Introduction to RTK and network RTK

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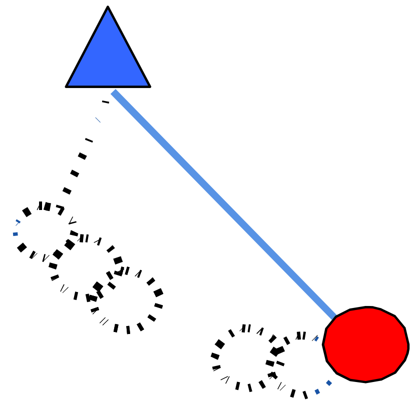
Outline

- Real time kinematic – RTK
- RTK in practise
- Single station RTK
- Network RTK and concepts
    - i-MAX
    - VRS
    - MAC
- An example – the FFL positioning system

Real time kinematic (RTK)



Relative carrier phase based positioning in real time

Requires at least two GNSS receivers, one located in a known position

Requires data link for transfer of data between reference station and rover

- Most common is mobile internet, but also UHF radio is used

Position of rover determined in real time using double differences, wide lane, and ambiguity search methods

- Distance between reference and rover max. 20-30 km
- Obtainable position accuracy 1 – 5 cm

Real time kinematic (RTK)

Used for applications with high accuracy requirements in real time:

- Land surveying
- Machine guidance in construction work and open mining
- Precision farming
- Forestry
- Autonomous driving
- Etc.

RTK positioning can be done:

- In kinematic mode, where the rover is continuously in motion
- In stop-and-go mode, where rover is left a few seconds in each position to obtain better position accuracy and reliability

RTK observation procedure

- Establish reference station in location with known coordinates
- Establish data connection between reference and rover receivers
- Initialize rover, i.e. wait while ambiguities are determined
- Move rover to locations with unknown coordinates and perform observations

Photo: www.trimble.com

RTK – Initialization

- Before the first position can be determined, the rover must be initialized
- During initialization, data is transmitted from reference to rover, double differences are determined in the rover and the ambiguities are resolved
- After initialization the position for the rover can be determined
- Initialization is the challenging part of RTK in practise, it can last several minutes depending on the conditions

Cycle slips and re-initialization

When cycle slips occur for one satellite, a new ambiguity is estimated for the given satellite while positioning is still ongoing

If contact to more satellites is lost so four or less satellites are observed, all ambiguities are re-set and a new initialization must be carried out

Positioning is not possible during re-initialization

This happens often in environments with much signal blockage e.g. city street canyons and forests, but can also happen if the data communication between reference and rover is poor

Error sources and RTK

Illustration: www.leica-geosystems.com

With relative carried phase based positioning, like RTK, the effect of the spatially correlated errors:

- Satellite clock error
- Satellite position error
- Atmospheric effects

is minimized

These errors are almost identical in reference and rover if the distance between the two receivers is short

Site dependent effects (multipath, signal blockage, antenna phase center variation etc.) are, however, not handled with RTK

Single station RTK

For single station RTK, one reference station is used

Data is transmitted from reference to rover (one way communication)

Position accuracy in the rover is dependent on distance between reference and rover

With a shorter distance, the spatially correlated errors are more correlated and better eliminated with double differences => better position accuracy for the rover

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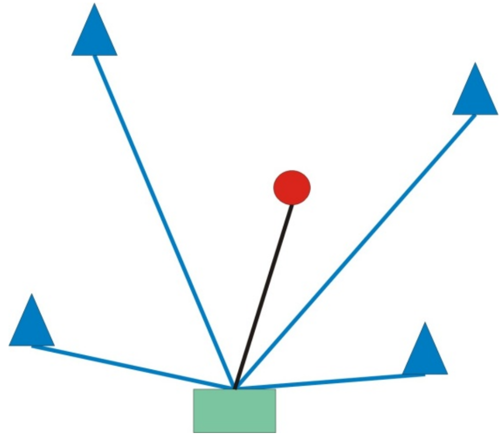
Network RTK



RTK with a network of reference stations

Data from reference stations is combined in a common data processing in a control centre

The control centre computes corrections for the spatially correlated errors within the network

These corrections are then transmitted to the rover

Distance to nearest reference station in the network can be increased up to e.g. 50 km

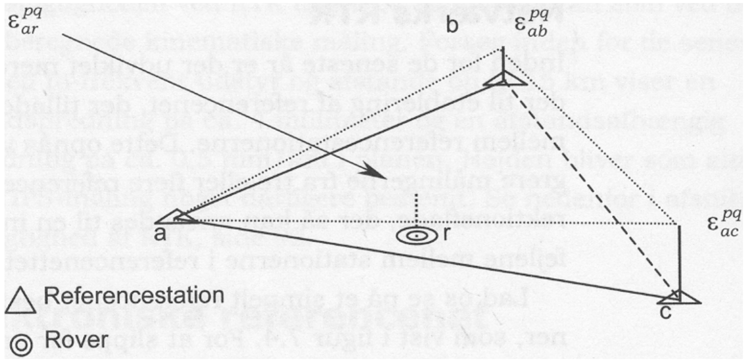
Network RTK

Basic principle:

Double differences between stations a, b and c in the network and the satellites p and q:

$$\Phi_{ab}^{pq}(t) = \rho_{ab}^{pq}(t) - \lambda N_{ab}^{pq}(t_0) + \varepsilon_{ab}^{pq}(t)$$

$$\Phi_{ac}^{pq}(t) = \rho_{ac}^{pq}(t) - \lambda N_{ac}^{pq}(t_0) + \varepsilon_{ac}^{pq}(t)$$



The value of the corrections, ε, are determined in a least squares adjustment – remember that ρ is known for the reference stations

ε contains residual effects of the spatially correlated errors as well as residual site dependent errors from the reference stations

Pros and cons

Advantage with network RTK compared to single station RTK:

- Better modelling of spatially correlated error over larger distances => distance between rover and reference station can be increased

Advantage with single station RTK compared to network RTK:

- With very short distance between referenced and rover single station RTK may provide better results since the spatially correlated errors will be basically identical so there is no need for the full network

Network RTK concepts

- Different concepts for estimation of network RTK corrections exist
- Common for the concepts is that ambiguities between reference stations in the network must first be estimated
- The concepts differ in the way error sources are handled
- Most important concepts today:
  - i-MAX originally developed by Leica Geosystems
  - VRS originally developed by Trimble
  - MAC originally from Leica Geosystems, further developed by GEO++

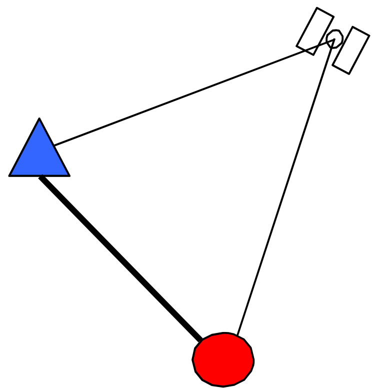
(Review based on Takac and Zelzer, 2008)

i-MAX concept

i-MAX - Individualised Master Auxiliary corrections

- Approximate position of rover transmitted to control center
- Data from a number of reference stations used for estimation of RTK corrections for the position of the rover
- Corrections used to correct raw GNSS data from one of the reference stations, selected as the ”master” station
- Corrected data from this reference station is transmitted to the rover

i-MAX concept



$$\tilde{\phi}_m^q = \phi_m^q + \delta\phi_{mr}^q$$

Where:

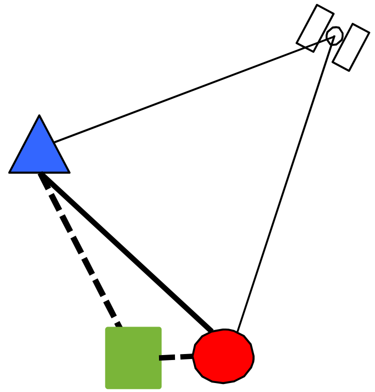
- $\tilde{\phi}_m^q$ is the observation from satellite q in reference station (the master) m, corrected for errors estimated for the rover position
- $\phi_{\mathrm{m}}^{\mathrm{q}}$ is the real observation from satellite q in reference station m
- $\delta\phi_{mr}^q$ is RTK error corrections for the single difference between reference station m, rover r and satellite q

VRS concept

VRS - Virtual Reference Station

- Approximate position of rover transmitted to control center
- Data from a number of reference stations used for estimation of RTK corrections for the position of the rover
- Corrections used to generate artificial (or virtual) GNSS data as they would have been if a reference station was located right beside the rover
- This VRS data is transmitted to the rover

VRS concept



$$\tilde{\phi}_v^q = \tilde{\phi}_m^q + s_{m,v}^q + T_{m,v} + A_{m,v}^q$$

Where:

- $\tilde{\phi}_v^q$ is estimated VRS observation from satellite q in point v
- $\tilde{\phi}_m^q$ is the observation from satellite q in reference station m, corrected for errors estimated for the rover position
- $s^q_{m,v}$ is the single difference between reference station m, point v and satellite q
- $T_{m,v}$ is the relative tropospheric effect between station m and point v
- $A^q_{m,v}$ is the antenna phase center correction for the single difference between station m, point v and satellite q

MAC concept

MAC - Master Auxiliary Concept

- Data from all reference stations sent to the control center
- For each pair of reference stations, corrections for the observations are estimated
- Corrections are estimated between the chosen reference station (the master) against the other reference stations in the network (auxiliary stations)
- Corrections are divided into dispersive and non-dispersive parts
- Raw observations from the master are transmitted to the rover along with the corrections
- Advantage is much flexibility for MCMF and possibility to use one-way communication to the rover. Disadvantage is need for more bandwidth in the data communication link

MAC concept

$$\delta\phi^{q}_{mk,i} = S^{q}_{mk} - \phi^{q}_{mk,i} + \Delta t_{mk} + A^{q}_{mk,i} + \frac{c}{f_i} a^{q}_{mk,i}$$

Where:

$\delta\phi^{q}_{mk}$	is RTK error correction for the single difference between master station m, auxiliary station k and satellite q
S^{q}_{mk}	is the computed geometric range for the single difference
$\phi^{q}_{mk,i}$	is the single difference of the raw observations between satellite q, master station m and auxiliary station k
Δt_{mk}	is the computed receiver clock error
$A^{q}_{mk,i}$	is the computed antenna phase center correction
$a^{q}_{mk,i}$	is the computed integer ambiguity in units of cycles
f_i	is frequency (e.g. L1 or L2)
c	is speed of light

MAC concept

- In order to solve the ambiguities, double differences are introduced, so the term $a^q_{mk,i}$ is further developed

- The corrections, $\delta\phi^q_{mk}$ are further factorised into:

  - $\delta\phi^q_{mk,\gamma}$ dispersive (frequency dependent) part
  - $\delta\phi^q_{mk,\chi}$ non-dispersive part

- In the rover, the raw observations from the master station are used together with a “choice” of the corrections

- Note the flexibility in applying more frequencies, and different approaches for estimating the corrections

The RTCM format

- Proprietary format for transmission of RTK corrections to users have been used extensively
- For compatibility across receiver brands, the RTCM data format has become a de facto standard
- The RTCM format is undergoing a major modernisation to meet the needs of RTK (and PPP) positioning with multiple constellations and multiple frequencies
  - More on the RTCM tomorrow!

Challenges with (network-) RTK

- Residual effects of the atmospheric errors are still a challenge

- Multipath and other site dependent effects are not mitigated with RTK
  - Ongoing research on this, e.g. the CLOSE projects (Sweden), integrity in reference networks (Norway) etc.

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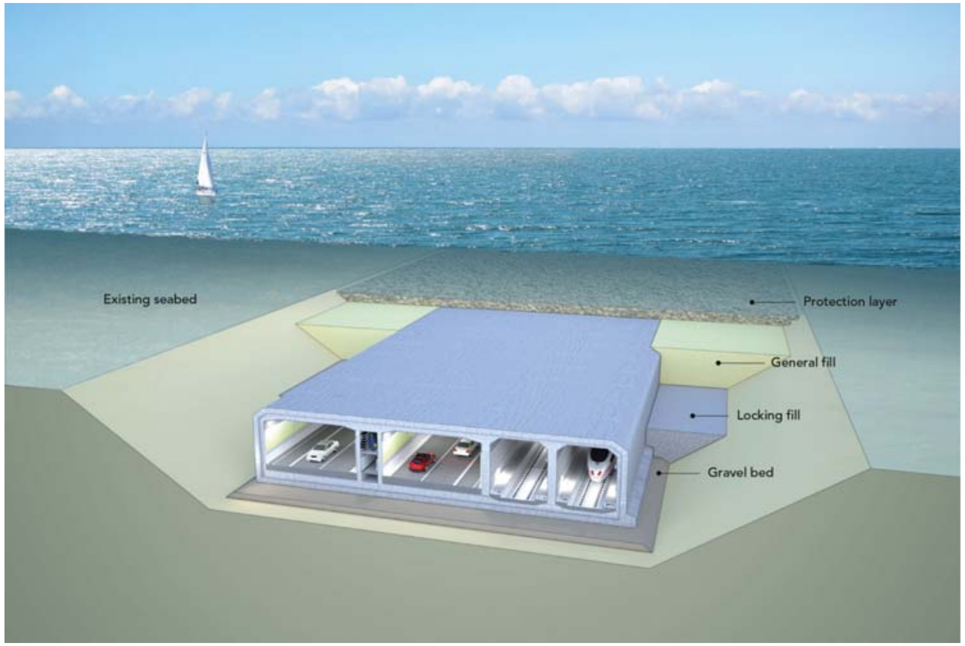
Example – the FFL positioning system

The following components are needed in order to establish a network RTK service

- Geodetic infrastructure
  - Geodetic reference frame and possibly geoid model
- Stable GNSS reference stations
- Data communication between reference stations and control center
- Software platform for data processing
- Data communication from control center to RTK users

Illustrated with an example of the positioning system for the Fehmarnbelt Fixed Link between Germany and Denmark

Case: Positioning system for the Fehmarn Fixed Link

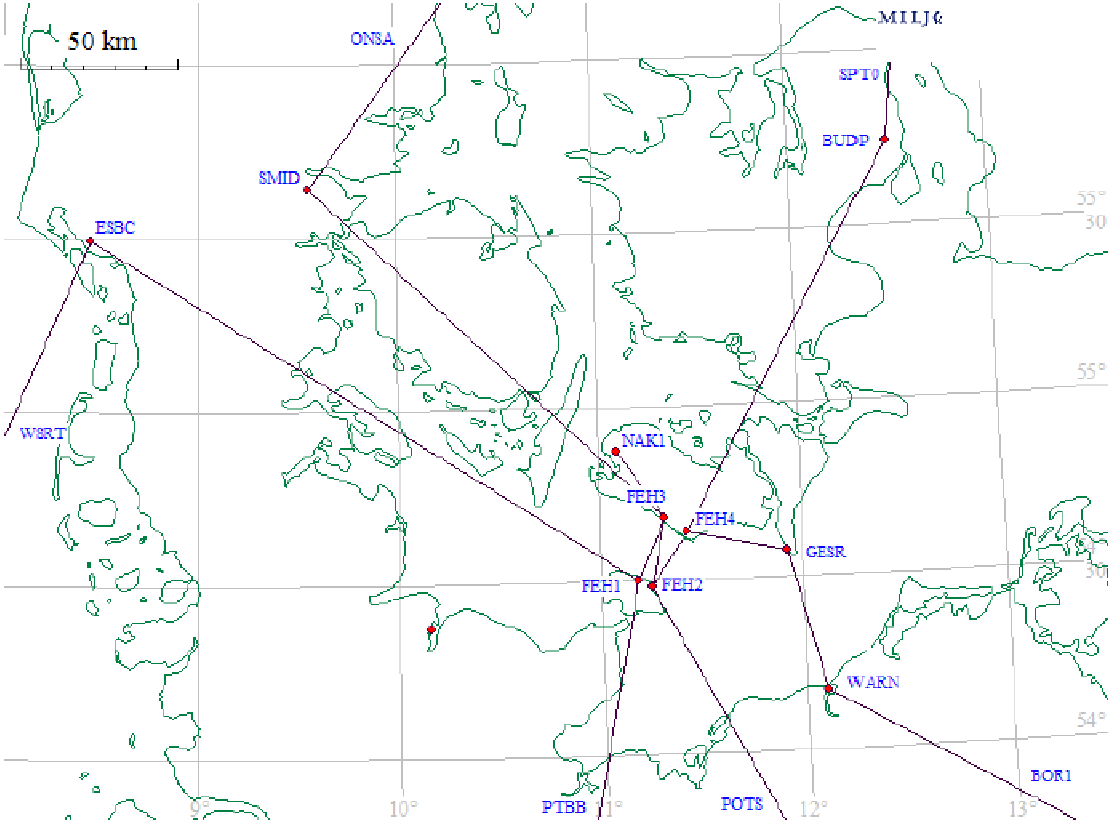


Figures from www.femern.com

Fehmarn Fixed Link – GNSS stations

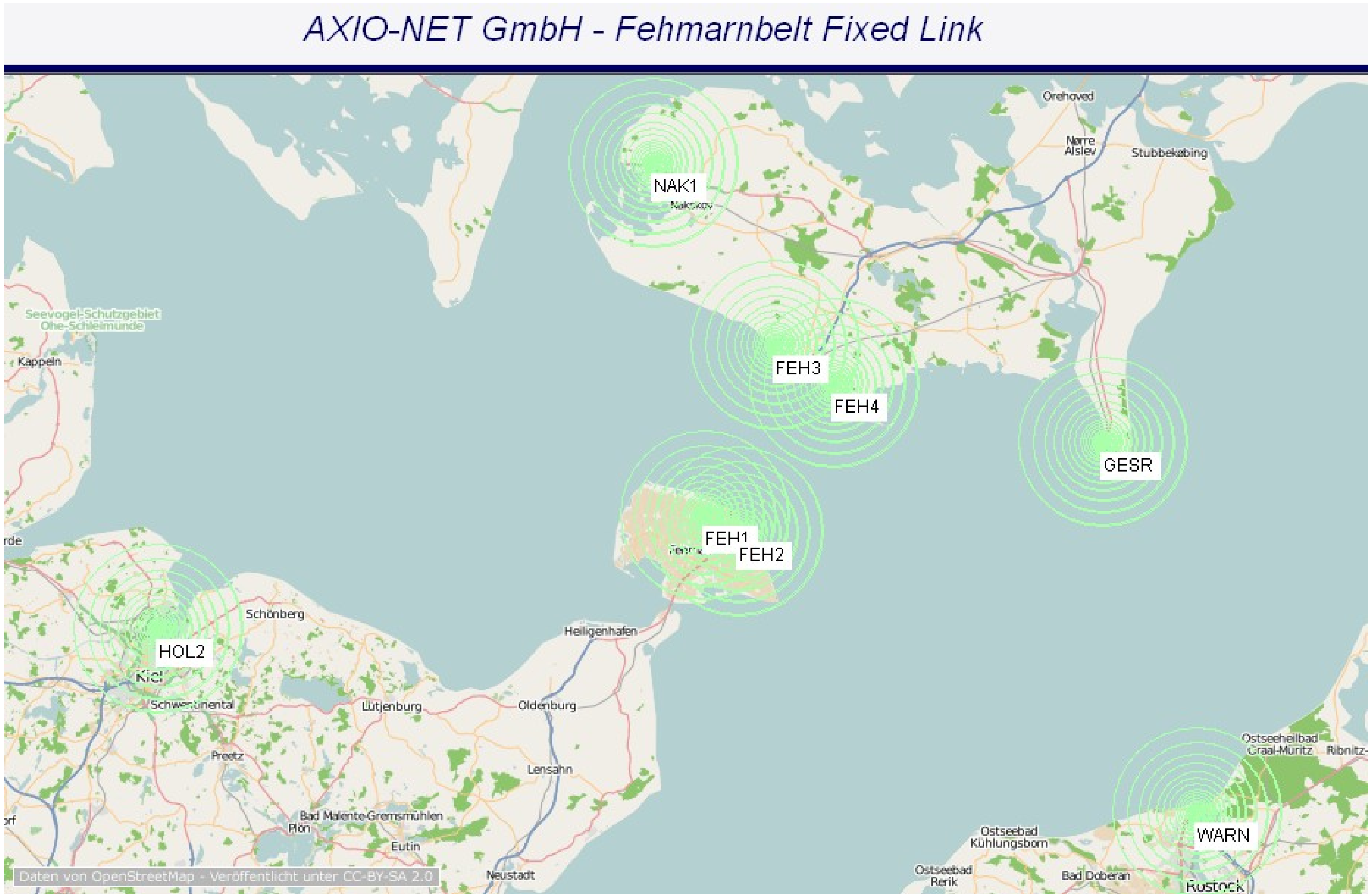
Case: Reference frame for the Fehmarn Fixed Link

Coordinates for the four permanent stations was determined with seven days of GPS-data and the Bernese software by the Danish Geodata Agency



Reference frame: ITRF2005

Case: Positioning system for the Fehmarn Fixed Link



FFL GNSS RTK-service

- Network RTK service
- Based on the GEO++ software platform
- Both VRS and MAC data transmitted
- Operated by AXIO-NET GmbH in Germany for Femern A/S in Denmark

FFL RTK service, redundancy

- A network RTK service with single station RTK as backup
- Three different methods for data communication between GNSS stations and control center
- Two redundant control centers at two different addresses in Germany
- RTK-data transmitted using the RTCM data format both via UHF radio and via mobile internet using the NTRIP protocol
  - UHF radio provides only MAC data, because VRS require two-way communication with users