSS services**
  - support of legacy and latest technology receivers on the market

GNSS System	# of Frequencies		# of Observations (receiver view*)
GPS	3	L1	9
		L2	10
		L5	3
GLONASS	3	G1	2
		G2	2
		G3	3
Galileo	5	E1	5
		E5a	3
		E5b	3
		E5(E5a+E5b)	3
		E6	5
BDS	3	B1	3
		B2	3
		B3	3
QZSS	4	L1	5
		L2	3
		L5	3
		L6	3
SBAS	2	L1	1
		L5	3
IRNSS	2	L5	4
		S	4

*: according to RINEX 3.03 GNSS Observation Codes

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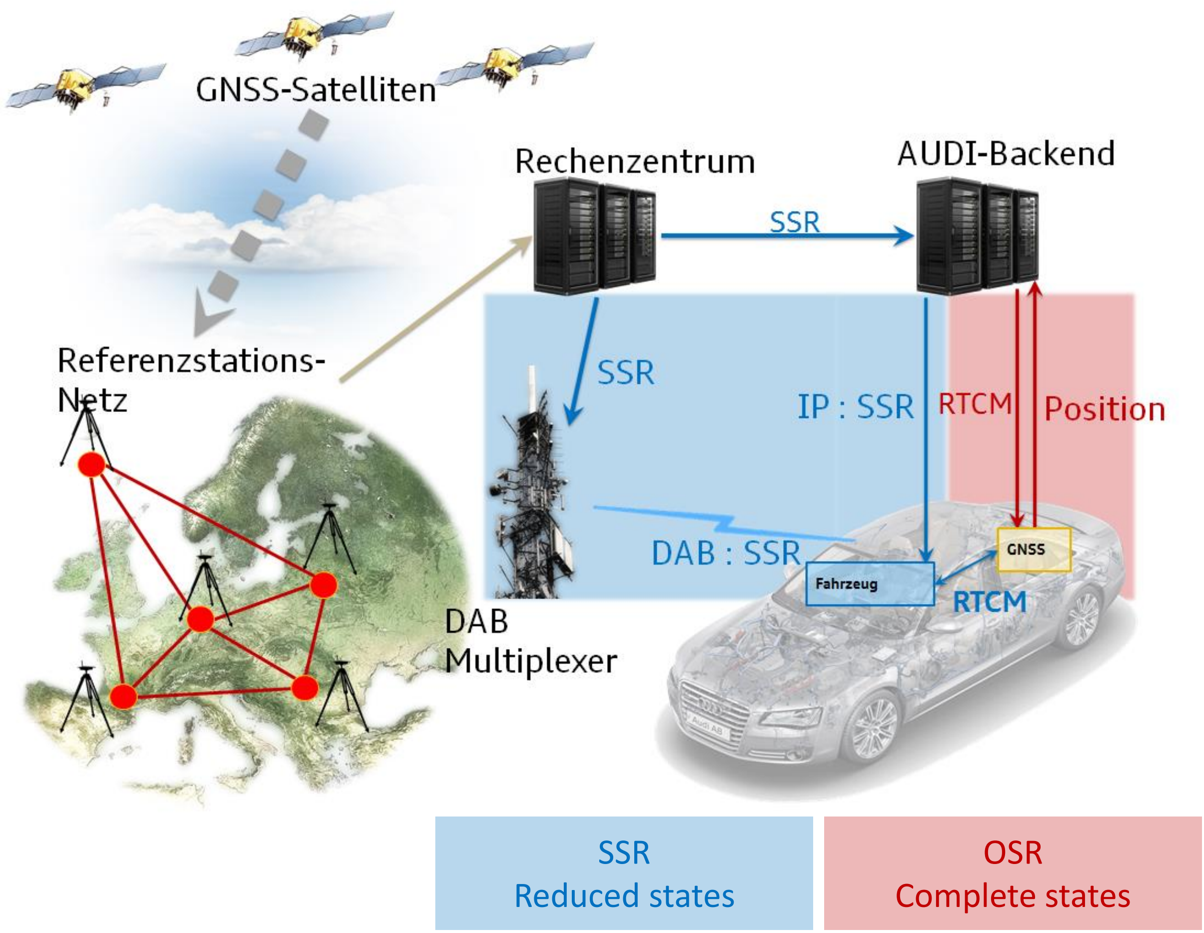
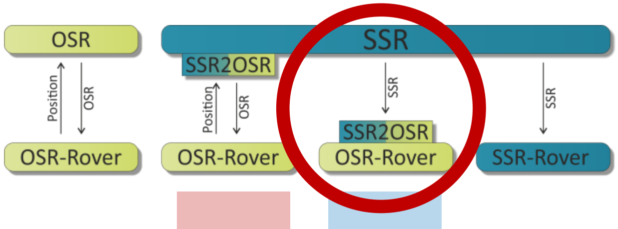
- **SSR Applications - Examples**
- Summary/Outlook

SSR Application via DAB - Broadcasting





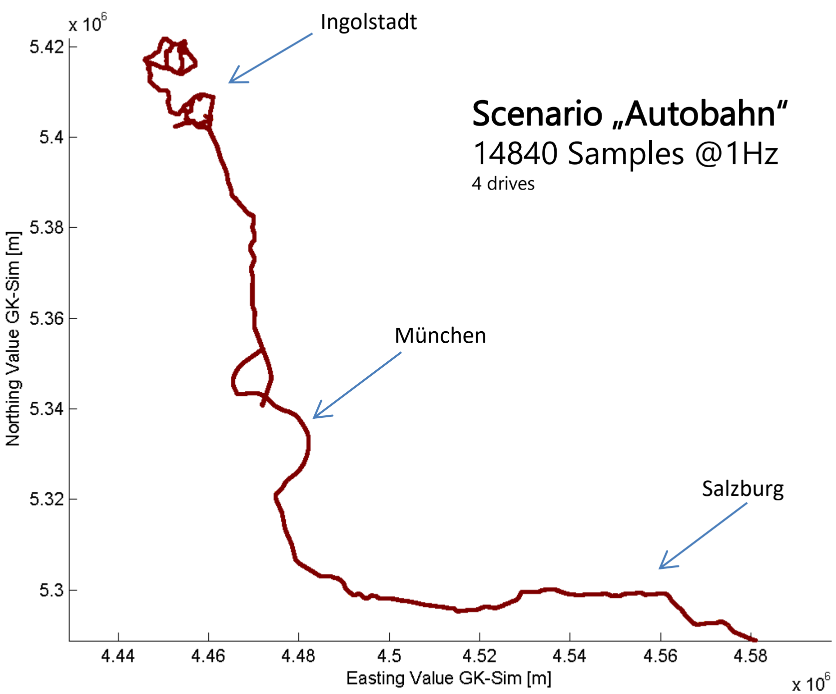
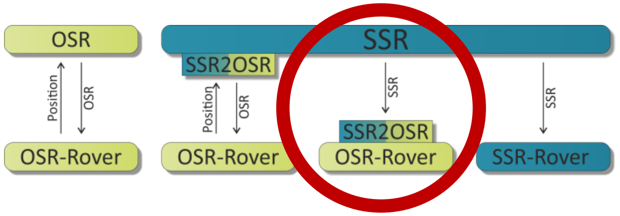


Figure from Florian Mickler:
"Lane-level vehicle localization through GPS with correction data distributed over digital radio broadcasting (DAB)", ELIV 2015

SSR Application via Satellite – TERIASAT

- TERIASAT broadcasts **SSR** corrections **via satellite** to provide RTK services in areas with insufficient mobile internet.
- **To reduce bandwidth**, different GNSS correction states are updated with different rates.
- SSR2OSR conversion in satellite terminal



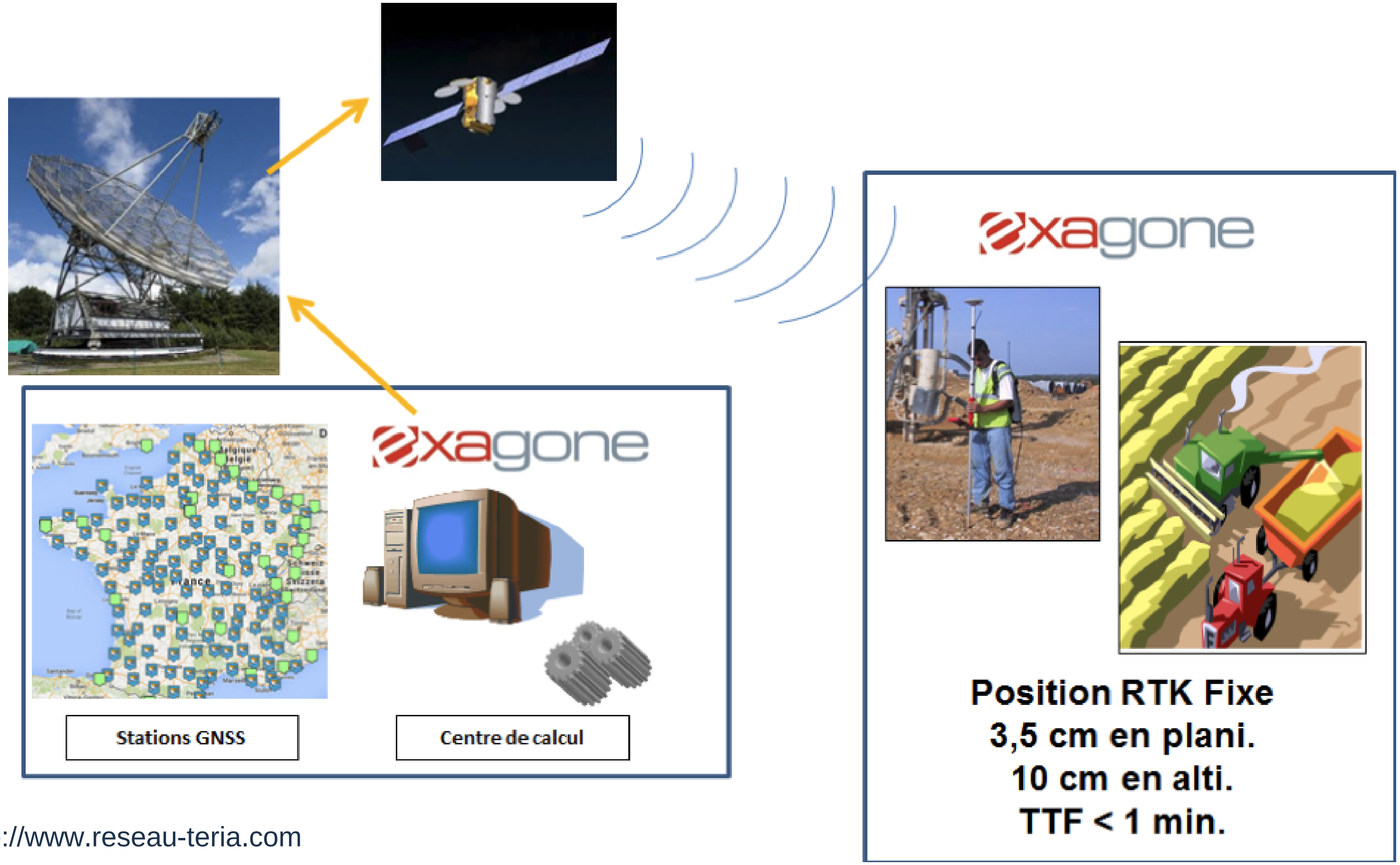
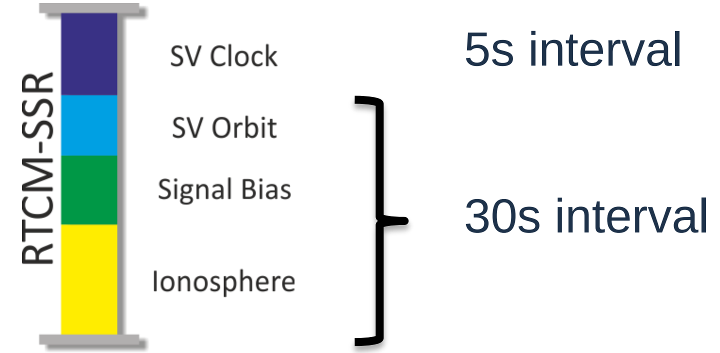
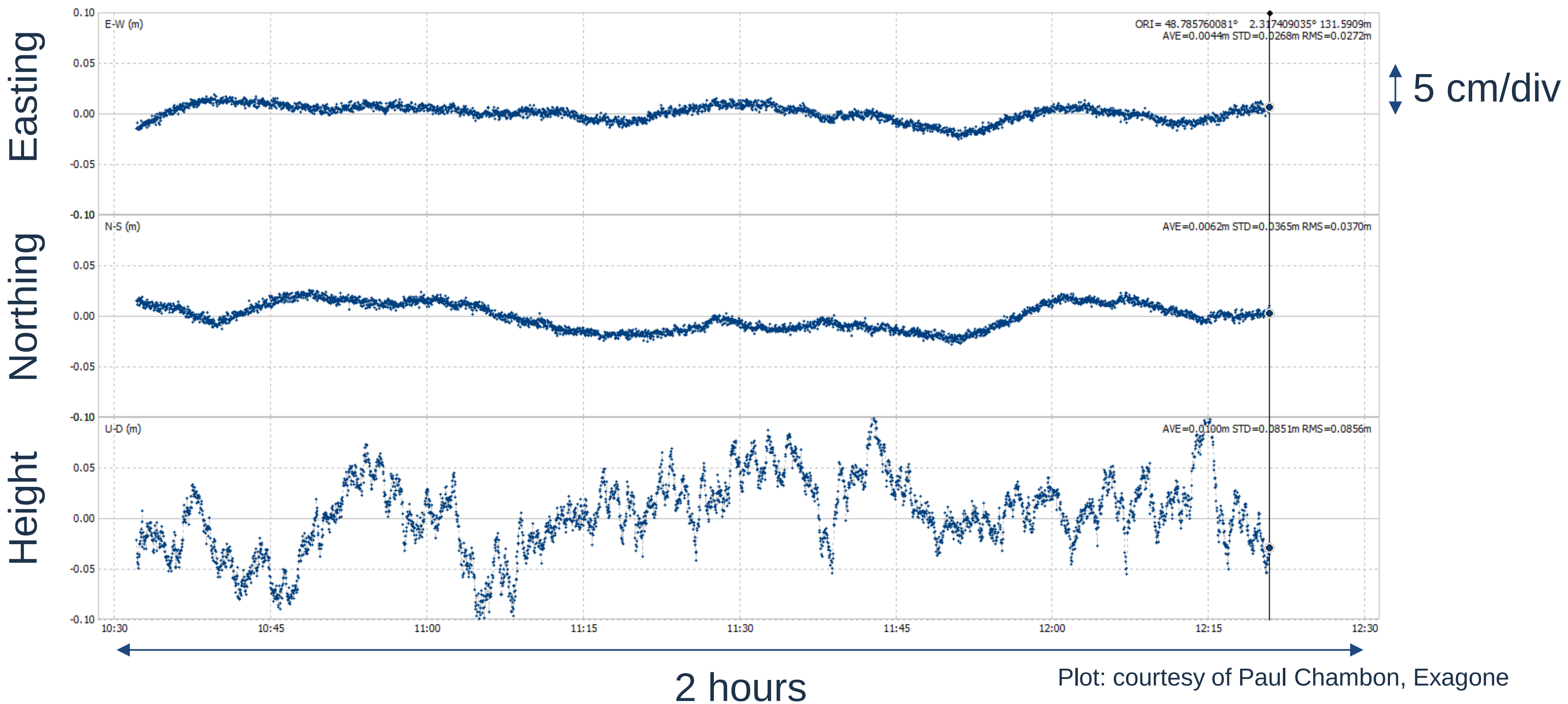


Figure from: http://www.reseau-teria.com

SSR Application via Satellite – TERIASAT

The TERIASAT service broadcasts SSR using **standardized** and **proposed RTCM-SSR** messages as well as **additional 4090** messages for STEC ionosphere.

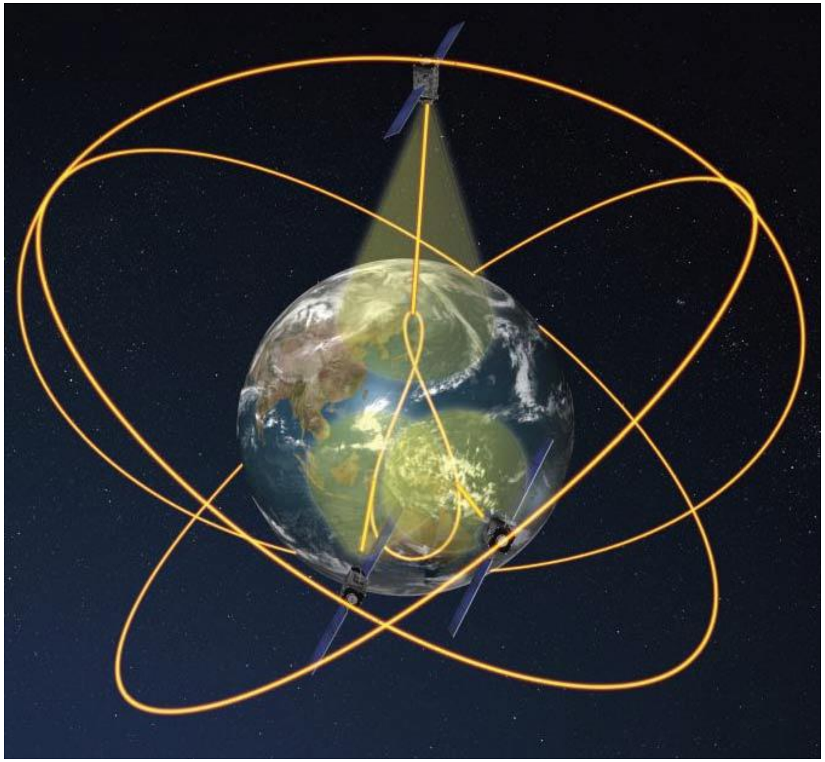




Plot: courtesy of Paul Chambon, Exagone

SSR Application - Quasi-Zenith Satellite System

- **Japanese QZSS**
  - Regional GNSS
  - SBAS System
  - Disaster alert
  - **CLAS,** Centimeter Level Augmentation Service



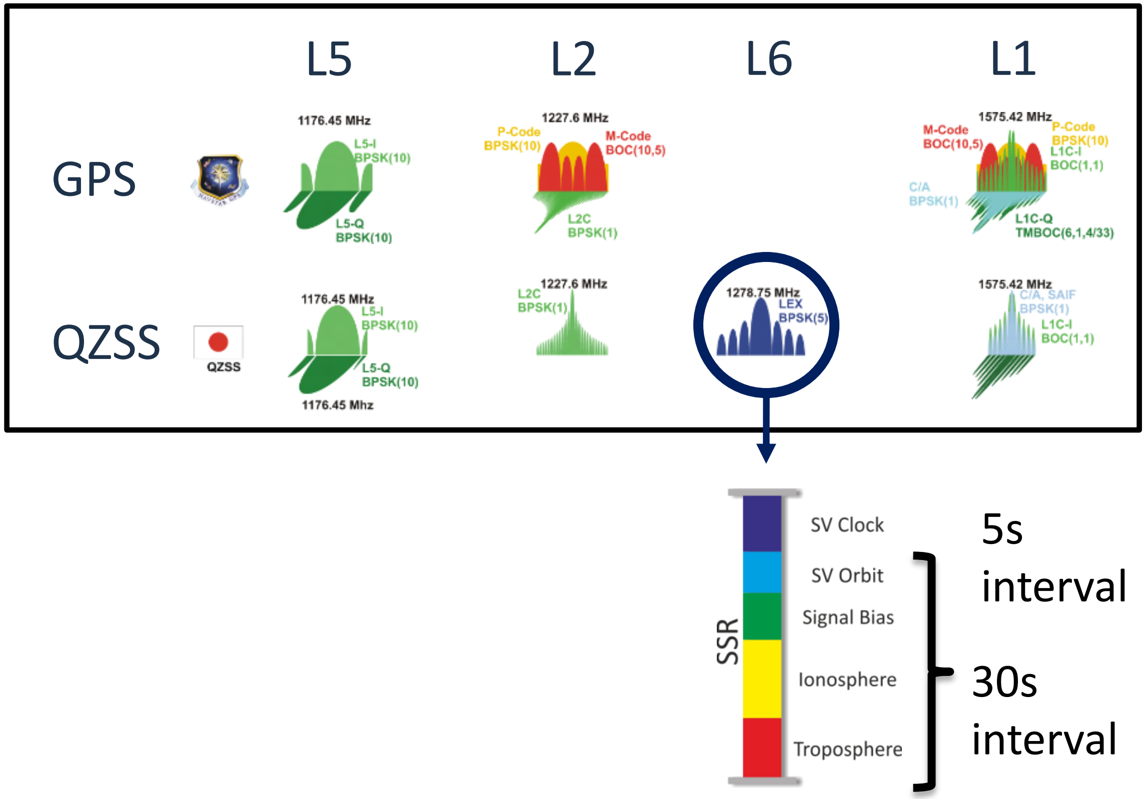
- **Evaluation phase** since 2010
  - 1 geosynchronous satellite „MICHIBIKI“

- **Operational phase** from 2018
  - 3 geosynchronous satellites
  - 1 geostationary satellite

- **Future constellation** from 2022
  - 7 geosynchronous/geostationary satellites

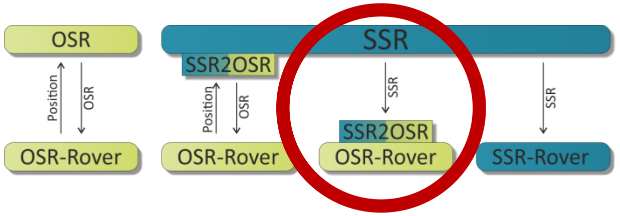
SSR Application - Quasi-Zenith Satellite System

- Each **QZSS satellite**
  - **broadcasts**
  - the **complete SSR** state vector
  - for the area of **Japan**
  - with a **bandwidth** of 1.7 kbps
  - on **L6**

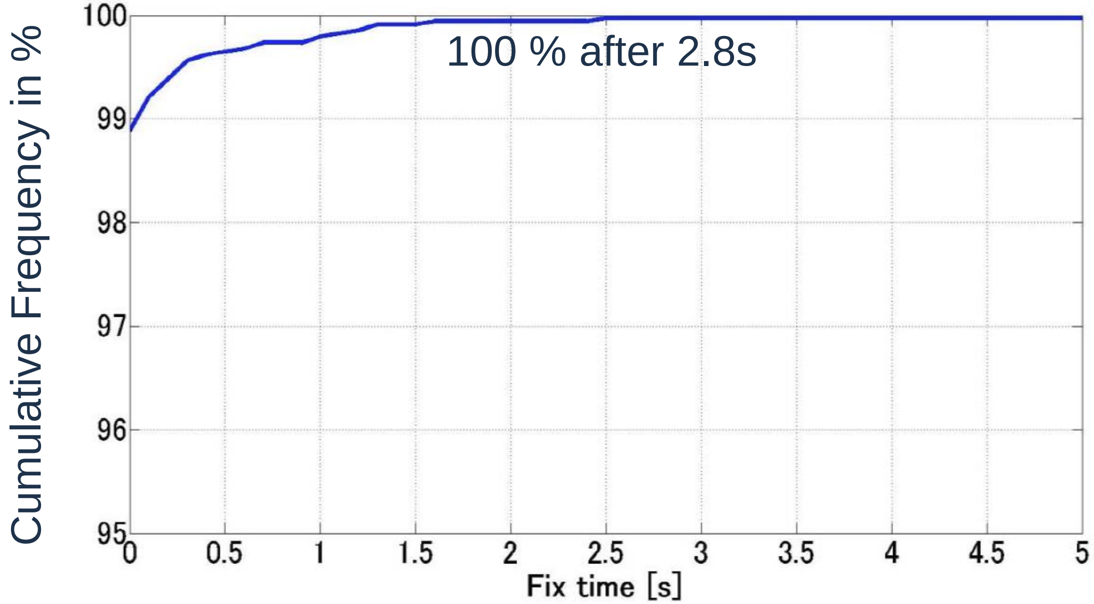


SSR Application - Quasi-Zenith Satellite System

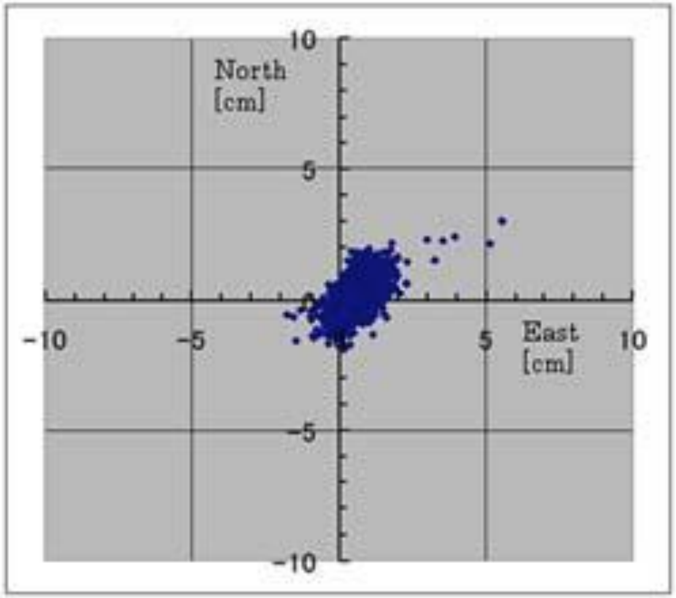
- **CLAS** performance
  - **fixing time** at hot start is < 3 s
  - **fixing time at cold start** is limited to 33 s due to the longest update interval of 30 s



Rover Fixing Performance



Kinematic Positioning Performance

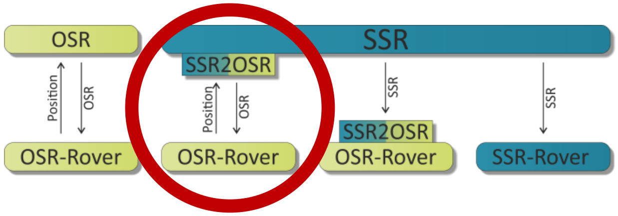


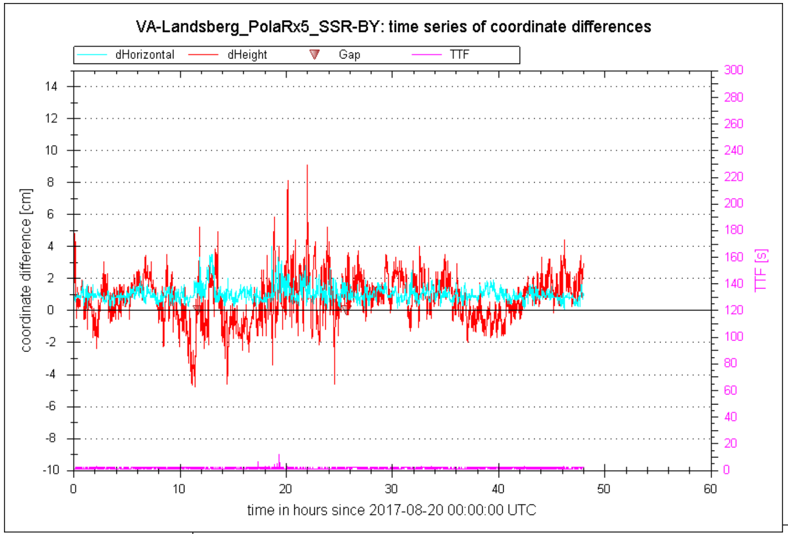
Horizontal	
Average error	0.6cm
Standard deviation (σ)	1.2cm
Vertical	
Average error	1.4cm
Standard deviation (σ)	1.9cm

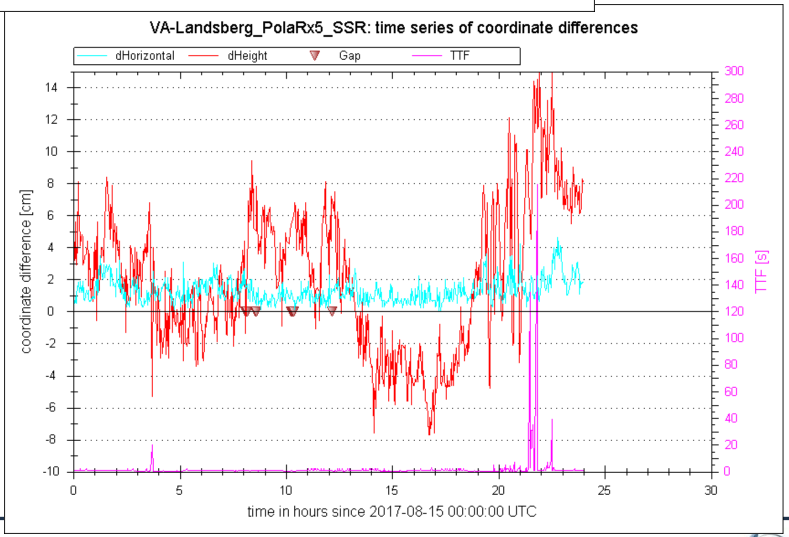
plots & data: Yuki Sato et al. at PPP-RTK & Open Standards Symposium 2012, Frankfurt, Germany
“Centimeter-class Positioning Augmentation Utilizing Quasi-Zenith Satellite System “

SSR Application – SSR2OSR

- **RTCM-SSR-Testbed of the AdV**
- AdV's project group „Precise Point Positioning“ (PPP) is operator of a **German-wide SSR-Testbed** (and Bavaria-wide)
- testing of **“from-the-shelf”** standard **GNSS RTK receivers**
  - differently “scaled” SSR (corrected states/reference station density)
- demonstration/**verification** of SSR2OSR for **legacy rovers**







- top: Bavarian-wide SSR, closest station 28 km, no complete ionospheric, with tropospheric correction
- bottom: German-wide SSR, closest station 70 km, no complete ionospheric, without tropospheric correction

AdV: Working Committee of the Surveying Authorities of the Laender of the Federal Republic of Germany, www.adv-online.de

plots: courtesy of Martin Freitag, SAPOS Bayern

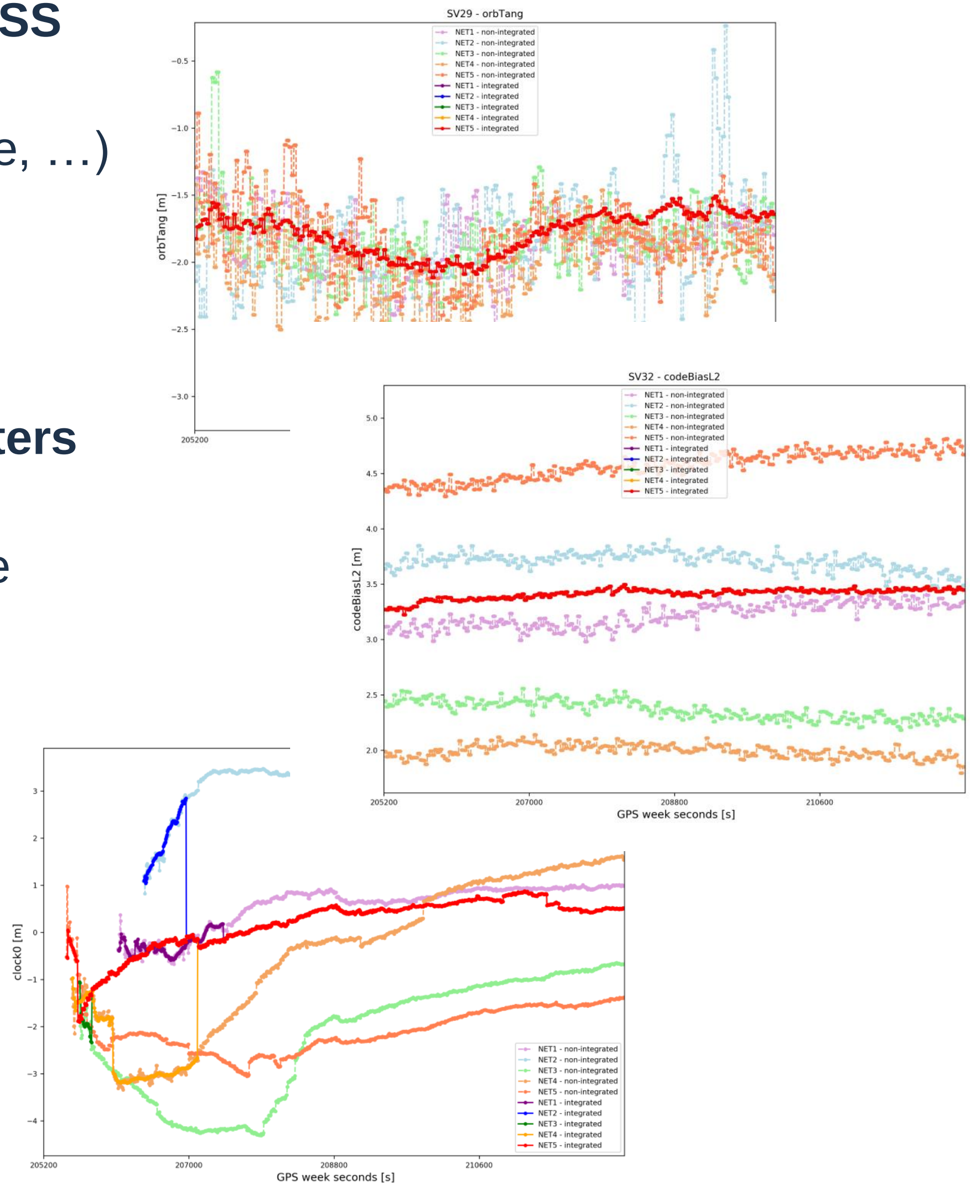
SSR – Integrator for State Space Parameters

- demand to **combine rigorously more GNSS** reference **stations**
  - to scale SSR (service aera, perforance, …)
  - to provide continuous SSR services
- leads to **low processing rate**

solution is combining state space parameters of serveral networks

- **distributed system** (Kernel split to mutiple servers)
- **global** or **regional** or **local** networks
- rigorous adjustment using
- use of **all observations** and of **all reference stations**
- more physical parameters estimation for individual network

- available with Geo++ GNSMART 2.x



- GNSS Augmentation in SSR and OSR Domain
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- **Summary/Outlook**

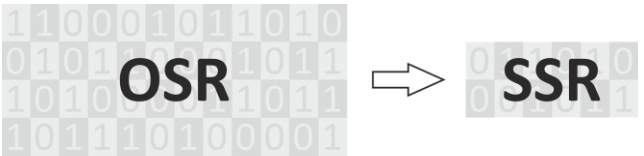
Summary/Outlook (1)

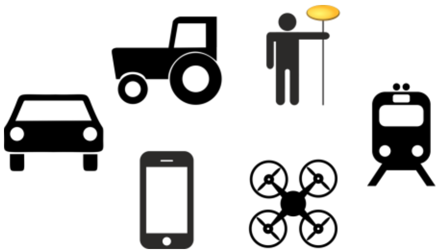
SSR technology provides

- broadcast GNSS corrections
- minimized bandwidth
- scalable GNSS services concerning
  - variety of GNSS and signals
  - positioning accuracy
  - service areas
- backward compatibility to GNSS applications

which are **essential benefits** for

scalable real-time GNSS applications





Summary/Outlook (2)

- State Space Representation (**SSR**) is most convincing **GNSS augmentation** technology **to cope with the increase of new signals and new constellations**.

- **enhancements** of

  SSR modeling or **representation**

  will **improve GNSS positioning**

- SSR **standardization is challenging**.

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

SSR – Fusion of GNSS Augmentations

GNSS augmentation with **SSR combines** the **accuracy of RTK** with the **broadcast** and low bandwidth benefits **of PPP**.

It is backward compatible to all legacy augmentation methods and can be **universally** adopted **to any reference station network**, no matter if

- global or regional
- high density or low density
- single, double or triple frequency.