Examples and results from the CLOSE project

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NKG Summer School, 30 August 2016

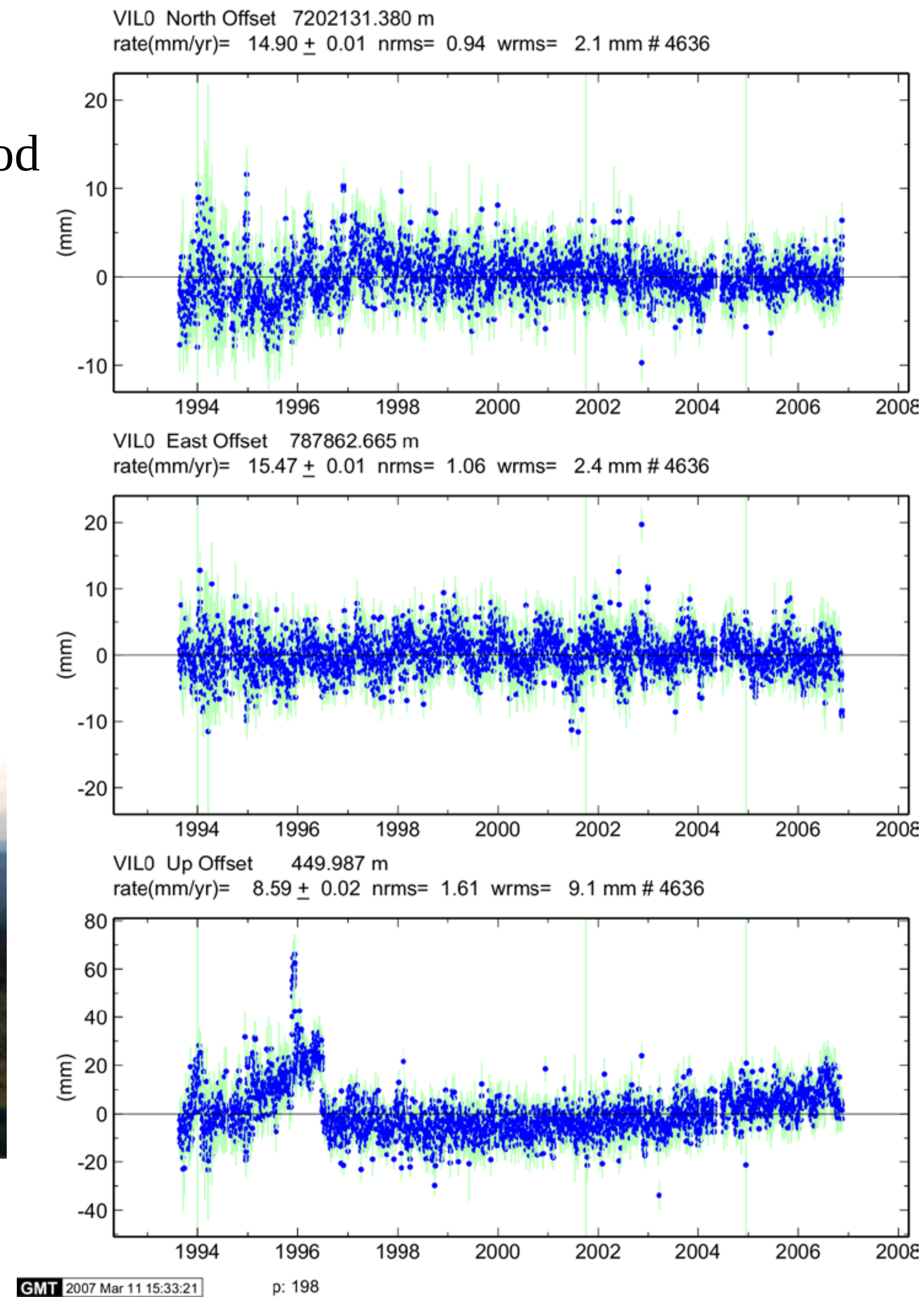
Example of time series of GPS positions

De-trended position time series from Vilhelmina (64° N) for the complete period Aug. 1993 – Oct 2006

1993-1996:
- some “bad” antenna radomes

PROBLEMS !!!???

Non-linear time-series in the vertical:
- Rate change after 2003 ???
- Model problems???



Used before summer 1996

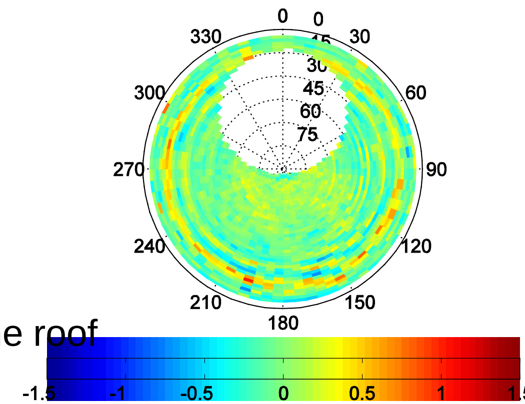
Used from late autumn 1996

Site dependent effects

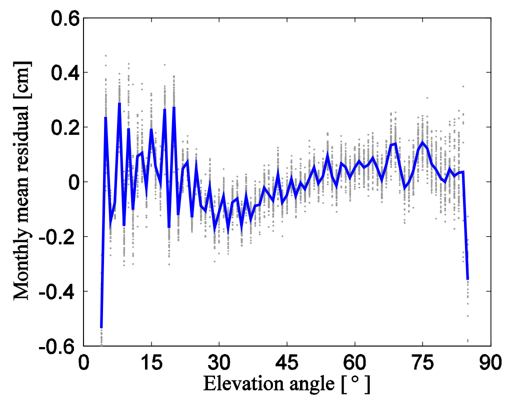
Several important issues:

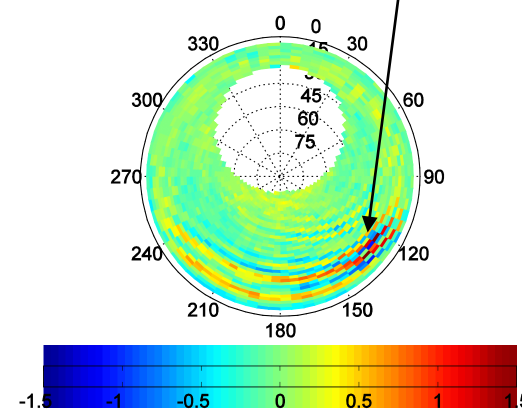
Antenna model and attachment
Radom model and attachment
Distance to reflective or blocking environment
Rain, condense, ice and snow

Elevation dependent systematic effects



Lovö GPS station:
- Hut built around pillar with a fence on the roof
- Steel construction in the south direction



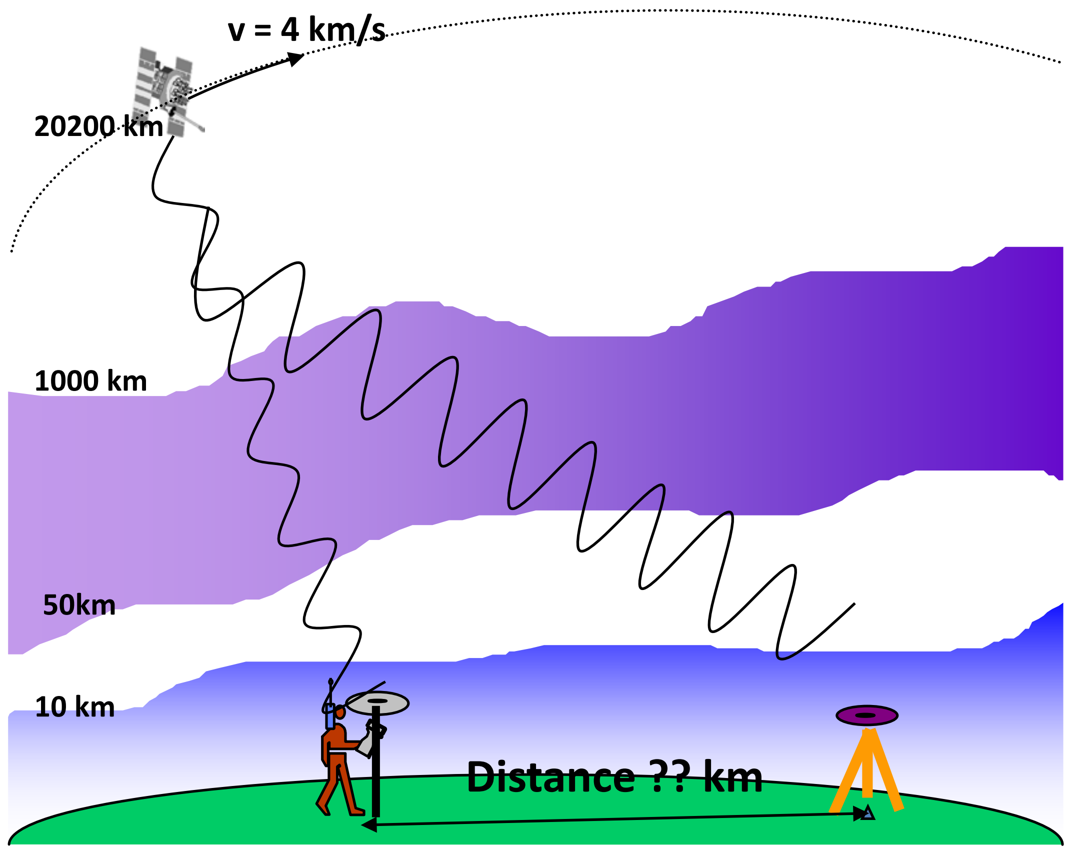


Visby GPS station:
- Large flat lime stone surface around the station
- Equipment hut in south east direction, ~15 m away

Using 6 years of data!

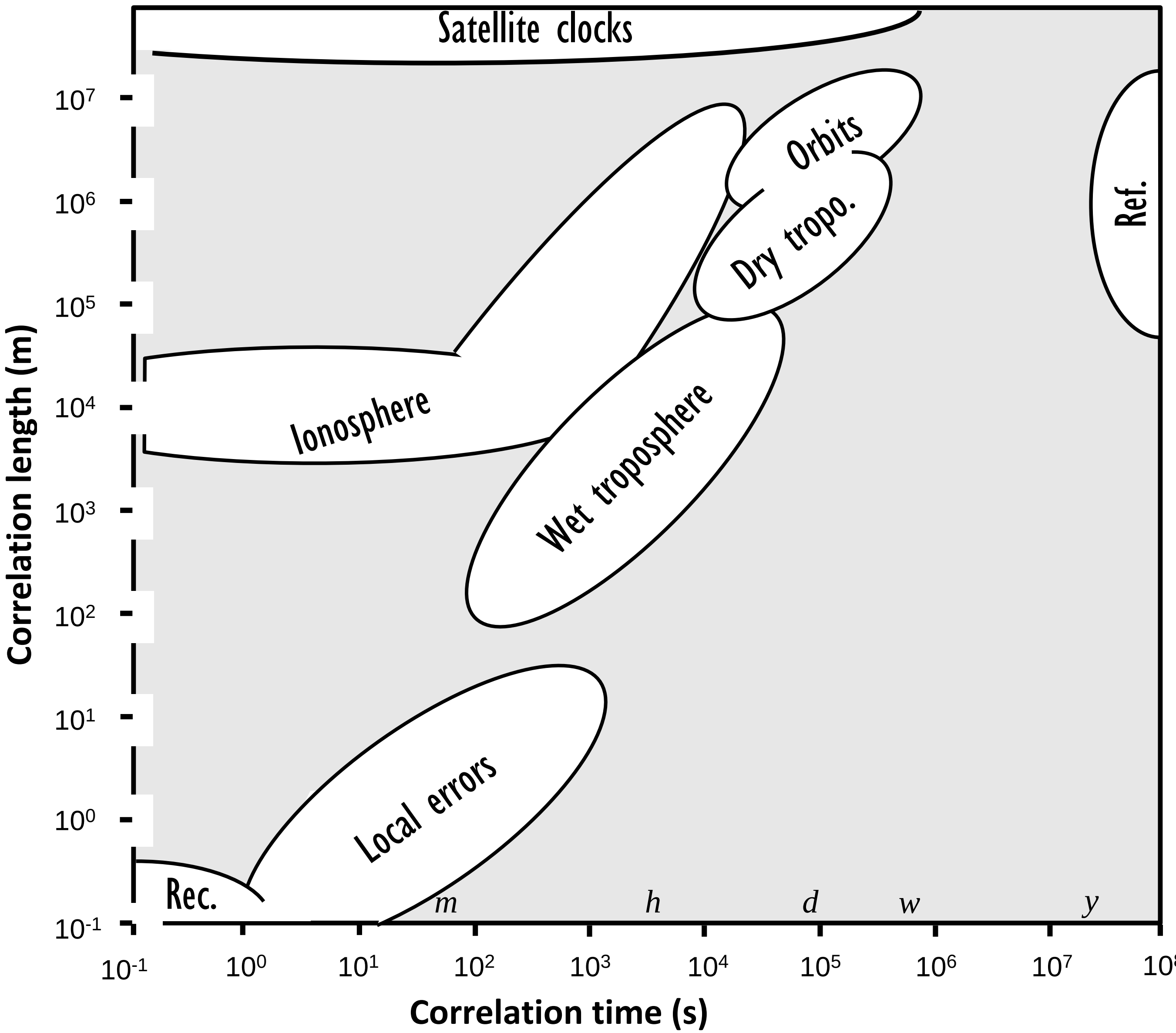
GNSS error sources

- Satellite clocks
- Satellite orbits
- Ionosphere
- Troposphere
- Local effects

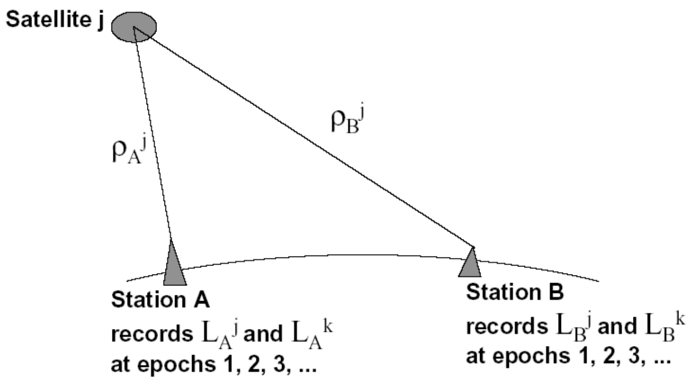


$$R = \rho + c_0\left(d\tau - dt\right) + d_{ion} + d_{trop} + v_R$$

Error sources - Spatial and temporal correlation



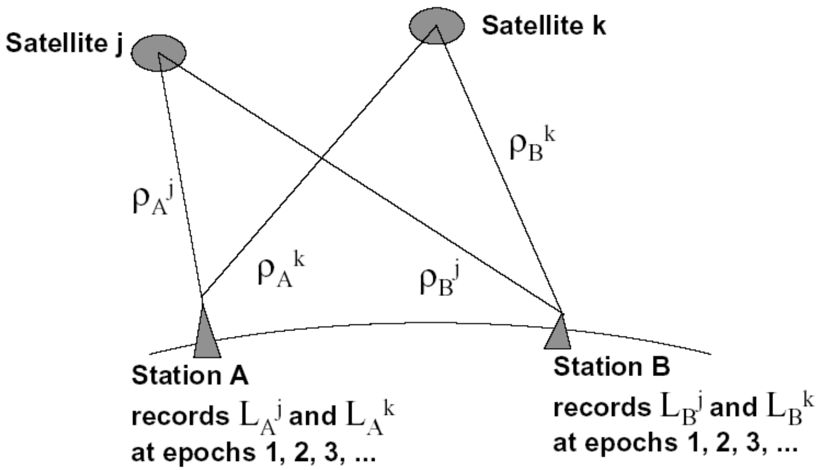
Single Differencing



$$L_A^j = \rho_A^j + c\tau_A - c\tau^j + Z_A^j - I_A^j + B_A^j$$
$$L_B^j = \rho_B^j + c\tau_B - c\tau^j + Z_B^j - I_B^j + B_B^j$$

$$\begin{aligned}
\Delta L_{AB}^j &\equiv L_A^j - L_B^j \\
&= \left(\rho_A^j + c\tau_A - c\tau^j + Z_A^j - I_A^j + B_A^j\right) - \left(\rho_B^j + c\tau_B - c\tau^j + Z_B^j - I_B^j + B_B^j\right) \\
&= \left(\rho_A^j - \rho_B^j\right) + \left(c\tau_A - c\tau_B\right) - \left(c\tau^j - c\tau^j\right) + \left(Z_A^j - Z_B^j\right) - \left(I_A^j - I_B^j\right) - \left(B_A^j - B_B^j\right) \\
&= \Delta\rho_{AB}^j + c\Delta\tau_{AB} + \Delta Z_{AB}^j - \Delta I_{AB}^j + \Delta B_{AB}^j
\end{aligned}$$

Double Differencing

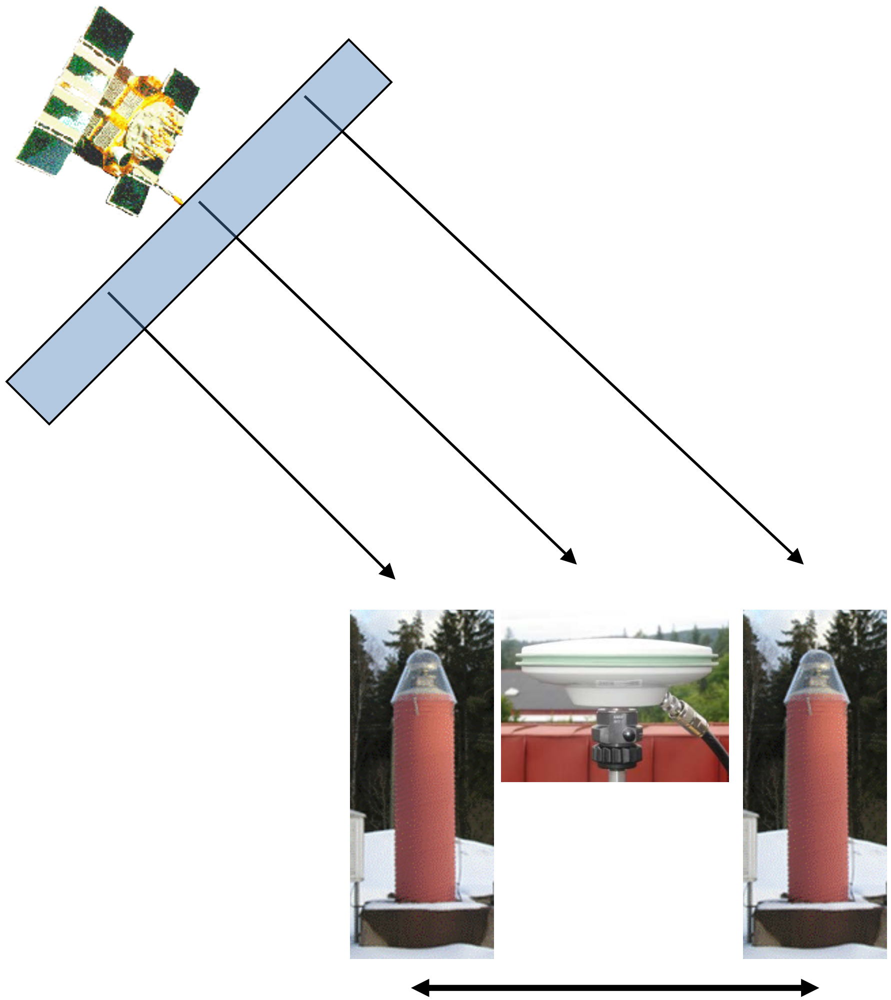


$$\Delta L_{AB}^{j} = \Delta\rho_{AB}^{j} + c\Delta\tau_{AB} + \Delta Z_{AB}^{j} - \Delta I_{AB}^{j} + \Delta B_{AB}^{j}$$
$$\Delta L_{AB}^{k} = \Delta\rho_{AB}^{k} + c\Delta\tau_{AB} + \Delta Z_{AB}^{k} - \Delta I_{AB}^{k} + \Delta B_{AB}^{k}$$

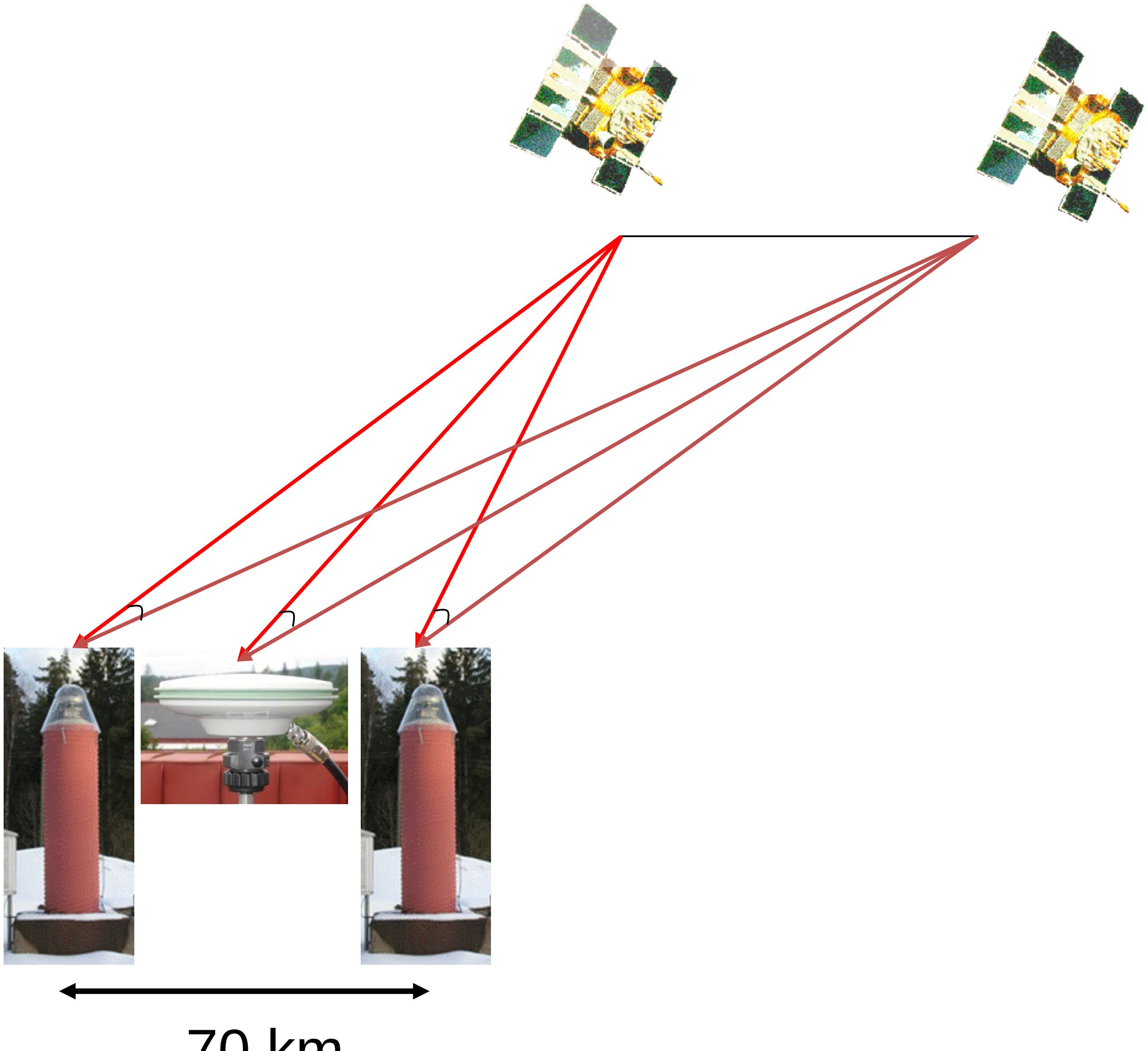
$$\begin{aligned}
\nabla\Delta L_{AB}^{jk} &\equiv \Delta L_{AB}^{j} - \Delta L_{AB}^{k} \\
&= \left(\Delta\rho_{AB}^{j} + c\Delta\tau_{AB} + \Delta Z_{AB}^{j} - \Delta I_{AB}^{j} + \Delta B_{AB}^{j}\right) - \left(\Delta\rho_{AB}^{k} + c\Delta\tau_{AB} + \Delta Z_{AB}^{k} - \Delta I_{AB}^{k} + \Delta B_{AB}^{k}\right) \\
&= \left(\Delta\rho_{AB}^{j} - \Delta\rho_{AB}^{k}\right) + \left(c\Delta\tau_{AB} - c\Delta\tau_{AB}\right) + \left(\Delta Z_{AB}^{j} - \Delta Z_{AB}^{k}\right) - \left(\Delta I_{AB}^{j} - \Delta I_{AB}^{k}\right) - \left(\Delta B_{AB}^{j} - \Delta B_{AB}^{k}\right) \\
&= \nabla\Delta\rho_{AB}^{jk} + \nabla\Delta Z_{AB}^{jk} - \nabla\Delta I_{AB}^{jk} + \nabla\Delta B_{AB}^{jk}
\end{aligned}$$

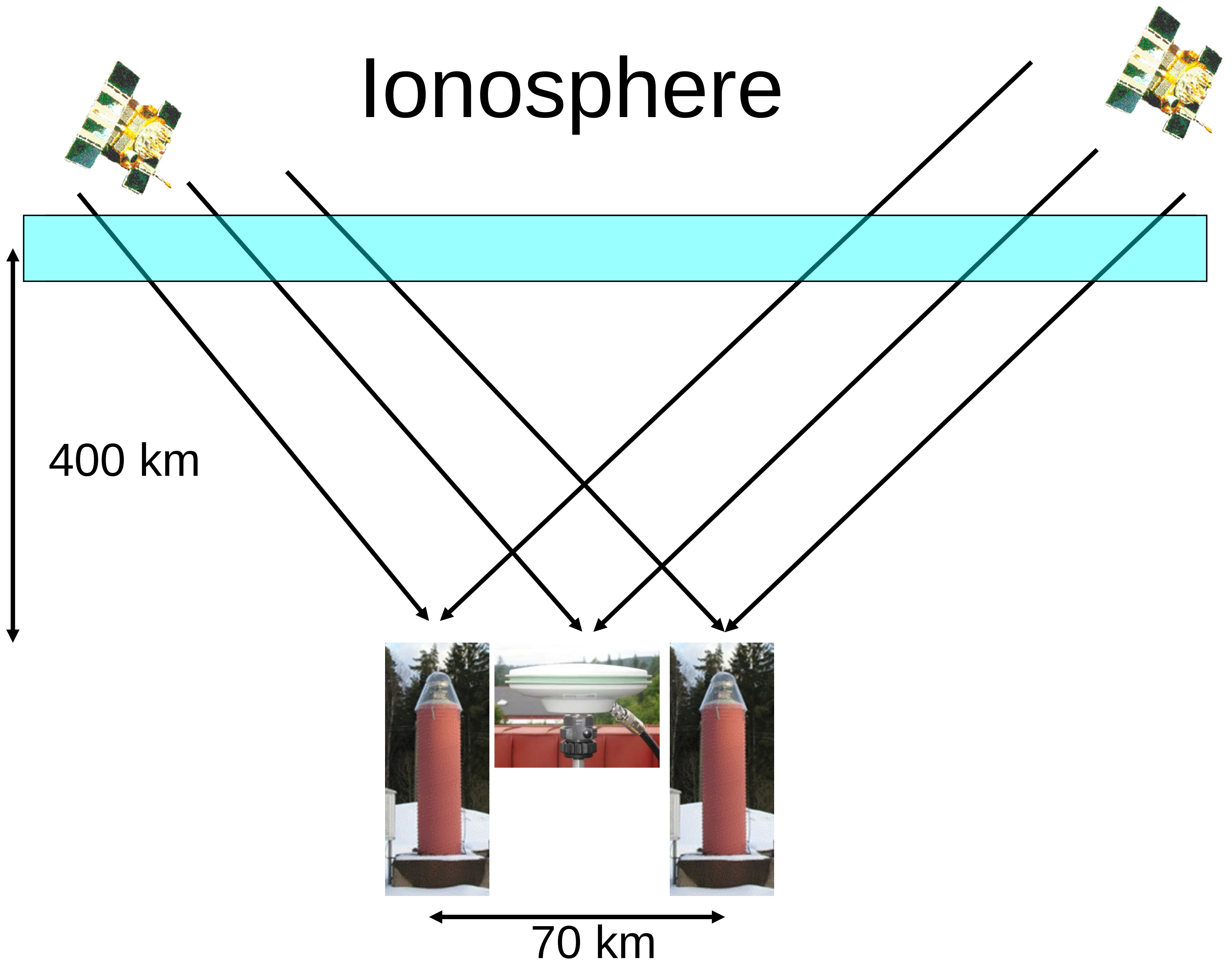
$$\nabla\Delta L_{AB}^{jk} = \nabla\Delta\rho_{AB}^{jk} + \nabla\Delta Z_{AB}^{jk} - \nabla\Delta I_{AB}^{jk} - \lambda_0 \nabla\Delta N_{AB}^{jk}$$

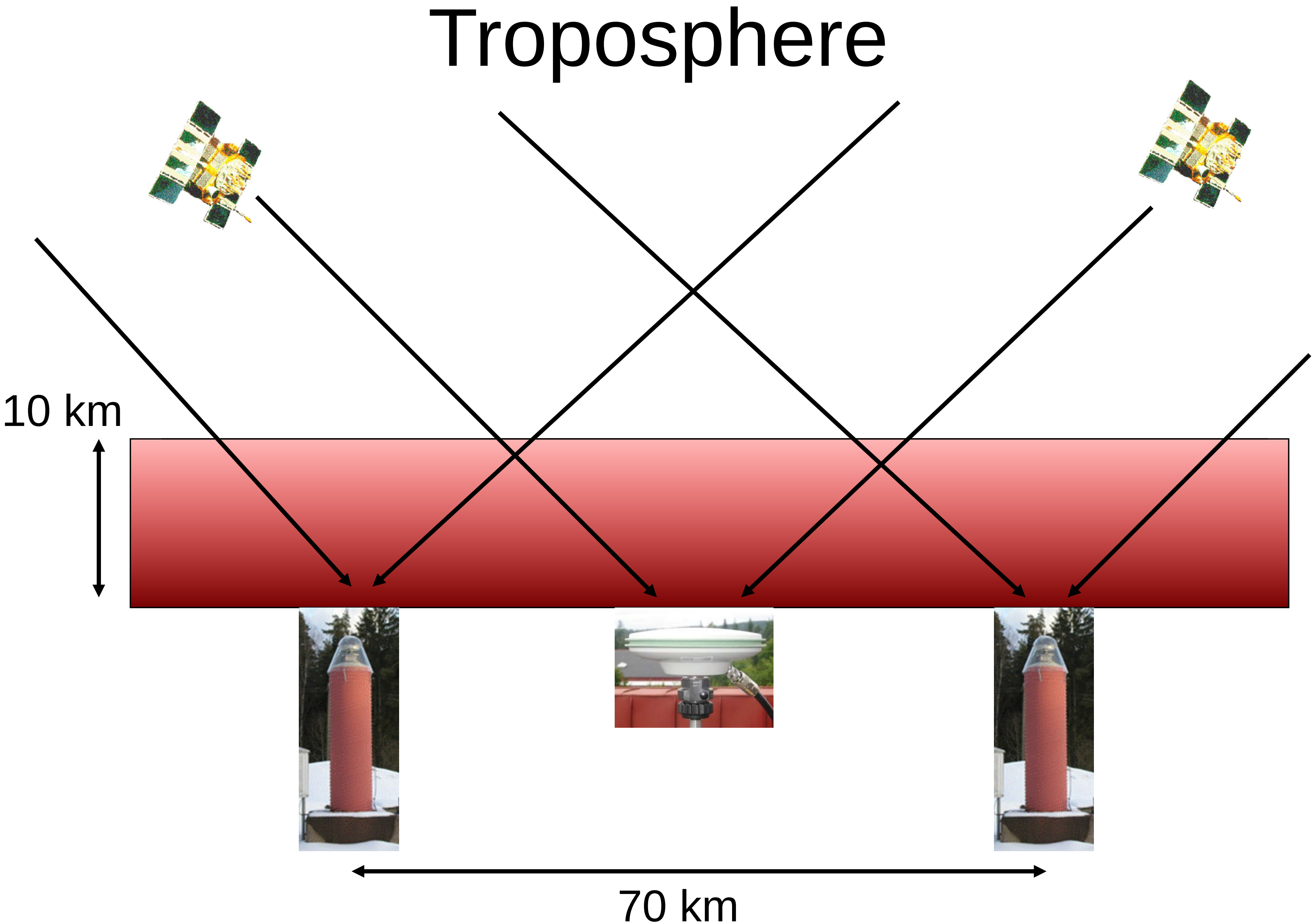
Satellite clocks



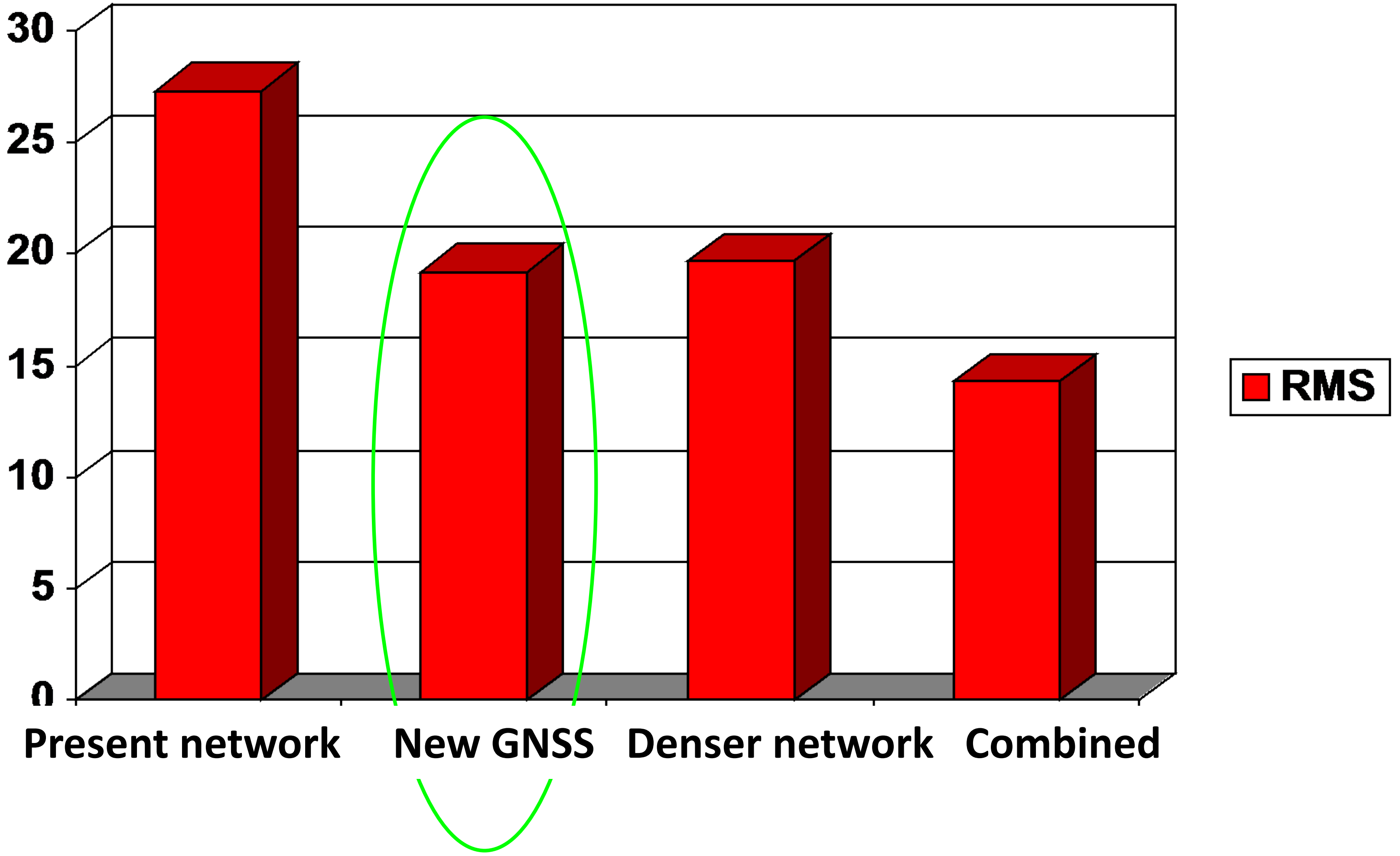
Satellite orbits



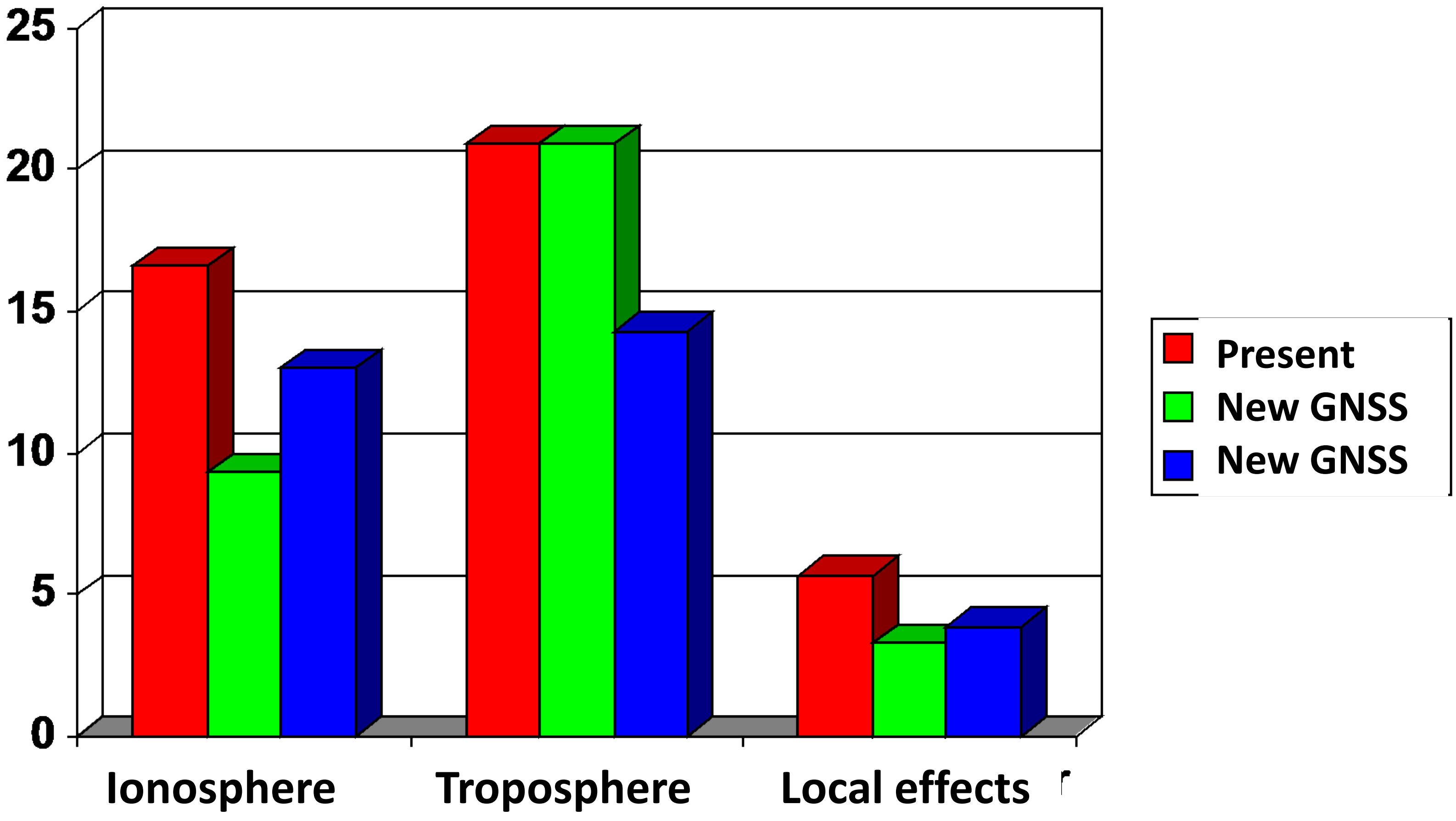

Ionosphere
400 km
70 km


Troposphere
10 km
70 km

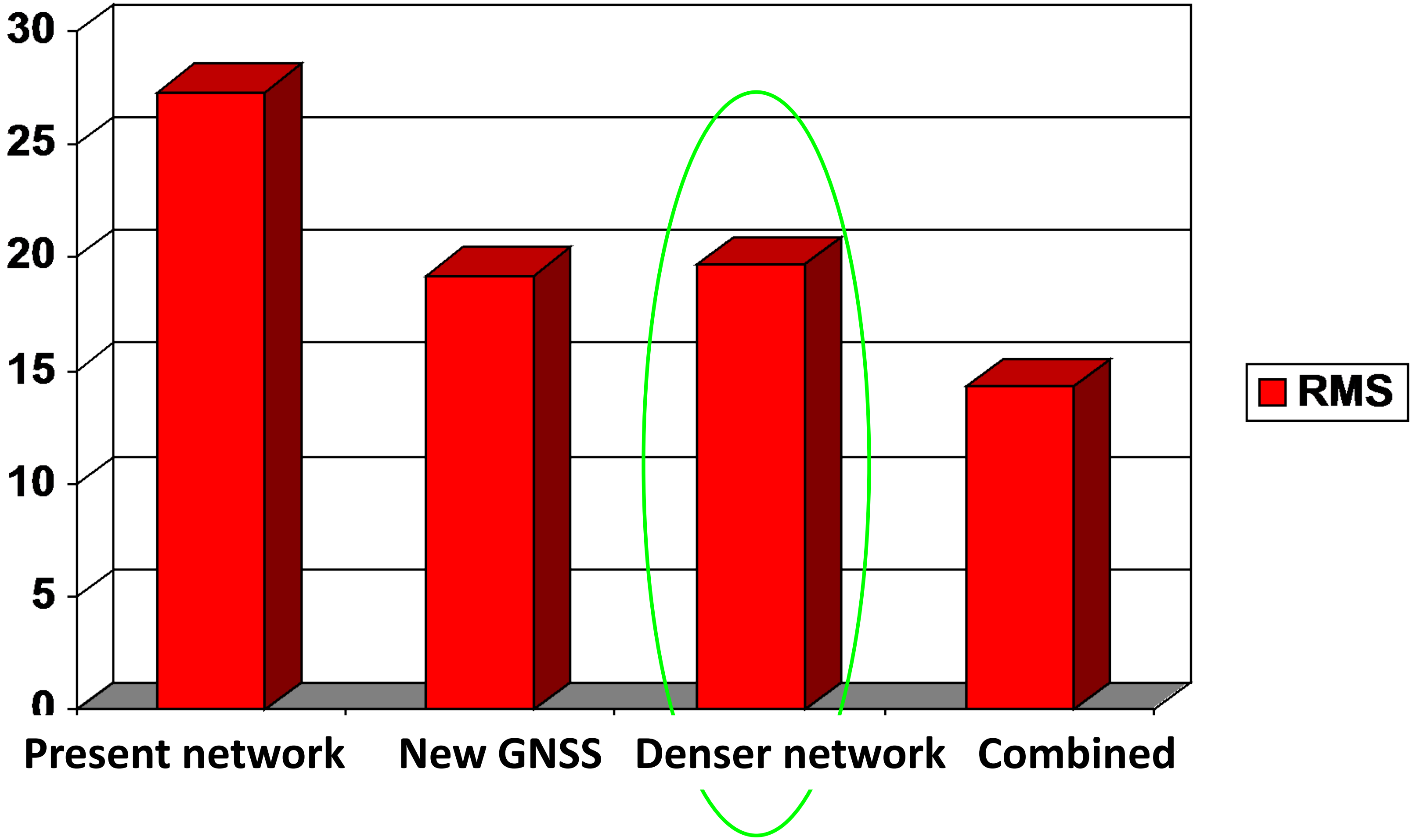
Vertical Error



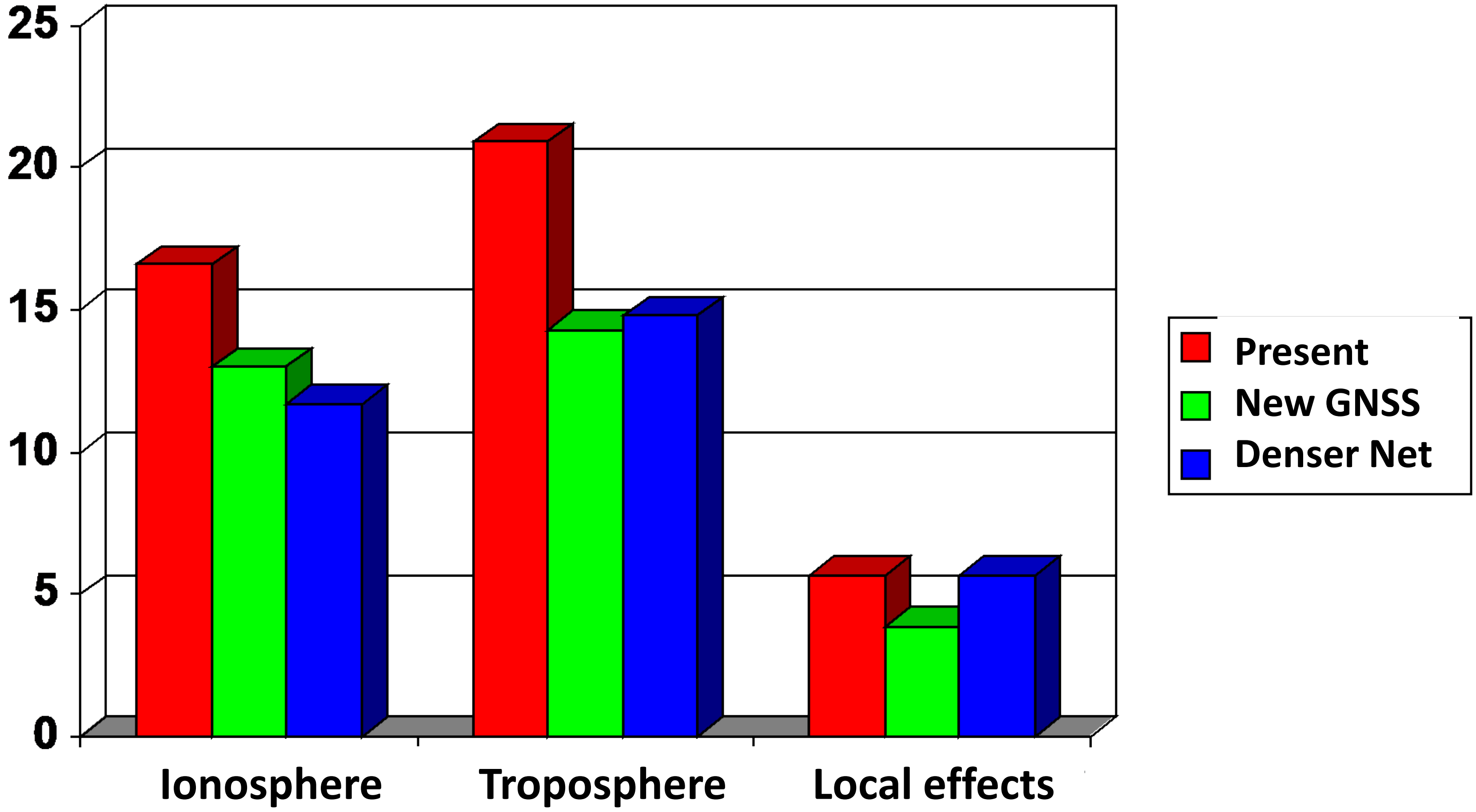
L1 - Processing



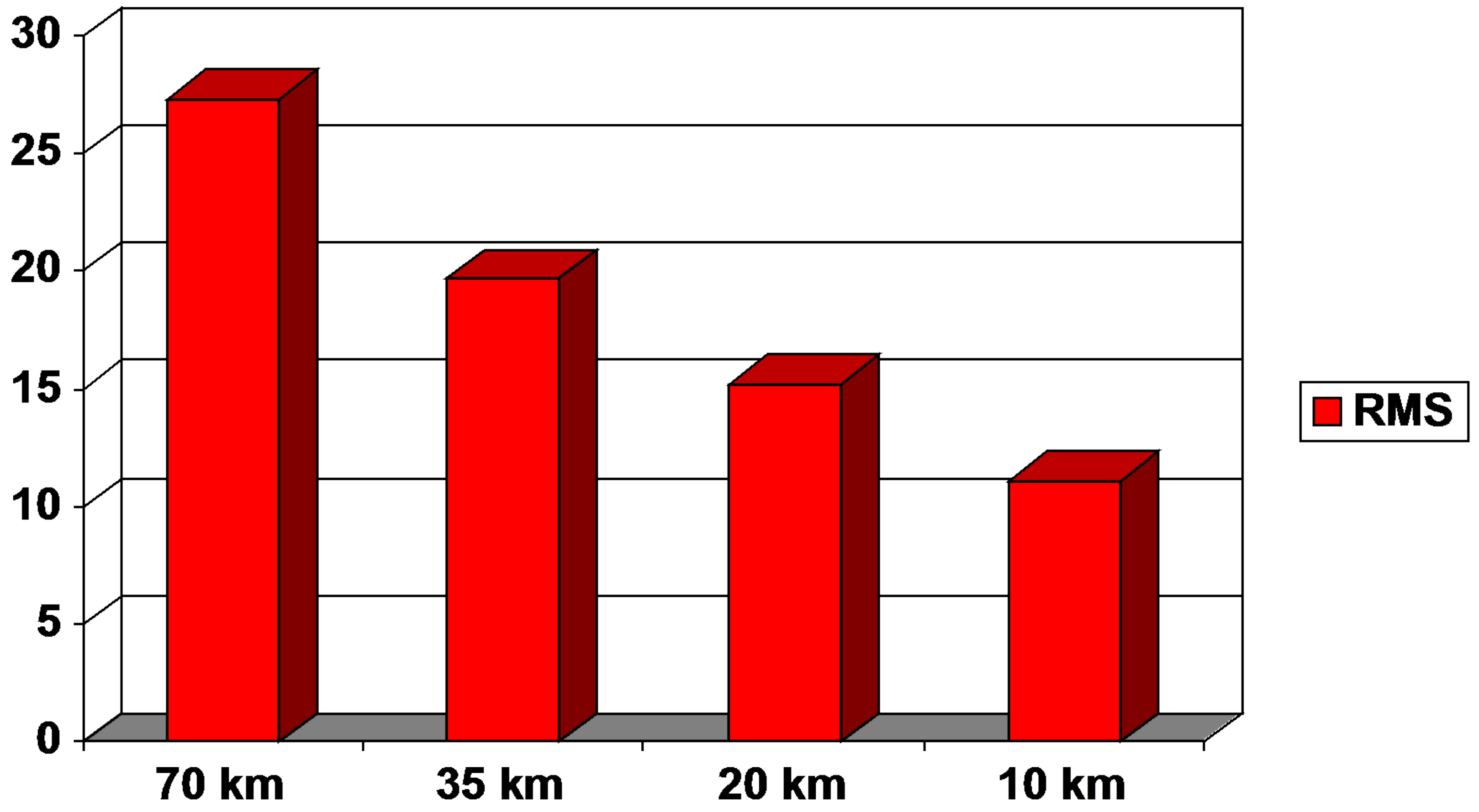
Vertical Error



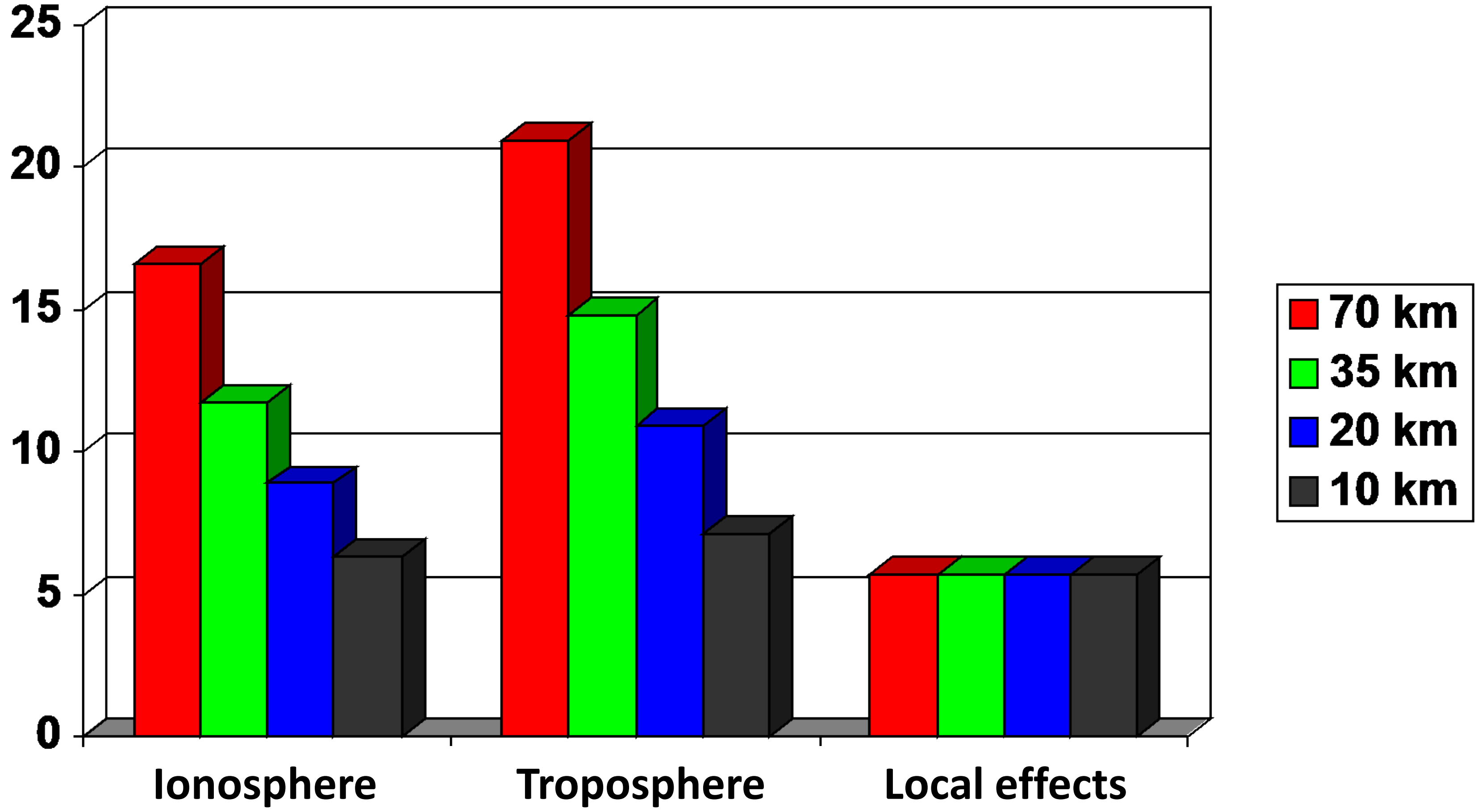
Contributing error sources



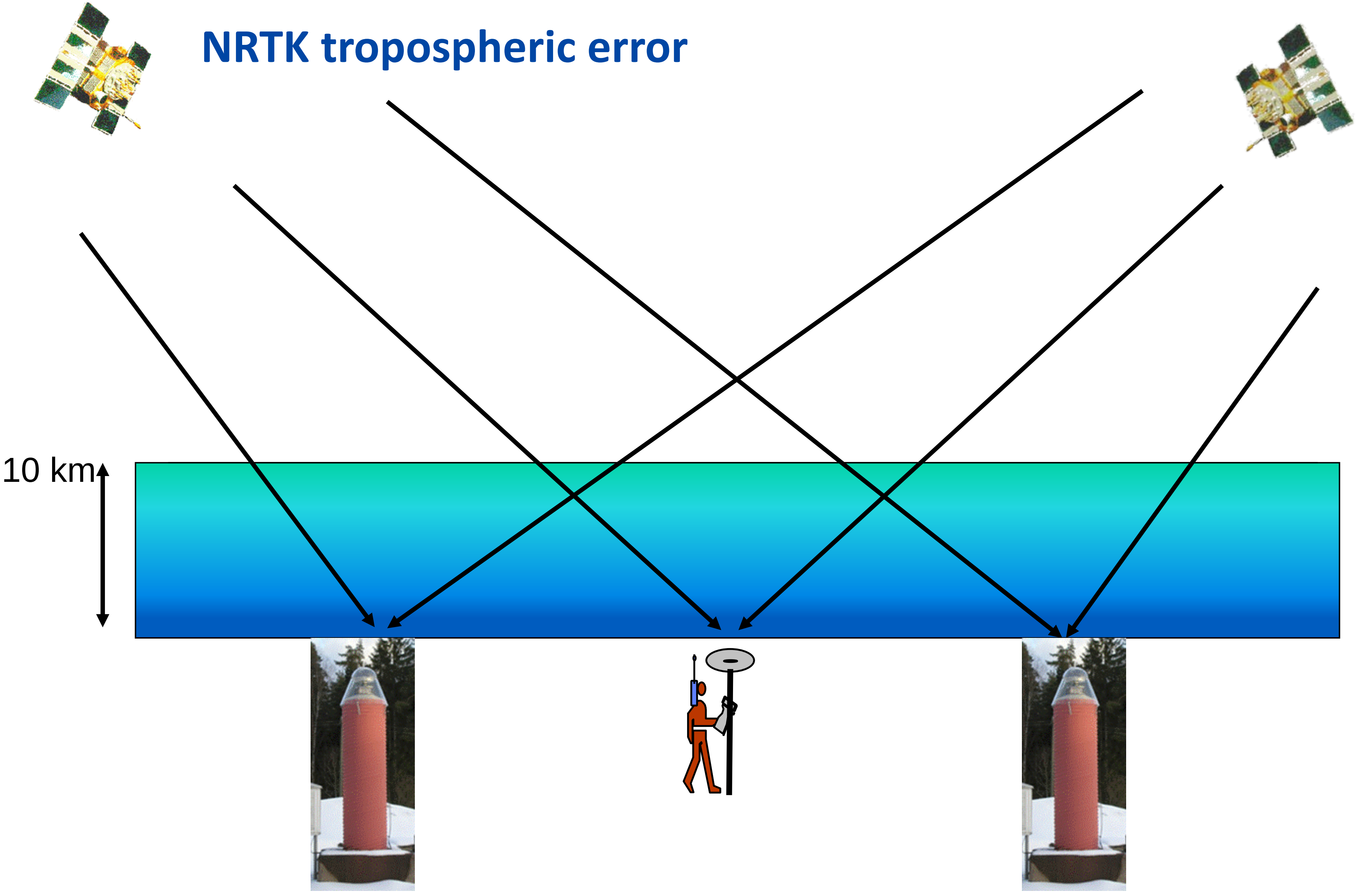
Vertical error – denser network



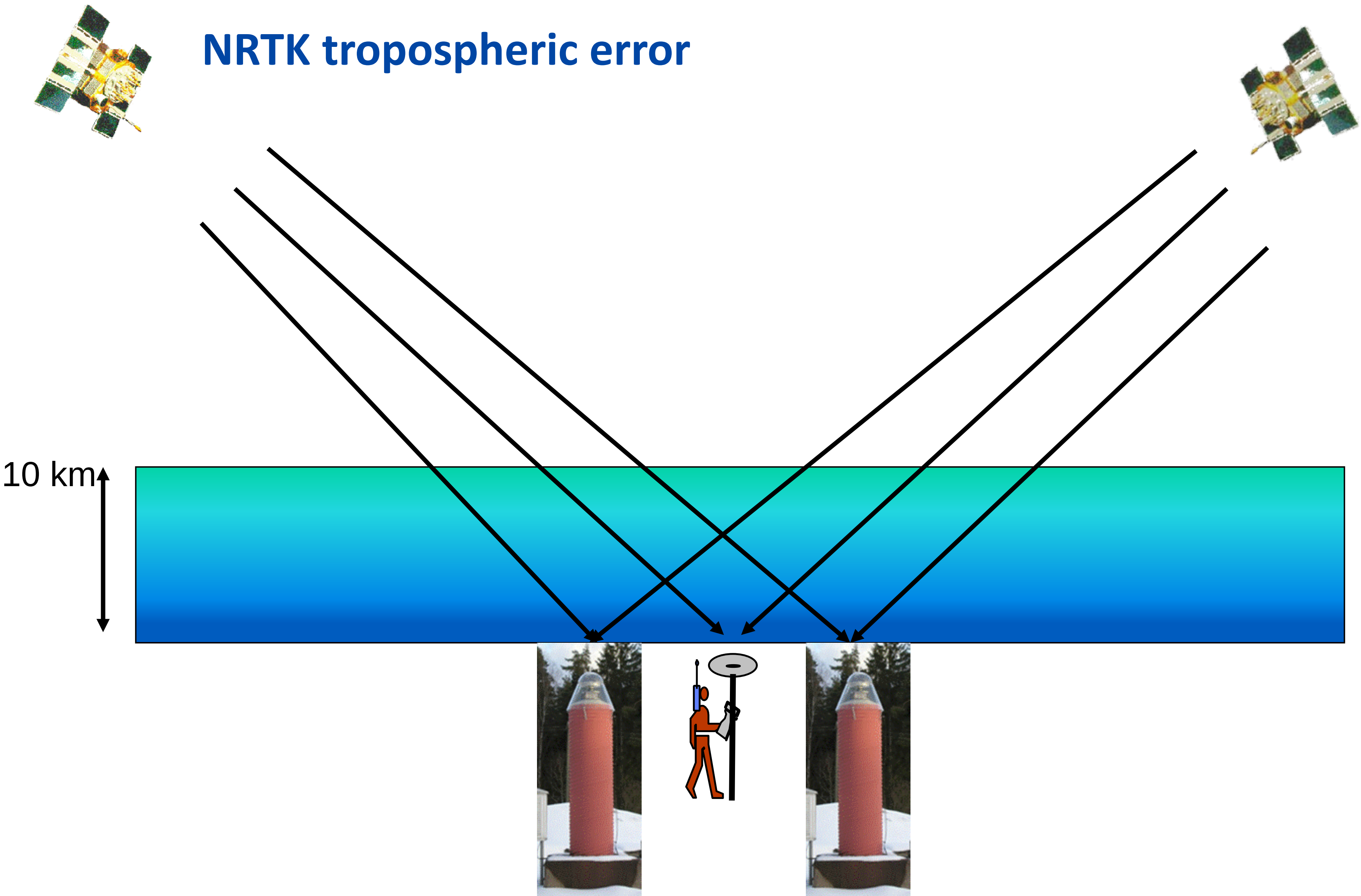
Standard - Processing



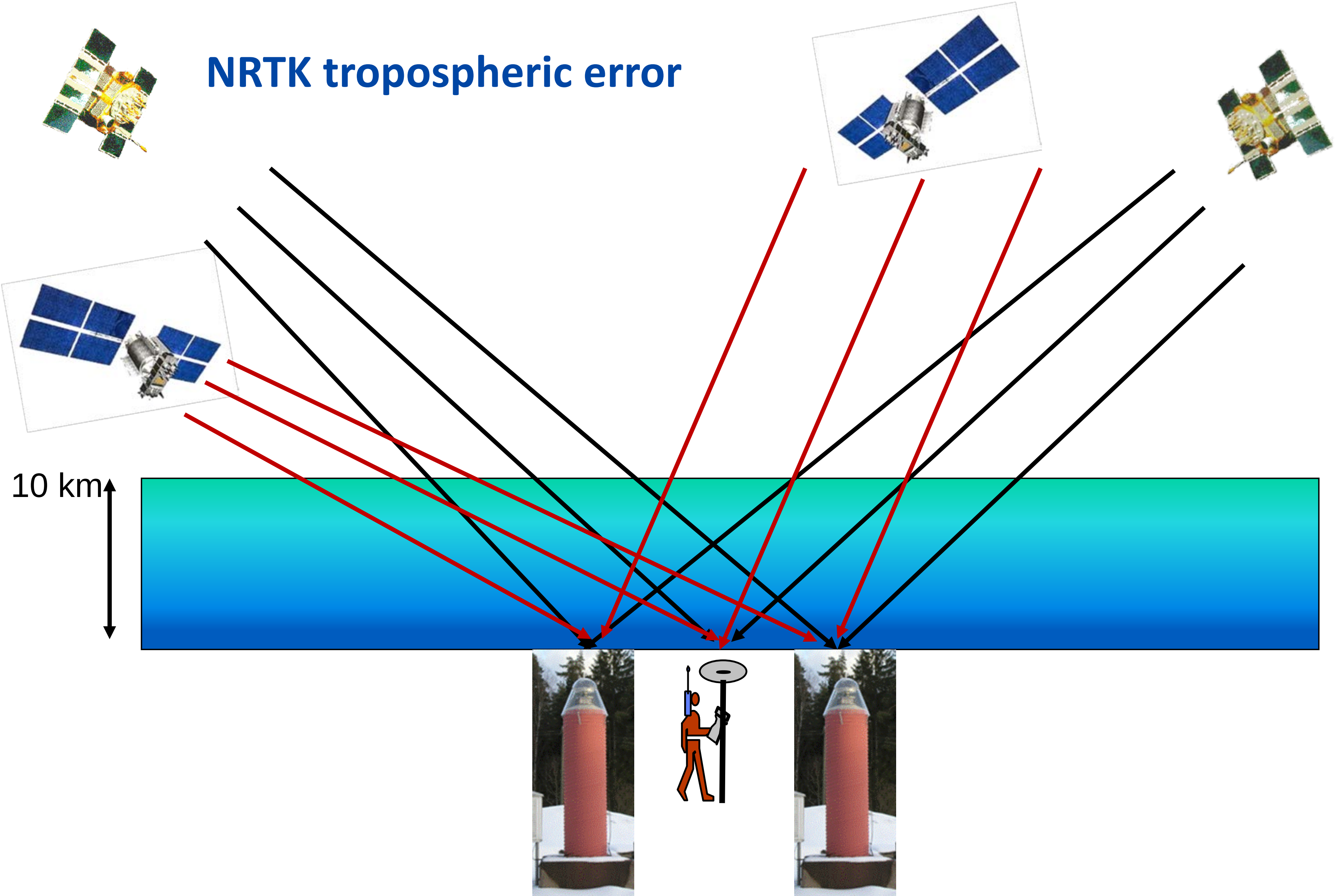
NRTK tropospheric error



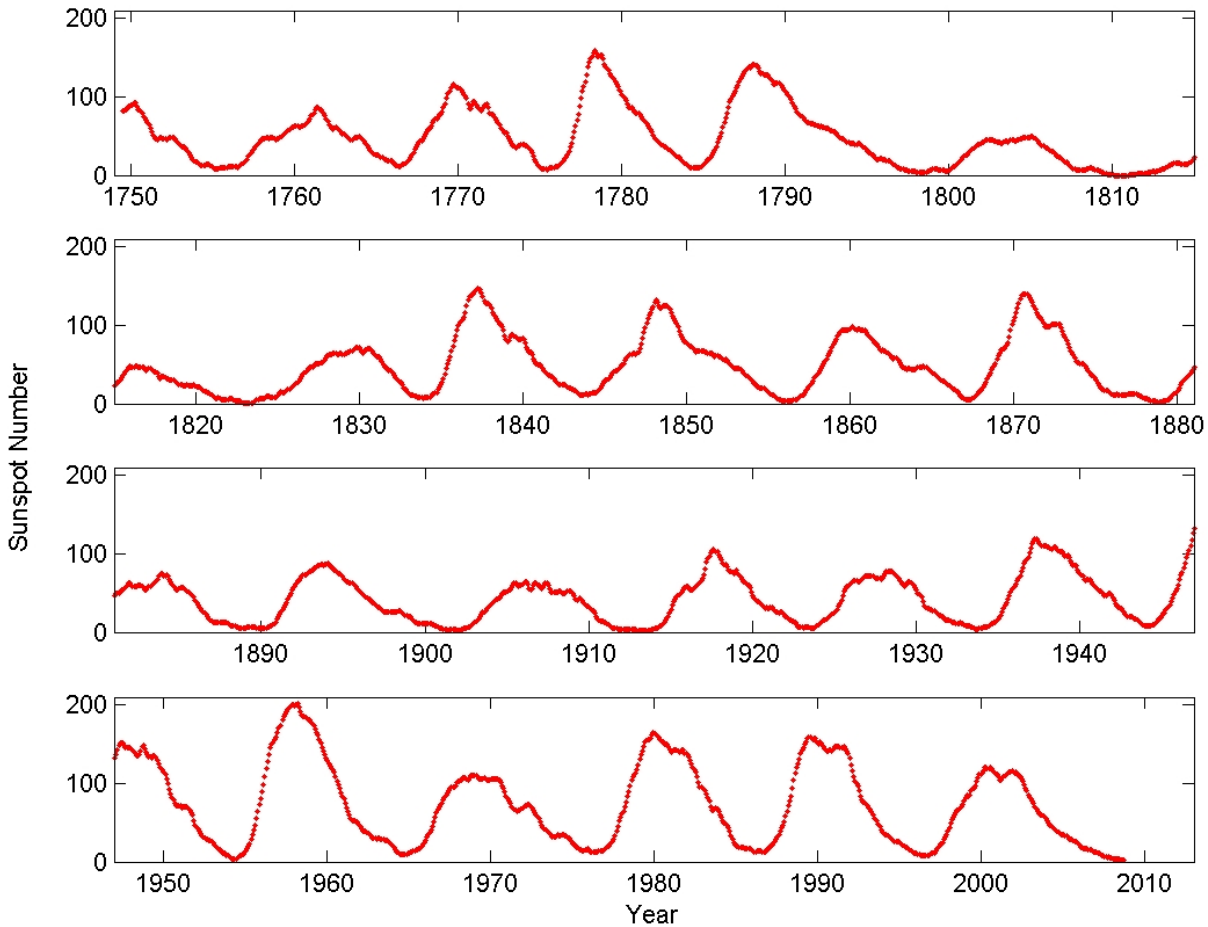
NRTK tropospheric error



NRTK tropospheric error

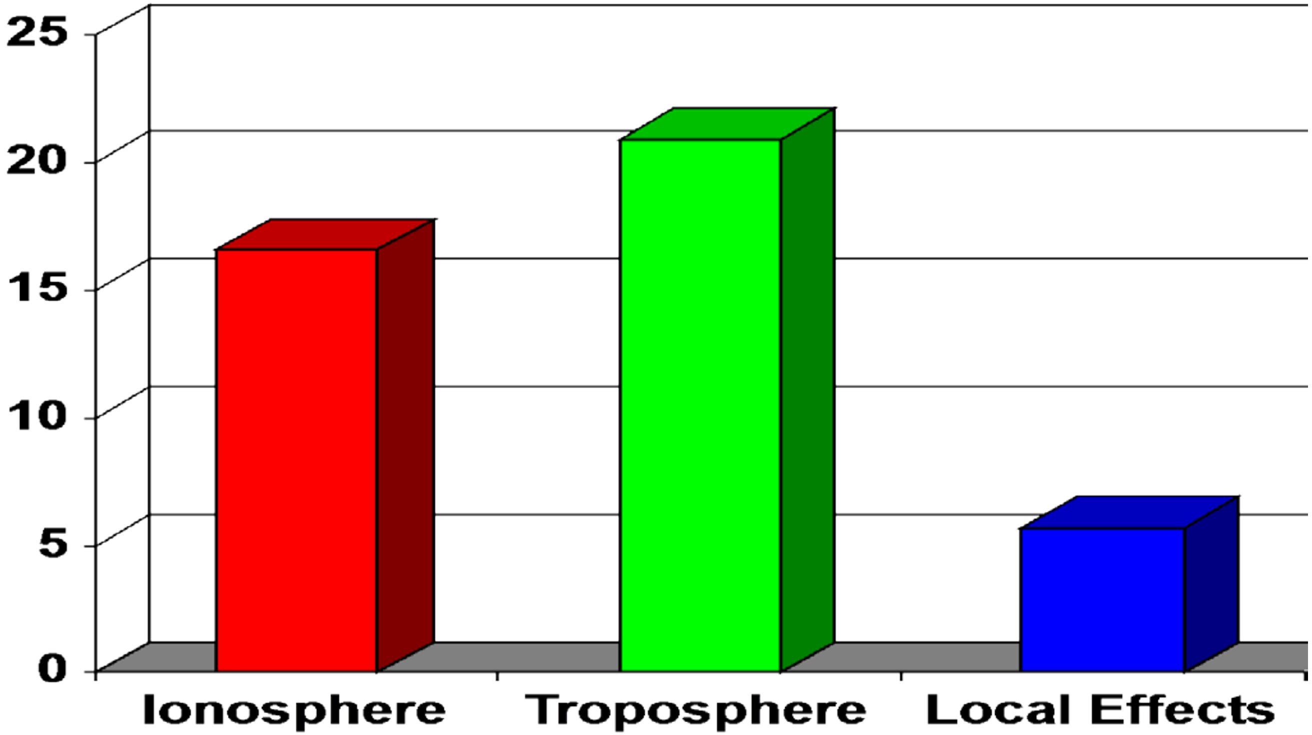


CLOSE-RTK 2
Ionosphere and the Solar cycle



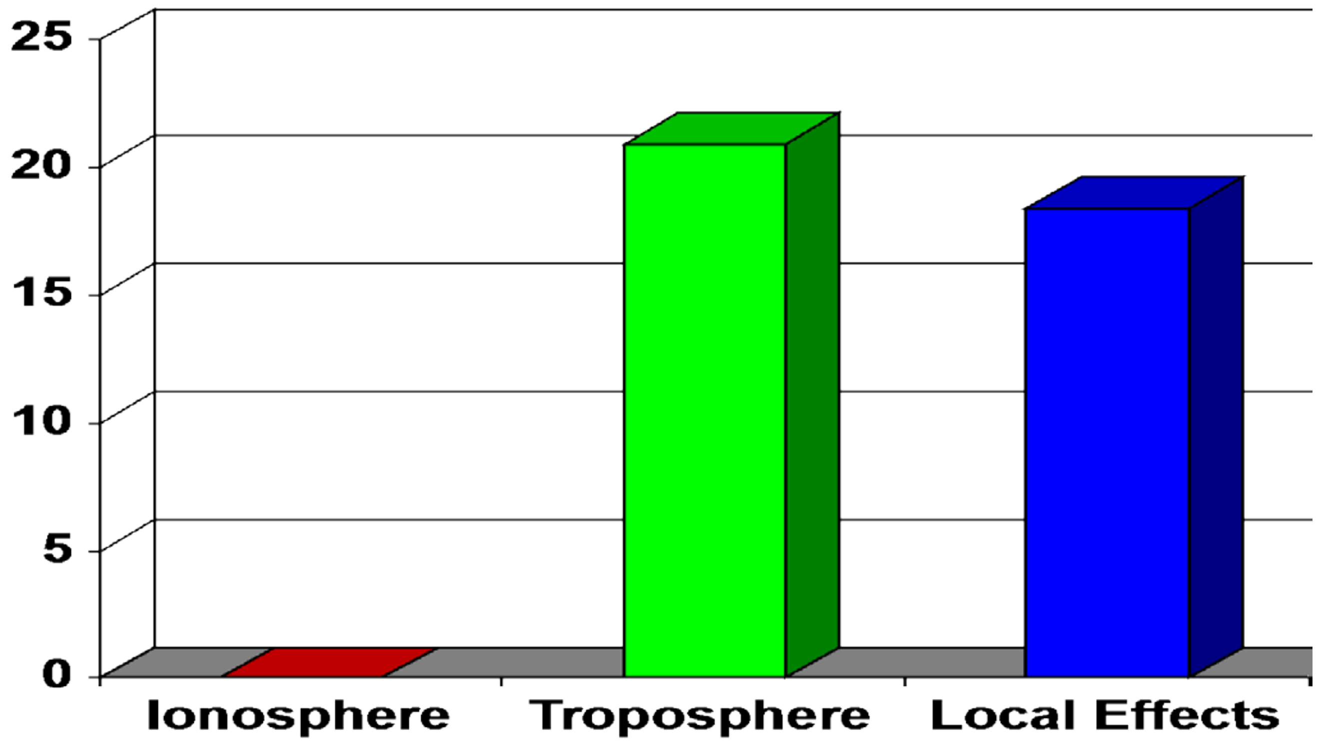
L1 - Processing

Total
27 mm

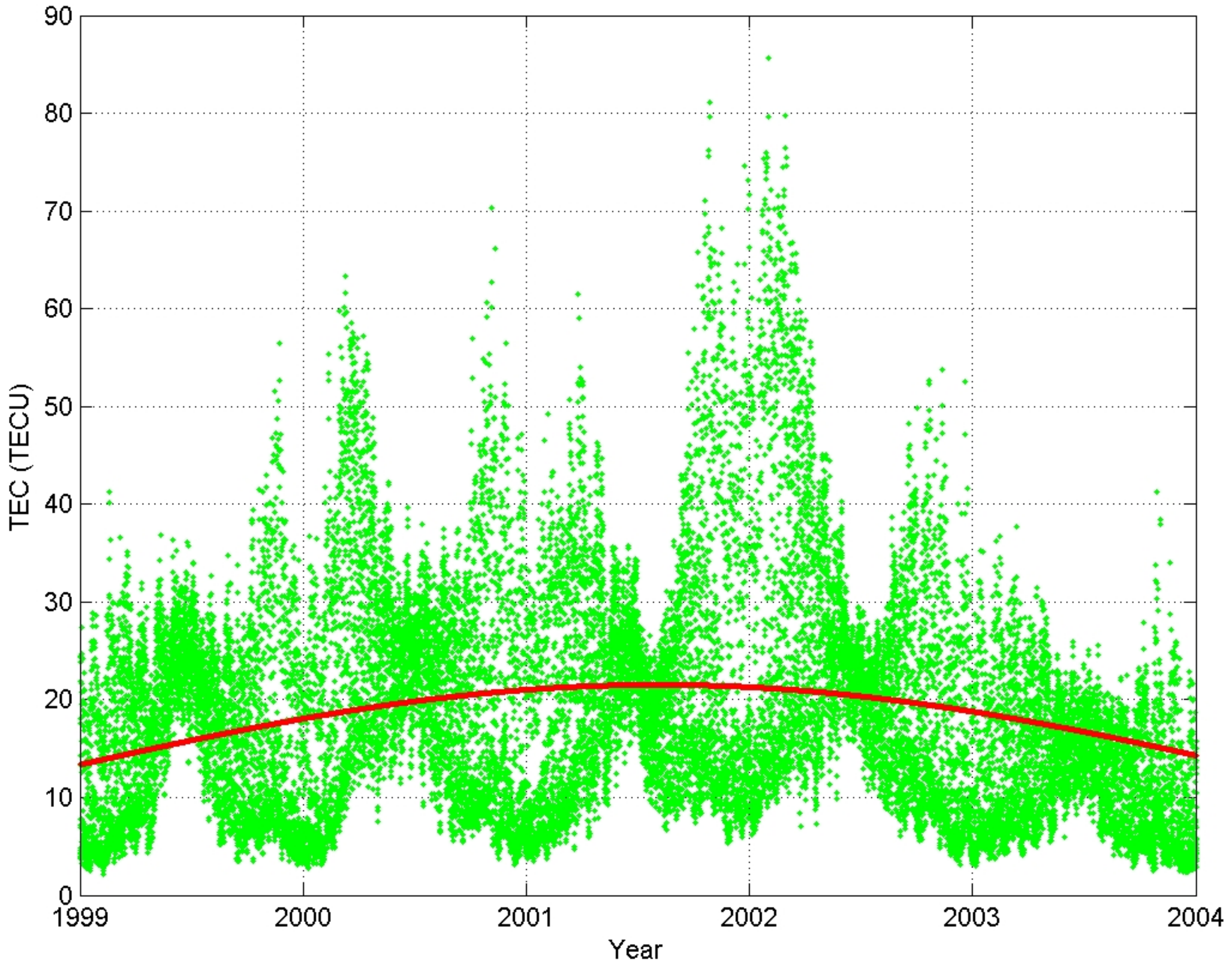


L3 - Processing

Total
28 mm

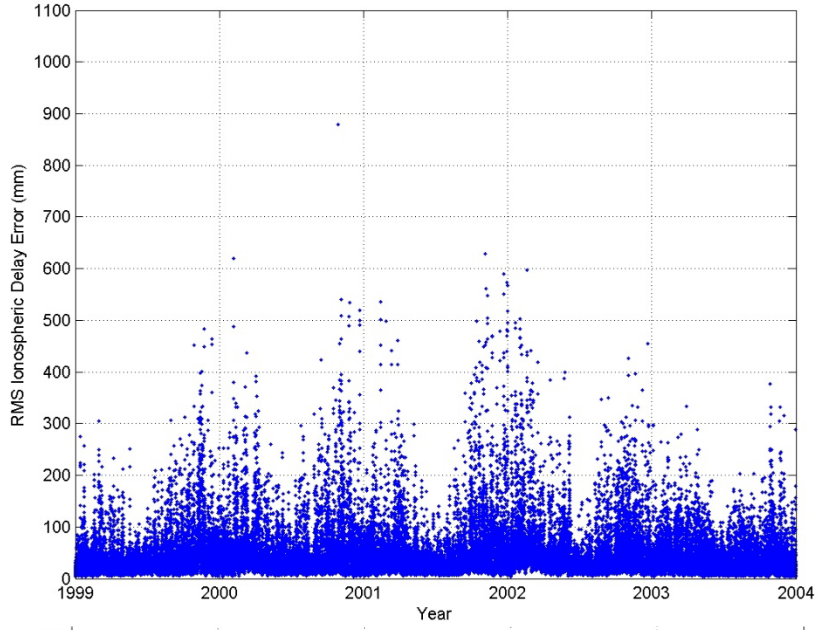


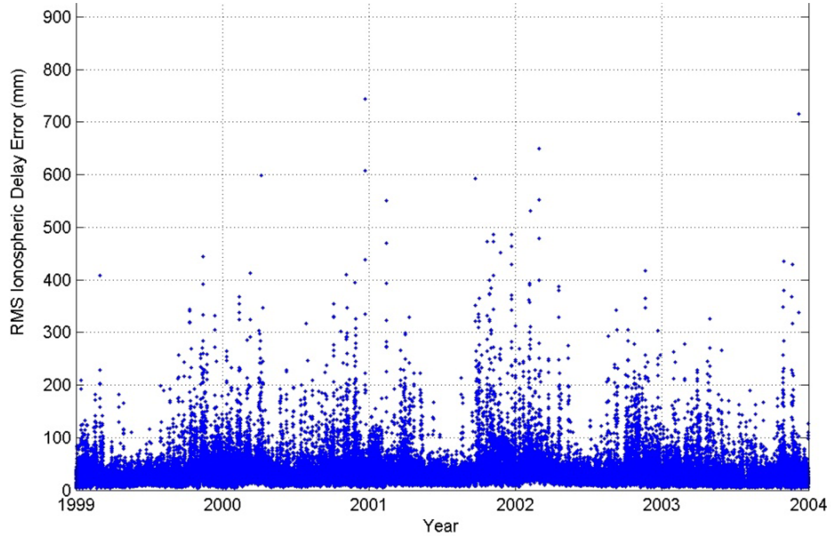
5 years



TEC (TECU)
Year
90
80
70
60
50
40
30
20
10
0
1999
2000
2001
2002
2003
2004

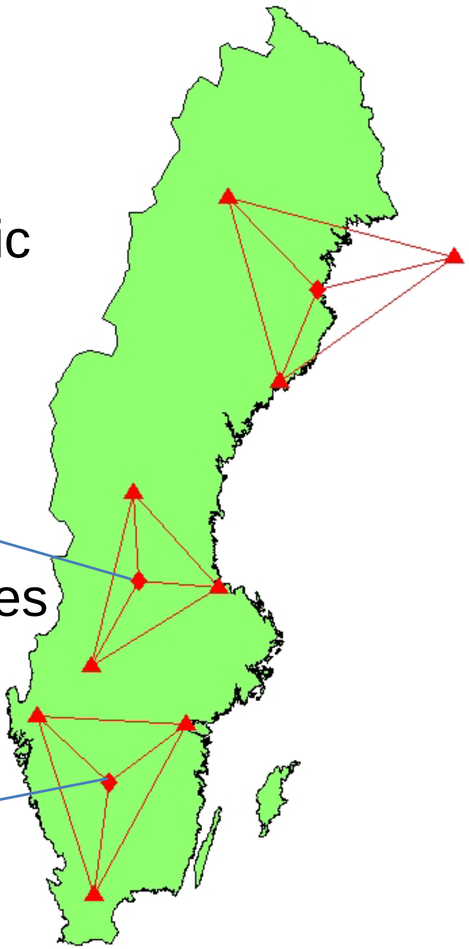
Interpolation



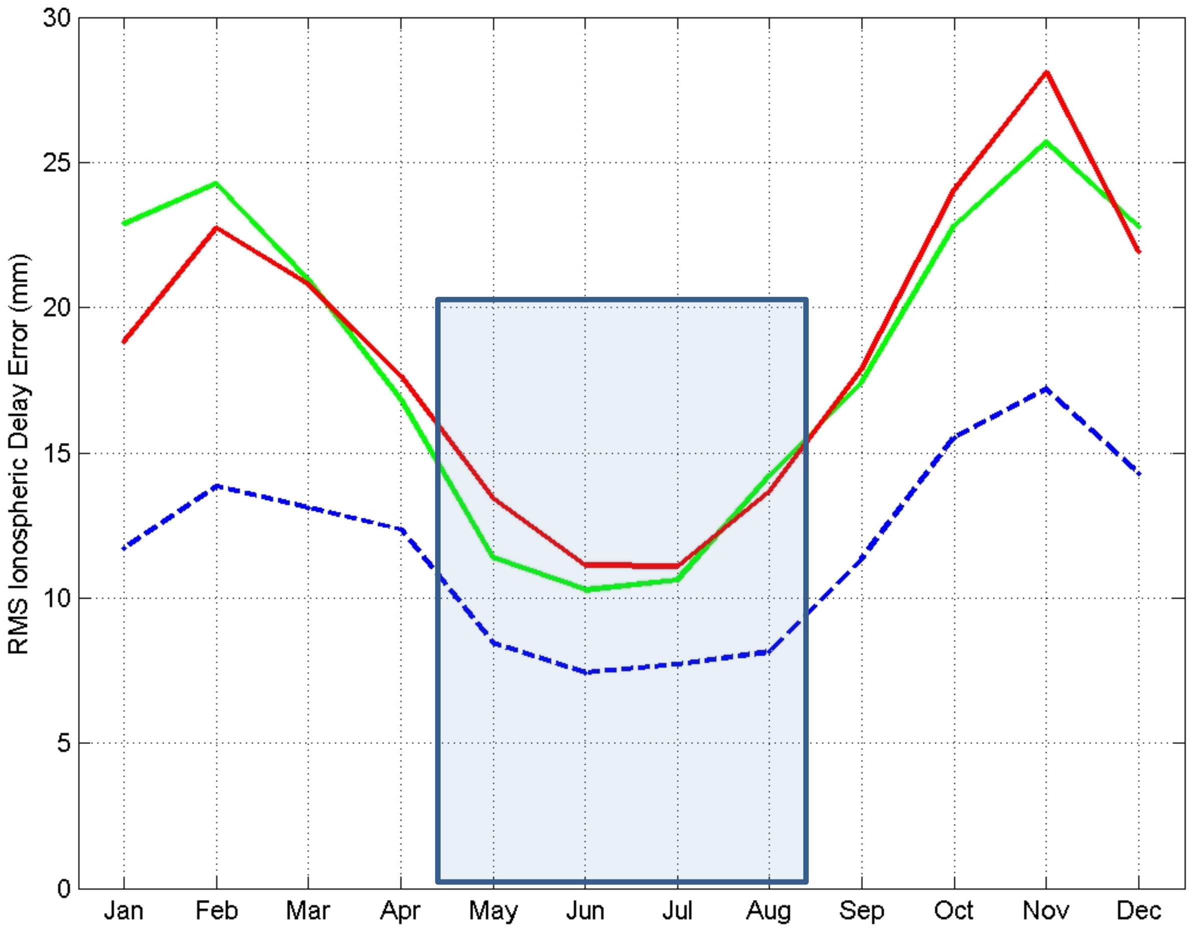


Zenith errors in the interpolated Ionospheric corrections.

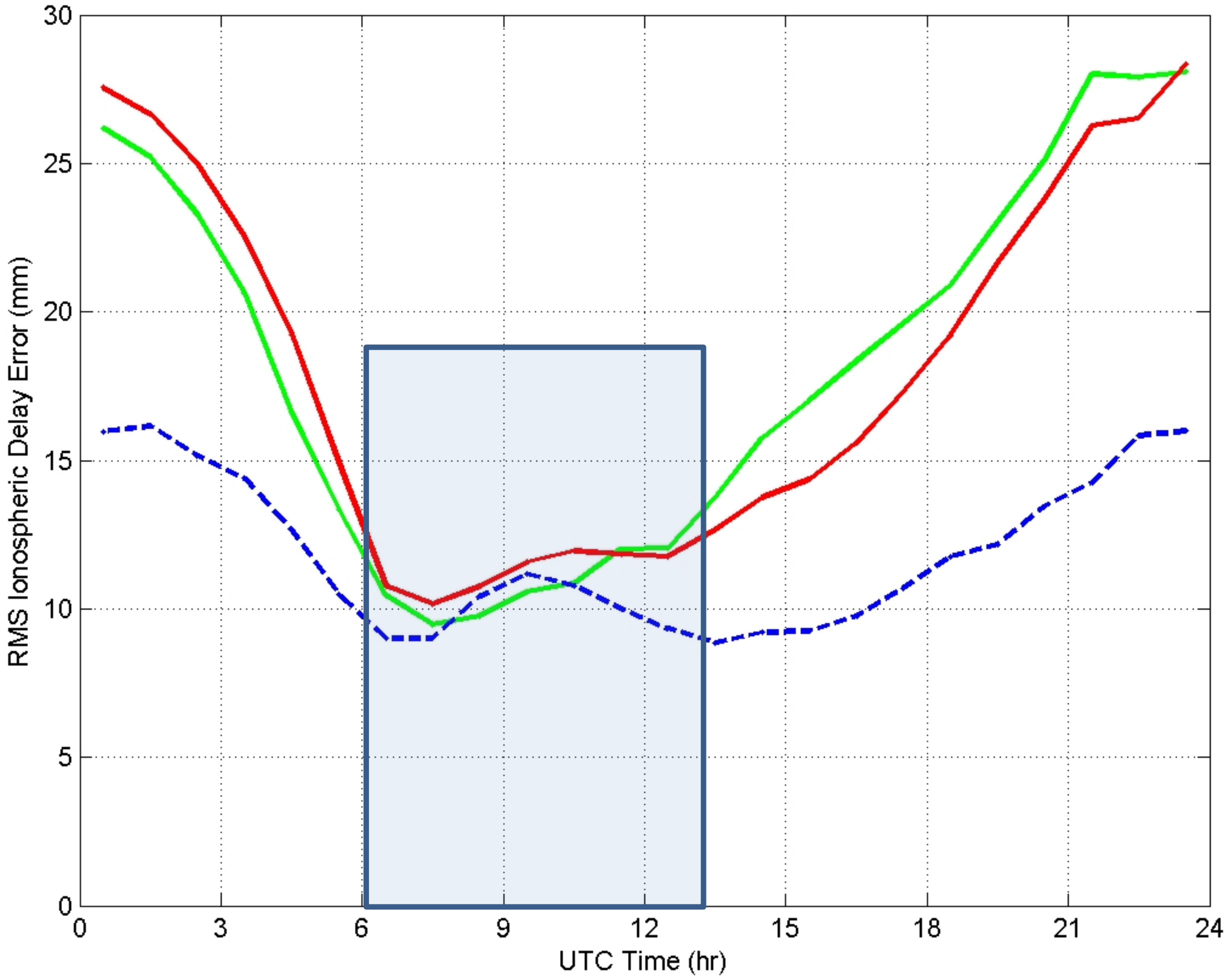
Plots show hourly values



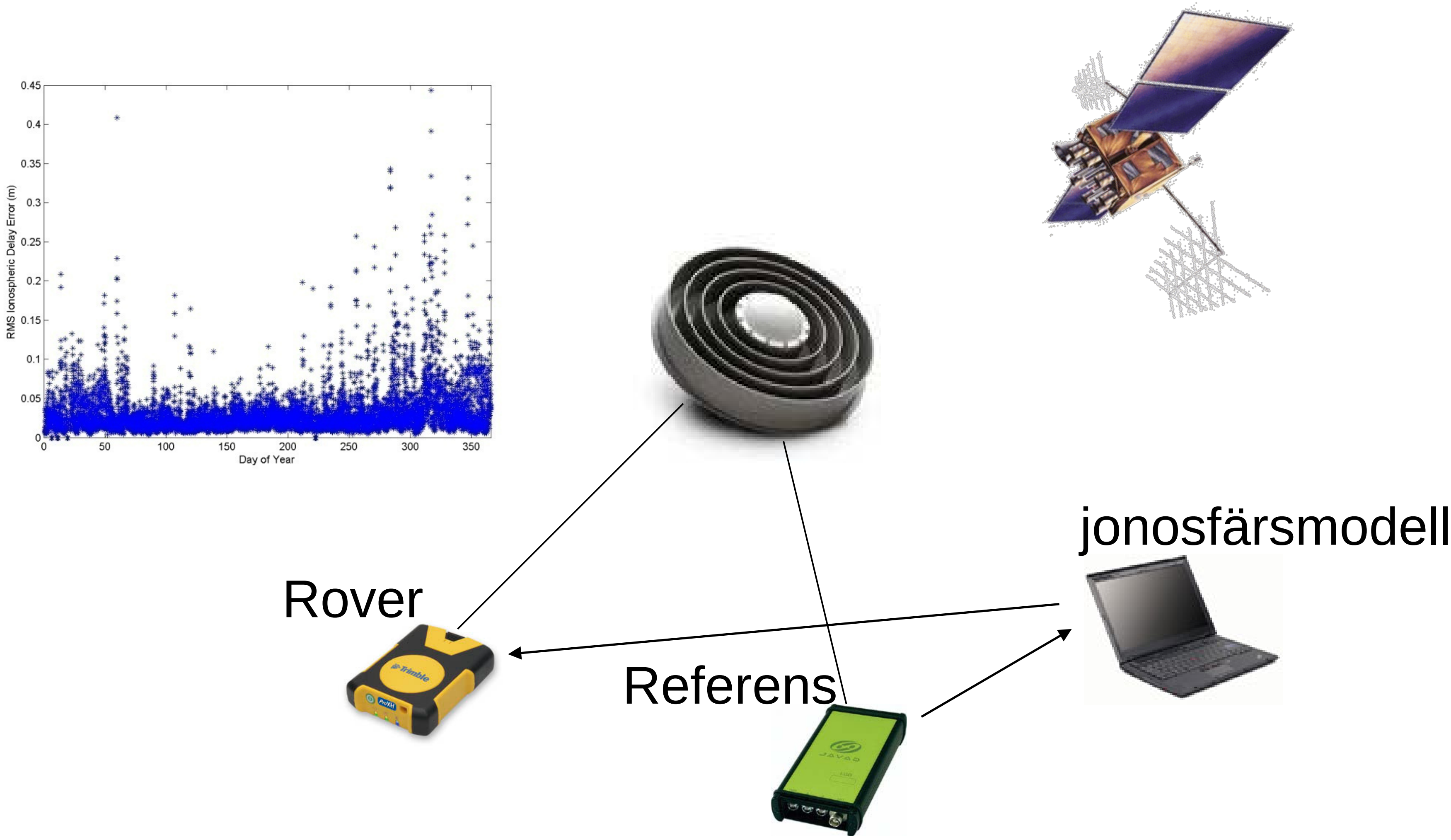
Ionospheric Delay Error- Annual signatures



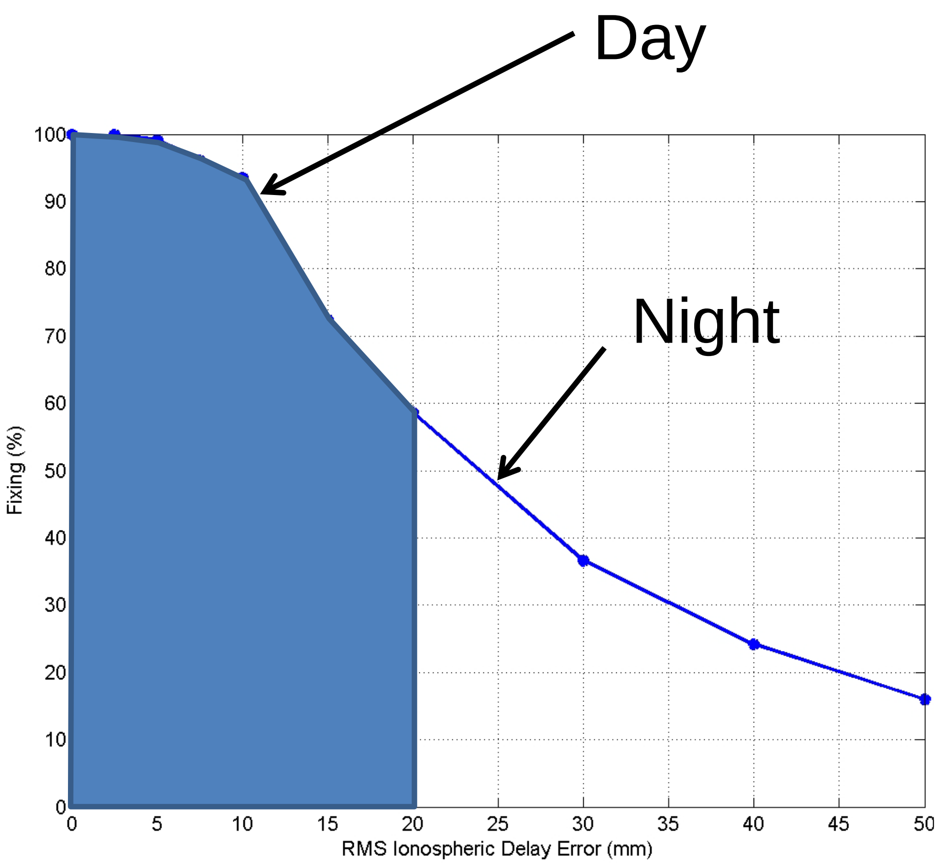
Ionospheric Delay Error-Daily signatures

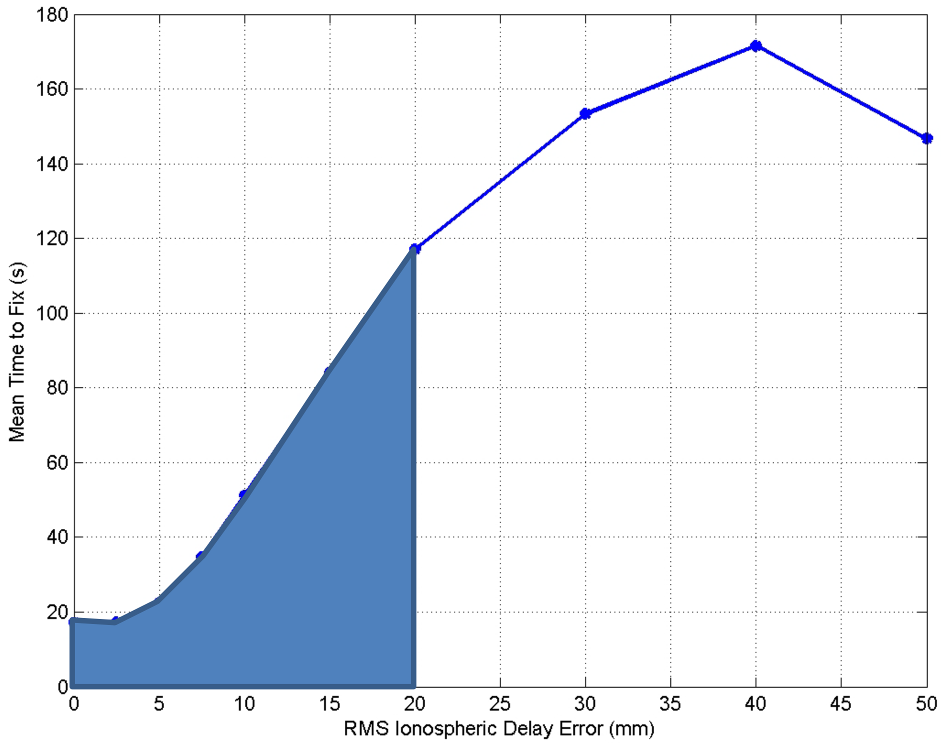


Studying the ambiguity fixing at the rover



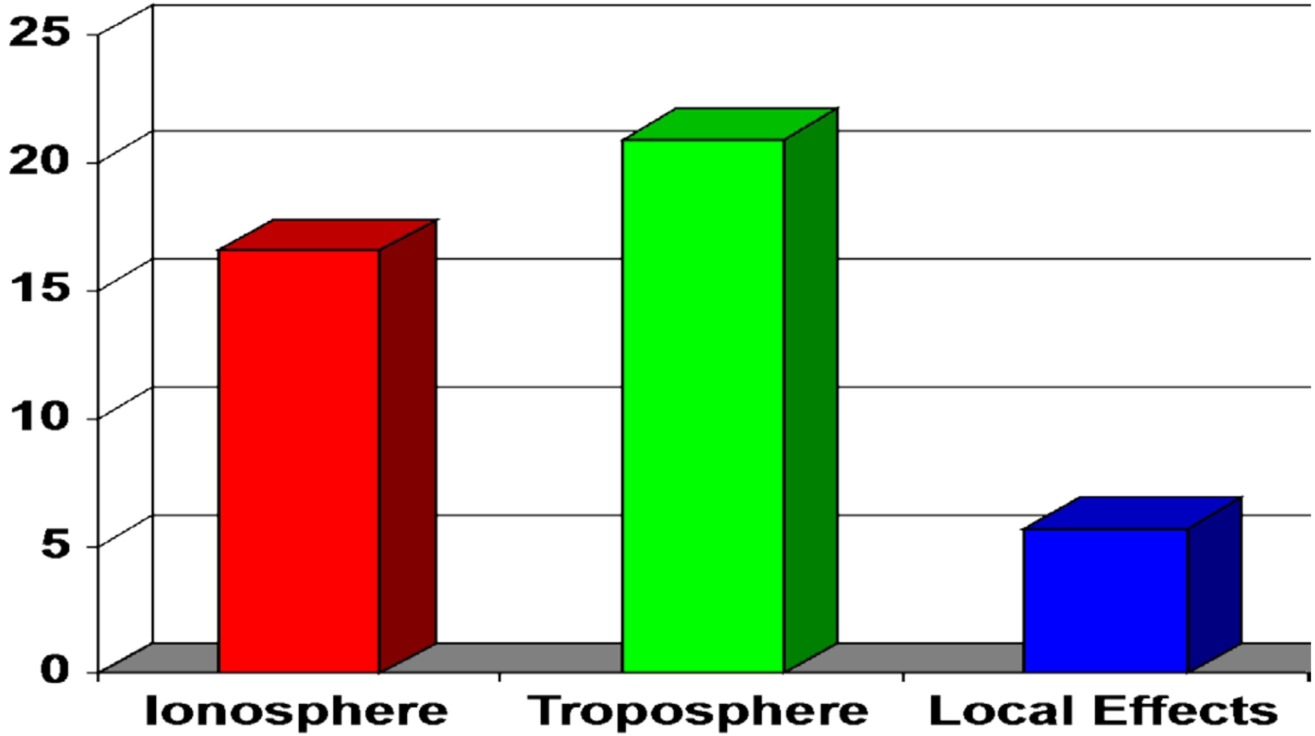
Javad – RTCM2


Day
Night
Fixing (%)
RMS Ionospheric Delay Error (mm)


Mean Time to Fix (s)
RMS Ionospheric Delay Error (mm)

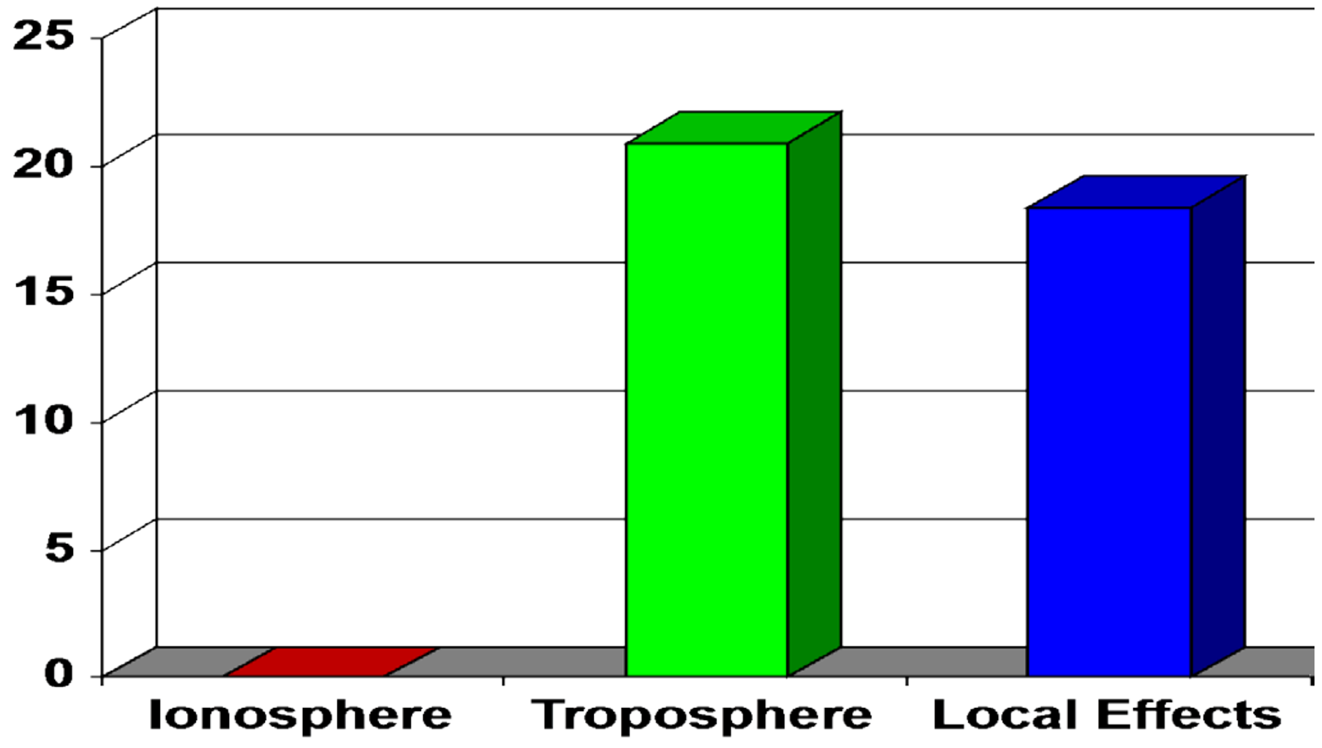
NRTK L1

Totalt
vertikalfel
27 mm



NRTK L3(L1+L2)

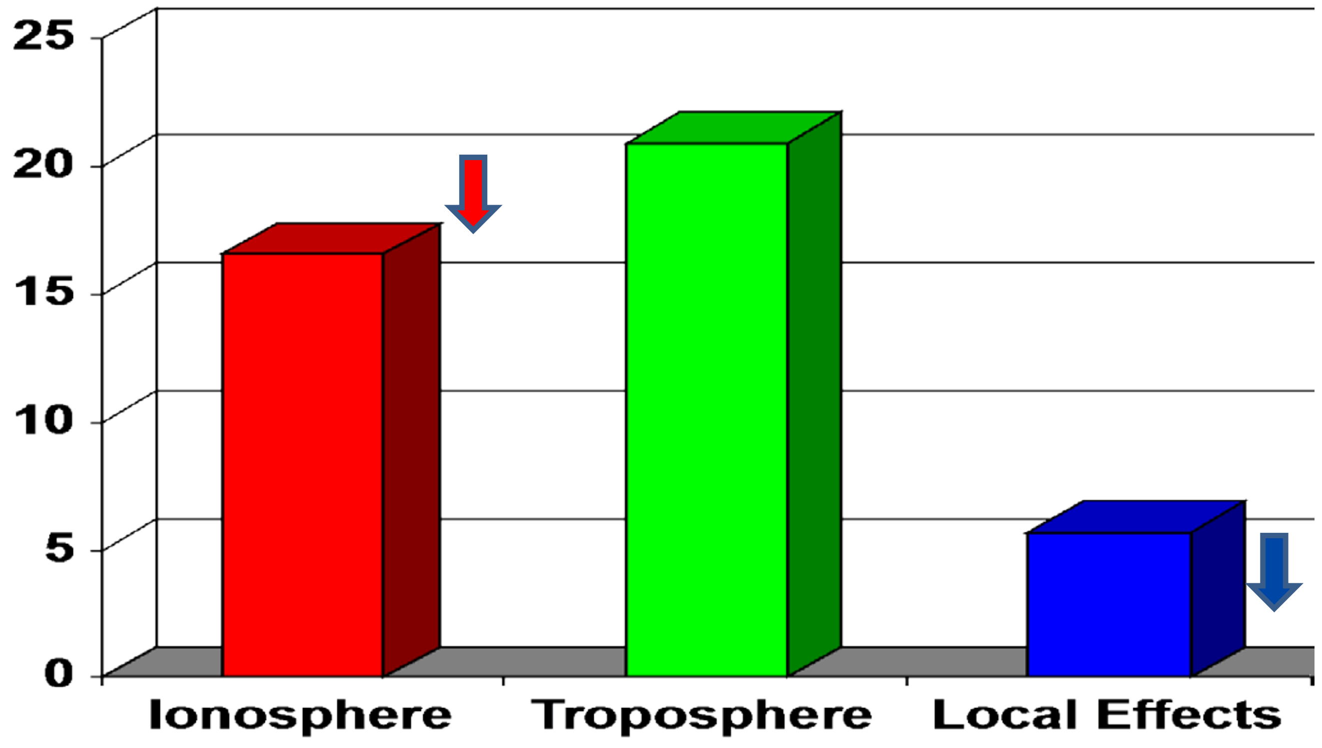
Totalt vertikalfel 28 mm



$L_3 = 2.546 * L_1 - 1.546 * L_2$

NRTK L1+L2+L5

Totalt
vertikalfel
?? mm



Summary CLOSE 1 and 2

- **New GNSS** will decrease the vertical error from 26 mm to **19 mm**
- A more **dense** network (35 km) will decrease the vertical error from 26 mm to **19 mm**
- **A combination** of a more dense network and new GNSS will result in a vertical error of **14 mm**
- The Ionosphere will periodically be the dominating error source
- The use of the L3 linear combination eliminate (almost) the Ionospheric error but unfortunately at the expense of an increased sensitivity to local environment
- Spatial and temporal variations in the ionosphere will obstruct the ambiguity fixing
  - Probability for fix at “solar maximum” is about **85%**
  - Average time to fix is **55 seconds**.

CLOSE-RTK 3

1. Developing the ”perfect” GNSS site
2. Site-specific calibration
3. New SWEPOS services

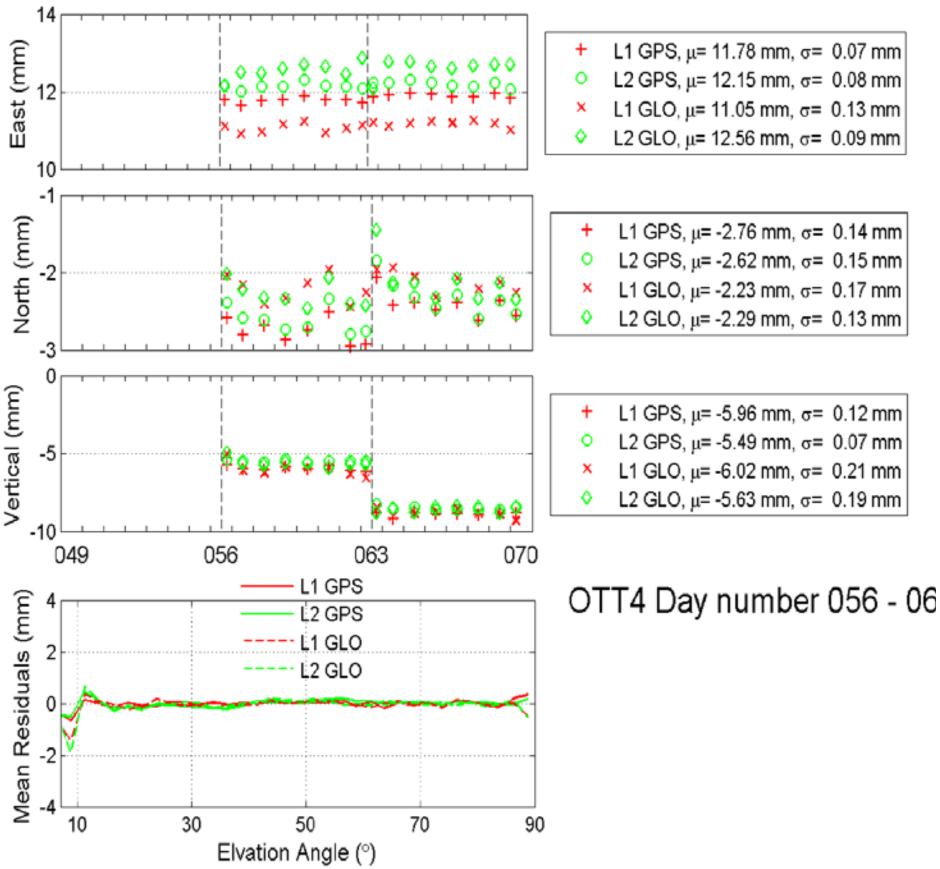
Nya GNSS-stationer vid Onsala Rymdobservatorium

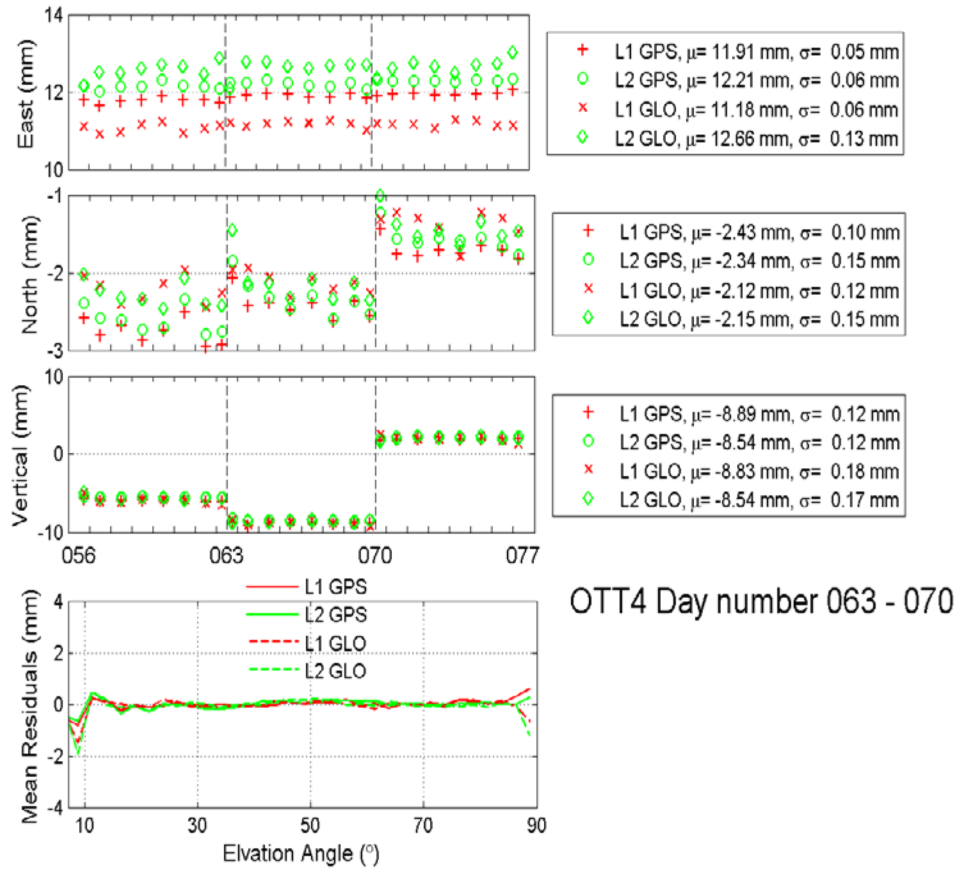
OTT-data analysis

- Changes at the stations OTT2 and OTT4
- OTT1 used as reference
- Analysis made using double-differencing between OTT1 and OTT2 as well as OTT1 and OTT4
- Using antenna-specific calibration values

Changes at OTT4

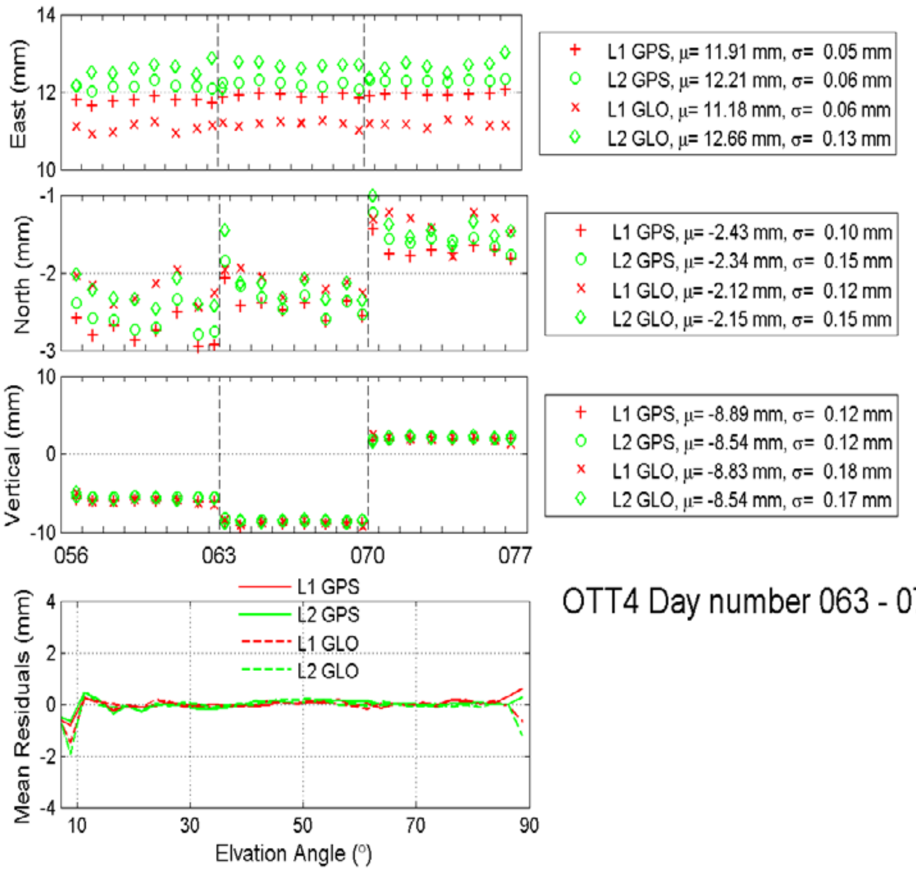
Changes at OTT4 =>
New station dependent effects



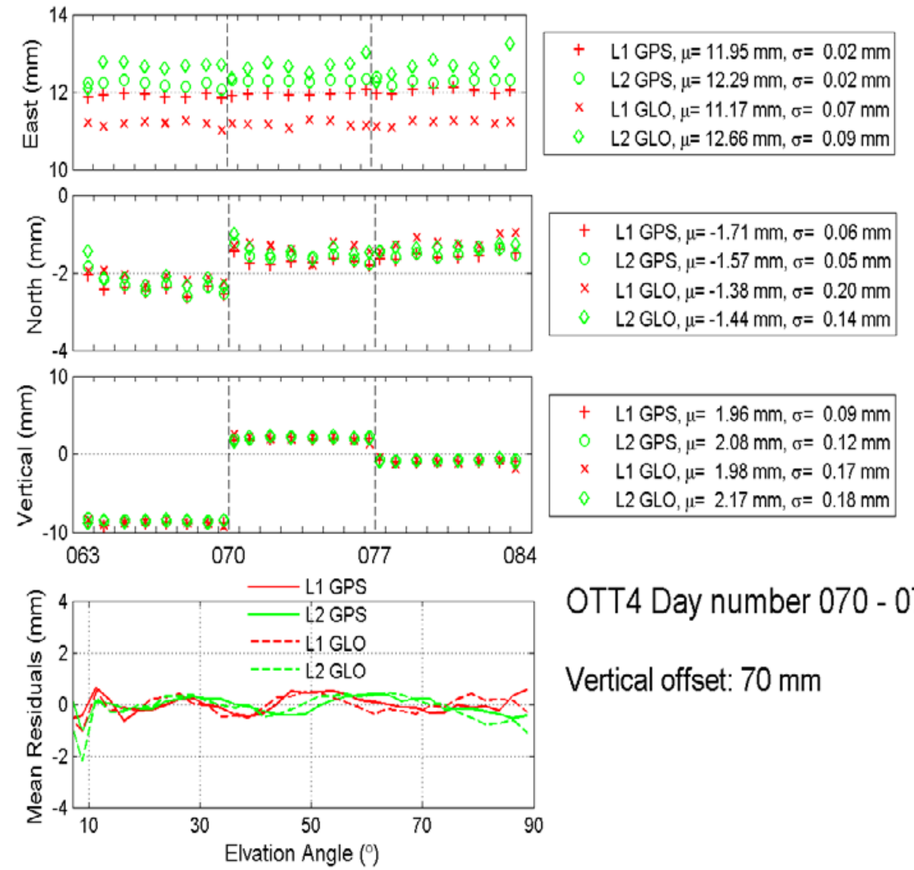


Double differencing with OTT1-OTT4 with OTT1 as reference and unchanged

Changes at OTT4 => New station dependent effects



OTT4 Day number 063 - 070



OTT4 Day number 070 - 077

Vertical offset: 70 mm

Double differencing with OTT1-OTT4 with OTT1 as reference and unchanged

Parameter estimation

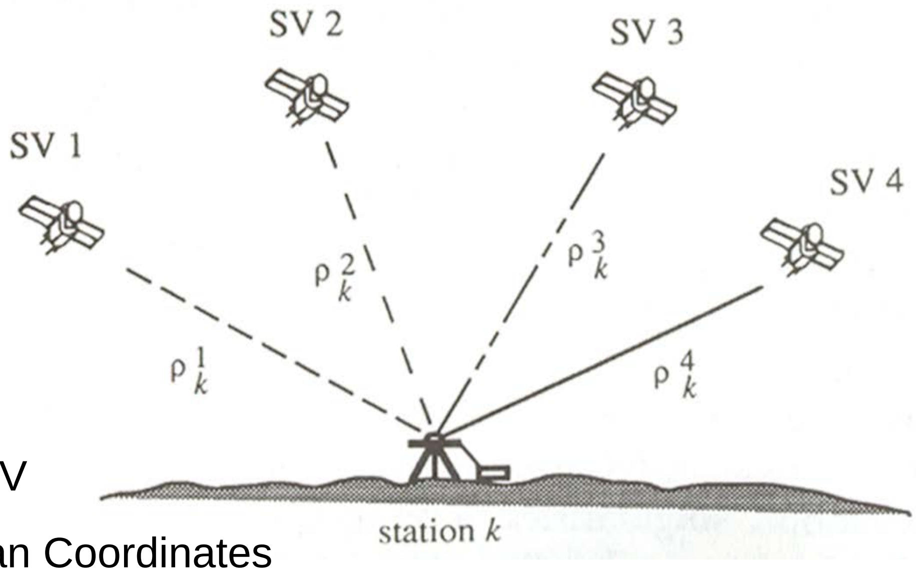
$$R = \rho + c_0\left(d\tau - dt\right) + d_{ion} + d_{trop} + v_R$$

$$\rho_1 = \sqrt{(X - X_1)^2 + (Y - Y_1)^2 + (Z - Z_1)^2}$$

$$\rho_2 = \sqrt{(X - X_2)^2 + (Y - Y_2)^2 + (Z - Z_2)^2}$$

$$\rho_3 = \sqrt{(X - X_3)^2 + (Y - Y_3)^2 + (Z - Z_3)^2}$$

$$\rho_4 = \sqrt{(X - X_4)^2 + (Y - Y_4)^2 + (Z - Z_4)^2}$$



Where:

P_i = Measured Pseudo Range to the i^th SV

X_i , Y_i , Z_i = Position of the i^th SV, Cartesian Coordinates

X , Y , Z = User position, Cartesian Coordinates, to be solved-for

Parameter estimation

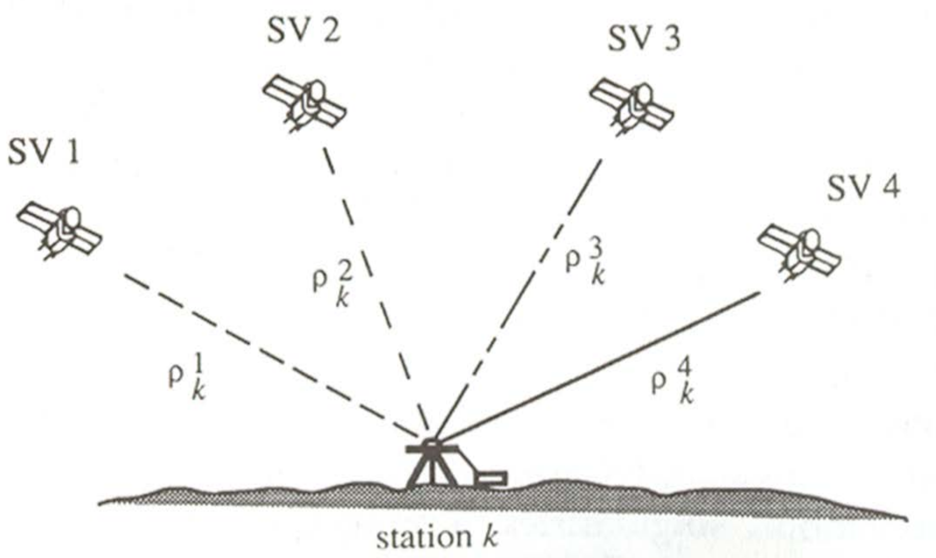
$$R = \rho + c_0\left(d\tau - dt\right) + d_{ion} + d_{trop} + v_R$$

$$z = Hx + v$$

$$z = R$$

$$x = \begin{bmatrix} r_e \\ r_n \\ r_v \\ d\tau \\ d_{trop} \end{bmatrix}$$

$$H = \delta z / \delta x$$

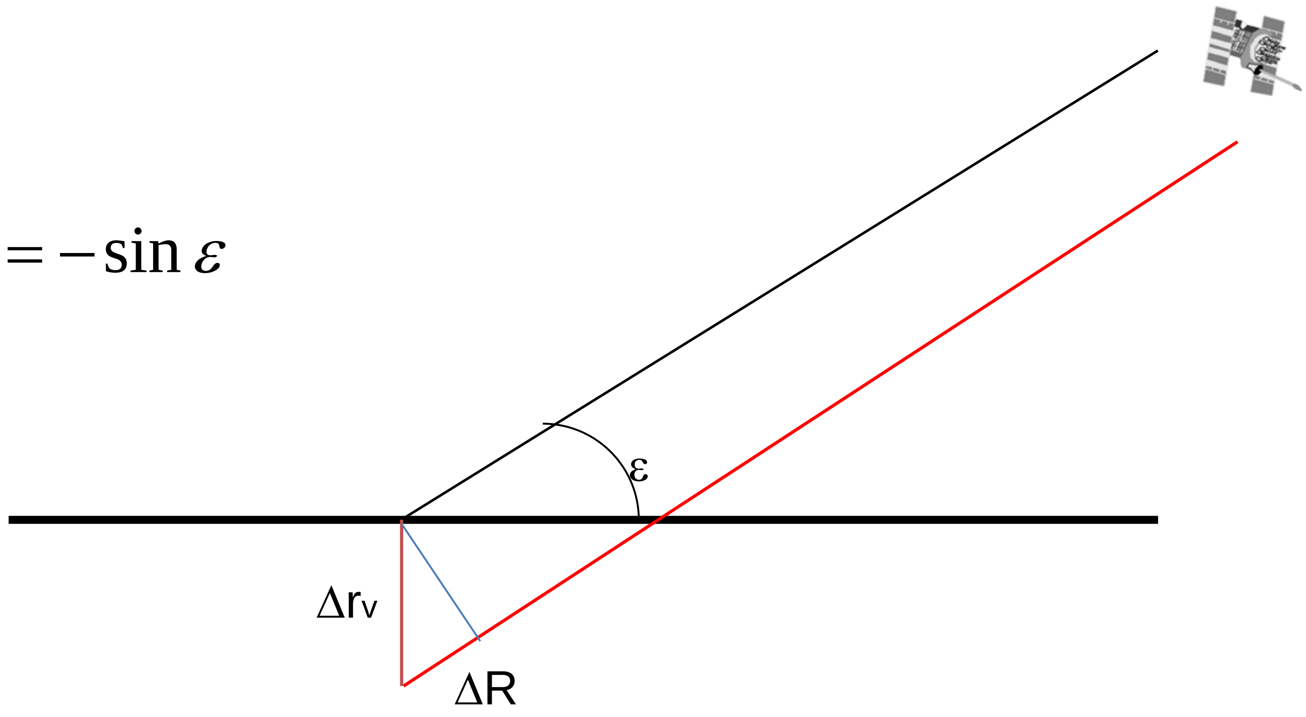


Partial Derivatives - vertical

$$H = \delta z / \delta x$$

$$H = \delta R / \delta r_v$$

$$H = \delta R / \delta r_v = -\sin \varepsilon$$

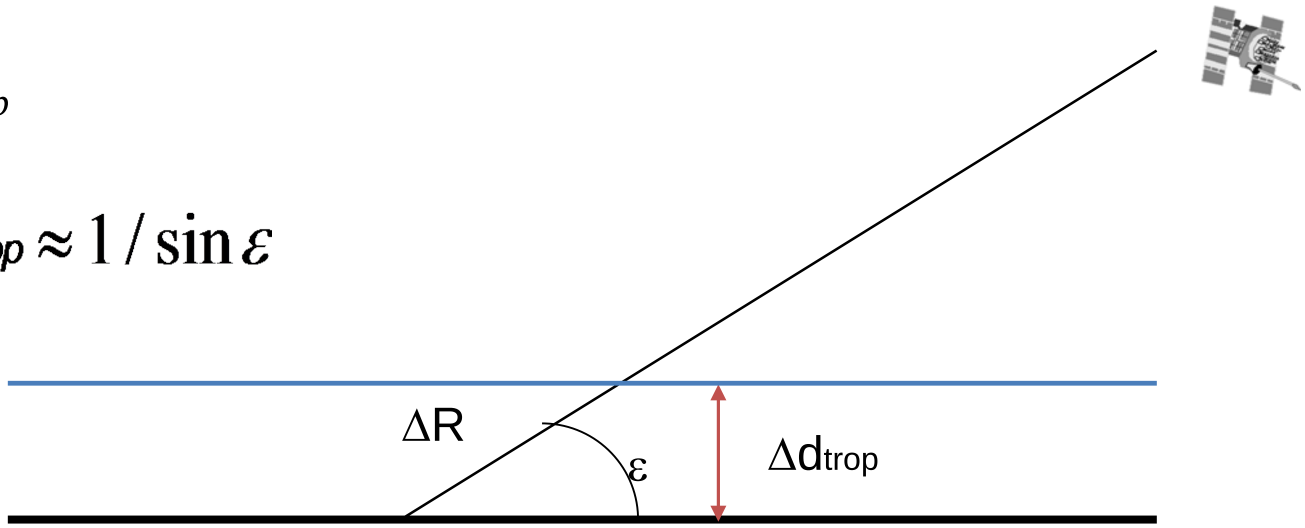


Partial Derivatives - troposphere

$$H = \delta z / \delta x$$

$$H = \delta R / \delta d_{trop}$$

$$H = \delta R / \delta d_{trop} \approx 1 / \sin \varepsilon$$



Parameter estimation

$$R = \rho + c_0 \left(d\tau - dt \right) + d_{ion} + d_{trop} + v_R$$

$$z = Hx + v$$

$$x = \begin{bmatrix} r_e \\ r_n \\ r_v \\ d\tau \\ d_{trop} \end{bmatrix}$$

$$H = \delta R / \delta r_v = -\sin \varepsilon$$

$$H = \begin{matrix} -\sin(az)\cdot\cos(\varepsilon) & -\cos(az)\cdot\cos(\varepsilon) & -\sin(\varepsilon) & 1 & 1/\sin(\varepsilon) \\ \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet \end{matrix}$$

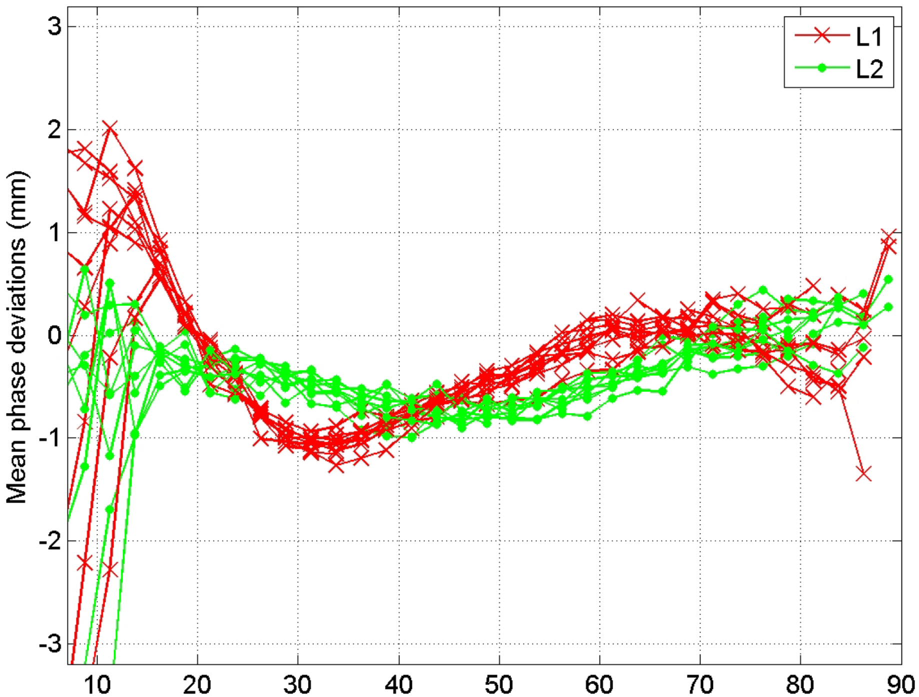
Least squares

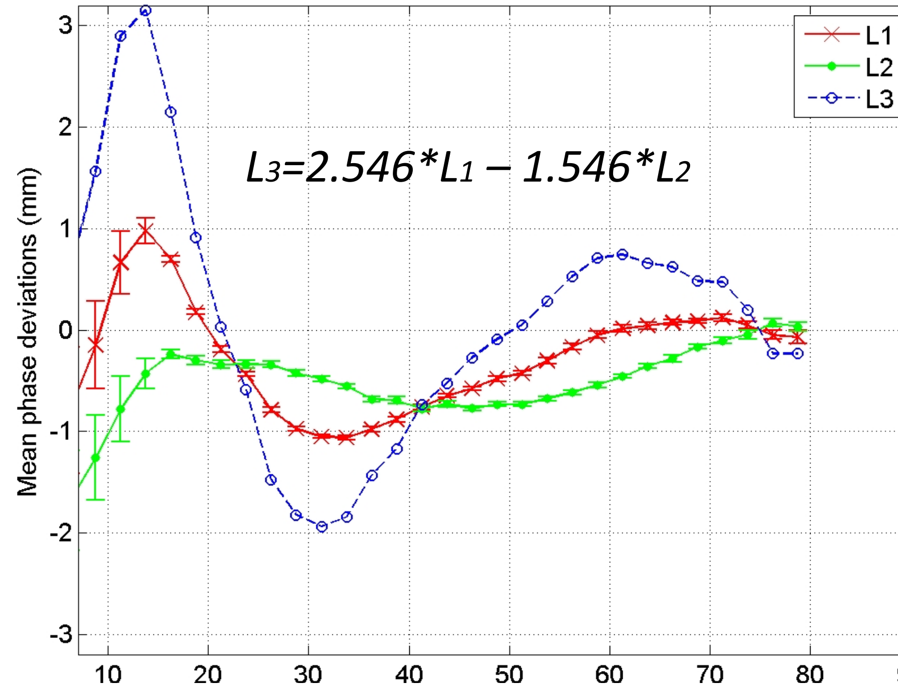
$$z = Hx + v$$

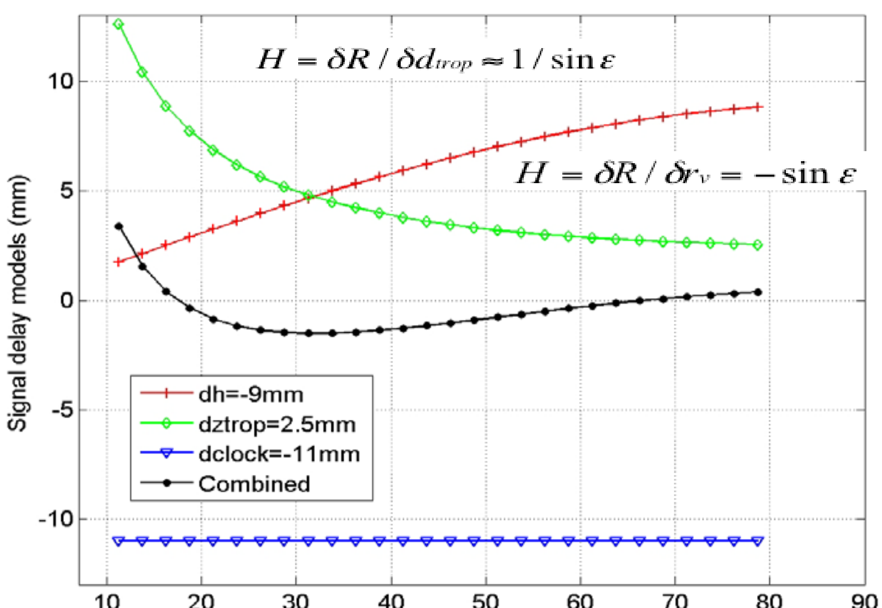
$$\hat{x} = \left(H^T H\right)^{-1} H^T z$$

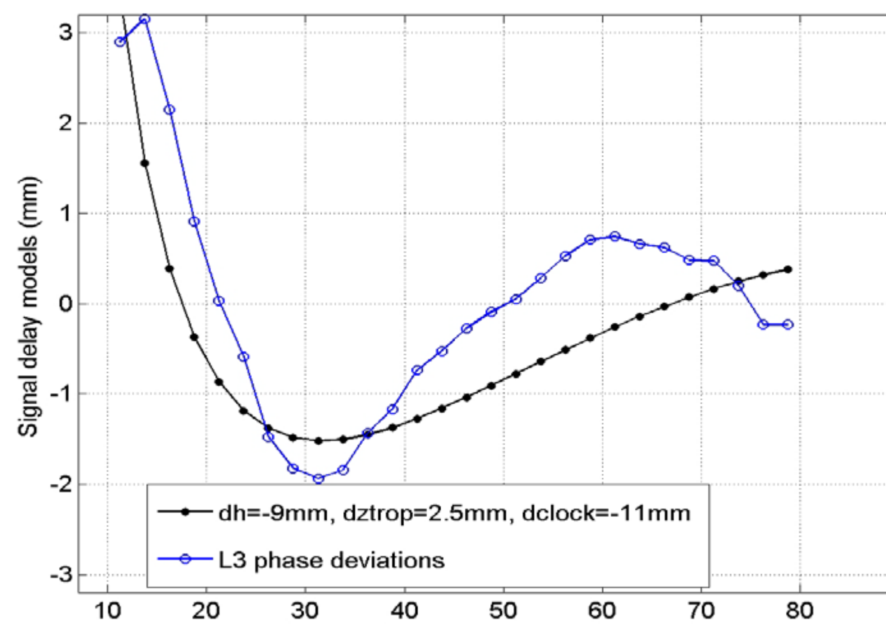
$$R = Cov\left(z\right)$$

$$\hat{x} = \left(H^T R^{-1} H\right)^{-1} H^T R^{-1} z$$


Mean phase deviations (mm)
L1
L2
3
2
1
0
-1
-2
-3
10
20
30
40
50
60
70
80
90

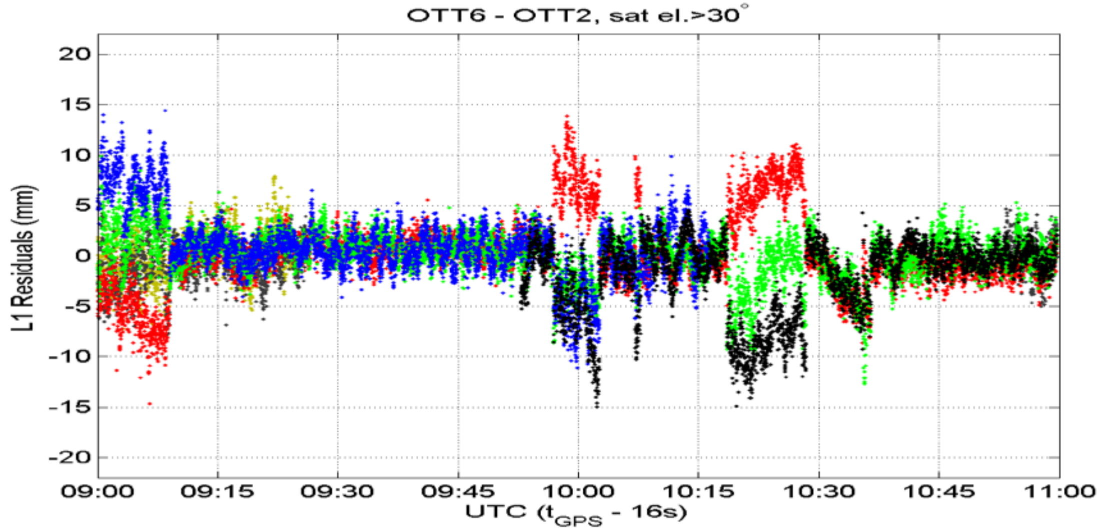

Mean phase deviations (mm)
L1
L2
L3
L3=2.546*L1 – 1.546*L2
3
2
1
0
-1
-2
-3
10
20
30
40
50
60
70
80

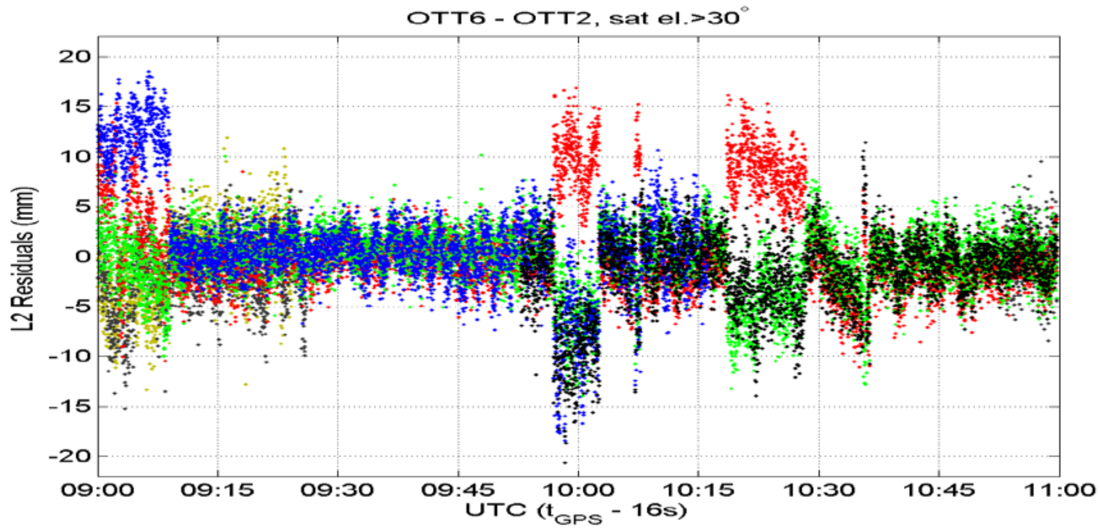

Signal delay models (mm)
$H = \delta R / \delta d_{trop} \approx 1 / \sin \varepsilon$
$H = \delta R / \delta r_v = -\sin \varepsilon$
dh=-9mm
dztrop=2.5mm
dclock=-11mm
Combined
10
5
0
-5
-10
10
20
30
40
50
60
70
80
90


Signal delay models (mm)
dh=-9mm, dztrop=2.5mm, dclock=-11mm
L3 phase deviations
3
2
1
0
-1
-2
-3
10
20
30
40
50
60
70
80

$$R = \rho + c_0\left(d\tau - dt\right) + d_{ion} + d_{trop} + d_{bird} + v_R$$

Bird visiting OTT6 (OTT2 reference)





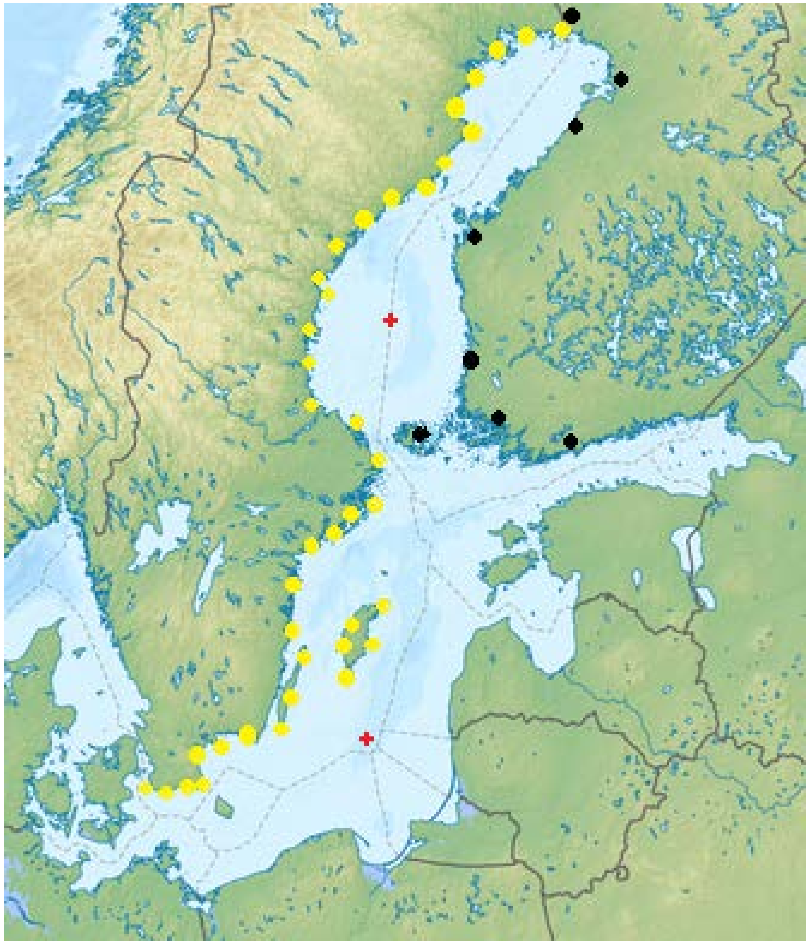
Baseline from 3 hour data when Galileo constellation is good

Baseline	East (m)	North (m)	Up (m)
	-28.9057	44.4554	-0.5079

+

Signal	East (mm)	North (mm)	Up (mm)
GPS L1	-0.2	-0.2	0.2
GPS L2	-0.4	0.6	-0.7
GLONASS L1	-0.2	1.4	-0.1
GLONASS L2	-0.2	1.4	-0.1
Galileo E1	0.3	0.3	1.4
Galileo E5	0.0	-0.7	-0.6
Galileo E7	-0.4	0.4	-0.9

GNSS-services in the Baltic Sea



- SWEPOS and FinnRef
- New stations
- NRTK, PPP or PPP-RTK