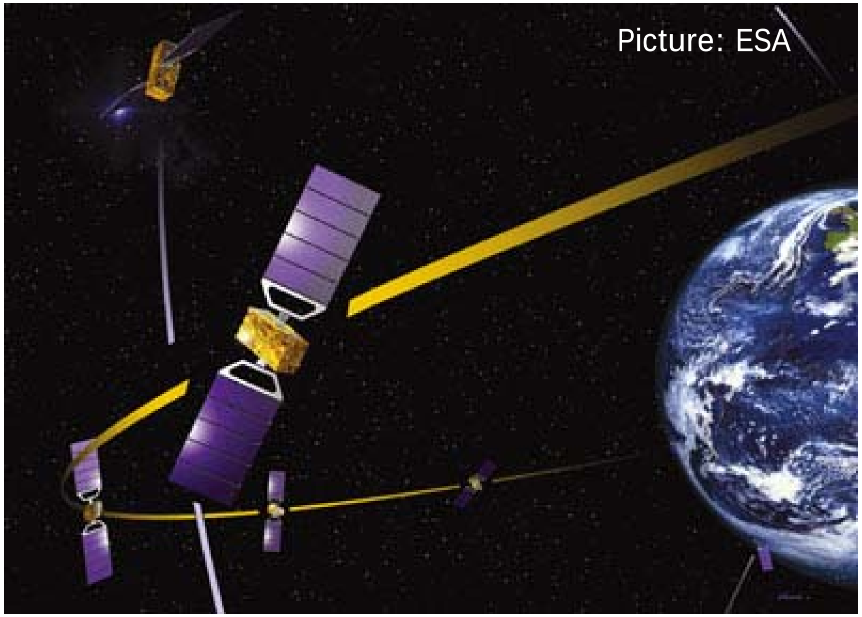
Satellite Navigation
Long baselines, PPP, SBAS



AE4E08

Sandra Verhagen and Hans van der Marel

Course 2010 – 2011, lecture 11

TU Delft

Organisation

Fieldwork: this or next week.
Contact r.j.p.vanbree@tudelft.nl

Available options:

- 2 March, morning or 3 PM
- 3 / 8 / 9 / 10 March

15 and 22 March, 8.45-10.30 AM: YOUR presentations – Assignment 4

[Space students will be in another room, to be announced]

Today’s topics

- Network RTK
- PPP
- SBAS

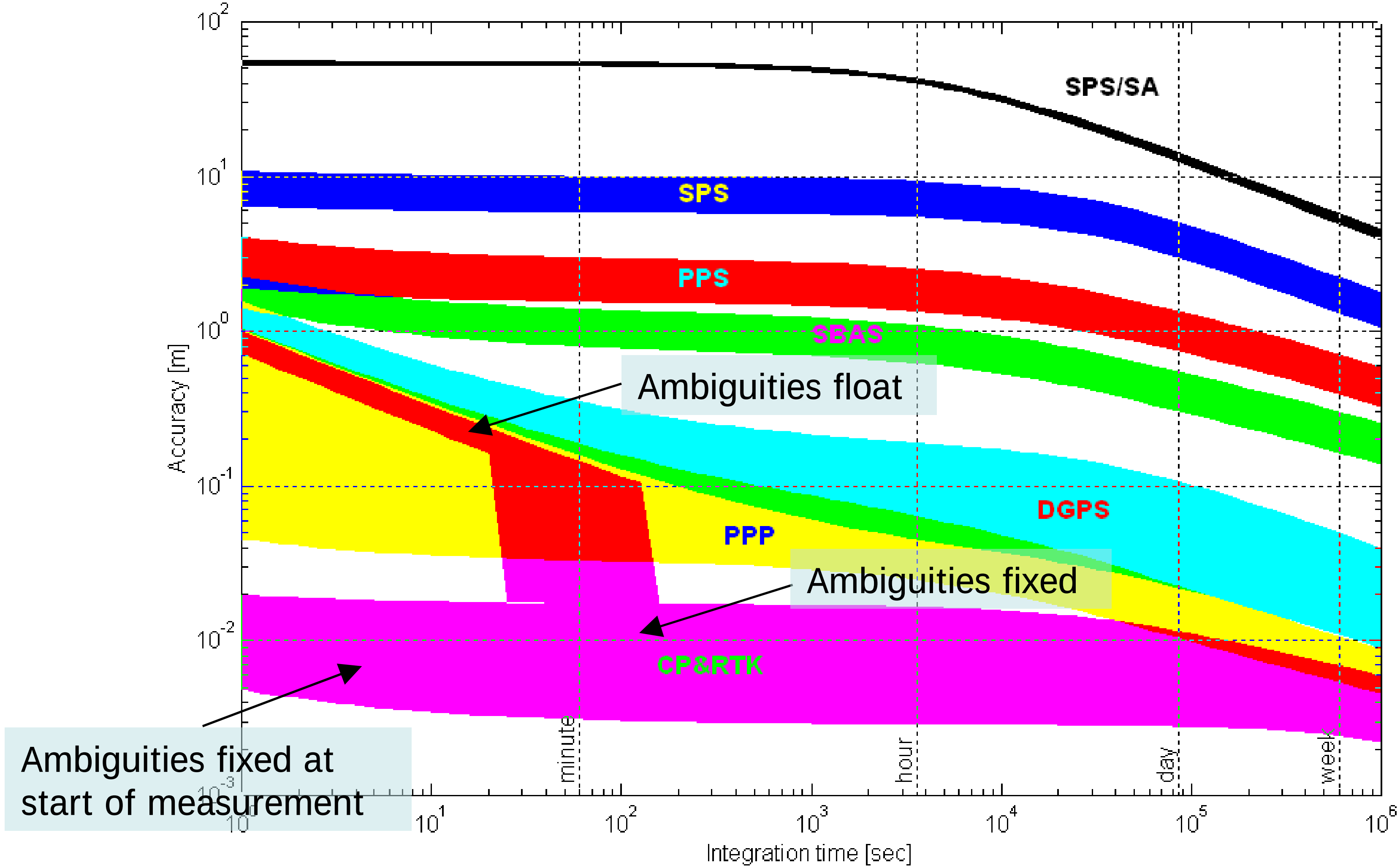
Topics are not covered in book (Misra&Enge)

Exam material: these slides + paper A.Q. Le (on blackboard)

Overview GPS Services

SPS / SA	**SPS**	**PPS**	**SBAS**	**DGPS**	**PPP**	**CP&RTK**
Standard positioning service **before May 2000**	Standard positioning service after May 2000	Precise positioning service	Satellite Based Augmentation System	Differential-GPS	Precise Point Positioning	Carrier Phase processing and RTK
1-freq mass market receiver		2-freq receiver	1-freq SBAS enabled receiver	1-freq DGPS enabled receiver	2-freq receiver	2-freq geodetic receiver
Uses free to air signals from GPS only			GEO satellite or Internet (via GPRS)	Radio link or Internet (via GPRS)	Internet (via GPRS) or GEO satellite	Radio link; GSM; or Internet (via GPRS)
Pseudo-range (code) measurements only; optional carrier-phase smoothing					Code & Carrier phase	Carrier phase mainly
Global				< 500 km	Global	Local - Global

Accuracy (1σ) of GPS Services



By: Hans van der Marel

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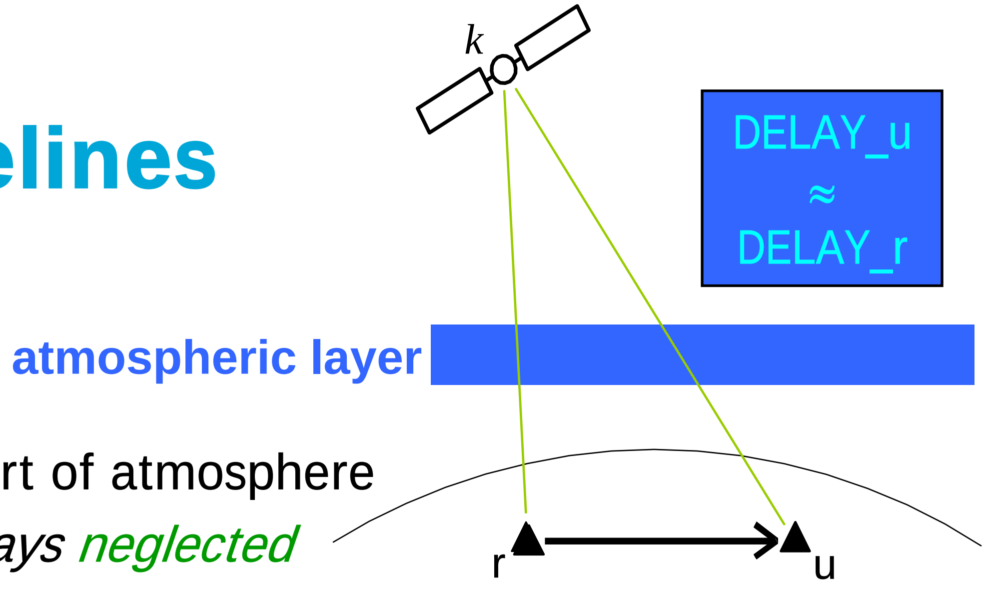
Short vs. long baselines



- **short baselines (few km):**
  signals travel through same part of atmosphere
  ⇒ *differential atmospheric delays neglected*

$$I_{ur}^{(k)} = 0, \quad T_{ur}^{(k)} = 0$$

⇒ beneficial for ambiguity resolution (less parameters)

- **long baselines (> few km):**
  differential ionospheric delays and Zenith Troposphere Delays (ZTD) need to be modeled (otherwise: wrong ambiguities and biased position)

Ionosphere and troposphere

- Ionosphere: per satellite, per epoch
  - 100-1000 km altitude → pierce points far apart, considerable spatial variations
  - large temporal variations
  - dispersive: can be estimated / eliminated with 2 or more frequencies
- Troposphere: only zenith wet delay
  (use model for hydrostatic delay)

Ionosphere-weighted GNSS model

$$\begin{bmatrix} \Phi_{ur}^{(kj)} \\ \Phi_{ur}^{(lj)} \\ \Phi_{ur}^{(mj)} \end{bmatrix} = \begin{bmatrix} \mathbf{U} & -\mu\mathbf{I} & \mathbf{\Lambda} \end{bmatrix} \begin{bmatrix} \mathbf{x}_{ur} \\ I_{ur}^{kj} \\ I_{ur}^{lj} \\ I_{ur}^{mj} \\ N_{ur}^{kj} \\ N_{ur}^{lj} \\ N_{ur}^{mj} \end{bmatrix}$$

use ionosphere corrections from network

Ionosphere-weighted GNSS model

corrections from network

$$\begin{bmatrix} \Phi_{ur}^{(kj)} \\ \Phi_{ur}^{(lj)} \\ \Phi_{ur}^{(mj)} \end{bmatrix} - [-\mu \mathbf{I}] \begin{bmatrix} I_{ur}^{kj} \\ I_{ur}^{lj} \\ I_{ur}^{mj} \end{bmatrix}_{corr.} = [\mathbf{U} \quad \mathbf{\Lambda}] \begin{bmatrix} \mathbf{x}_{ur} \\ N_{ur}^{kj} \\ N_{ur}^{lj} \\ N_{ur}^{mj} \end{bmatrix}$$

$\mathbf{B}$ $\quad \mathbf{x}_I$

Ionosphere-weighted GNSS model

DD GNSS phase / code data ↓ (points to $\mathbf{y}$)

coordinates, ambiguities, ZTD, ionosphere, ... ↓ (points to $\mathbf{x}$)

Expectation: $E\{\mathbf{y} - \mathbf{B}\mathbf{x}_I\} = \mathbf{A}\mathbf{x}$

Network RTK ionosphere corrections (↑ $\mathbf{x}_I$ in the expectation, ↓ $\mathbf{x}_I$ in the dispersion)

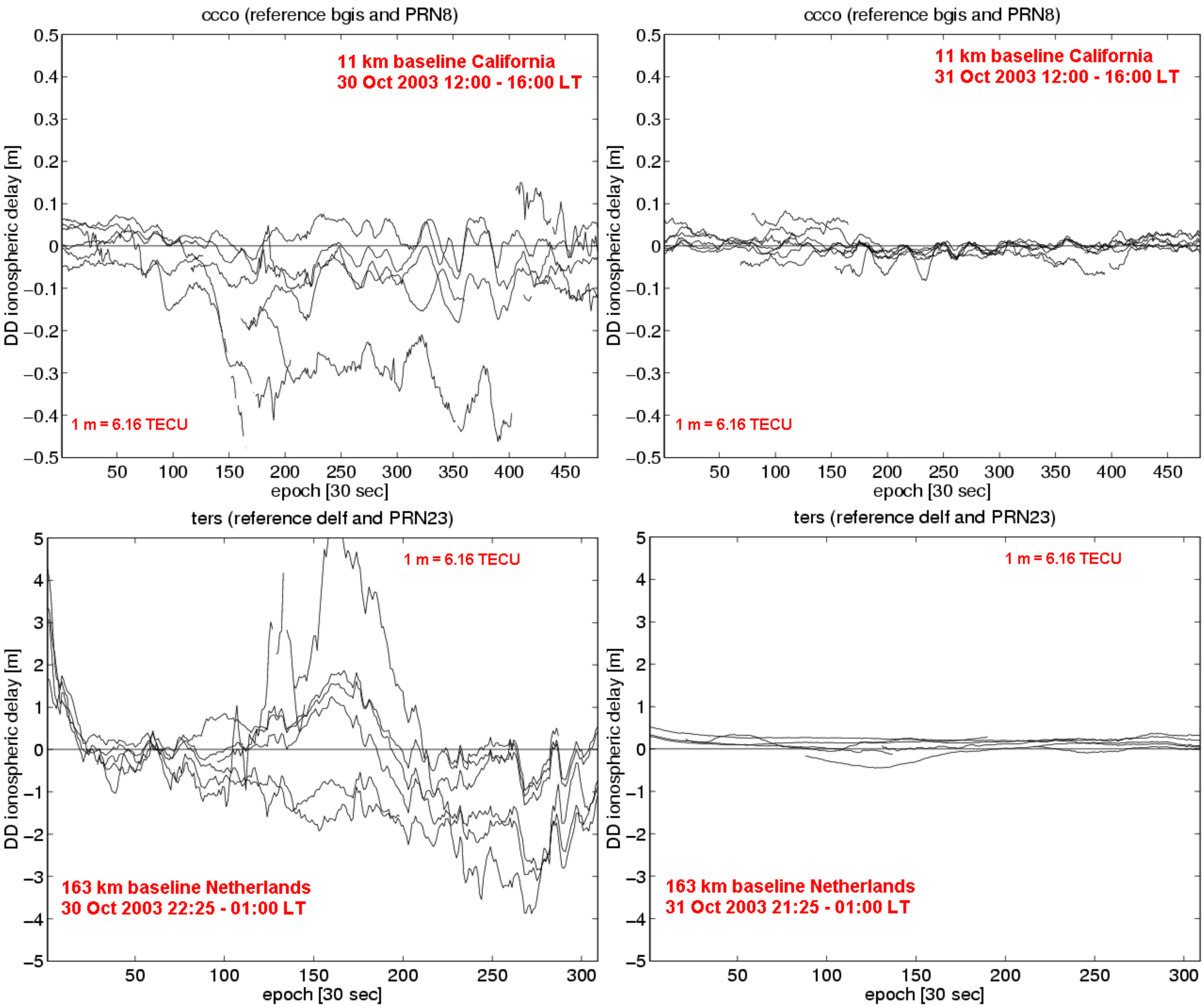
Dispersion: $D\{\mathbf{y} - \mathbf{B}\mathbf{x}_I\} = \mathbf{Q}_{\mathbf{yy}} + \mathbf{B}\mathbf{Q}_{\mathbf{x}_I\mathbf{x}_I}\mathbf{B}^{\mathrm{T}}$

ionospheric variance matrix (↑ $\mathbf{Q}_{\mathbf{x}_I\mathbf{x}_I}$)
("inverse ionosphere weights")

$\mathbf{Q}_{\mathbf{x}_I\mathbf{x}_I} = 0$ **Ionosphere-*fixed* model** (deterministic iono corr)

$\mathbf{Q}_{\mathbf{x}_I\mathbf{x}_I} = \infty$ **Ionosphere-*float* model** (iono corr not used at all)

Double Difference Ionosphere delay



GPS-RTK

- ☺ Centimeter accuracy within seconds to minutes
- ☹ Must be near to a GPS-RTK base station (< 20-30 km)
- ☹ Occasionally won't work at all (ionospheric disturbances) or gives wrong results (fixed wrong ambiguities) without warning (bad integrity)
- 😐 Uses only one base station at a time... wouldn't it be nice to use 3 or 4?

Solution: Network RTK

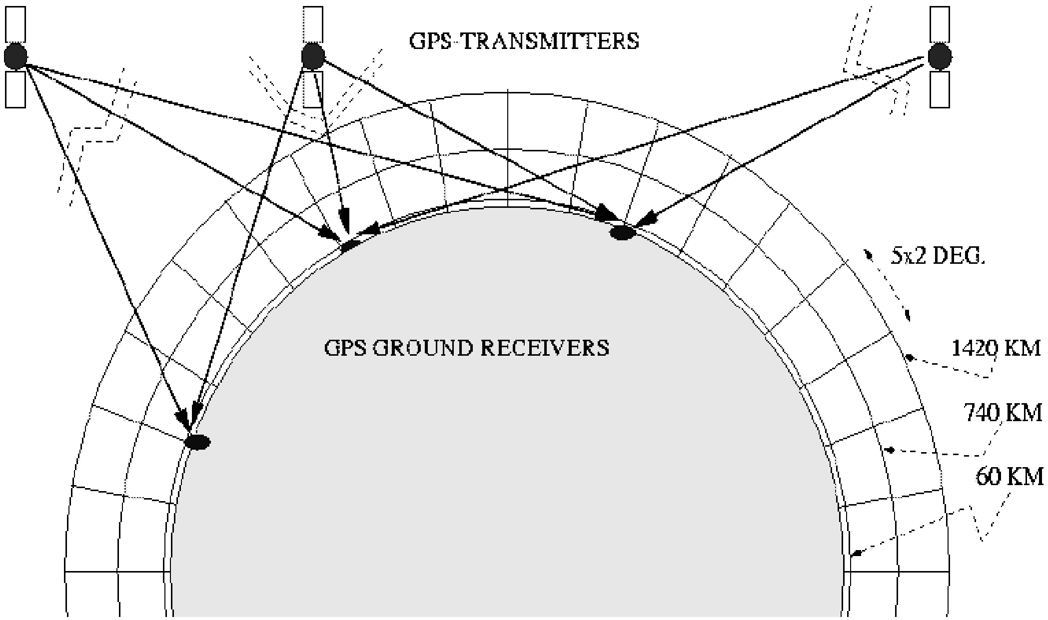
Network RTK

- Network (three or more permanent stations, data processed together in single adjustment) instead of single baseline
  → improved integrity, availability
- Interpolation of atmospheric delays
  → larger distances between RTK stations (50-70 km)
- Network RTK implementations
  - Virtual GPS reference stations (VRS, see next slides); more centralized processing
  - Master-auxiliary concept (MAC or MAX) and Flachen-Korrektur-Parameter (FKP); efficient packing of data of multiple reference stations, processing by user receiver

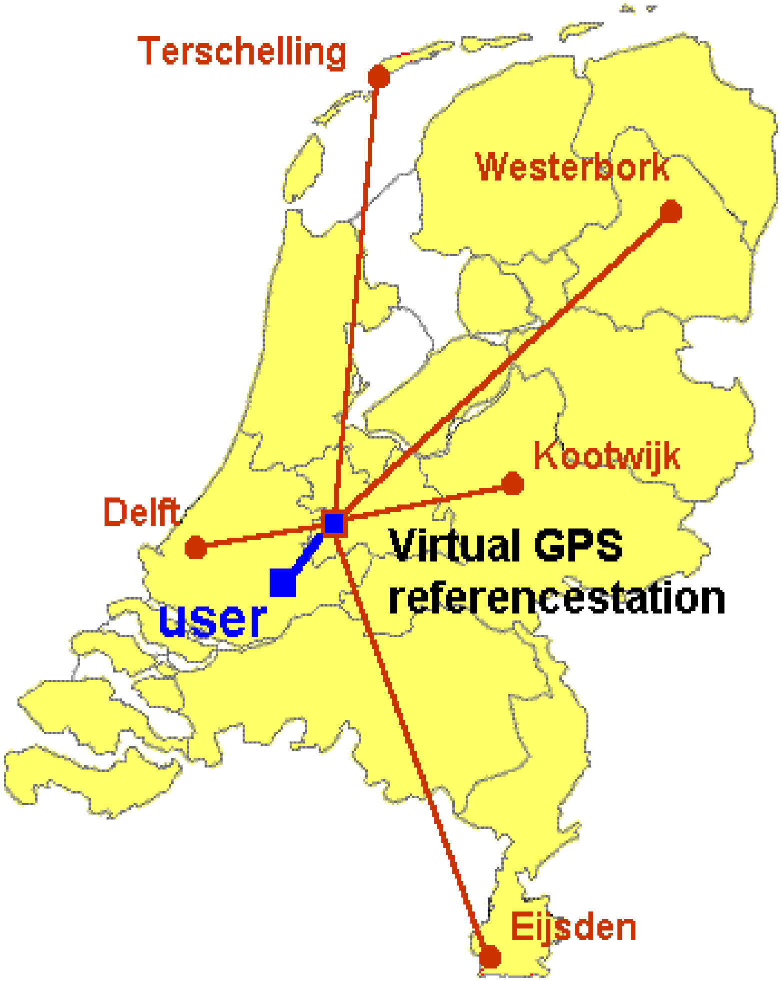
Wide Area RTK

- Network station spacing >> 100 km
- Main issue: ionosphere corrections

  → Use 3D dual-layer ionospheric tomography model *(Hernandez-Pajares et al., 1999)*



Virtual GPS Reference Station (VRS)



Adjustment in steps

1. AGRS.NL network (*once*)
2. Virtual station & user data

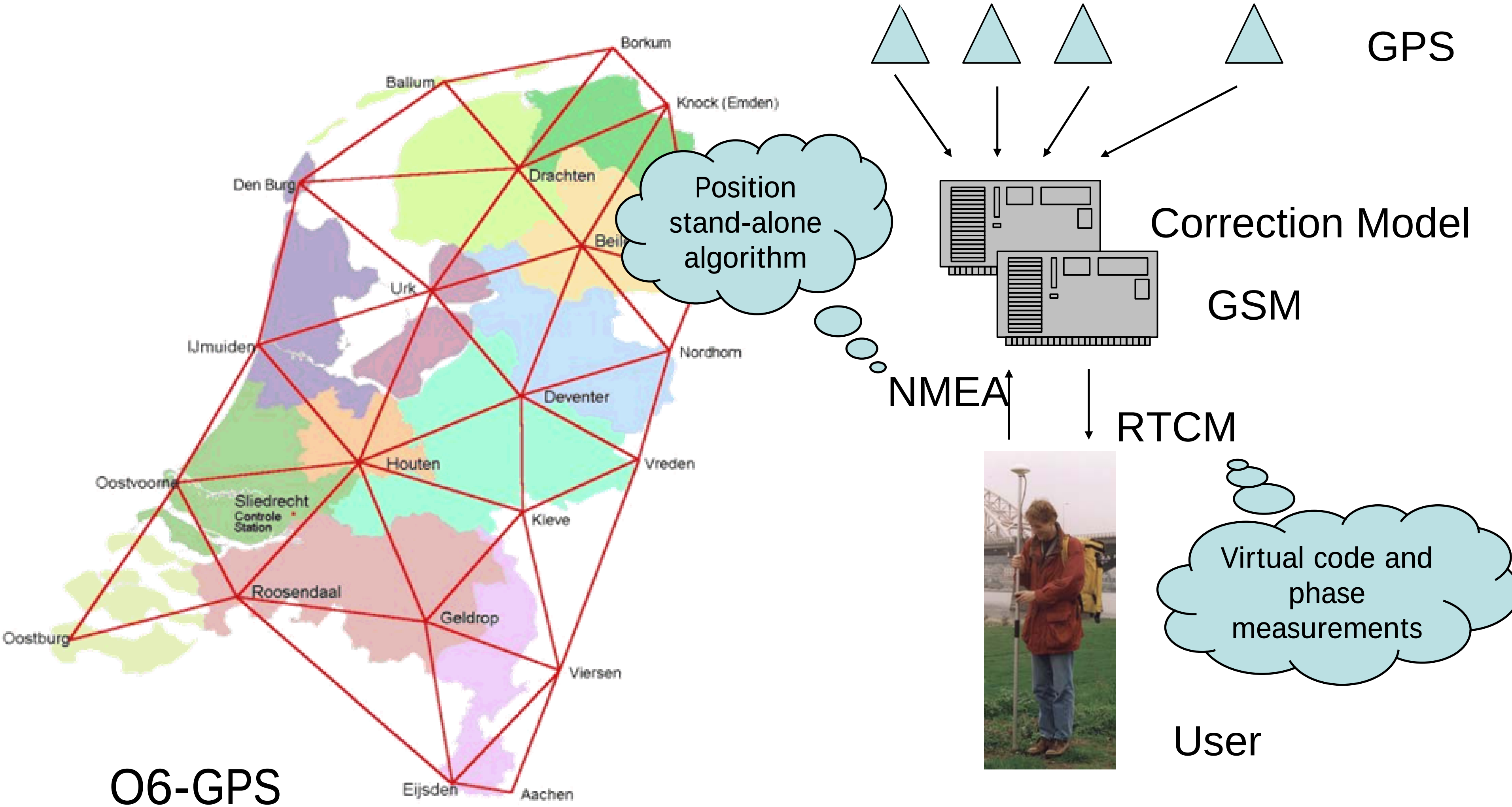
Virtual station

- *Remove* atmospheric & antenna delays at reference stations
- *Restore* atmospheric and antenna delays for virtual station
- *Shift* using precise ephemeris

Benefits for users

- strength of a network solution
- one virtual station instead of many reference stations
- standard commercial software
- shorter observation times

VRS Network



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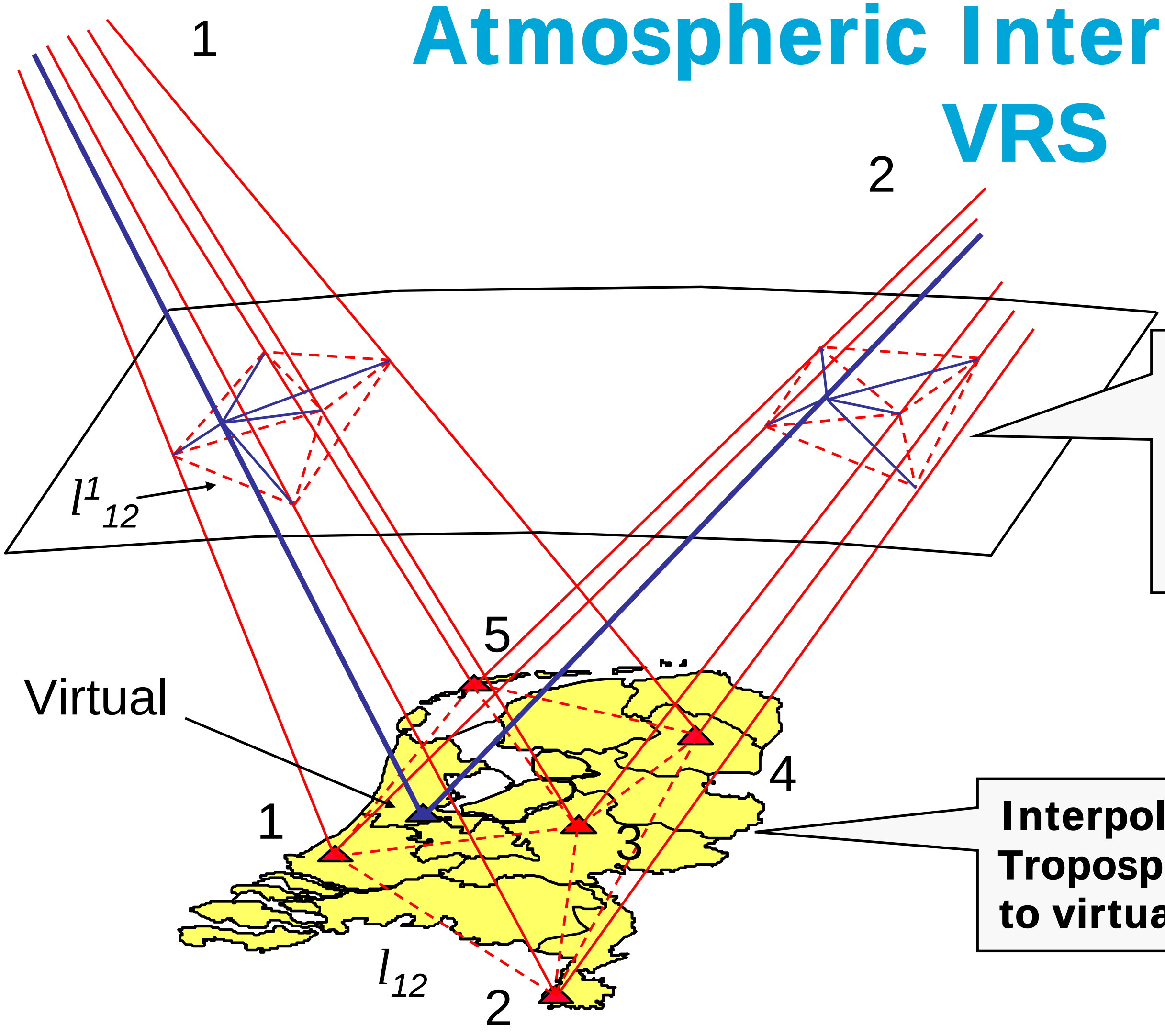
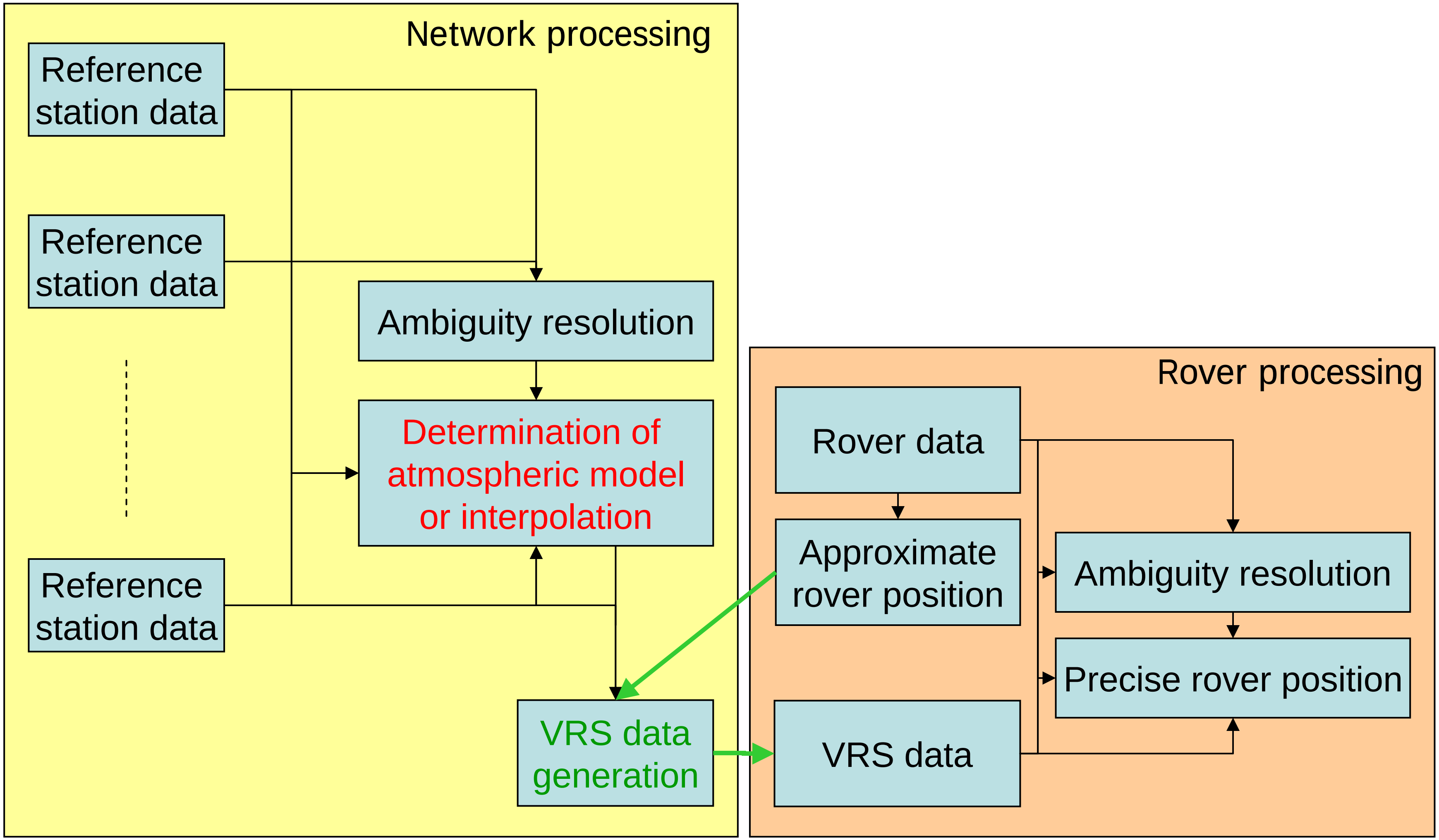
Atmospheric Interpolation for VRS



Interpolation of Ionospheric Delays within patches (one per satellite) to virtual ionospheric point

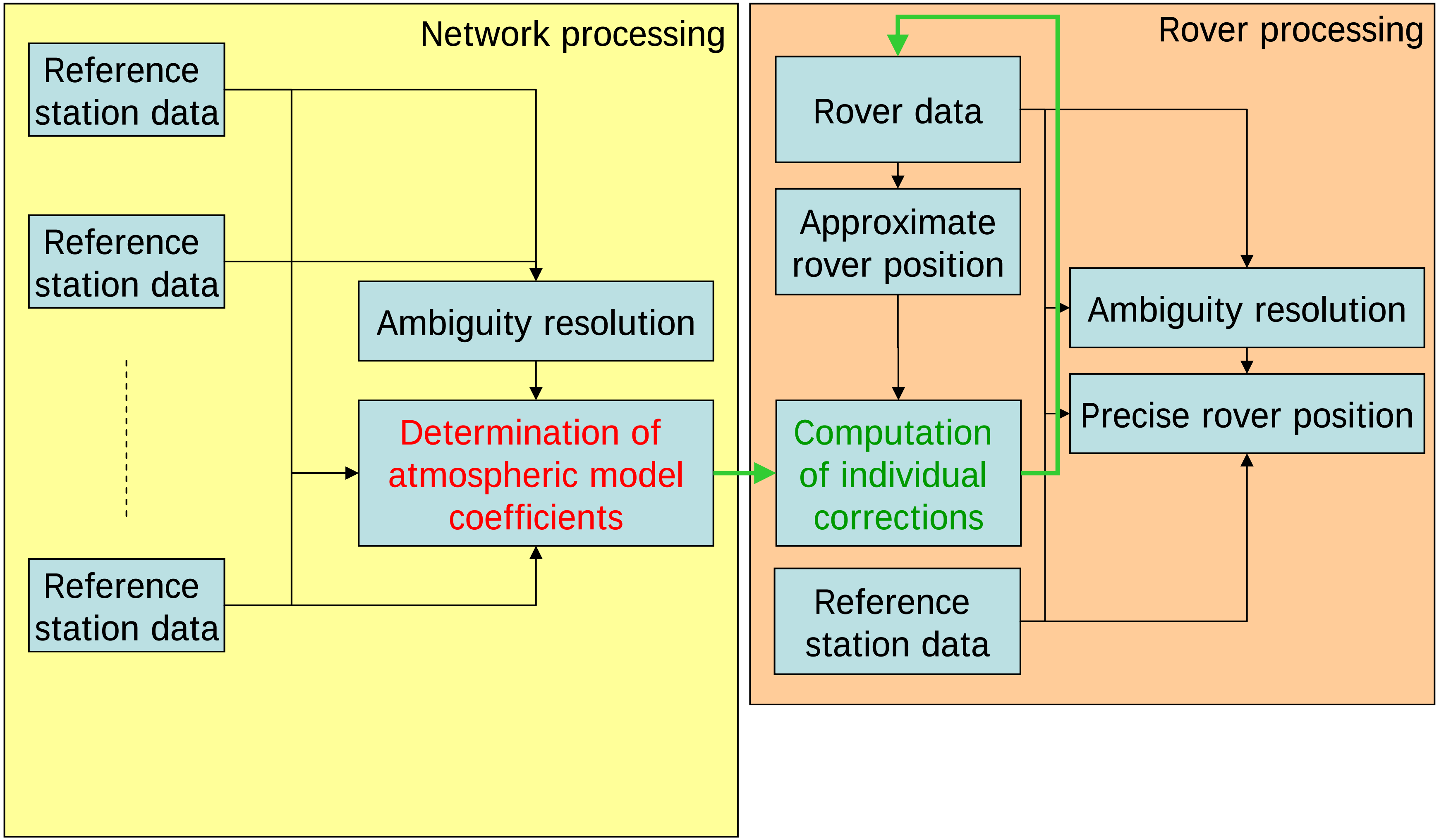
Interpolation of Tropospheric Zenith Delay to virtual location

VRS concept



Network processing
Reference station data
Reference station data
Reference station data
Ambiguity resolution
Determination of atmospheric model or interpolation
VRS data generation
Rover processing
Rover data
Approximate rover position
Ambiguity resolution
Precise rover position
VRS data

FKP concept



Network processing
Reference station data
Reference station data
Reference station data
Ambiguity resolution
Determination of atmospheric model coefficients
Rover processing
Rover data
Approximate rover position
Computation of individual corrections
Reference station data
Ambiguity resolution
Precise rover position

Comparison VRS, FKP, MAC

VRS:

- Generates GNSS data for user as if coming from local near reference station
- Allows complex atmospheric modeling at computing center
- User has to broadcast its approximate position to computing center (2-way communication link needed)
- User does not have to correct its own data
- Commercial product: Trimble Virtual Reference Station

FKP:

- Coefficients of spatial model for atmosphere are computed at computing center and broadcast to users
- One-way communication is sufficient
- Requires new data format
- Proposed as network-RTK RTCM format by Leica and Geo++

MAC:

- Correction differences of dispersive and non-dispersive data per satellite-receiver pair (ambiguities fixed in network) [note: corrections for Master station; differences for auxiliary stations]
- One- or two-way communication possible (Leica MAX and i-MAX)
- RTCM format

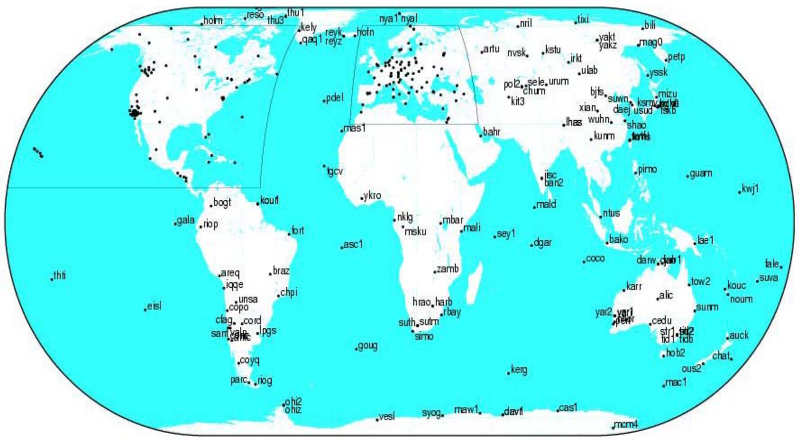
Web based processing service

- User upload his data instead of downloading external data, and receives back the coordinates
- Processing carried out on an external computer
    - Using precise point positioning (PPP) approach
    - Using Virtual Reference Station (VRS) approach
- Always up to data and state of the art software

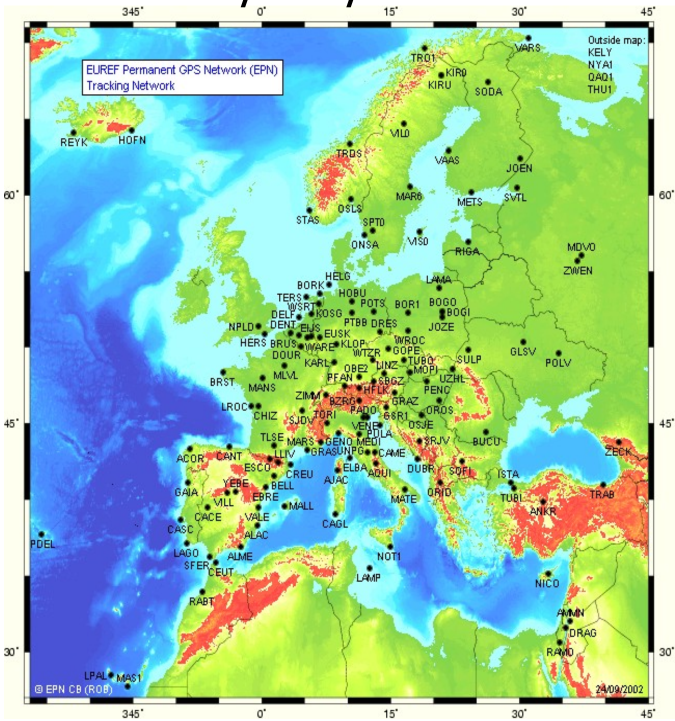
Permanent GNSS Networks

http://epncb.oma.be/

> International GNSS Service (IGS)



http://igscb.jpl.nasa.gov/



> EUREF Permanent Network (EPN)

> National Permanent Networks (many)

> Network RTK and VRS (real-time)

International GNSS Service (IGS)

Network of more than 200 GNSS stations, 5 regional and 3 global data centers, 9 analysis centers and a central bureau

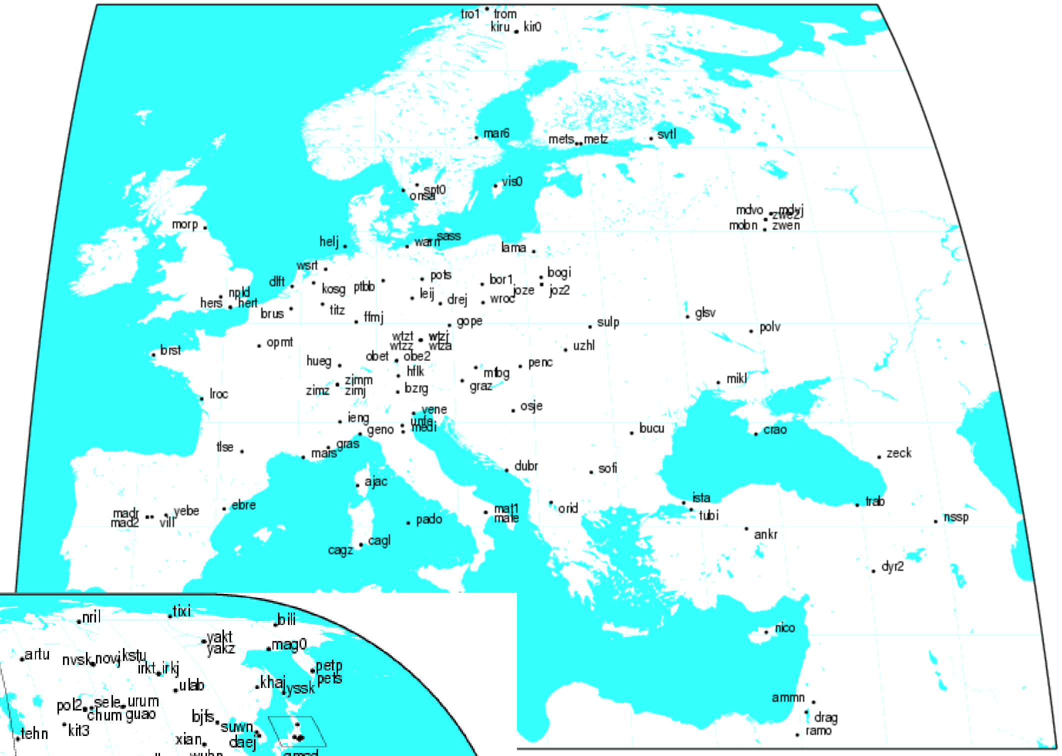
IGS products

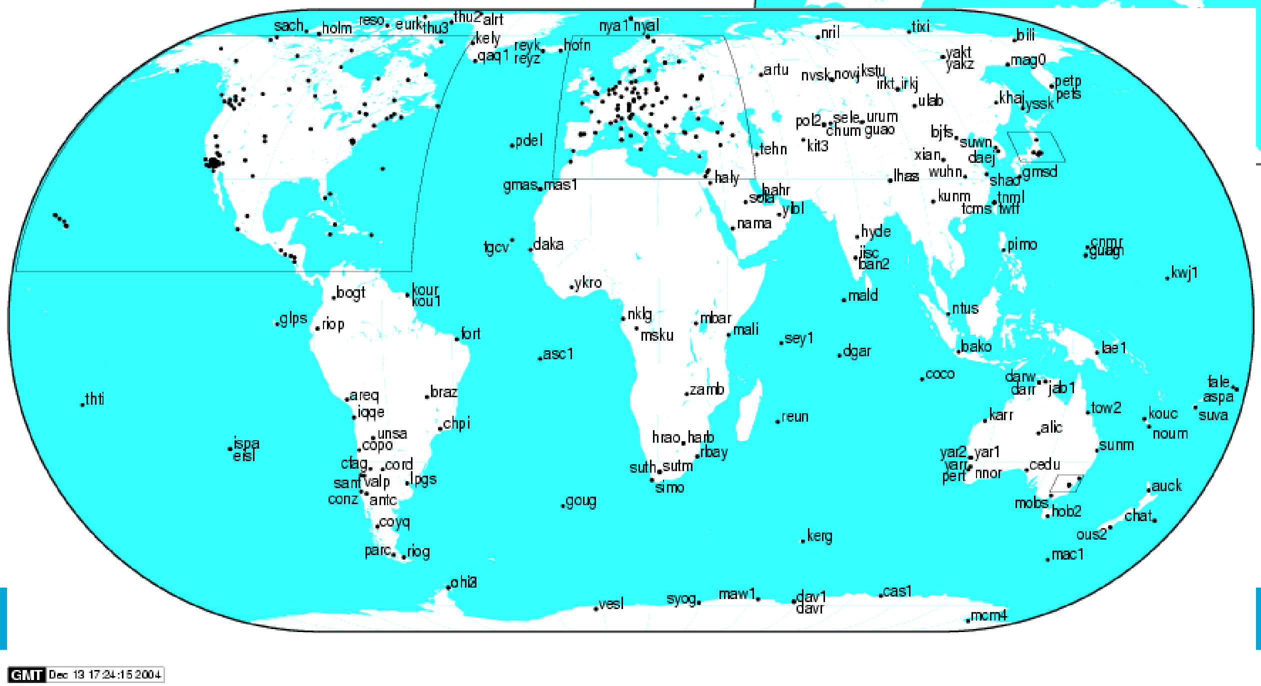
- GNSS satellite orbits and clocks
  - Final and Rapid products for post-processing
  - Ultra rapid products for (near-) real-time processing

  → orbit and clock data are correlated (must be used together)
- Earth rotation parameters
- IGS stations coordinates and velocities
- Atmosphere parameters (Total Electron Content, Water Vapour)
- Tracking data of the IGS stations

Includes GPS and GLONASS

IGS Worldwide tracking network





Accuracy of IGS products
from http://www.igs.org

included for comparison (Broadcast)

		Accuracy (RMS)	Latency	Sample interval
Broadcast	orbit	~100 cm	real-time	daily
	clocks	~ 5 ns		
Ultra-rapid (predicted)	orbit	~ 5 cm	real-time	15 min
	clocks	~ 3 ns		
Ultra-rapid (observed)	orbit	~ 3 cm	3-9 hr	15 min
	clocks	~ 150 ps		
Rapid	orbit	~ 2.5 cm	17-41 hr	15 min
	clocks	~ 75 ps		5 min
Final	orbit	~ 2.5 cm	12-18 days	15 min
	clocks	~ 75 ps		30 s

Note: ultra-rapid products contain orbit data for 48 hours: first half is observed, second half is predicted

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What is Precise Point Positioning?

- Stand-alone GNSS receiver processing, using
  - Carrier phase (and pseudo-range) observations (no differencing)
  - External GNSS satellite orbit and clock products
  - Optionally: Ionosphere maps (for single freq. users)
- Static and moving receivers
- Both post-processing and real-time
  - Post-processing using IGS products
  - Real-time using extra data link and service provider
- Initially dual frequency, but now also single frequency
- High accuracy (cm - dm) anywhere on the globe

Classic PPP

- Ionosphere free linear combination of carrier phase data
- Use IGS orbit and clock products
- Solve for
  - Station coordinates (static)
  - Carrier-phase ambiguities (float)
  - Receiver clock (kinematic) / Single difference
  - Zenith total delay (one per hour)
- 24 hour period
- Software and models used for PPP must be the same as used to generate orbit and clock products for the best results
- Precision: 3-5 mm in horizontal, 8+ mm vertical
- As good as network solution, well almost…, because
  - No ambiguity fixing
  - Correlations in network neglected
  - Differences in modelling

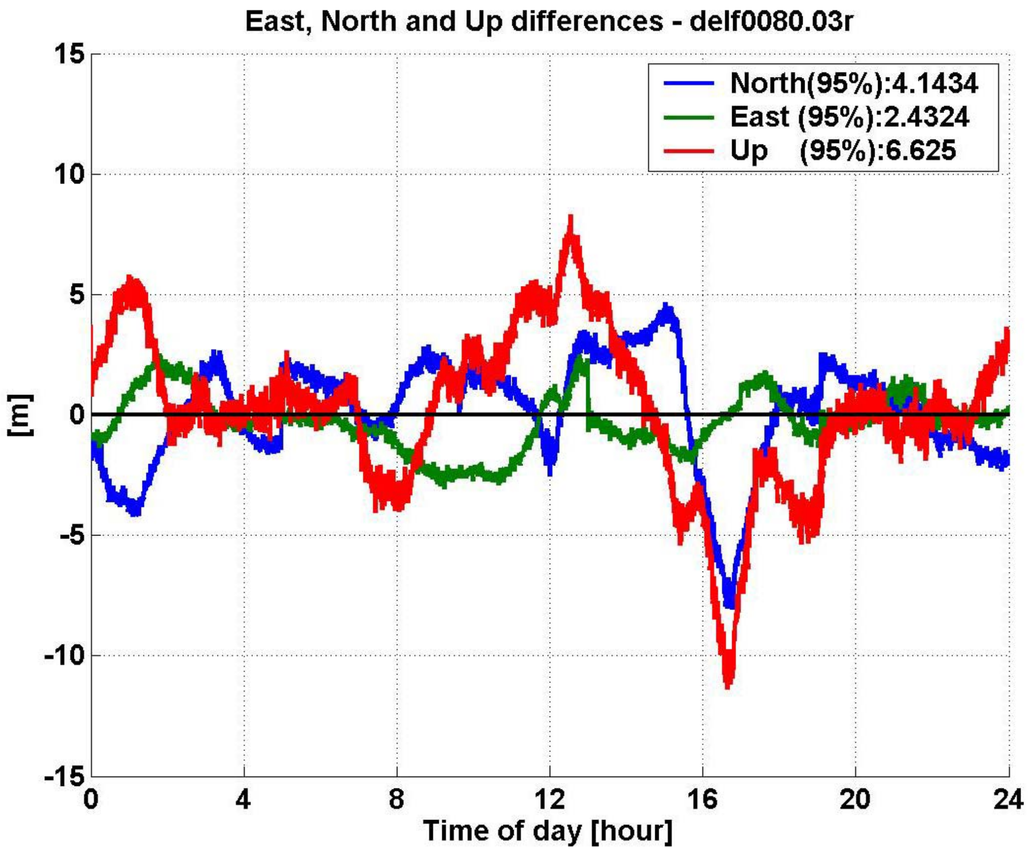
PPP – Static receiver

- Suitable for scientific and research applications:
  high accuracy, latency not important, full network solution too complicated or computer-time consuming

PPP – Moving receiver

- Real-time orbit and clock solutions (JPL, DLR, others) allows for a wide range of applications such as offshore positioning, airborne remote sensing, high-precision farming and meteorology.
- Main problem: relatively long convergence time (~ 10-40 min)

Positioning with broadcast data

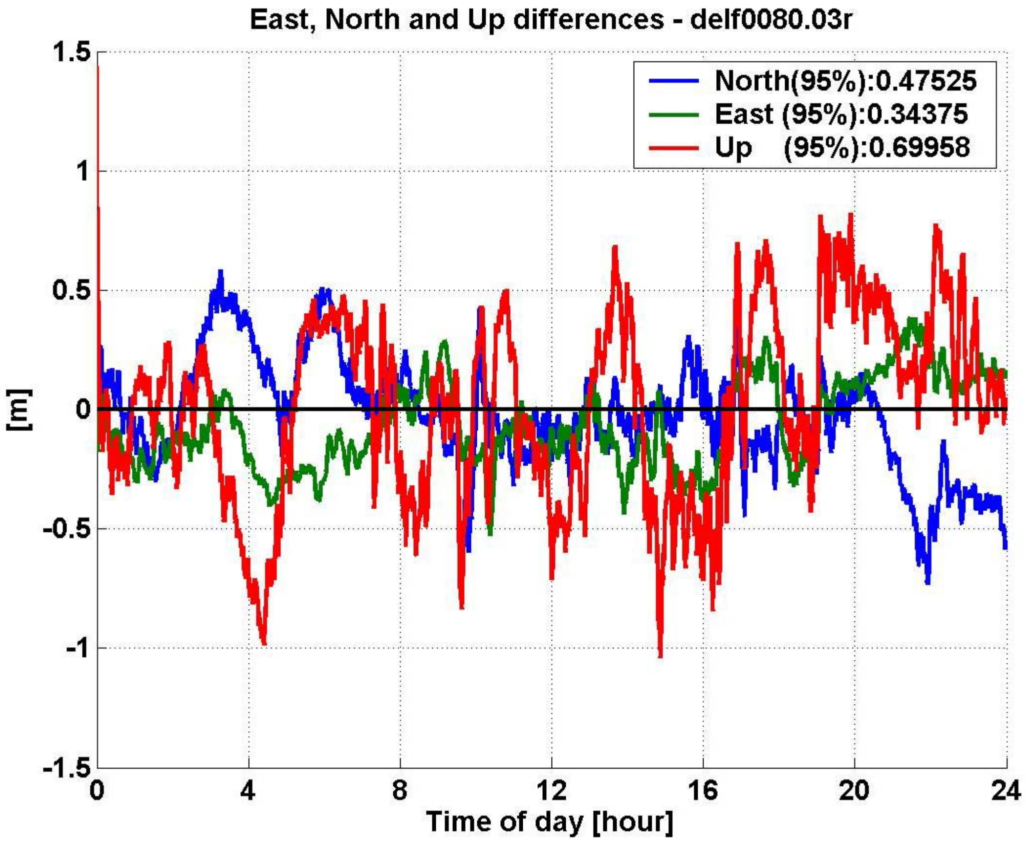


L1 pseudo range measurements

Broadcast orbits, clocks and ionosphere model

Standard Positioning Service

Positioning with IGS products



L1 pseudo range measurements

IGS orbits, clocks, ionosphere map and Galileo troposphere model

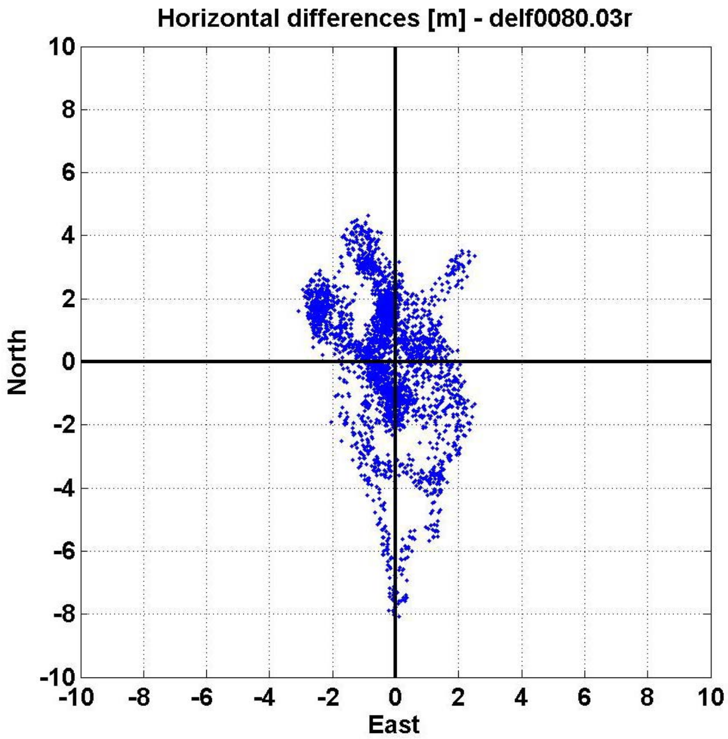
St.Dev. 10x smaller

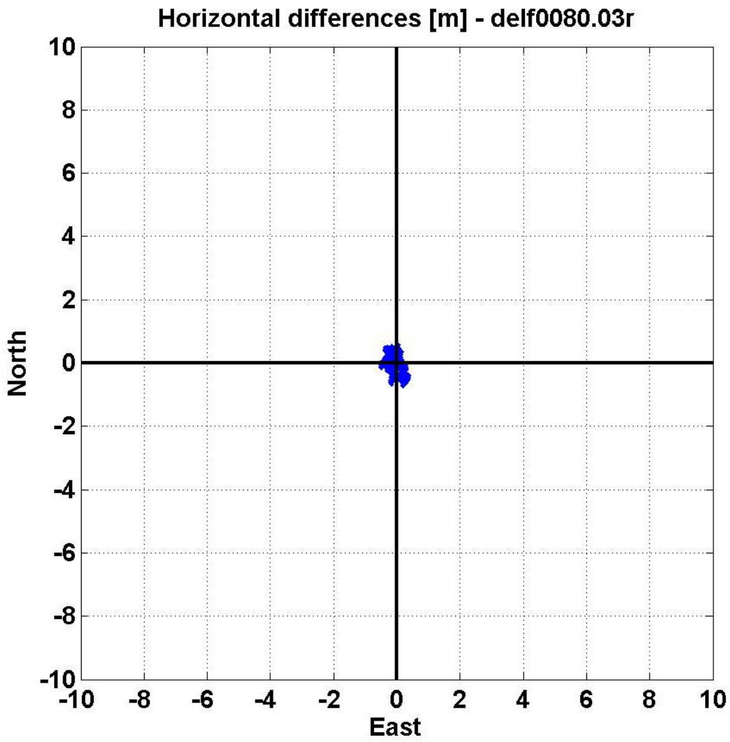
Post-Processing

Positioning with IGS products

broadcast

IGS orbits, clocks and Ionosphere map





L1 pseudo range measurements

Ionosphere free l.c. of carrier phase can give cm accuracy (static)

Precise Point Positioning (PPP)

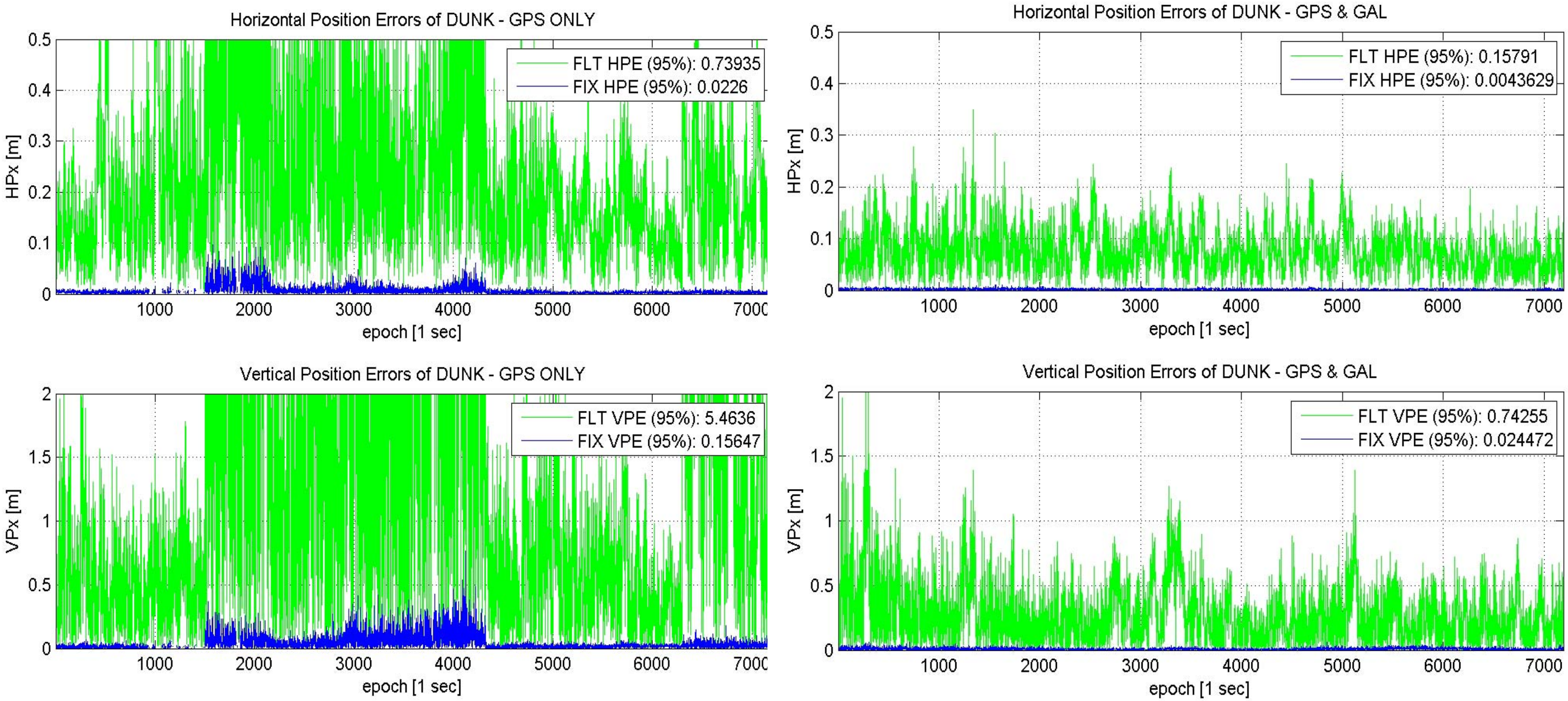
- State vector approach
- Use satellite orbits and clocks, optionally ionospheric maps
- Must include whole scale of site displacement and other corrections
- Long initialization / convergence time*
- Global (incl. oceans)

* might be improved if ambiguities resolved, and with multi-GNSS

Network or Wide Area RTK

- Relative positioning w.r.t. (virtual) reference station
- Atmospheric interpolation
- Ambiguity resolution
- Short initialization times
- Local to regional
- Higher precision

WARTK example



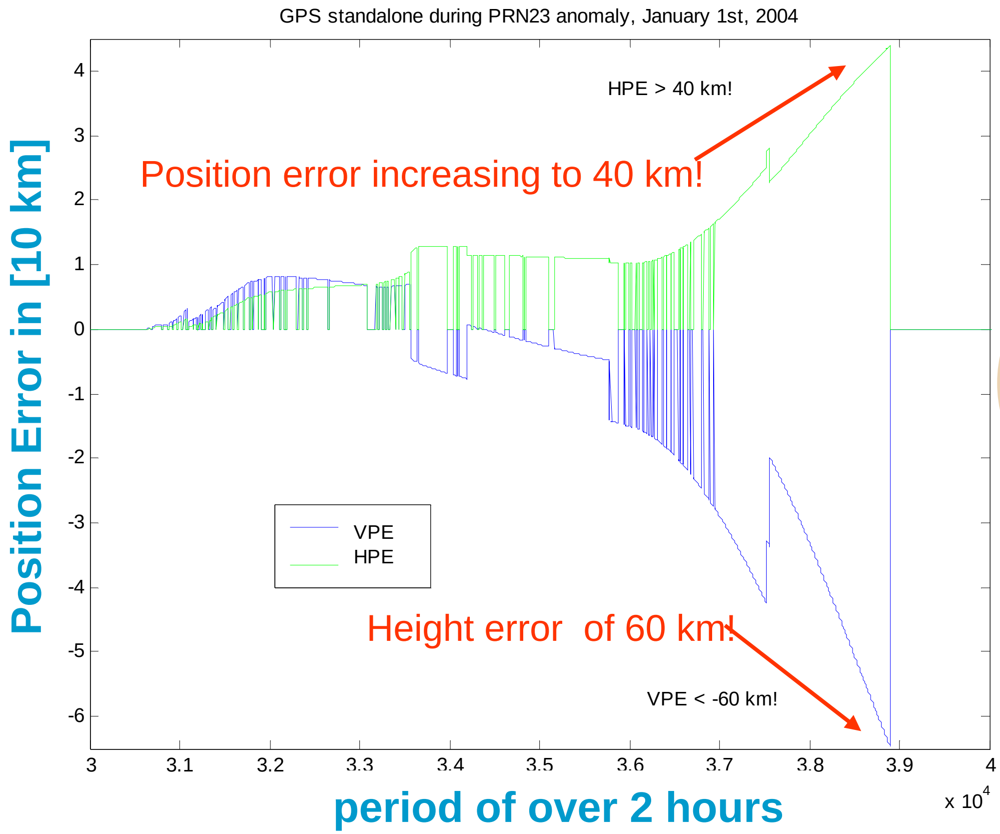
Space Based Augmentation Systems

- Purpose: provide aircraft guidance throughout the enroute, terminal, non-precision, and precision approach phases of flight (ICAO)
- Wide-area differential GPS concept:
  - categorization of GPS error sources (state vector correction)
  - error models for: satellite clock, satellite ephemeris, ionospheric delay, and local errors (tropospheric delay, multipath, receiver noise and hardware bias)
  - improved ability to capture the spatial decorrelation of the error sources
- Real time GPS network and (satellite) communication links
- Accuracy, integrity, continuity and availability

Why Space Based Augmentation Systems?

- Disadvantages of GPS only:
  - Performance inadequate for aviation and shipping in congested situations, ...
  - Military system → no guarantees
- Disadvantages of DGPS
  - Only local coverage
- Advantages SBAS
  - Guaranteed integrity
  - Improved precision

Example of inadequate GPS integrity



The real risk is with smaller errors that are not this easy to spot

Position Errors (NovAtel OEM3) during PRN23 anomaly (satellite clock) (1 January 2004, between 18:30 and 20:48 UT)

Space Based Augmentation Systems

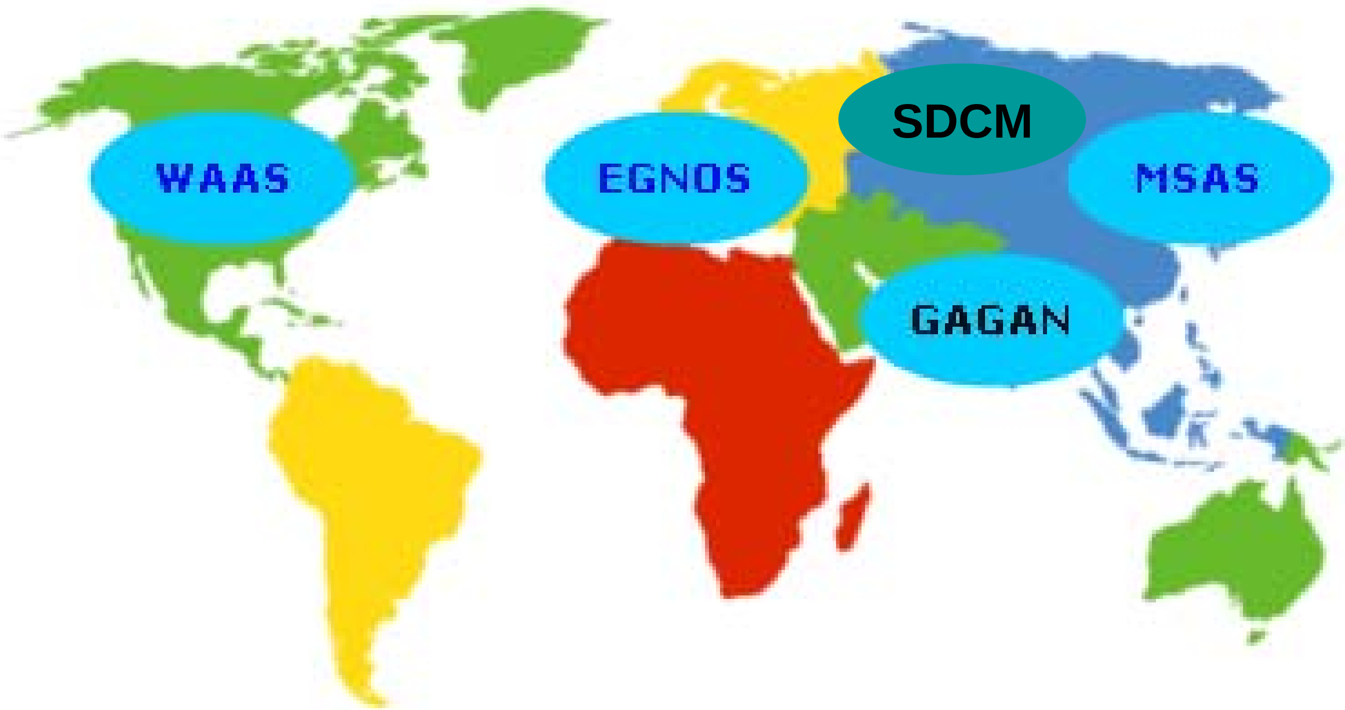


Image: ESSP

Applications

Images: ESSP

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What is SBAS Providing?

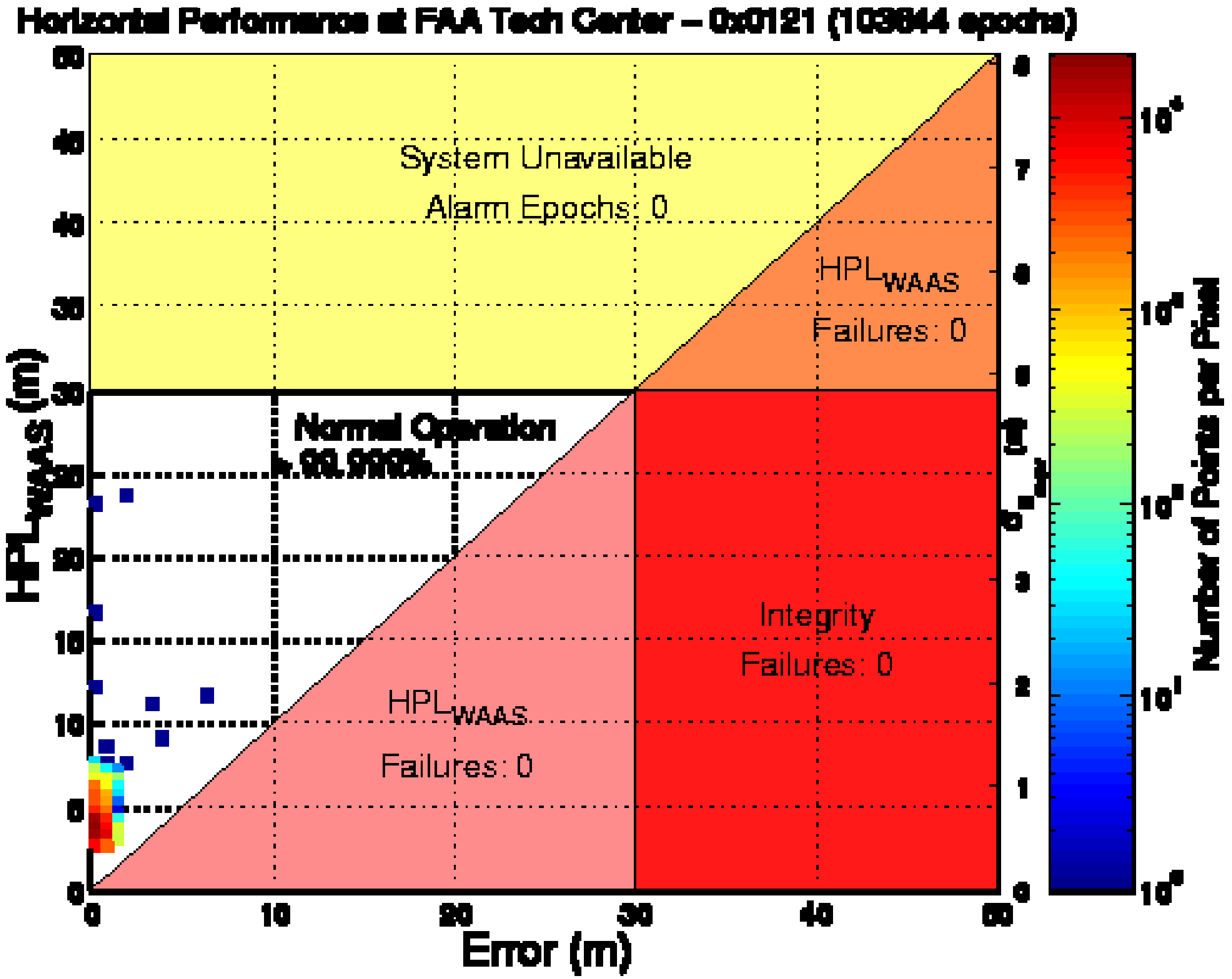
- Improved availability
  - The GEOs can be used as additional ranging sources (GPS-like)
- Improved accuracy
  - Thanks to differential corrections
- Improved integrity
  - Thanks to real-time monitoring (6s TTA)
- Improved continuity

- See http://waas.stanford.edu/metrics.html

SBAS Performance Requirements

Type of Operation	Horizontal Accuracy (95%)	Horizontal Alert Limit	Vertical Accuracy (95%)	Vertical Alert Limit	Integrity	Time To Alert	Continuity	Availability
En Route (RNP 20-10)	3704m	7400m	N/A	N/A	10^{-7}/h	300s	$1x10^{-4}$/h to $1x10^{-8}$/h	0,99 to 0,99999
En Route (RNP 5-2)	740m	3700m	N/A	N/A	10^{-7}/h	15s	$1x10^{-4}$/h to $1x10^{-8}$/h	0,999 to 0,99999
En Route (RNP 1)	740m	1850m	N/A	N/A	10^{-7}/h	15s	$1x10^{-4}$/h to $1x10^{-8}$/h	0,999 to 0,99999
NPA	220m	556m	N/A	N/A	10^{-7}/h	10s	$1x10^{-4}$/h to $1x10^{-8}$/h	0,99 to 0,99999
APV-I	220m	556m	20m	50m	$2x10^{-7}$ per approach	10s	$1\text{-}8x10^{-6}$ in any 15s	0,99 to 0,99999
APV-II	16m	40m	8m	20m	$2x10^{-7}$ per approach	6s	$1\text{-}8x10^{-6}$ in any 15s	0,99 to 0,99999
CAT-1	16m	40m	6m to 4m	15m to 10m	$2x10^{-7}$ per approach	6s	$1\text{-}8x10^{-6}$ in any 15s	0,99 to 0,99999

Stanford plots
http://waas.stanford.edu/metrics.html



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Stanford plots
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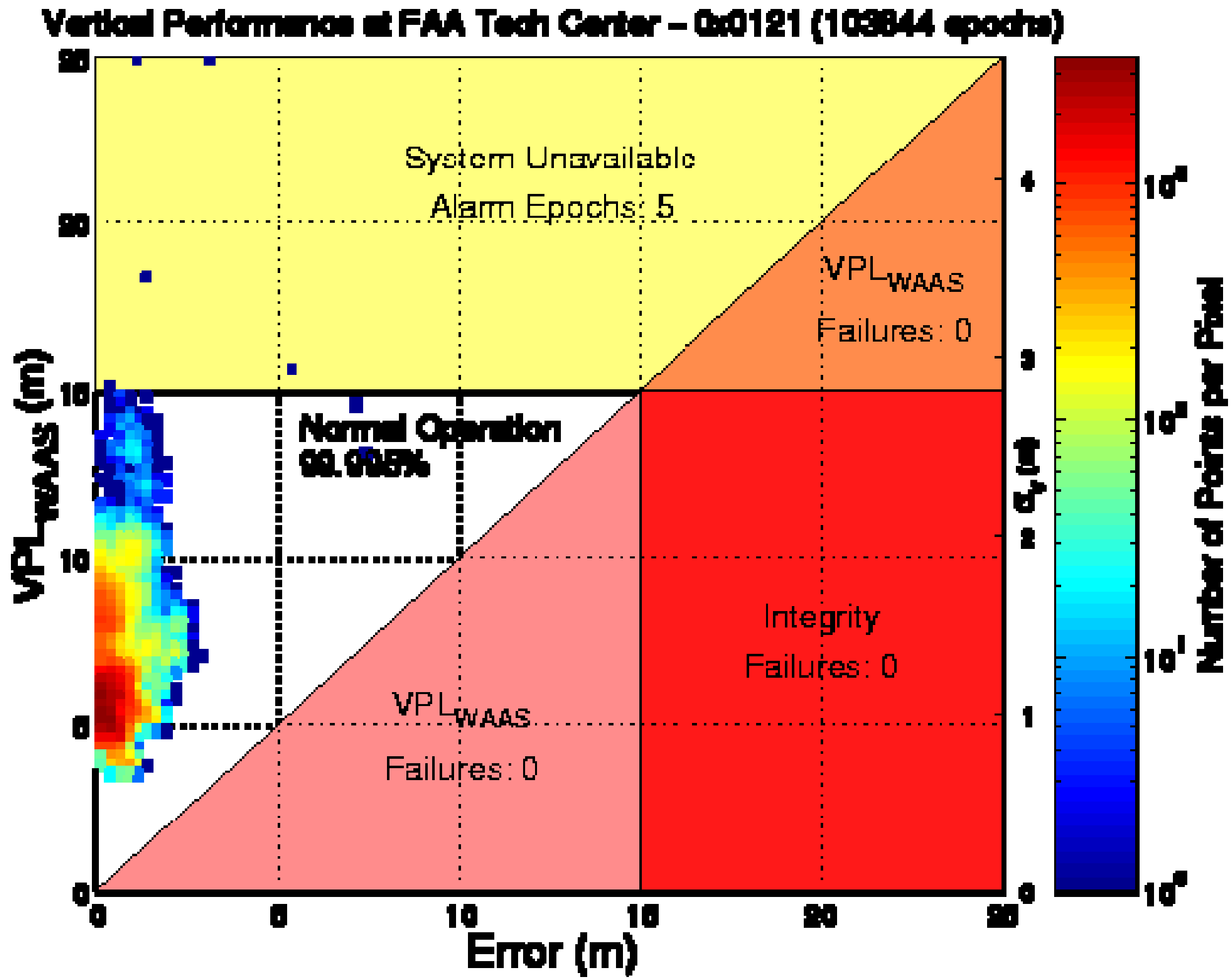

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European Geostationary Overlay System (EGNOS)

- ‘First’ European satellite navigation system
  - European Space Agency (ESA)
    - Technical responsibility
  - European Commission (EC)
    - Political responsibility
  - EUROCONTROL
    - System validation

EGNOS

- Real-time network of dual-frequency GPS reference stations
- Master control centre computes
  - Slow and fast corrections for GPS orbits and clocks
  - Ionosphere corrections (distributed as a map)
  - Signal in Space accuracy and Integrity measures (use / do not use)

  sent to INMARSAT geosynchronous communication satellites
- Geosynchronous satellites transmit the SBAS signal modulated on a GPS L1 ranging code (using PRN numbers 120,121,122,....)
- Users compute Horizontal and Vertical Protection limits (HPL/VPL)
  - Integrity flag set: do not use this satellite
  - HPL > limit | VPL > limit ➔ system is not available
- Compatible with WAAS (USA)

EGNOS System Architecture

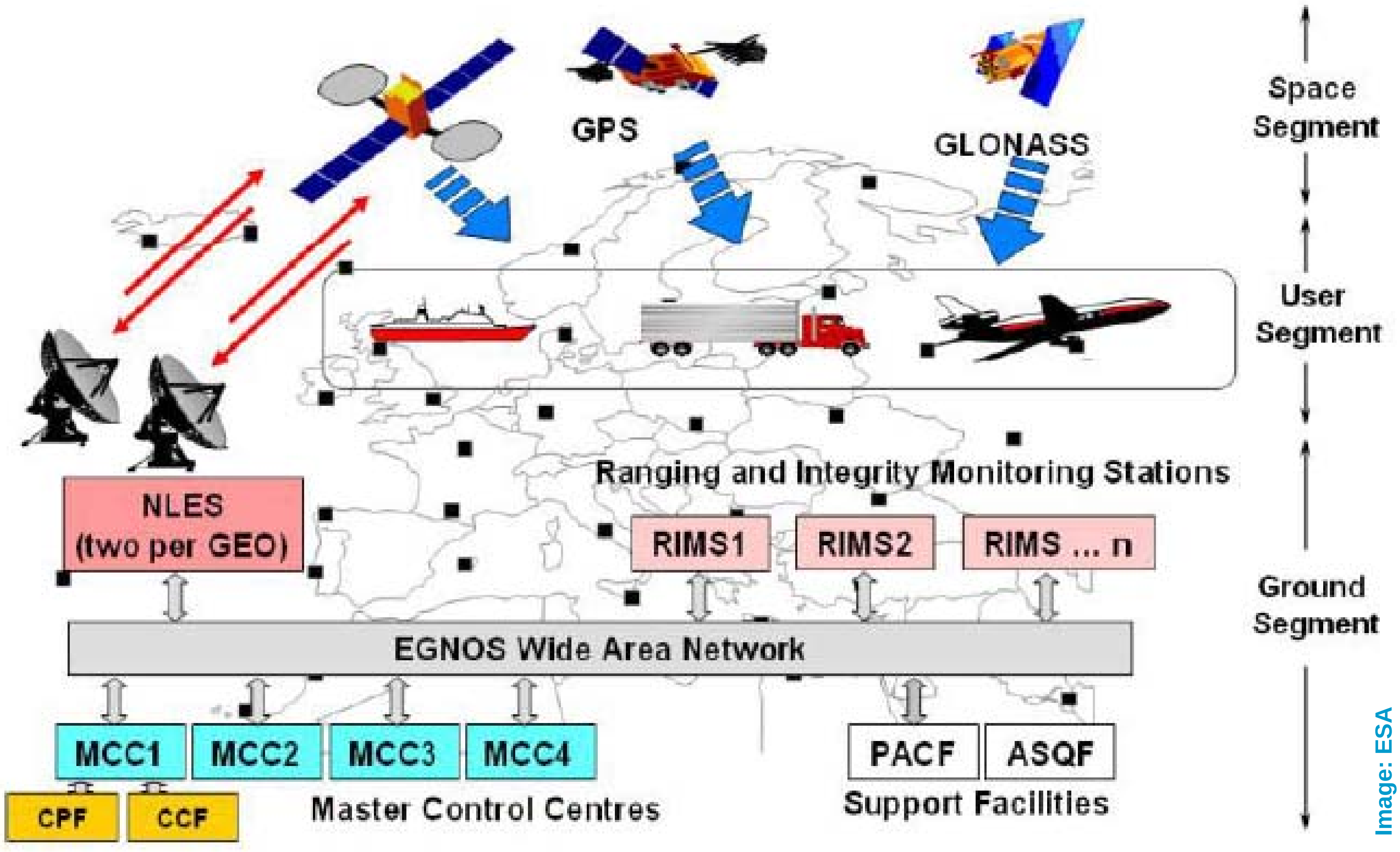


Image: ESA

EGNOS Ground Segment

Ranging and Integrity Monitoring Stations (RIMS)

- Equipped with an L1/L2 receiver and atomic clock for precise timing
- Track GPS, GLONASS and GEO

Master Control Centres (MCC)

- Central Processing Facility (CPF)
  - Automatic processing of raw data coming from RIMS
  - Independent check of measurements of RIMS A by RIMS B
  - Compute integrity, differential and ionosphere corrections
- Central Control Facility (CCF)
  - Monitoring and control of EGNOS

Navigation Land Earth Station (NLES)

- Transmitting the augmentation message to each GEO satellite

EGNOS Space Segment

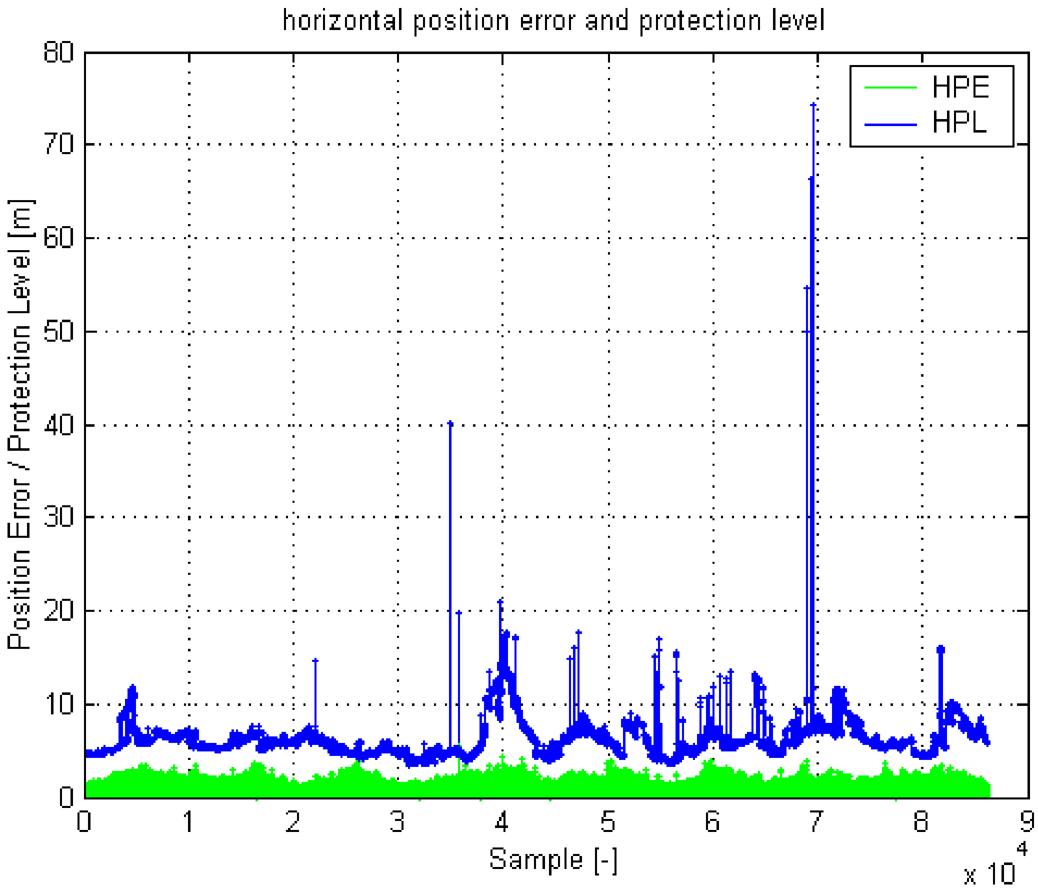
- Existing GPS and GLONASS constellations
- 3 Geostationary Satellites
  - Inmarsat AOR-E (PRN 120)
  - Inmarsat IOR-W (PRN 126)
  - Artemis (PRN 124)
- Broadcasting an augmentation signal on GPS frequency L1

EGNOS User Segment

- Any user equipped with a GPS receiver with firmware able to process SBAS data (EGNOS is broadcast on L1)
- Mainly navigation applications
  - Civil aviation
  - Road transports
  - Maritime
  - Rail

- **SISNET: The EGNOS data message is also provided over the Internet! This is important in cities where signal reception from geostationary satellites is problematic**

Example: plot HPE + HPL



HPE = Horizontal Position Error

HPL = Horizontal Protection Level

Protection level is upper limit for the position error (probability $< 10^{-7}$)

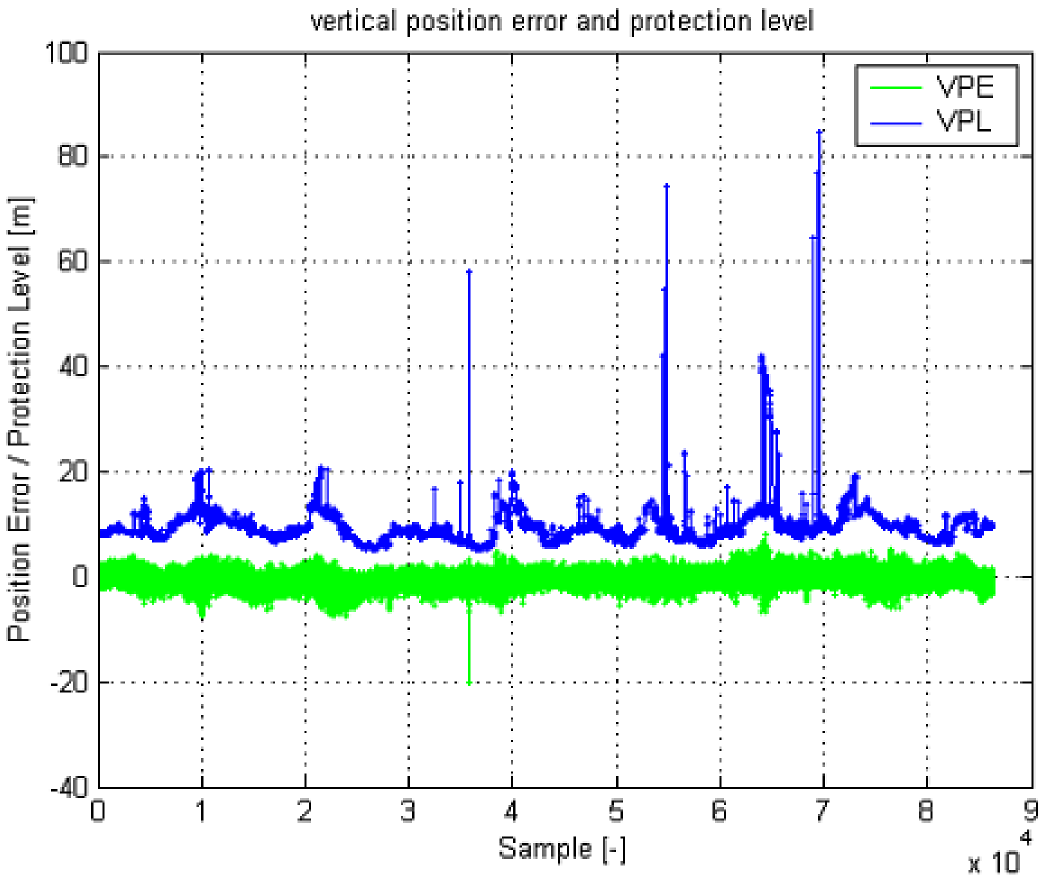
When HPE exceeds HPL we have an integrity problem:

Results 25 july 2002:

-95th percentile HPE 1.7 m

-95th percentile HPL 9.9 m

Example: plot VPE + VPL



VPE = Vertical Position Error

VPL = Vertical Protection Level

Protection level is upper limit for the position error (probability < 10-7)

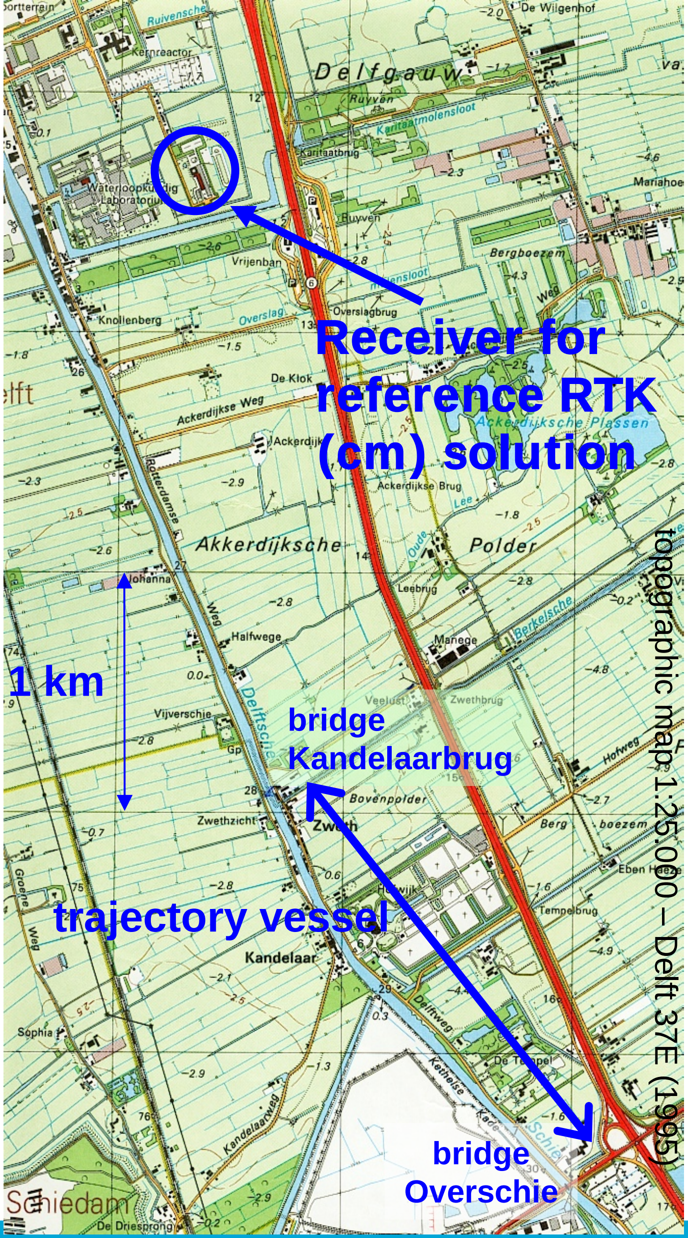
When VPE exceeds VPL we have an integrity problem

Results 25 july 2002:

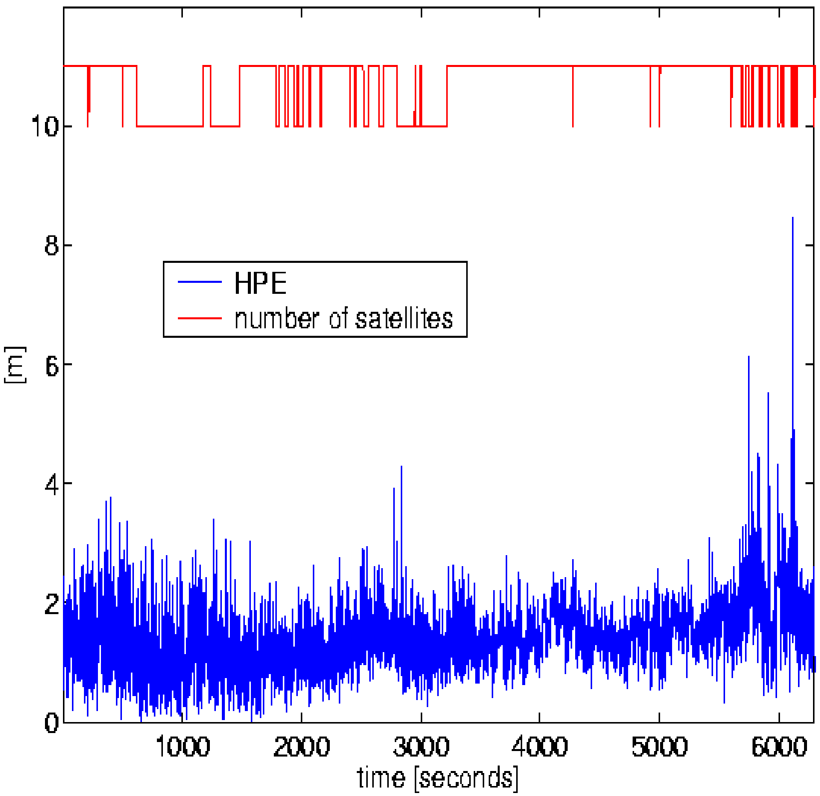
95th percentile VPE 2.8 m

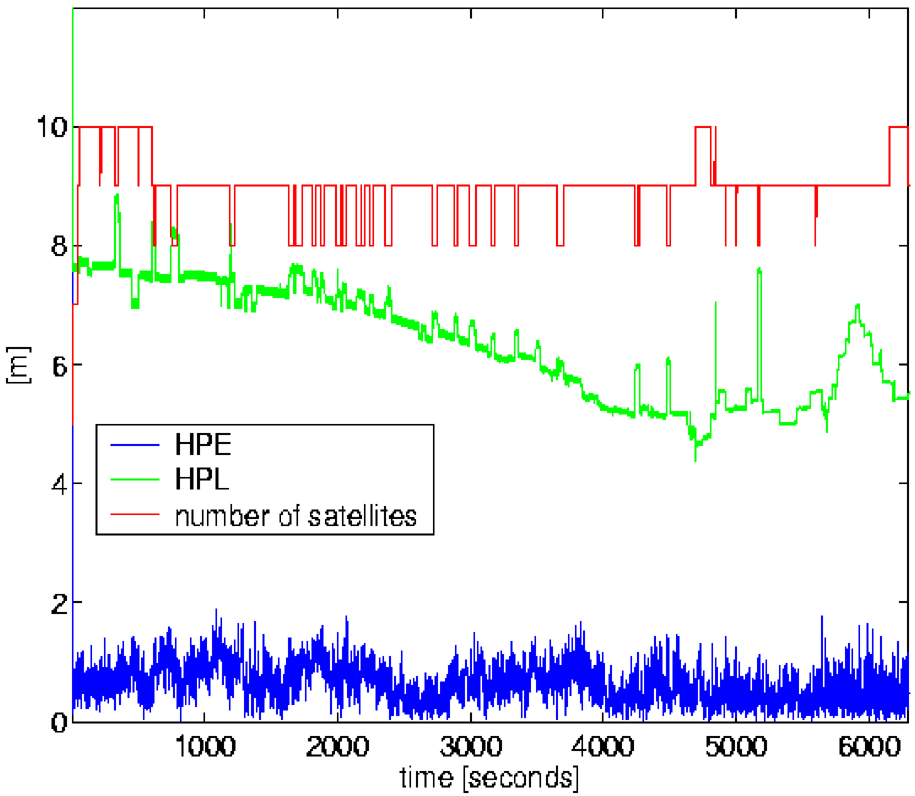
95th percentile VPL 13.6 m

Example of Kinematic Experiment with EGNOS on Schie canal Delft

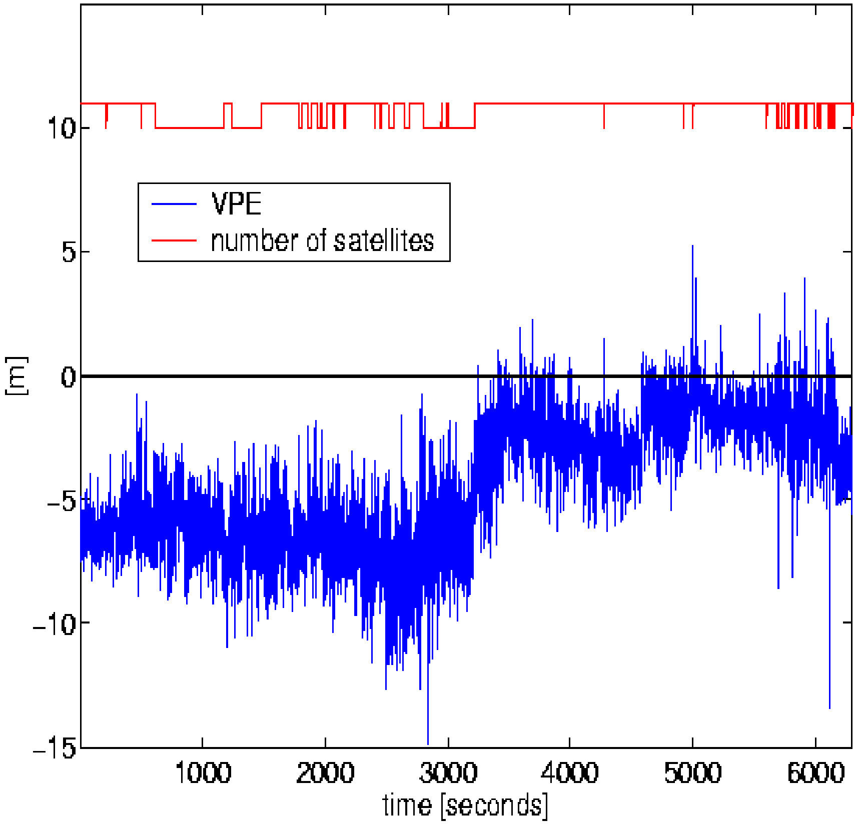


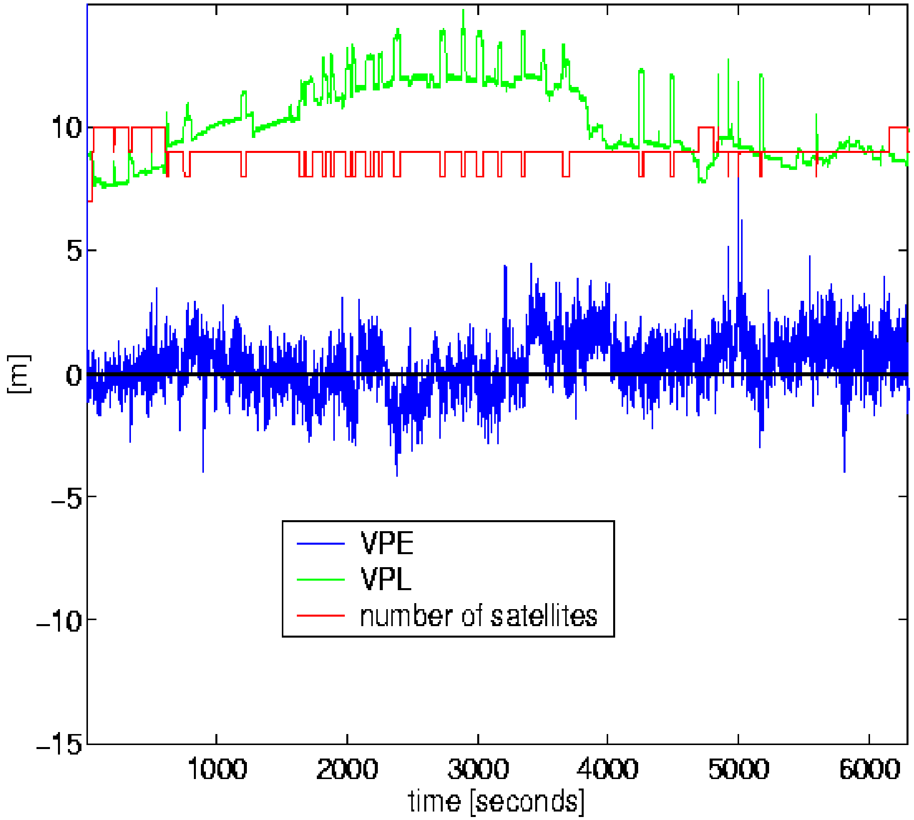
HPE trajectory





VPE trajectory





TU Delft

Overview results

SBAS mode	Static Mean	95%	Kinematic Mean	95%
HPE	0.74	1.35	0.65	1.20
VPE	-0.04	2.31	0.38	2.36
HPL		7.63		7.65
VPL		12.85		12.87

GPS only mode	Static Mean	95%	Kinematic Mean	95%
HPE	2.27	4.18	1.41	2.41
VPE	-6.21	10.66	-4.38	8.48

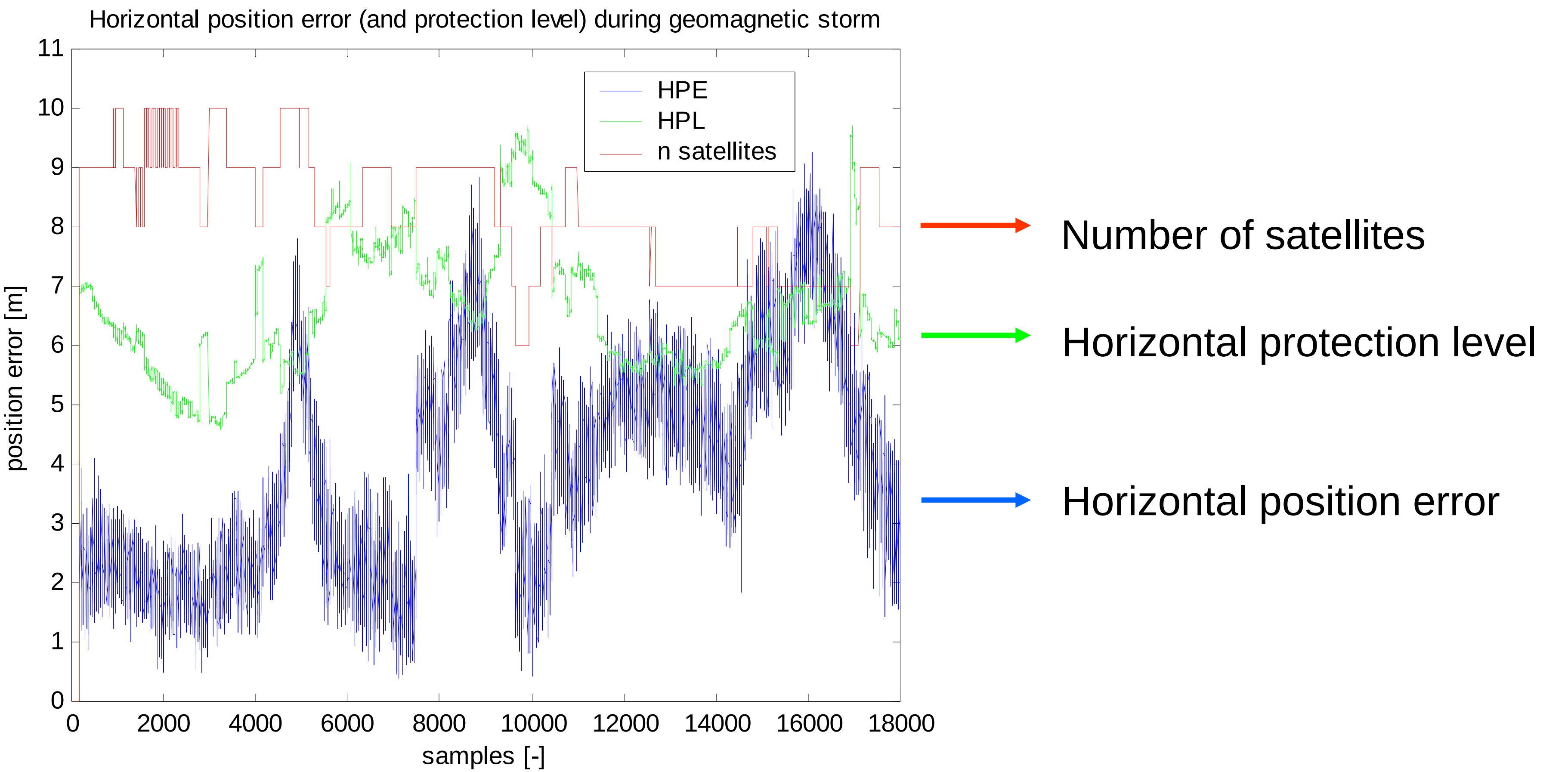
Note: all in [m]; standard deviation (std) about mean

Case study: Ionosphere

Auroral display 30 October 2003 [20.00-23.30 UT].

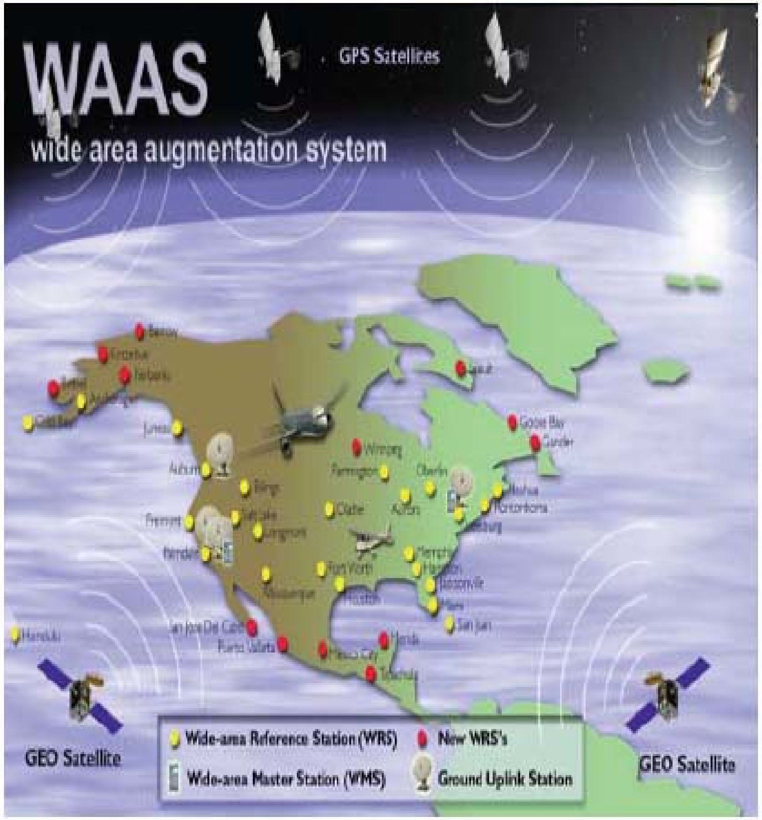
Auroral display **30 October** 2003 [20.00-23.30 UT].
The observation was made from a farm in Beesd, thirty kilometers south of Utrecht (NL).
www.astro.uu.nl/~plarends/aurora3010.html

Case study: Ionosphere



Zoom (20:00 – 1:00 UT) peaks HPE (in blue) 5-8 meter resulting in 2002 LOIs

WAAS Architecture

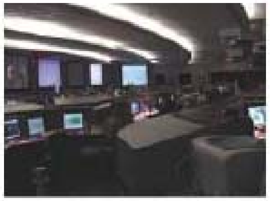


38 Reference Stations

3 Master Stations

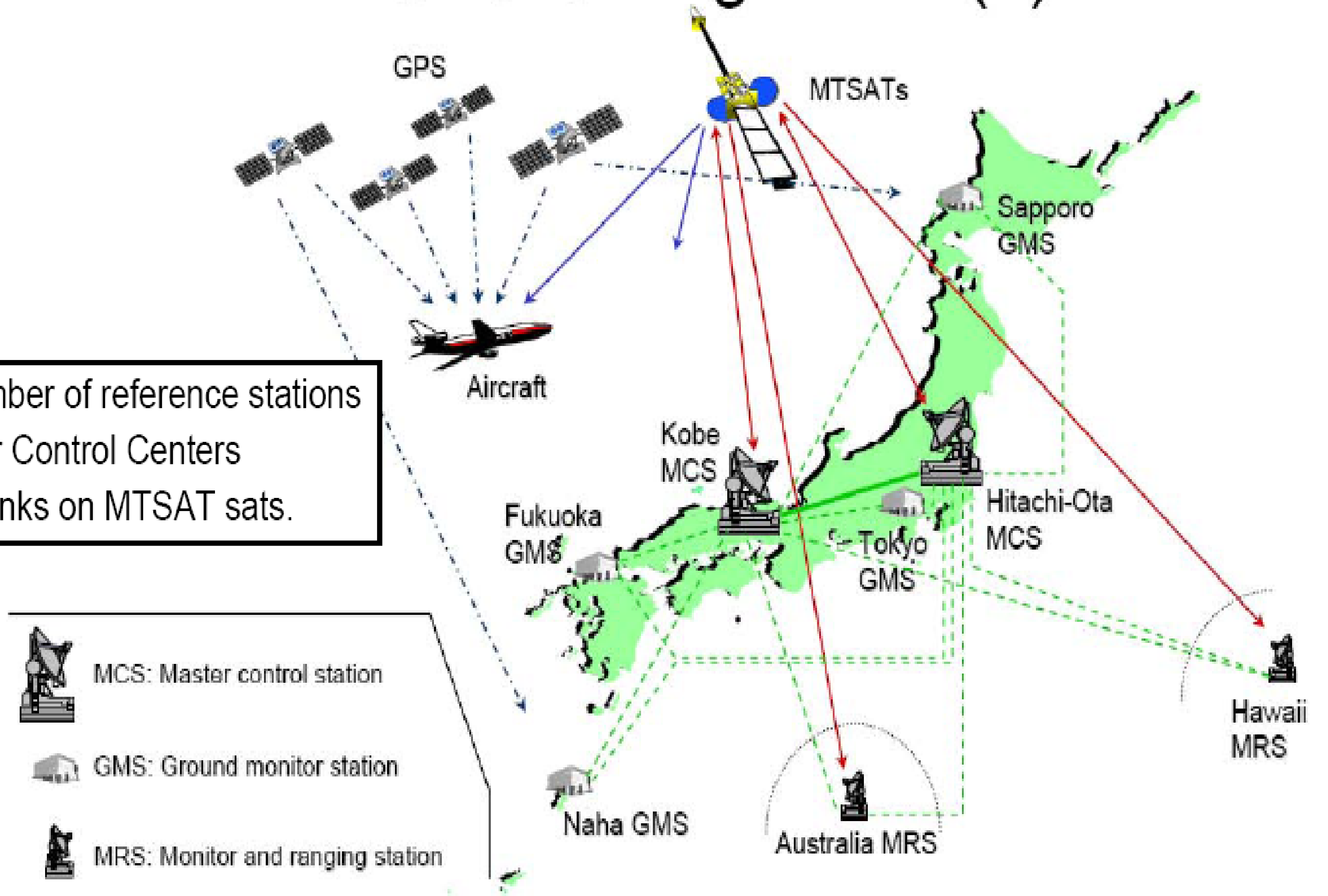
4 Ground Earth Stations

2 Geostationary Satellite Links



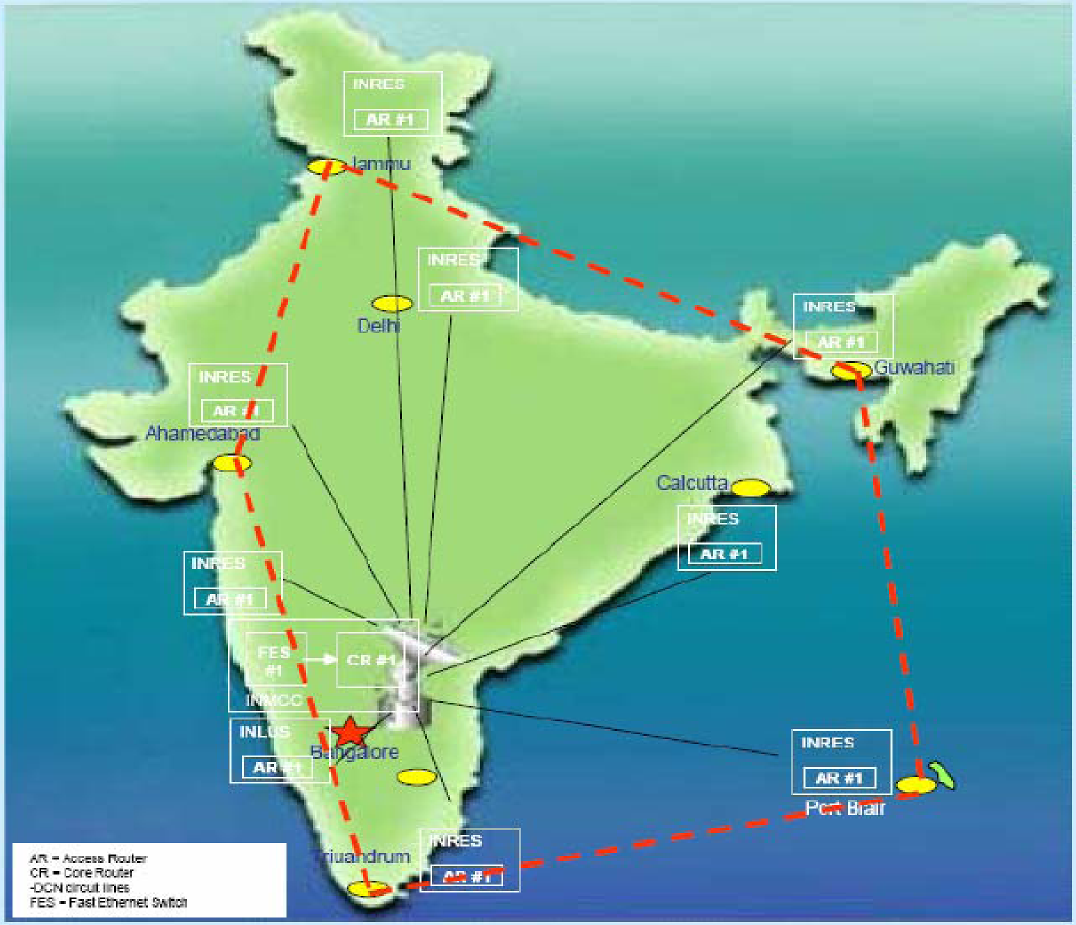
2 Operational Control Centers

MSAS Configuration(1)



- Low number of reference stations
- 2 Master Control Centers
- 2 GEO links on MTSAT sats.

GAGAN Current Configuration



Ground Segment

- 8 INRES: 2 INREEs
- 1 INMCC
- 1 INLUS
- 1 ring of OFC (7 INRES)
- 1 VSAT link (GPB)

Space Segment

- INMARSAT-4F1

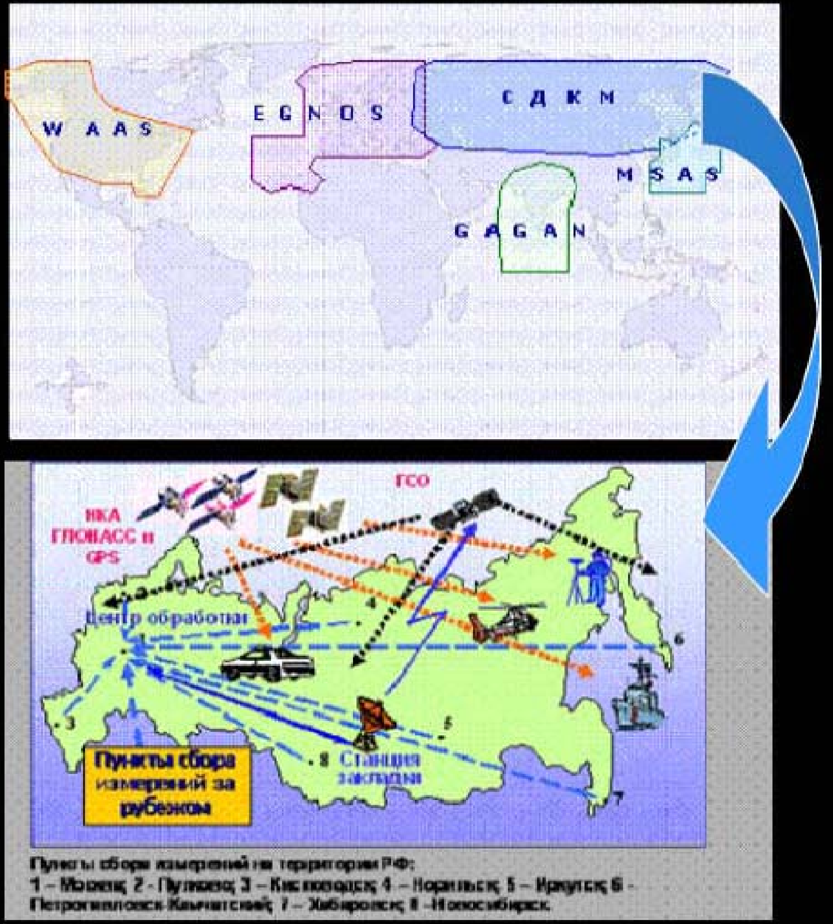
GAGAN Status and Plans

- Current Configuration aimed to Technology Demonstration
- Full Operational Capability by 2010:
  - More reference stations with 3 chains each
  - 1 additional master control center
  - 1 additional up-link station
  - 2 additional GEO links (L1/L5) plus one in-orbit spare

TUDelft

System of Differential Corrections and Monitoring (SDCM) – wide area aurmentation

- **Main Objectives:**
  - Orbit and clock correction transmission to users
  - Integrity provision
- **Status:**
  - Limited monitoring network deployed
  - Operation tests
- **Validation**
  - 2010



Summary and outlook

- Signals, observations, errorrs, PVT estimation
- DGPS, RTK, Network RTK, PPP

Next:

12. Quality control, ambiguity resolution

13,14. Applications