Generation of Consistent GNSS SSR Corrections for Distributed CORS Networks

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Abstract

Generation of Consistent GNSS SSR Corrections for distributed CORS Networks

Classical CORS (continuously operating reference station) networks providing a GNSS RTK (Real Time Kinematic) service enable centimeter level accuracies with immediate ambiguity resolution. The service area is typically limited to the area covered by some 10s of reference stations on national or provincial level. In contrast, PPP (Precise Point Positioning) services typically cover the entire globe but lack the accuracy and convergence speed of RTK services. The reason for this is mainly the missing information about local disturbances of the ionosphere. This information is essential for the instant and reliable discrimination of the correct integer ambiguity level.

The generalization of PPP is known as SSR (state space representation) which is a technique that, in addition to the orbits, clocks and sometimes biases found in most PPP approaches, also allows the broadcasting of local tropospheric and especially ionospheric corrections.

One important aspect for high performance operation of SSR based RTK services is the consistent and seamless generation of all SSR parameters covering the complete service area.

Here, we present our realization to generate consistent GNSS SSR corrections, enabling the broadcast of a full SSR state vector for CORS networks of arbitrary size. We show how the difficulty of excessive computational load can be overcome by distributing the system among several processing machines. We also demonstrate how this concept can be used to combine several existing RTK networks into a larger SSR cluster that generates consistent corrections for the whole area by resolving the ambiguities between the individual networks.

This paves the way for novel augmentation services, delivering true RTK performance to users in a very large service area. It is ideally suited for space-based transmission via GEO satellites or even via the GNSS satellites themselves as demonstrated by the QZSS CLAS signal that is powered by this technology.

Overview

- Introduction
- GNSS CORS Services
- GNSS Processing Approach
- Consistent GNSS SSR Corrections
- Consistent SSR Benefits & Example
- Conclusion

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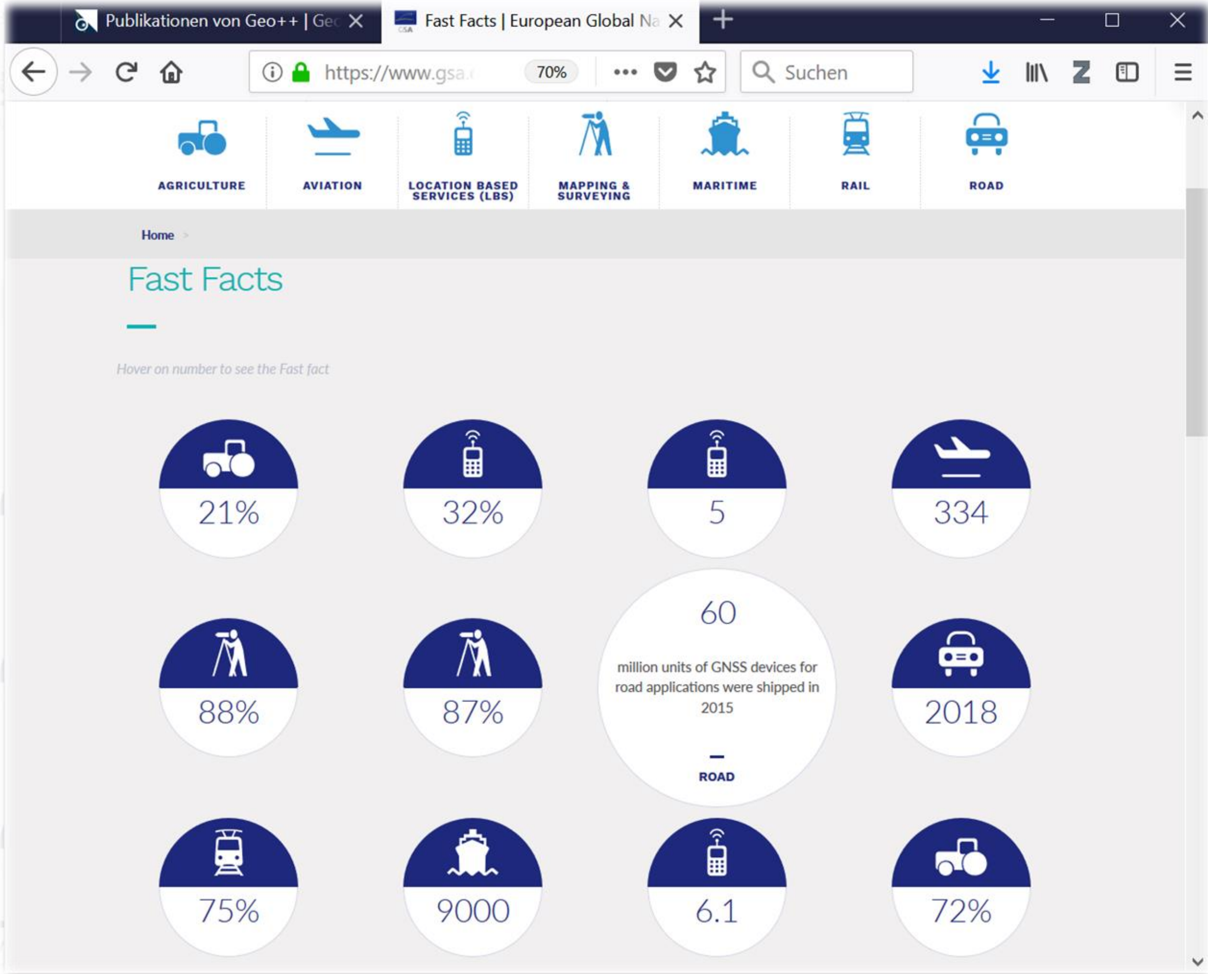
Introduction

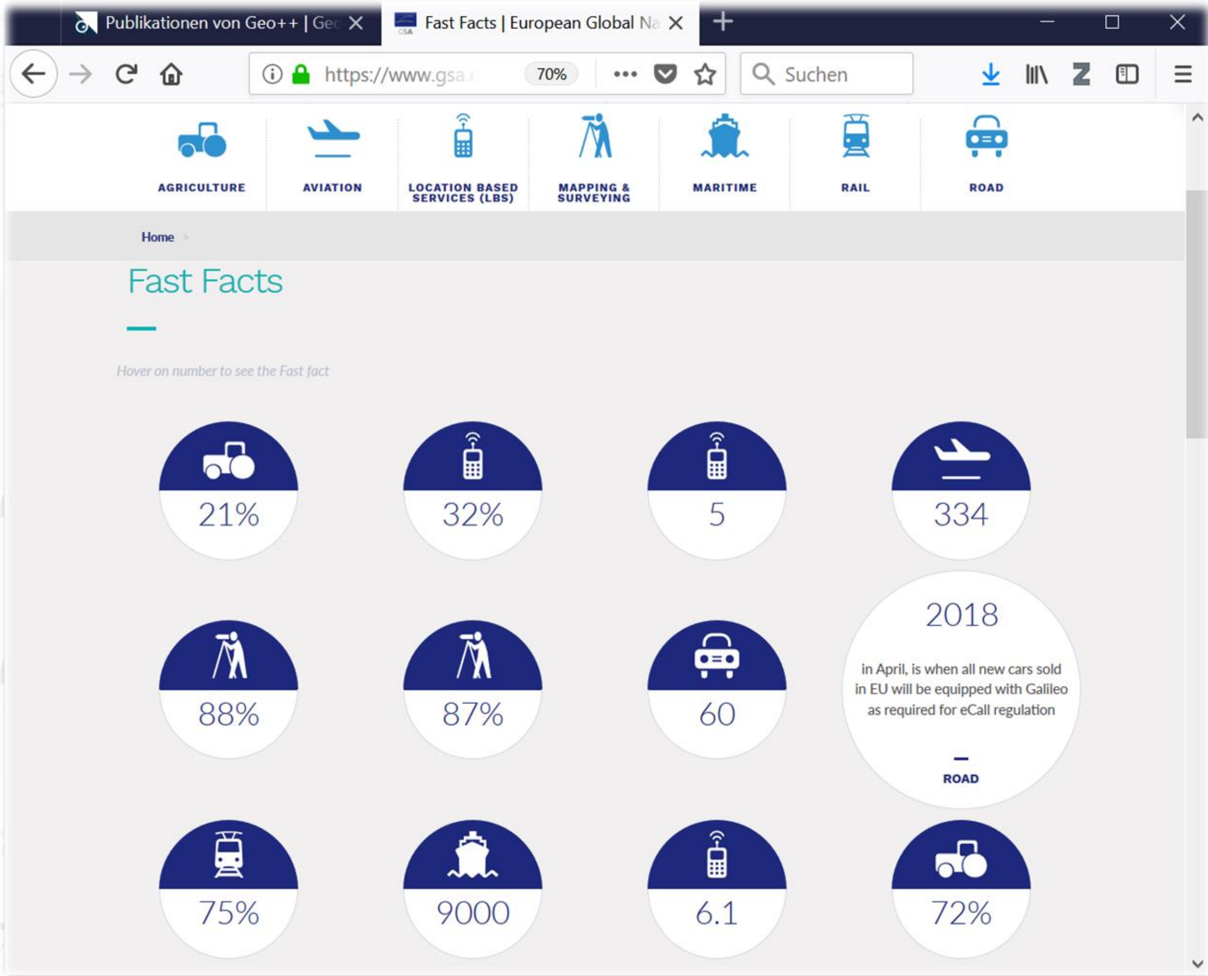
- some arbitrary facts from European Global Navigation Satellite System Agency (GSA)
  - 60 million units of GNSS devices for road applications were shipped in 2015



https://www.gsa.europa.eu/fast-facts

Introduction

- 60 million units of GNSS devices for road applications were shipped in 2015
- **2018 in April, is when all new cars sold in EU will be equipped with Galileo as required for eCall regulation**



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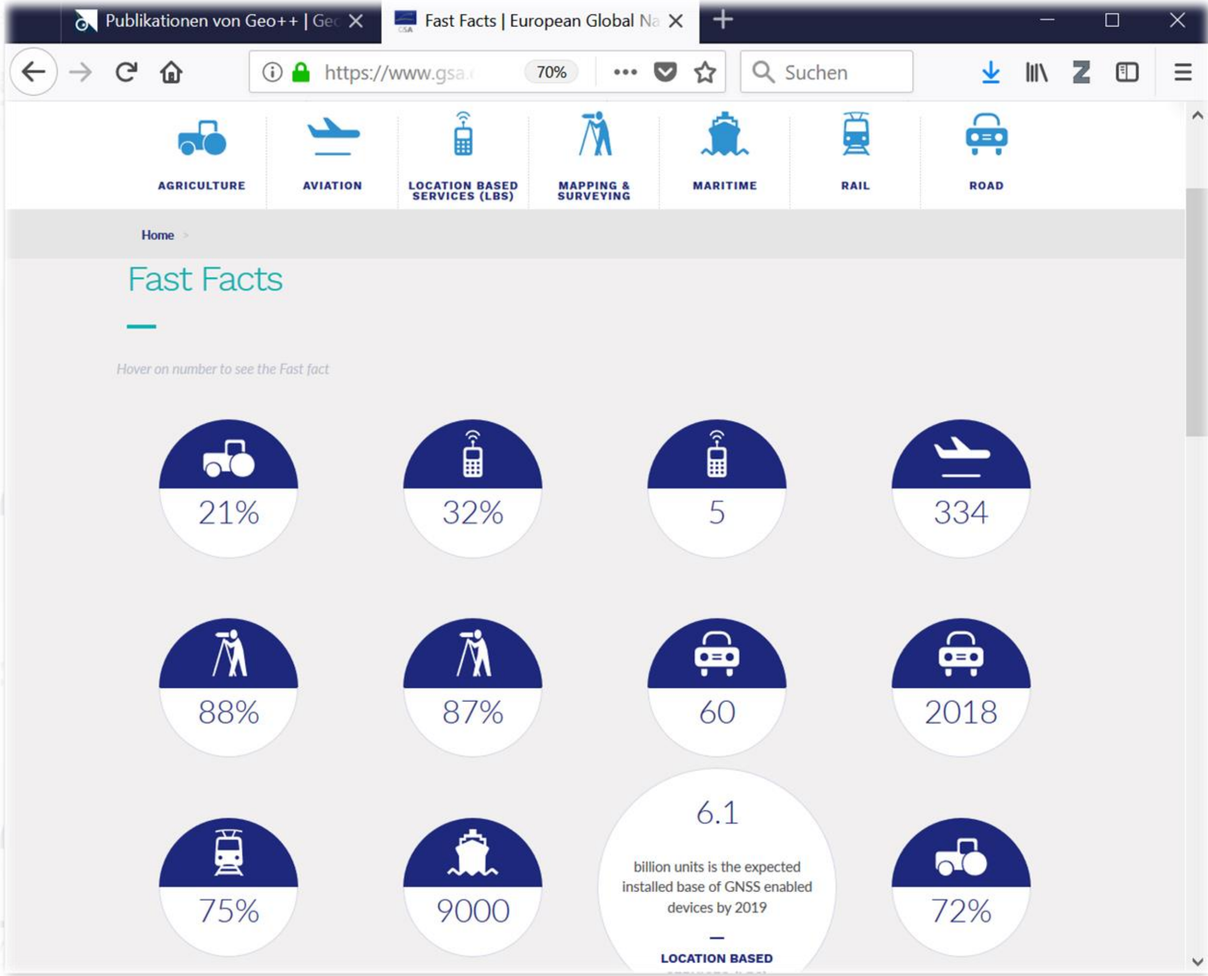
Introduction

- 60 million units of GNSS devices for road applications were shipped in 2015
- 2018 in April, is when all new cars sold in EU will be equipped with Galileo as required for eCall regulation
- **6.1 billion units is the expected installed base of GNSS enabled devices by 2019**



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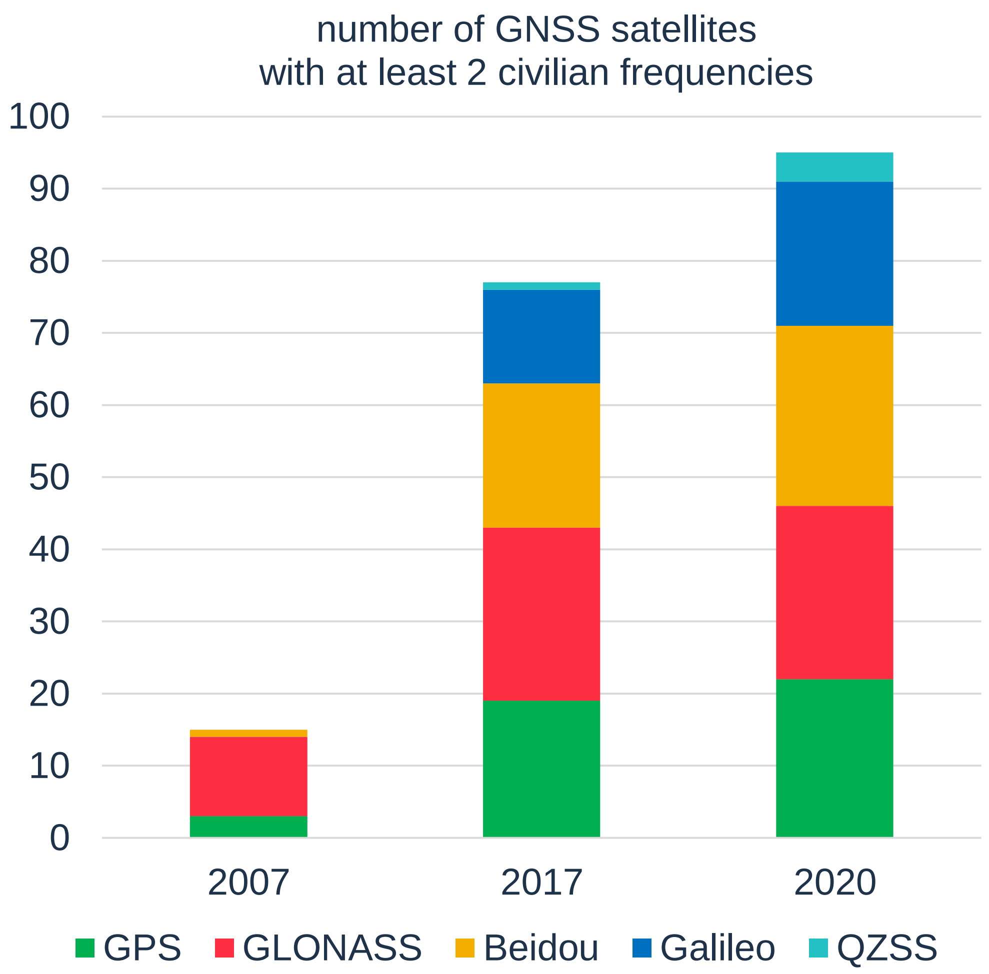
Introduction

- **GNSS SSR expectation** is,
  a significantly **increasing demand**
  for GNSS correction
  for worldwide positioning application
- **due to e. g.**
  - more usable satellites
  - low-cost 2-frequency receivers
    (including phase measurements)
  - mass market applications
  - novel applications
  - increasing demand in accuracy and availability
  - …



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GNSS CORS Services vs. PPP GNSS Services

- **classical GNSS CORS** (continuously operating reference station) networks
  - provide GNSS RTK (Real Time Kinematic) services
  - enable **centimeter** level accuracies with **immediate ambiguity resolution**
  - **service area** is typically **limited** to the area covered by some 10s of reference stations on national or provincial level

- **PPP** (Precise Point Positioning) GNSS services
  - provide GNSS correction products
  - **lack in accuracy and convergence time** compared to RTK services
    - main reason is missing information about local disturbances of the ionosphere
    - ionospheric information is essential for instant and reliable discrimination of the correct integer ambiguity level
  - **typically** cover the **entire globe**

GNSS CORS Services - Networking Tasks

- primary task (pre-requisite)
  - carrier phase **ambiguity resolution** within network through adequate modeling
  - **determine distance** (and site) dependent **GNSS errors**
  - use minimum number (density) of reference stations
  - **ambiguity free distance dependent GNSS errors** required
- secondary task
  - represent all network information
  - take all reference station dependent errors into account
  - **provide all relevant** (distance dependent) **GNSS errors**
  - provide **consistent GNSS corrections** to users

GNSS CORS Services – Provider Tasks

- GNSS service provider task
  - consistent SSR products
  - consistency means
    - application of **SSR parameters**
    - for highest positioning service
    - **enables immediate ambiguity resolution**
    - with **RTK accuracy**
- SSR consistency is essential, which is obtained with
  - rigorous **State Space Modeling** (SSM)
  - separation of all individual GNSS errors
- state space approach serves for all CORS networking/provider tasks

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GNSS Processing Approach

- **parameter estimation**
  - **un-differenced** GNSS **observables**
  - **all parameter are estimated**
  - no mathematical correlation
  - absolute position X, Y, Z
  - smallest noise
  - complete variance-covariance-matrix with physical correlations
  - realistic stochastic
  - **higher processing time/large state size**

- **parameter elimination**
  - differences of GNSS observables
    (e. g. **double differences** between two stations/satellites)
    eliminate errors
  - estimation of parameter residual
  - mathematical correlation
  - relative position ΔX, ΔY, ΔZ
    (not all combinations independent)
  - increased noise
  - variance-covariance-matrix
  - optimistic stochastic
  - **short processing time/small state size**

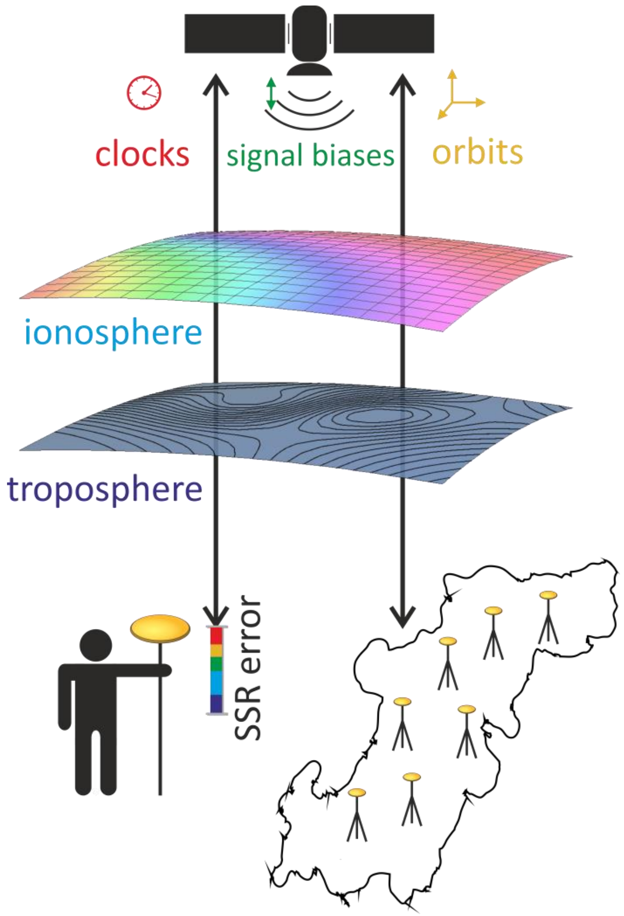
State Space Approach

- **Kalman filter** for **real-time** applications
- complete SSM of **all GNSS errors with mm-accuracy**
- multi-station **real-time GNSS network** solution
- **undifferenced** observables
  - network operates in absolute mode
  - no mathematical correlation between observations
  - complete variance-covariance matrix
- **simultaneous** multi-**frequency**/multi-**signal**/multi-**GNSS** adjustment
  - allows rigorous modeling of correlations between linear combinations
  - rigorous modeling of common parameters possible (e.g. biases for satellite and receiver)
  - improvement of noise level for derived state parameters
- **rigorous GNSS multi-network**
  - enables generation of consistent GNSS SSR corrections

concept of Geo++ GNSMART

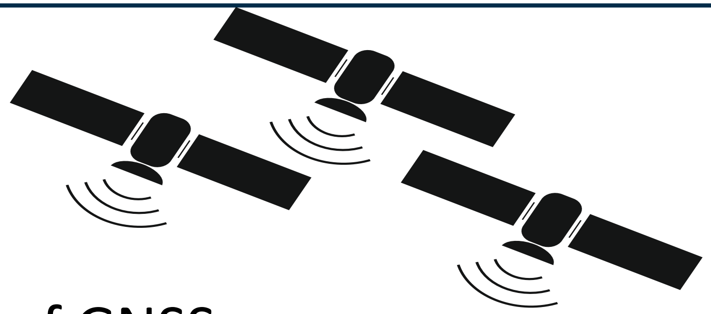
State Space Model (SSM)

- **state parameter** of state space model (SSM*)
  - satellite **clock** synchronization error
  - satellite signal **delays** (phase and code)
  - satellite **orbit** error (kinematic orbits)
  - **ionospheric** signal propagation changes (multiple stage model)
  - **tropospheric** signal delays (multiple stage model)
  - carrier phase **ambiguities**
  - receiver **clock** synchronization error
  - receiver signal **delays** (phase and code)
  - receiver **coordinates**



* simplified SSM according to Geo++ GNSMART

GNSS State Space Vector Size - The Challenge

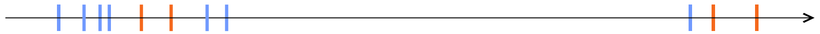


number of states

year 2010

×3

number of GNSS satellites



×3

number of GNSS frequencies

number of GNSS signals

×5

L2/1227.60	C/A	C2C
	L1(C/A)+(P2-P1) (semi-codeless)	C2D
	L2C (M)	C2S
	L2C (L)	C2L
	L2C (M+L)	C2X
	P (AS off)	C2P
	Z-tracking and similar (AS on)	C2W
	Y	C2Y
	M	C2M
	codeless	

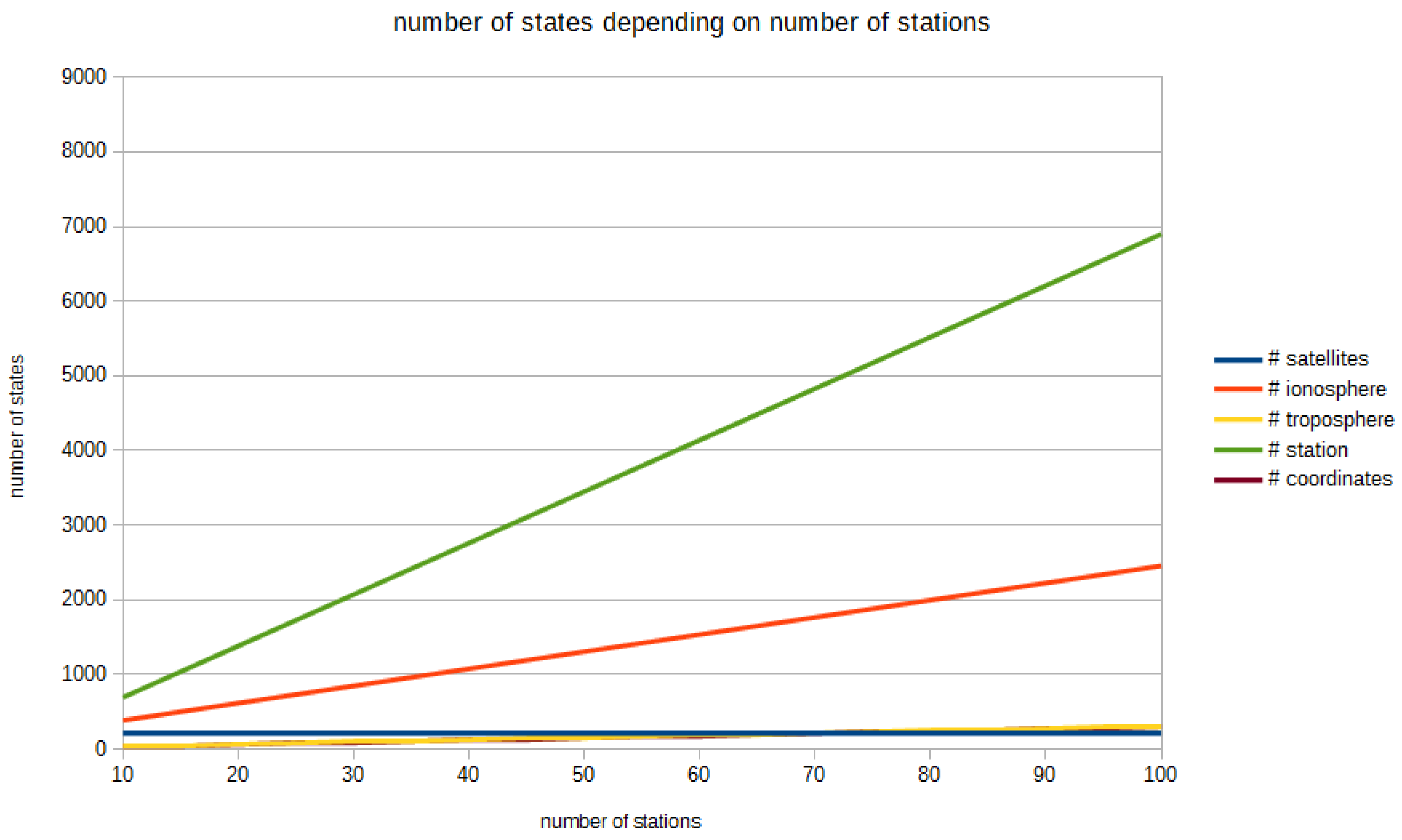
year 2020

30 – 50 times larger **state vector**

Analysis State Space Vector Size (1)

- one GNSS network
  - typical SSM modeling
  - simplified assumptions GNSS
    - **three GNSS** with **two signals each** for **three frequencies**, **23 satellites in total**
  - **increase in** number of **stations**

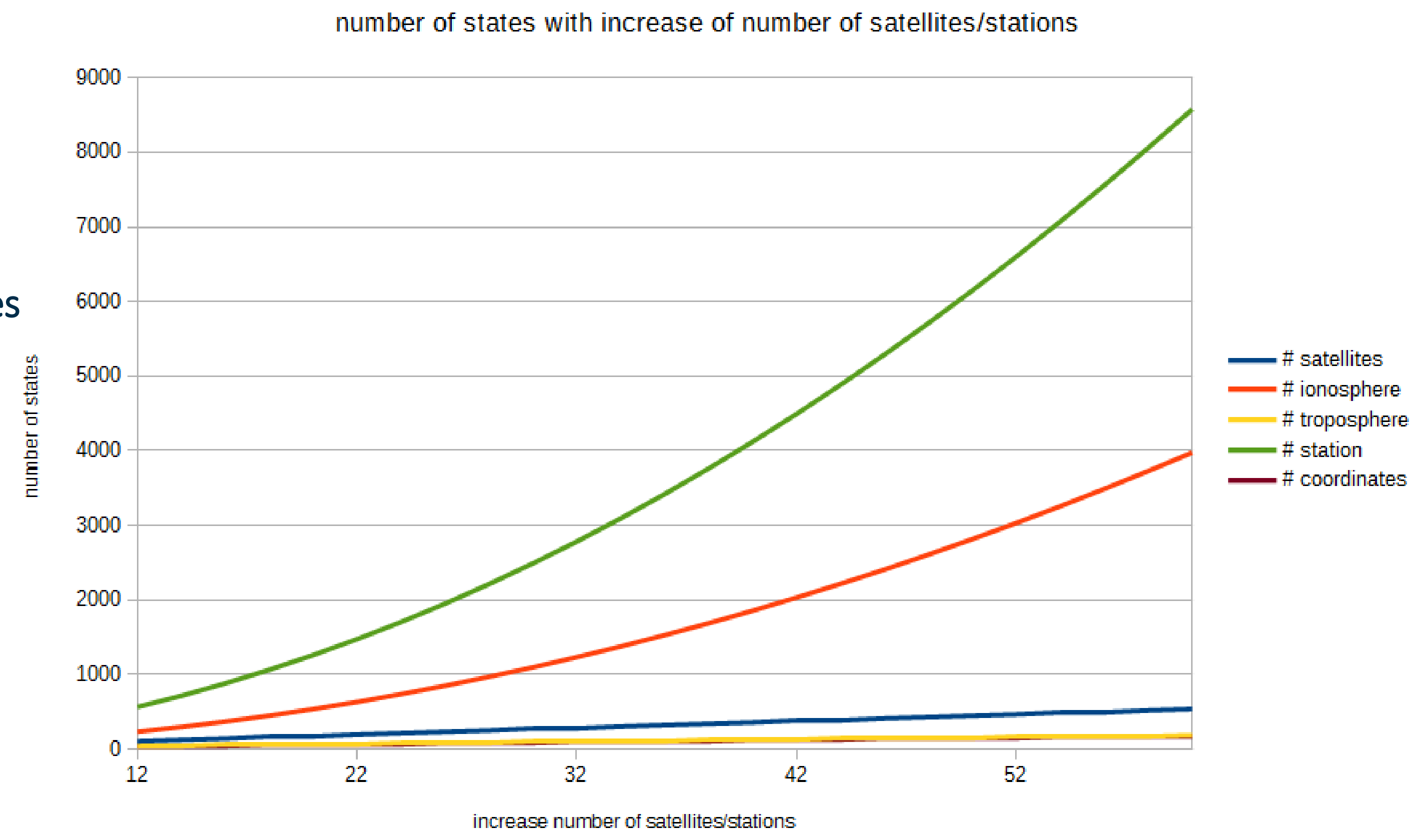
- increase of state parameters mainly for
  - **station dependent error** models
  - **ionosphere modeling**



Analysis State Space Vector Size (2)

- one GNSS network
  - typical SSM modeling
  - simplified assumptions GNSS
    - **three GNSS** with **two signals each** for **three frequencies, 12 /23 stations/satellites**
  - **linear increase** in number of **stations+satellites**

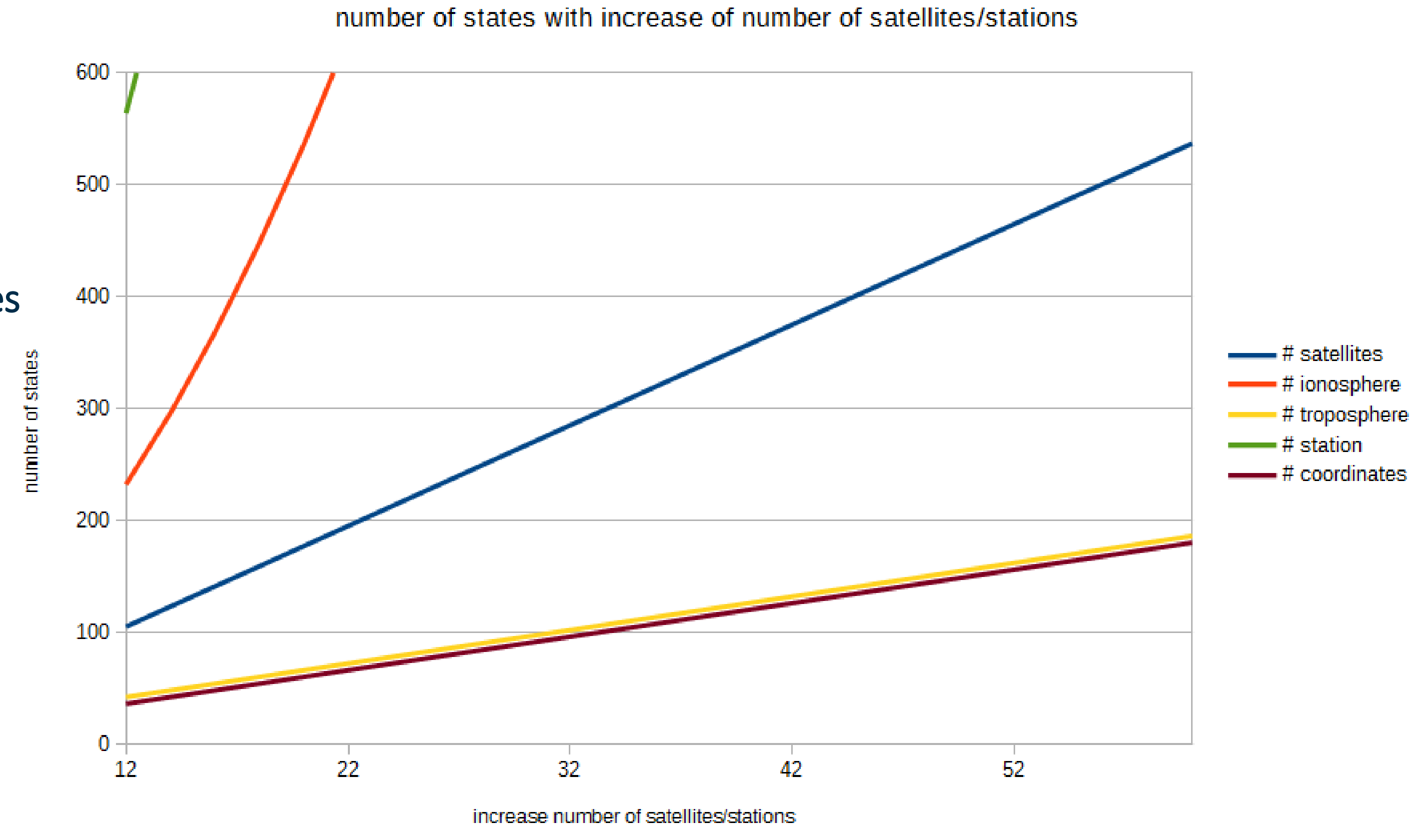
- **increase of state parameters still mainly for**
  - **station dependent error** modeling
  - **ionosphere modeling**



Analysis State Space Vector Size (3)

- one GNSS network
  - typical SSM modeling
  - simplified assumptions GNSS
    - **three GNSS** with **two signals each** for **three frequencies, 12 /23 stations/satellites**
  - **linear increase** in number of **stations+satellites**

- increase of state parameters small for
  - **satellite dependent error** modeling
  - **troposphere dependent error** modeling
  - coordinates



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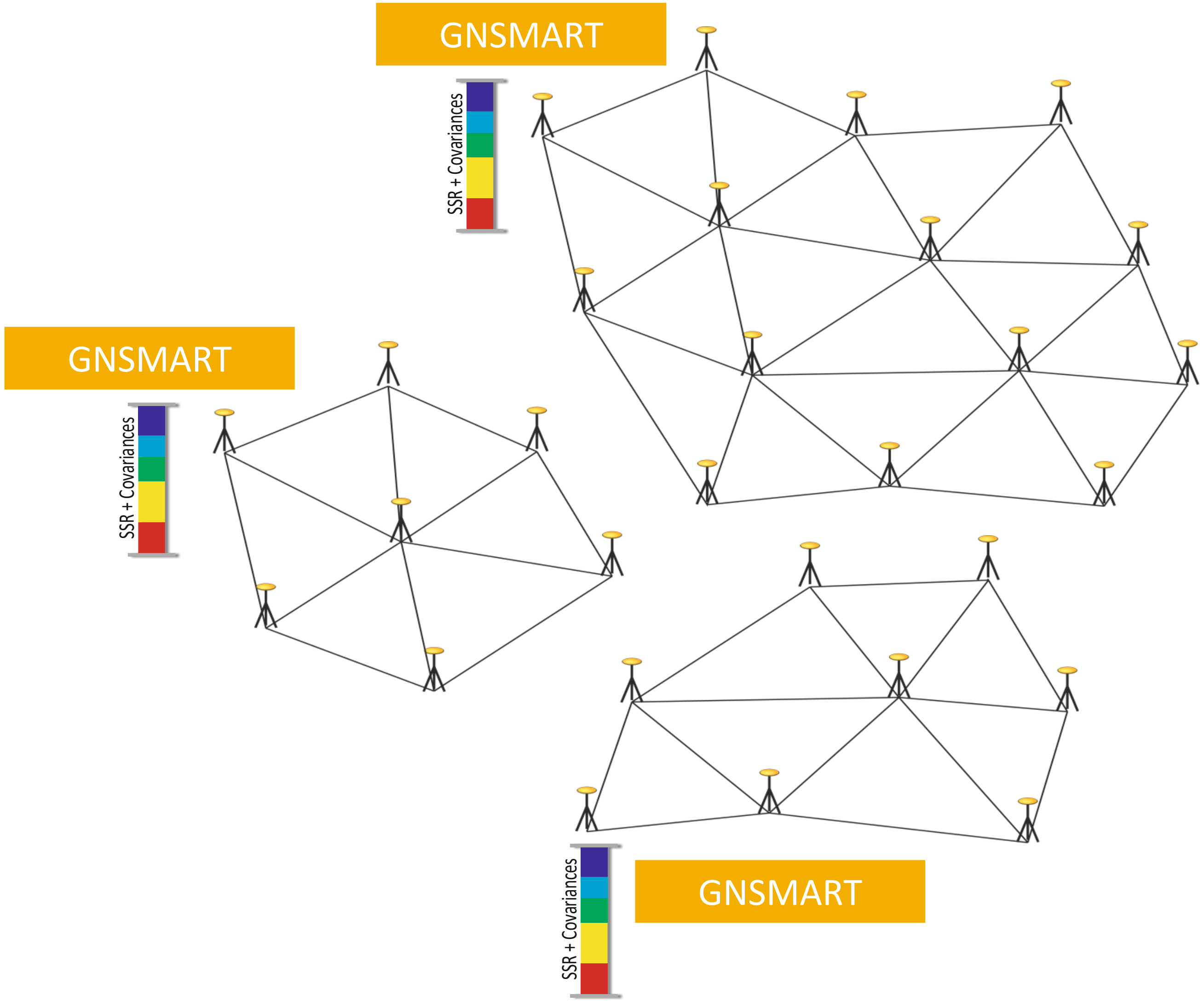
Consistent GNSS SSR Corrections - How to Generate?

- integration of states from multiple networks with a federated filter approach

Network Integrator



concept of Geo++ GNSMART

Consistent GNSS SSR Corrections - How to Generate?

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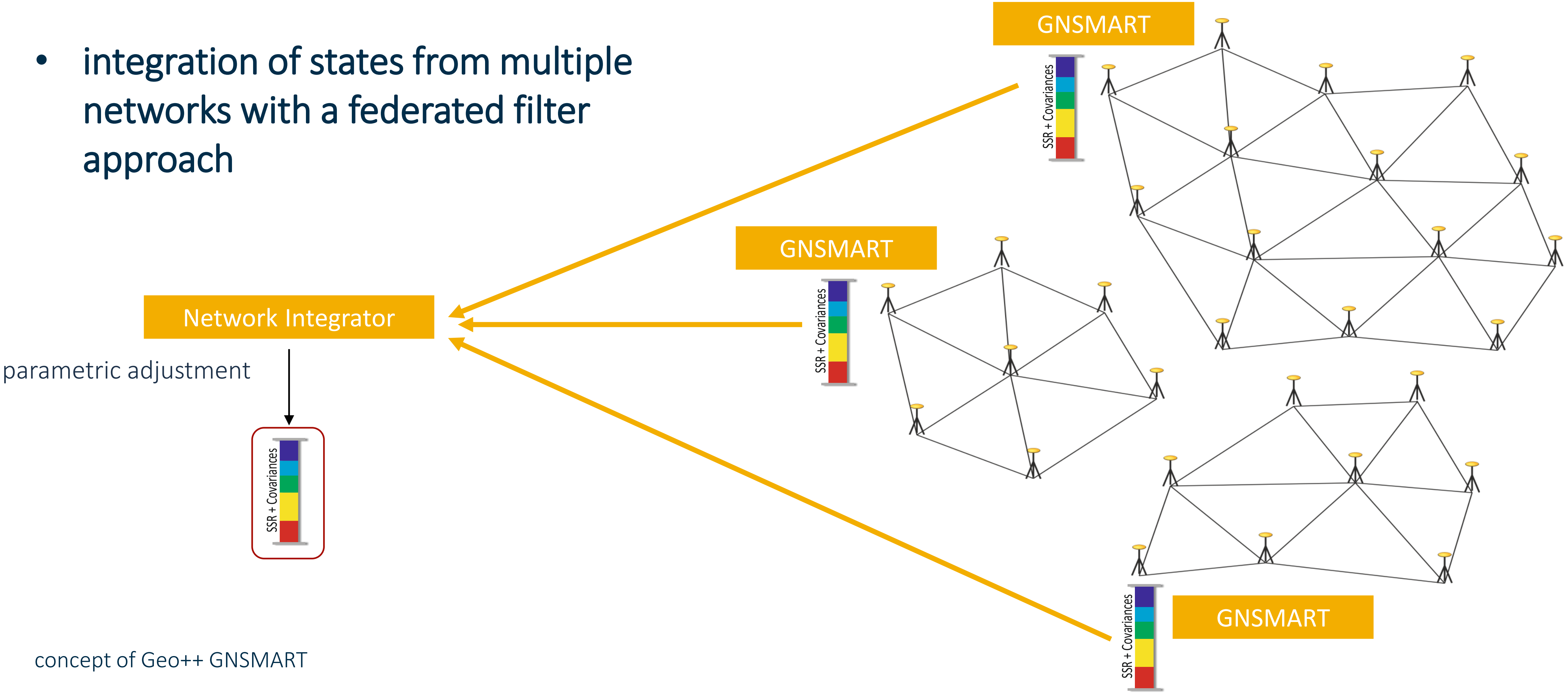

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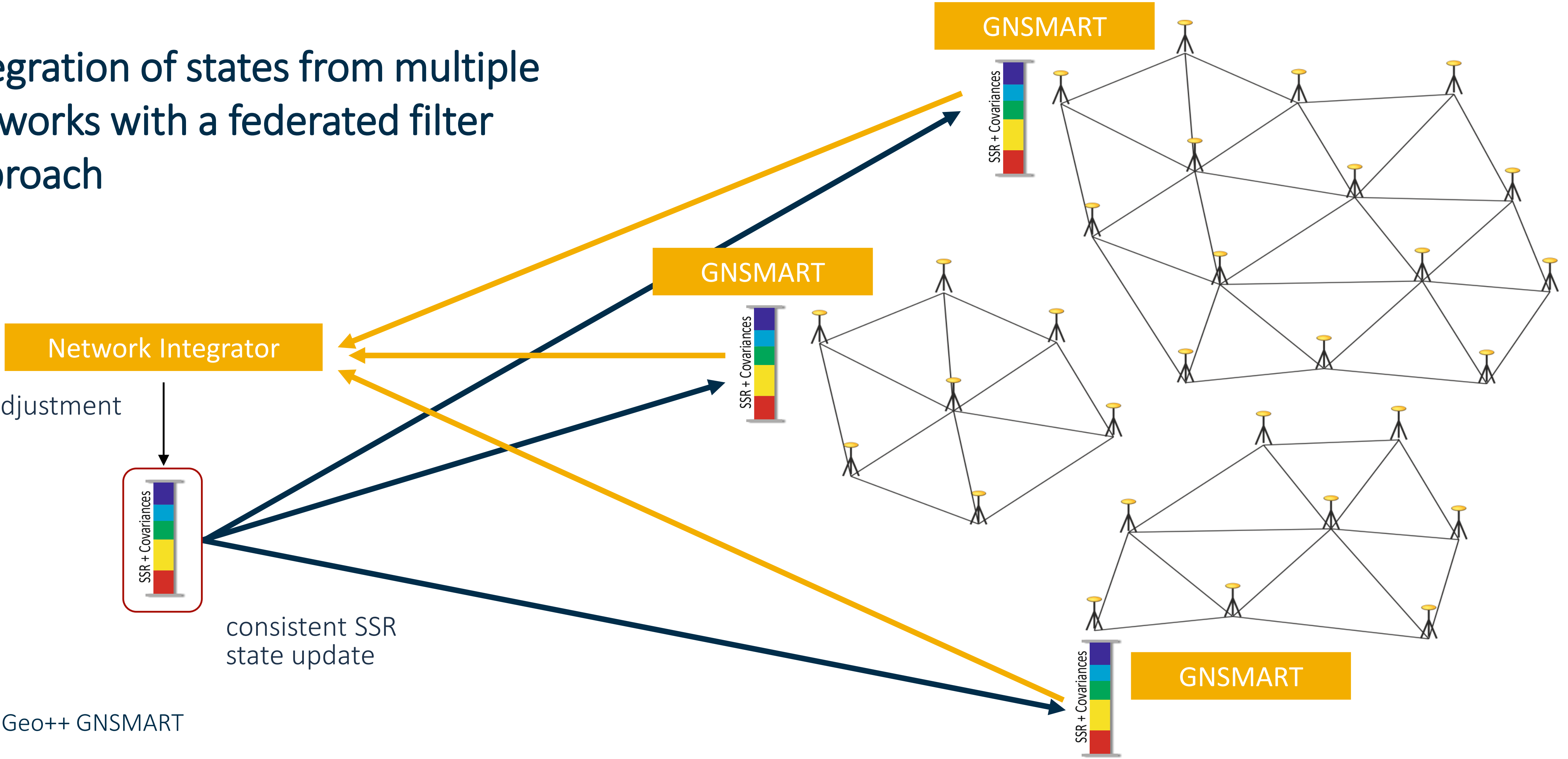
Integrating GNSS Networks

- integration of states from multiple networks with a federated filter approach



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Integrating GNSS Networks

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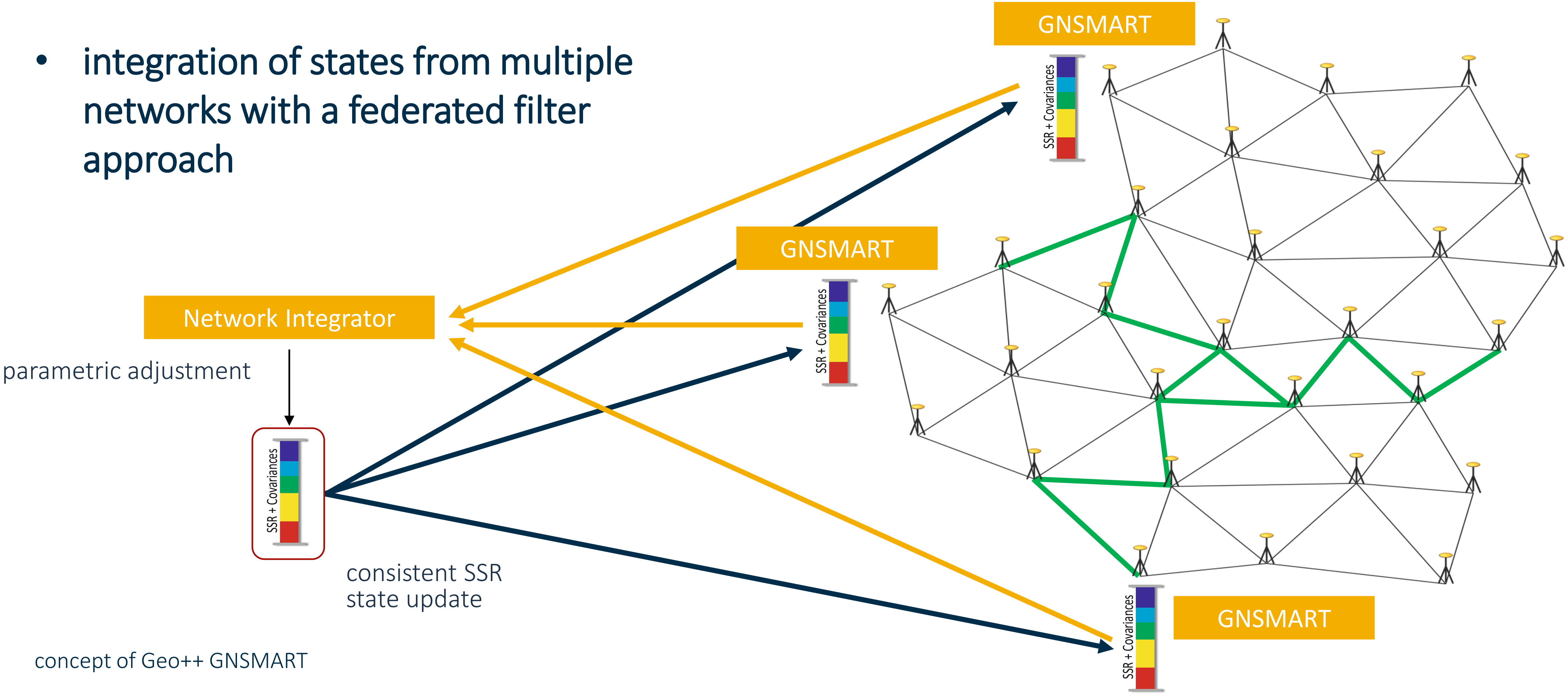

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Generating Consistent GNSS SSR Corrections

- use distributed CORS networks
  - **integrate smaller networks** to reduce state vectors size
  - rigorous adjustment using stochastic
  - **adjust SSR** parameters **rigorously** instead of extending the general number of CORS stations
  - maintain **SSR consistency** for any service area

- benefits
  - **reduce processing burden** with small state vectors
  - distributed system (Kernel split to multiple servers)
  - consistent SSR allows **ambiguity resolution** with minimized or **no convergence time**
  - **seamless services** for large area
  - better physical parameter estimation for individual network
  - **scalable** SSR performance
  - service area can local or regional or global networks

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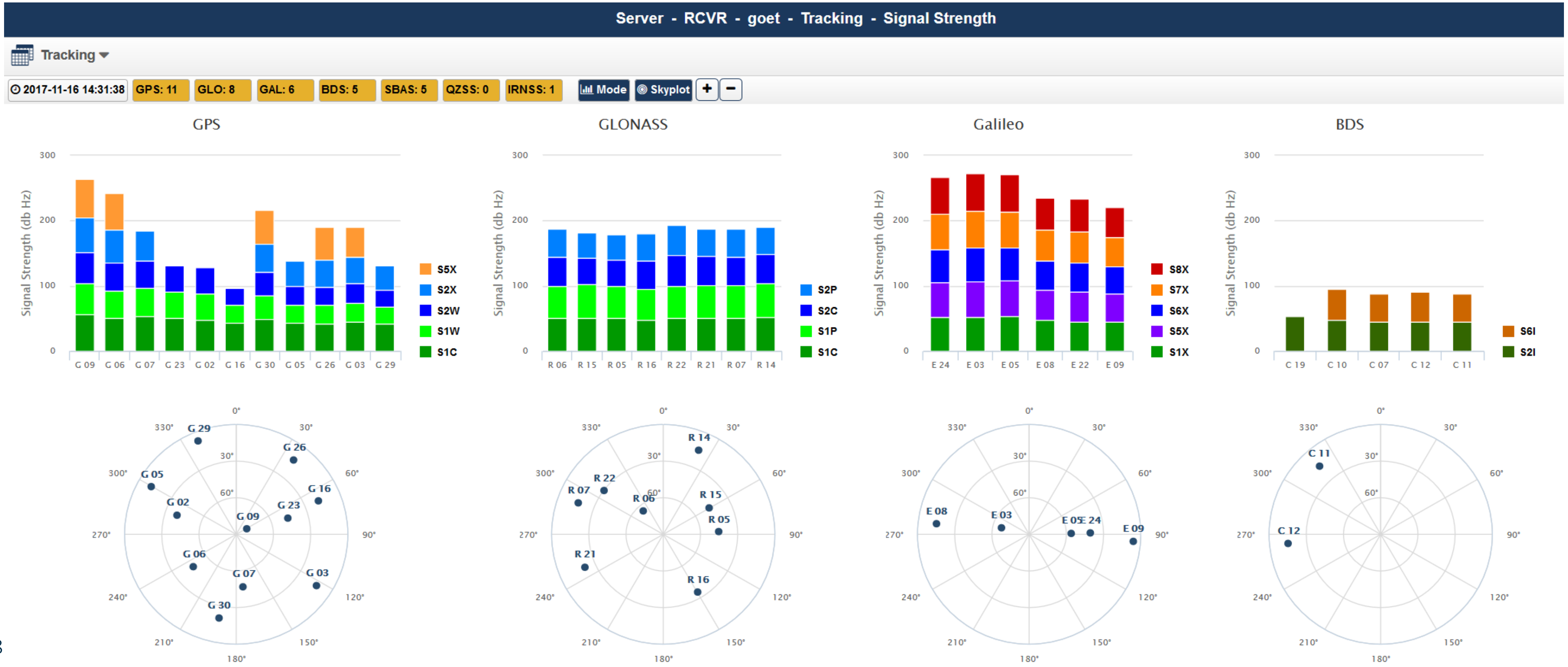
Support of All GNSS Signals

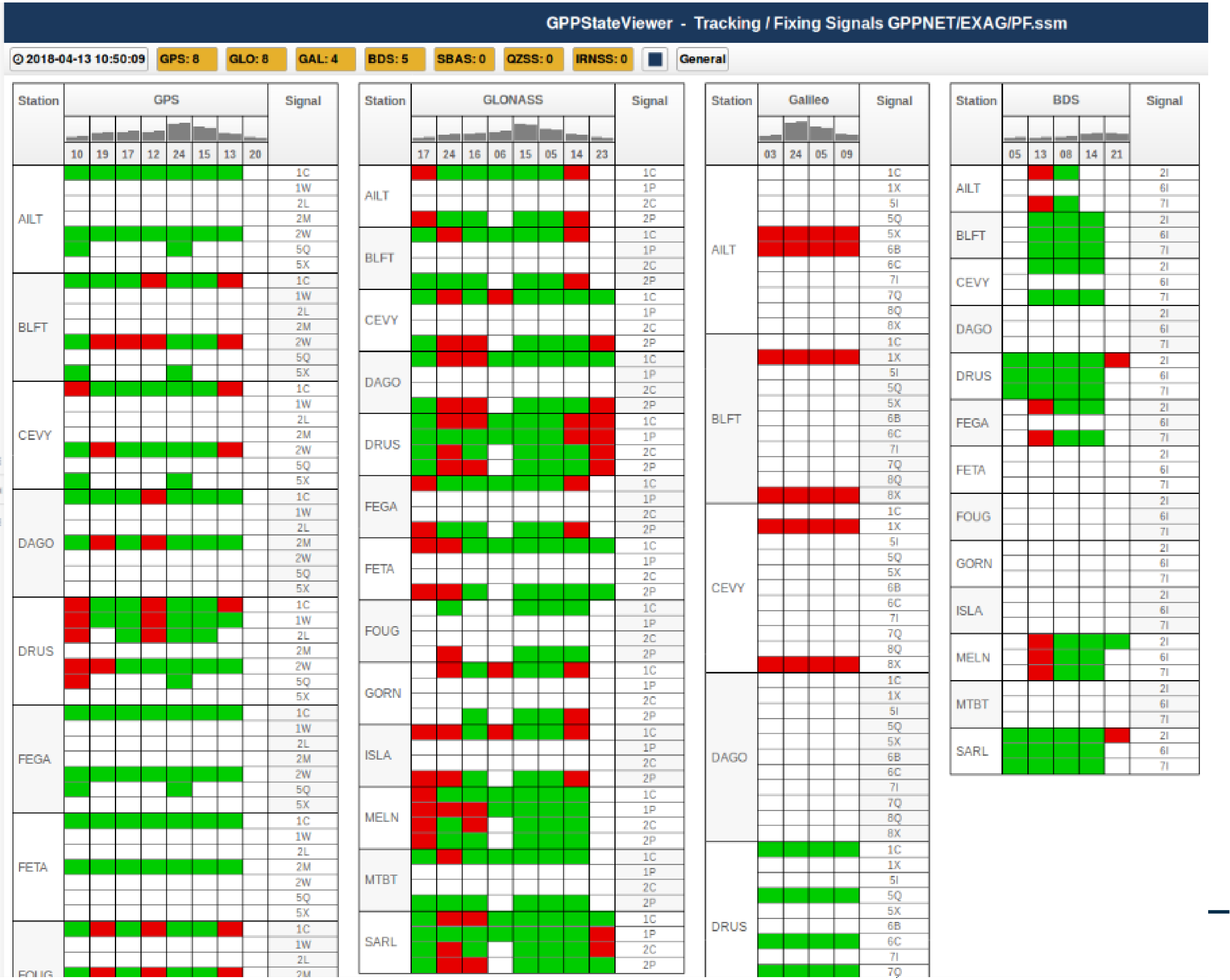
- variety of GNSS CORS service and user hardware
- supports of all available signals and frequencies



GNSMART 2 snapshot taken
from BKG GREF/DB Netz AG network, 2018

Support of All GNSS Signals

- supports of all available signals and frequencies
- example from TERIA network*
  - 7 GPS signals
  - 4 GONASS signals
  - 11 Galileo signals
  - 3 BDS signals

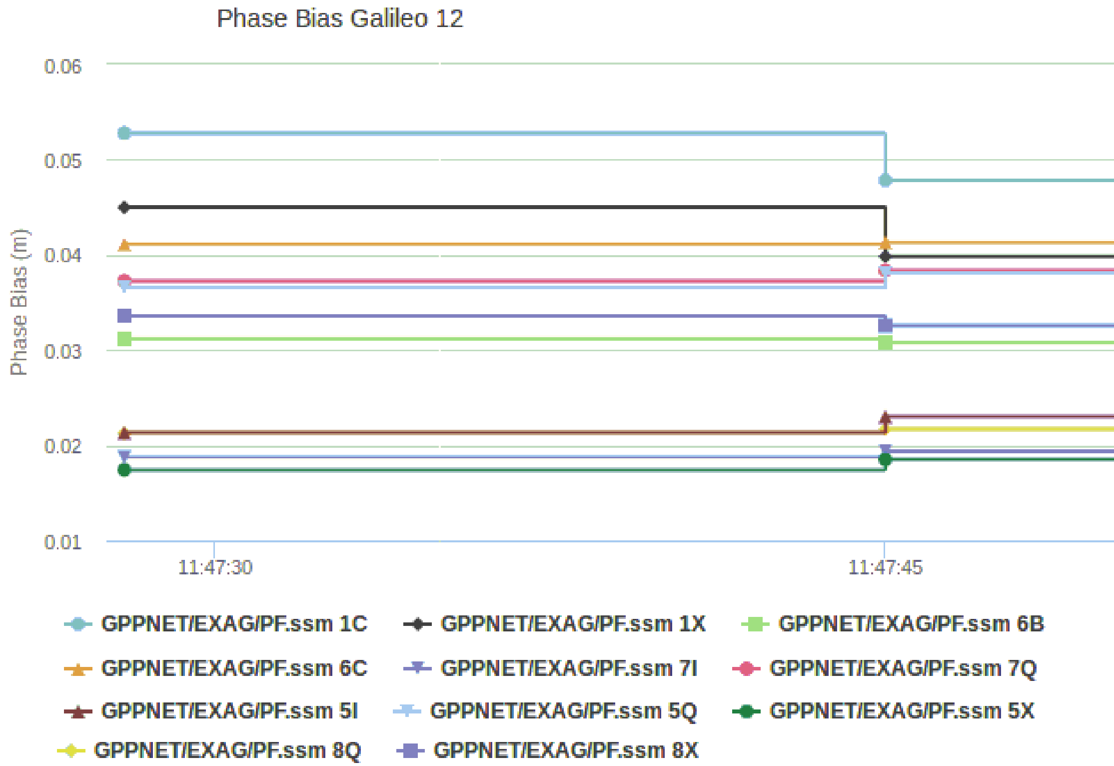


GNSMART 2 testing and evaluation

* based on TERIA CORS network, EXAGONE, France

Integrating GNSS Networks - Signal Biases

- supports of all available signals and frequencies
- requires estimation of phase and code biases
  - example Galileo phase biases



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GNSMART 2 testing and evaluation
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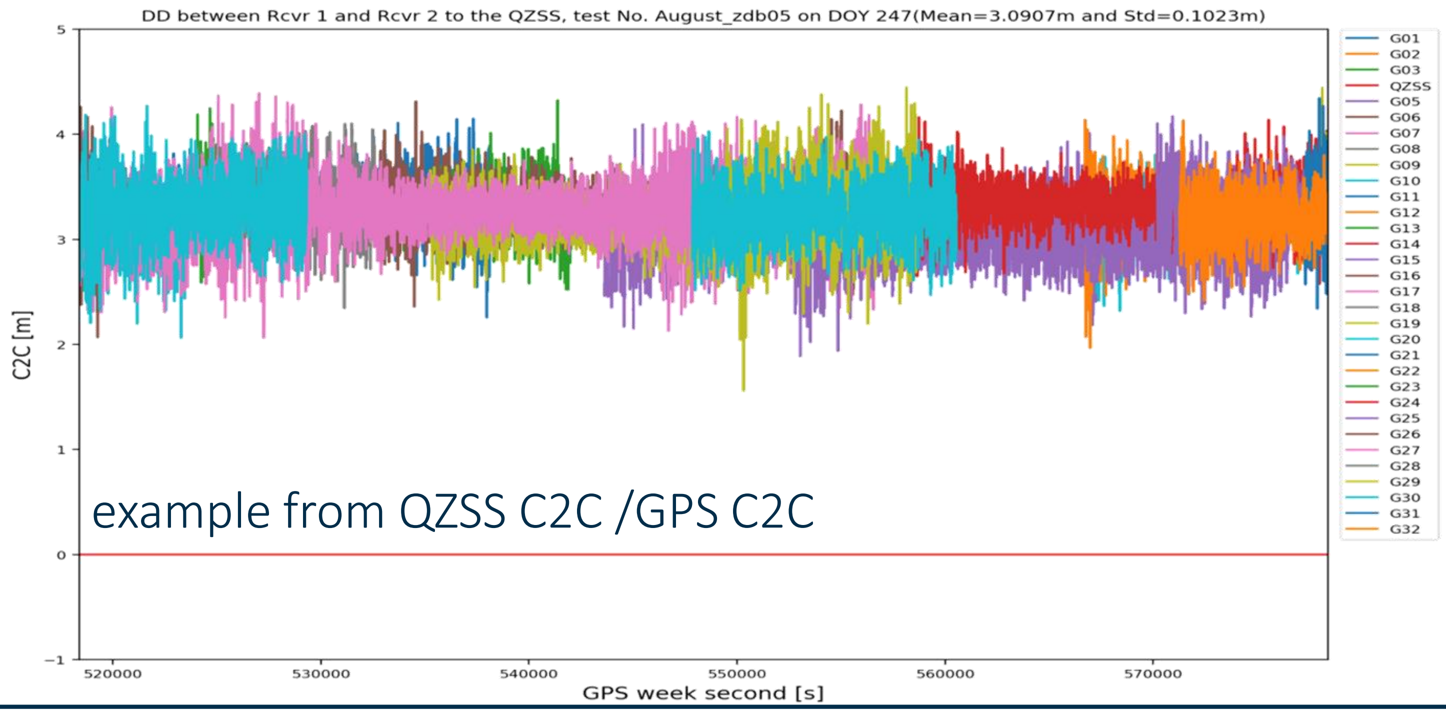
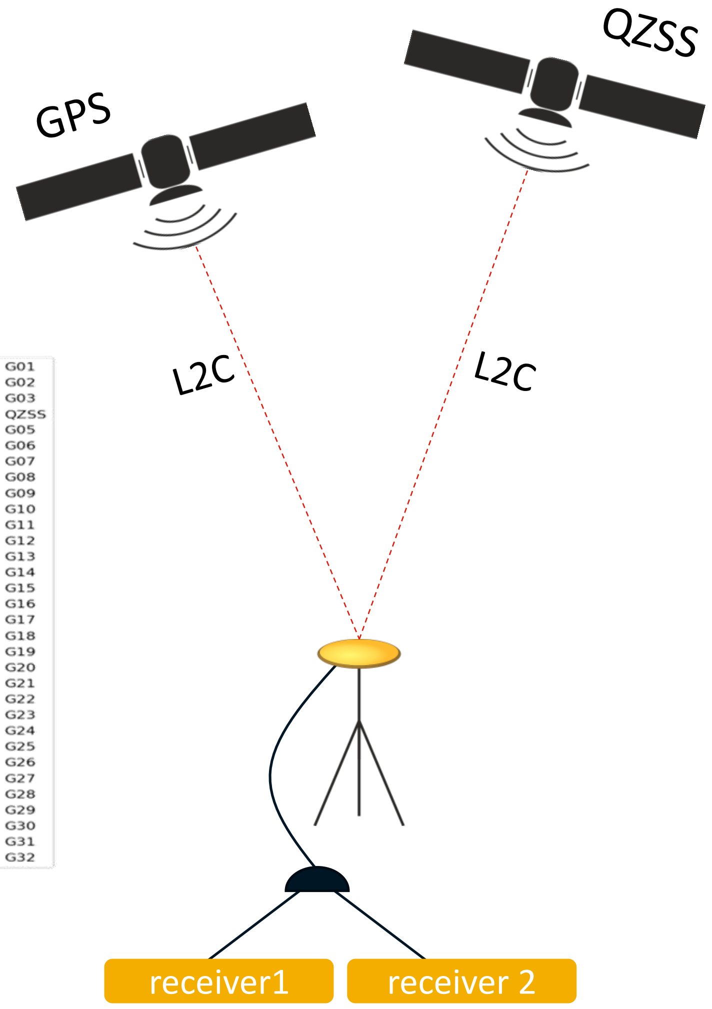
Independent on GNSS Hardware Biases

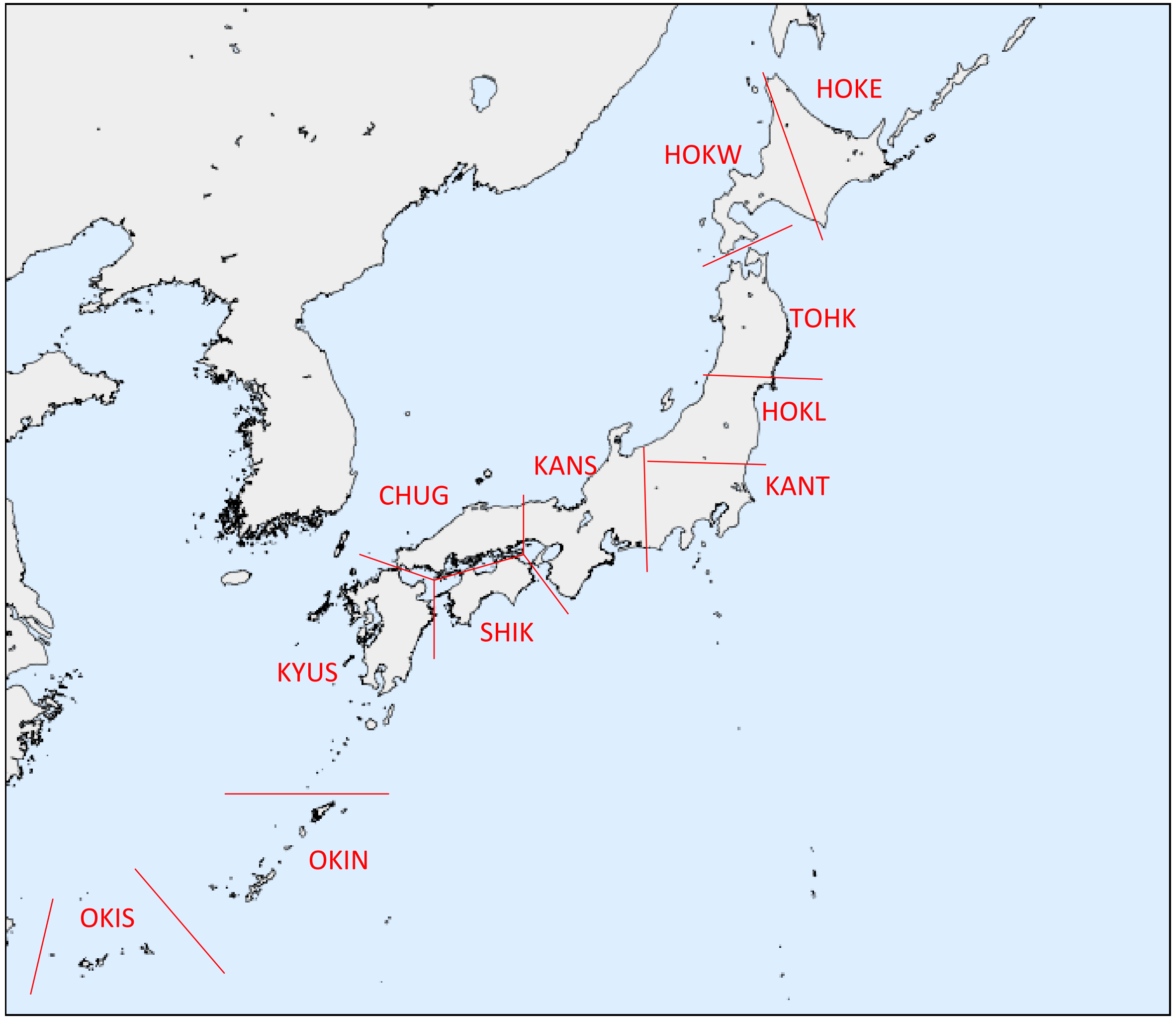
- phase and code biases depends on
  - receiver type
  - receiver firmware
  - receiver settings (multipath mitigation)





Integrating GNSS Networks - Example

- QZSS of Japan
- L6 CLAS signal of QZSS
  - 300 reference stations
  - about 1300 km x (50 km – 240 km)
  - 11 sub-networks
  - consistent SSR datasets every 5s/30s
- Network Integration
- one consistent SSR data set
  - for complete area of Japan
  - about 1700 bit/second



using Geo++ GNSMART 2

network overview courtesy of Rui Hirokawa (2018)

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Conclusion

- **demand** for **consistent GNSS corrections** is increasing
- **solution** are **integrated GNSS networks**
  - **combine** GNSS CORS networks **at the state space level**
  - provide **consistent** GNSS corrections
  - maintain small convergence time/**immediate AR with RTK accuracy**
  - enable **scalable** GNSS SSR services
  - step **towards ubiquitous precise GNSS** correction data

Conclusion ...

extending
the **range** of
CORS GNSS networks
for
consistent SSR
corrections