The effect and use of Meteorological data in VLBI processing at GSFC

- Importance and strategy to improve and use the databases in CALC/Solve

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VLBI is aiming for 1 mm precision and 0.1 mm/yr stability for the ITRF

- NRC Decadal Survey (2007) goal
  - Required for global change investigation of effects like global sea level change (several mm/yr)

Contents

- The use of meteorological data in VLBI processing
- The effect of missing and bad meteorological data
- Sources of meteorological data
  - Sensordata
  - Modeldata
- Systematic Differences
  - Pressure
  - Temperature
- Changes in CALC/Solve

- At GSFC we use CALC/Solve to analyze VLBI data.
- CALC/Solve :
  - Set of programs that supports scheduling, operating, processing, archiving and analysis of geodetic VLBI experiments.
  - When analyzing it estimates targeted parameters, such as station positions and velocities.

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- Meteorological data (met data) used in CALC/Solve:

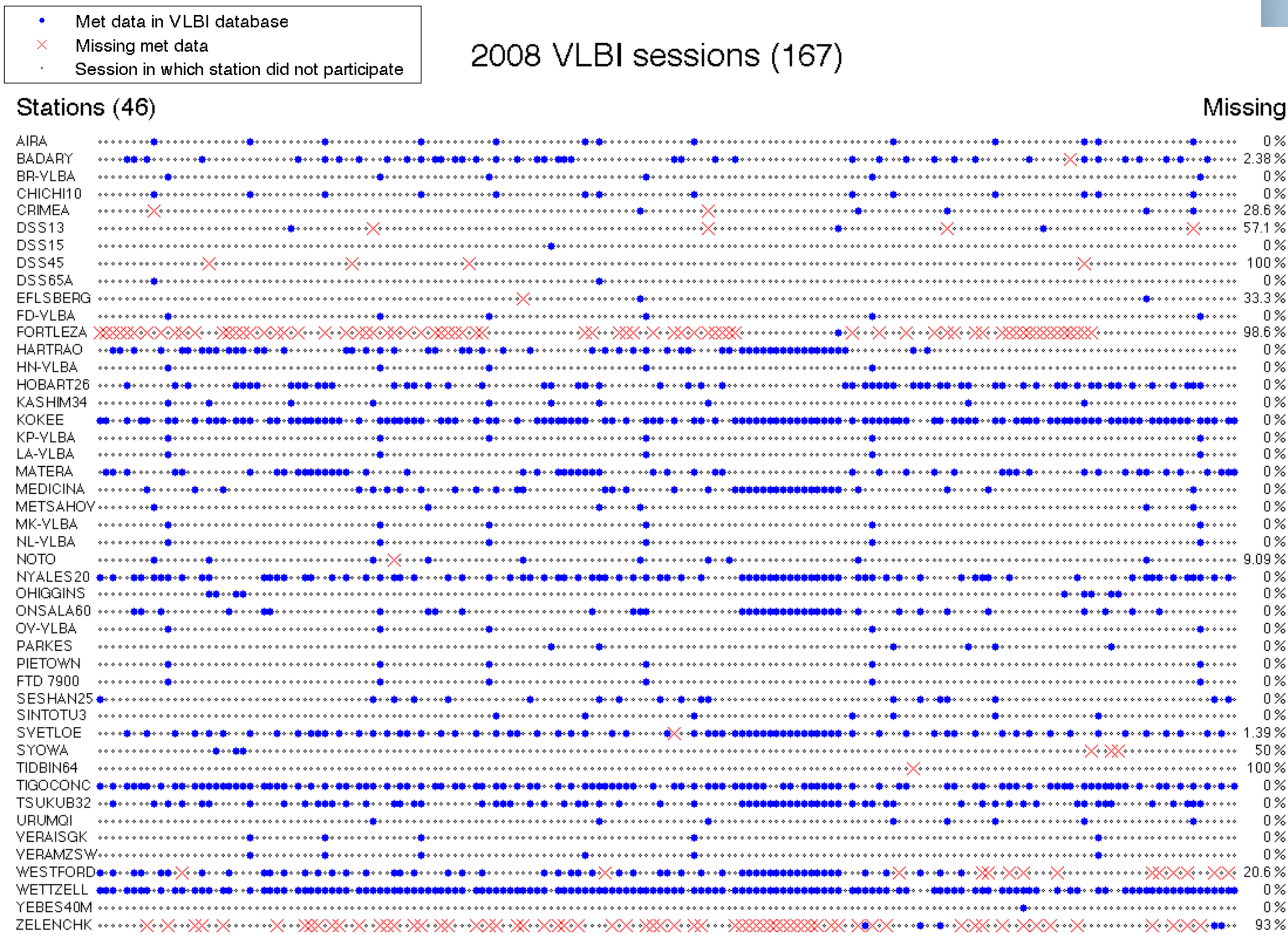
  - Pressure is used to calculate the zenith hydrostatic delay.

  - VLBI telescopes are deformed by time-dependent temperature effects. CALC/Solve uses a temperature mean to calculate the linear expansion of the telescope components.

⇒Met data affects the results of CALC/Solve and therefore the precision of VLBI calculations.

- CALC/Solve uses met data from a database, ideally these are observations by a met sensor on site.

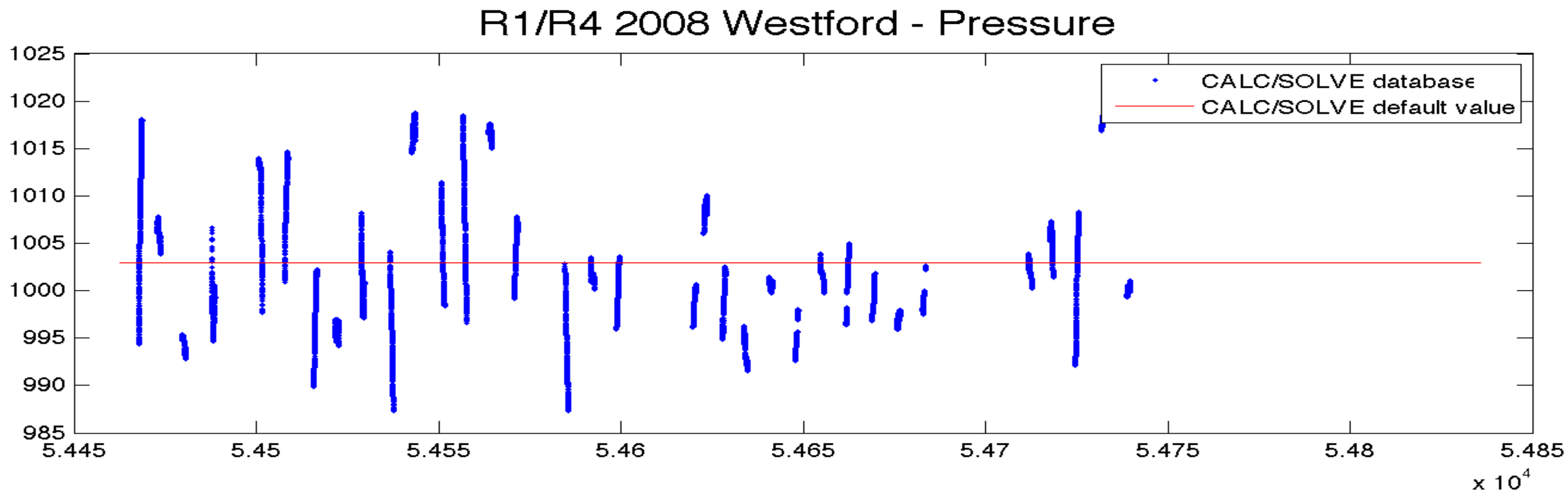
Missing meteorological data - Example

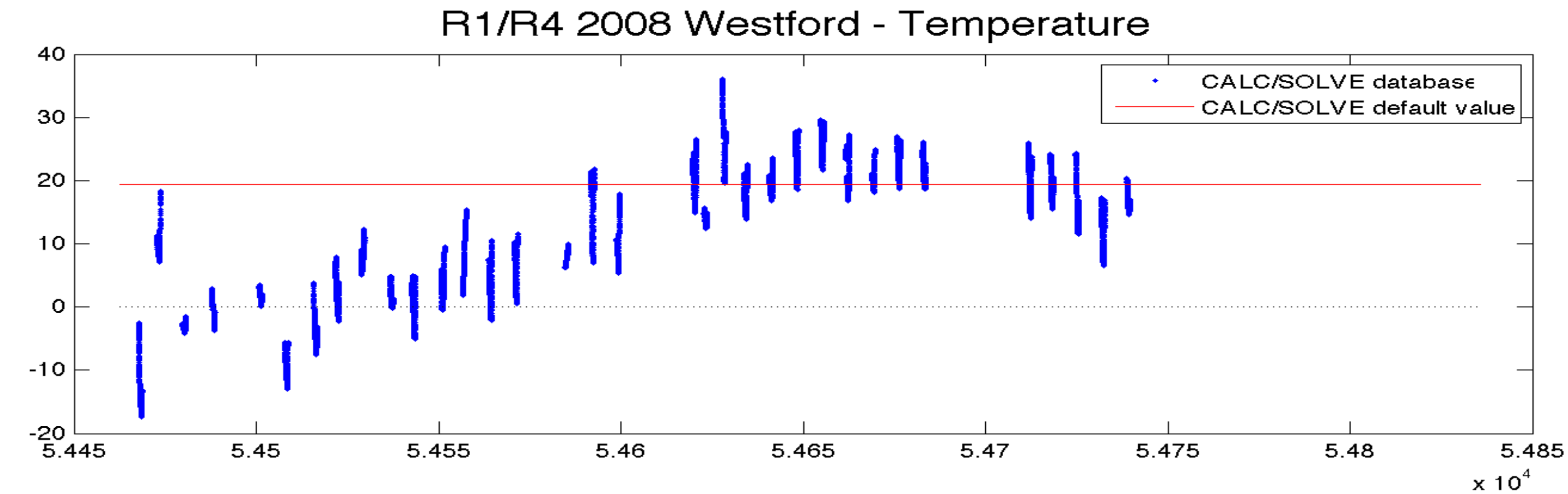


In 2008, ZELENCHUKSKAYA and FORTLEZA, two of the major stations of the VLBI network, are missing more than 90% of their data.

Missing meteorological data - Example

Contents of the database

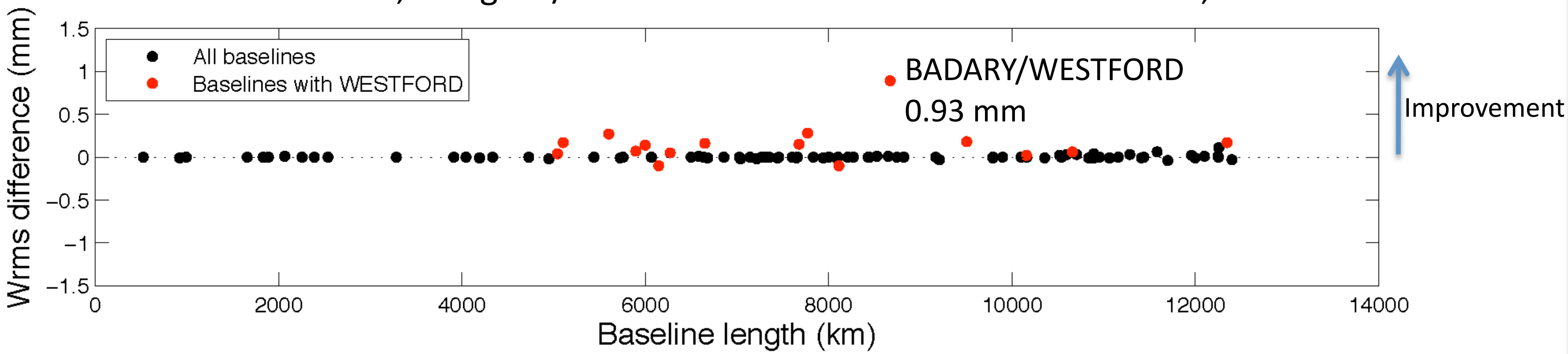




Missing meteorological data - Impact

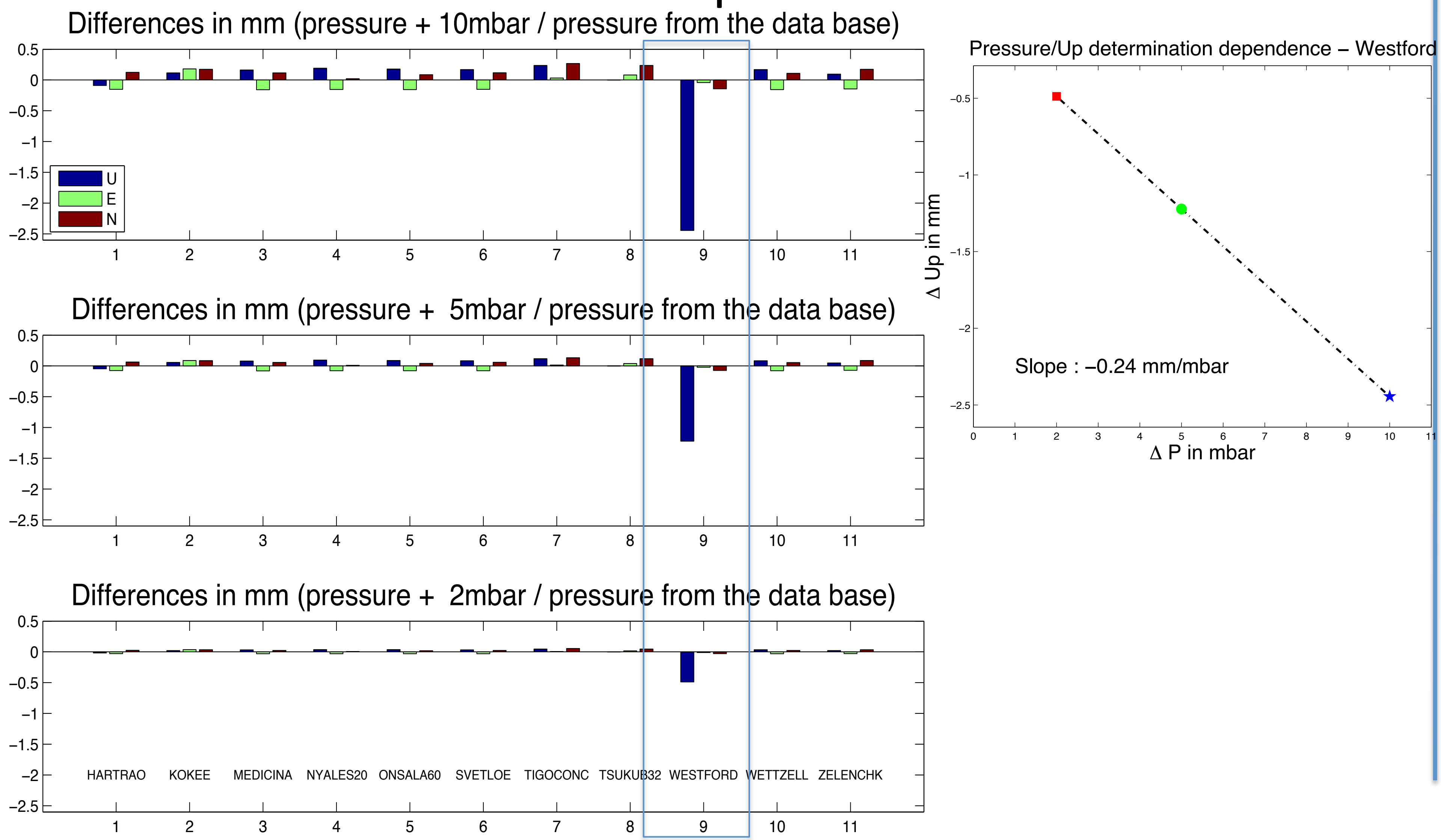
- WRMS
  - Measurement of baseline repeatability.
  - When compared to the database, shows an improvement if bigger than zero.
- Tests have shown that using a default value affects the WRMS as well as the determination of the Up component.
- Example: WESTFORD over the year 2008.
  - Using VMF data (model data) for WESTFORD instead of the database improves baseline repeatability.

Difference in WRMS, using DB/default value – VMF data for WESTFORD, EVGA 2011



Systematic differences

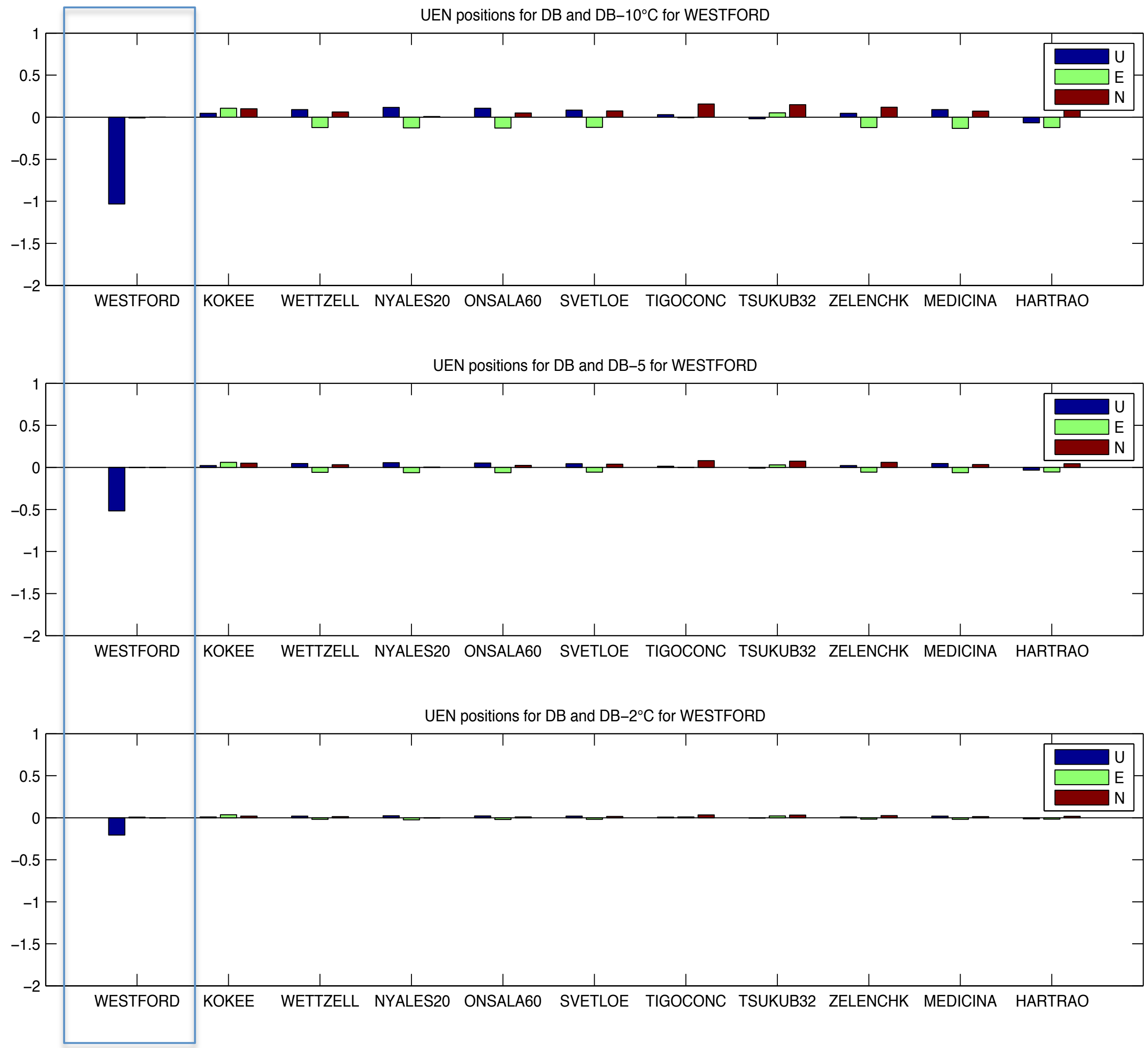
WESTFORD analyzed over CONT08 - pressure

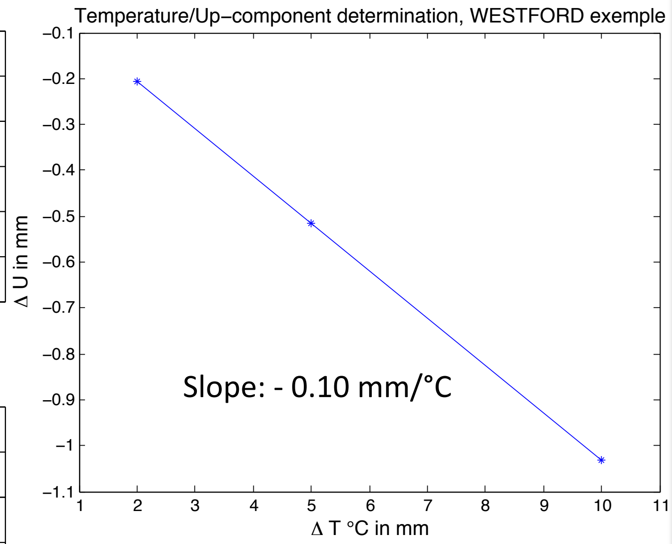


Systematic differences

WESTFORD analyzed over CONT08

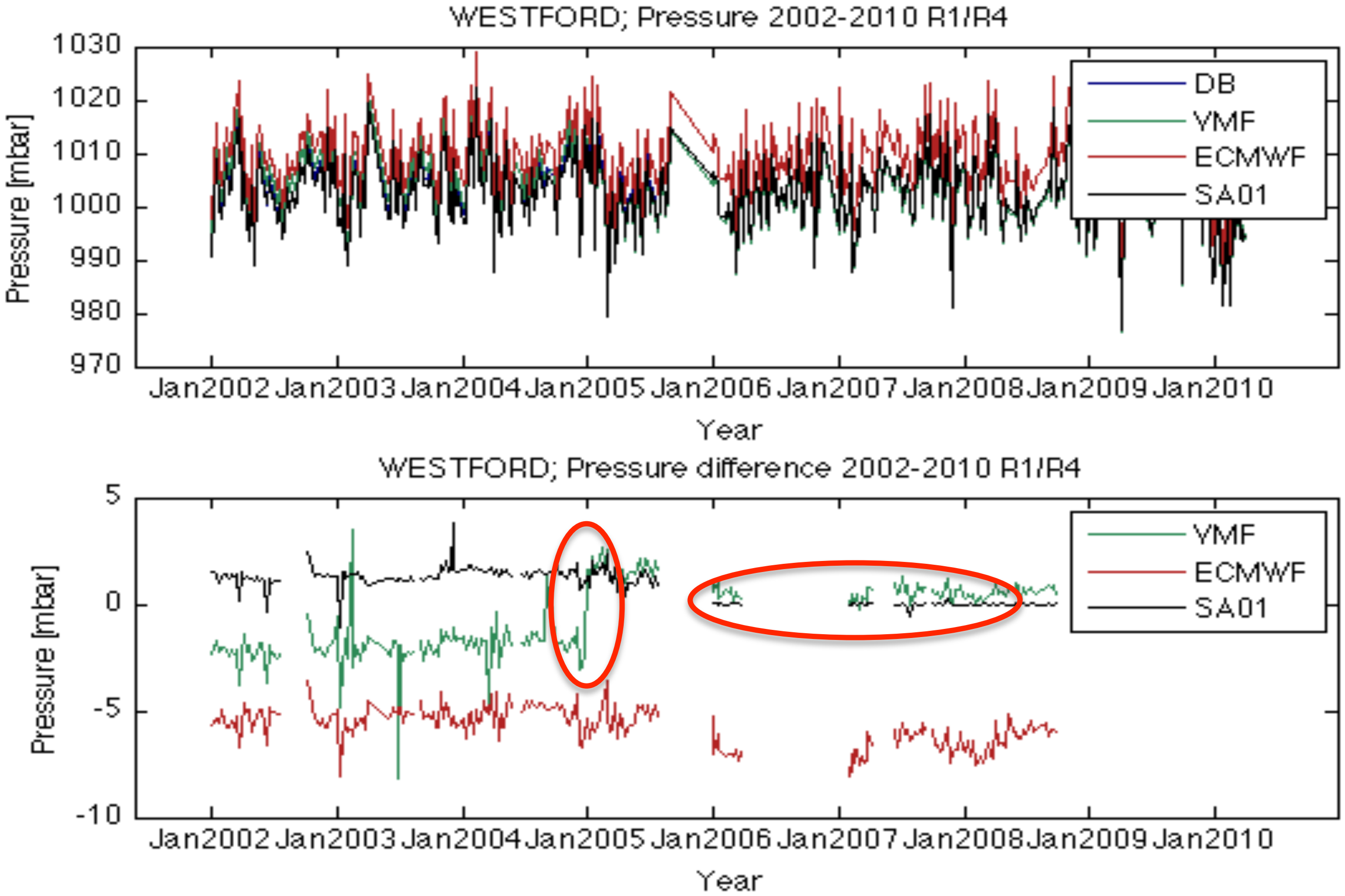
- temperature



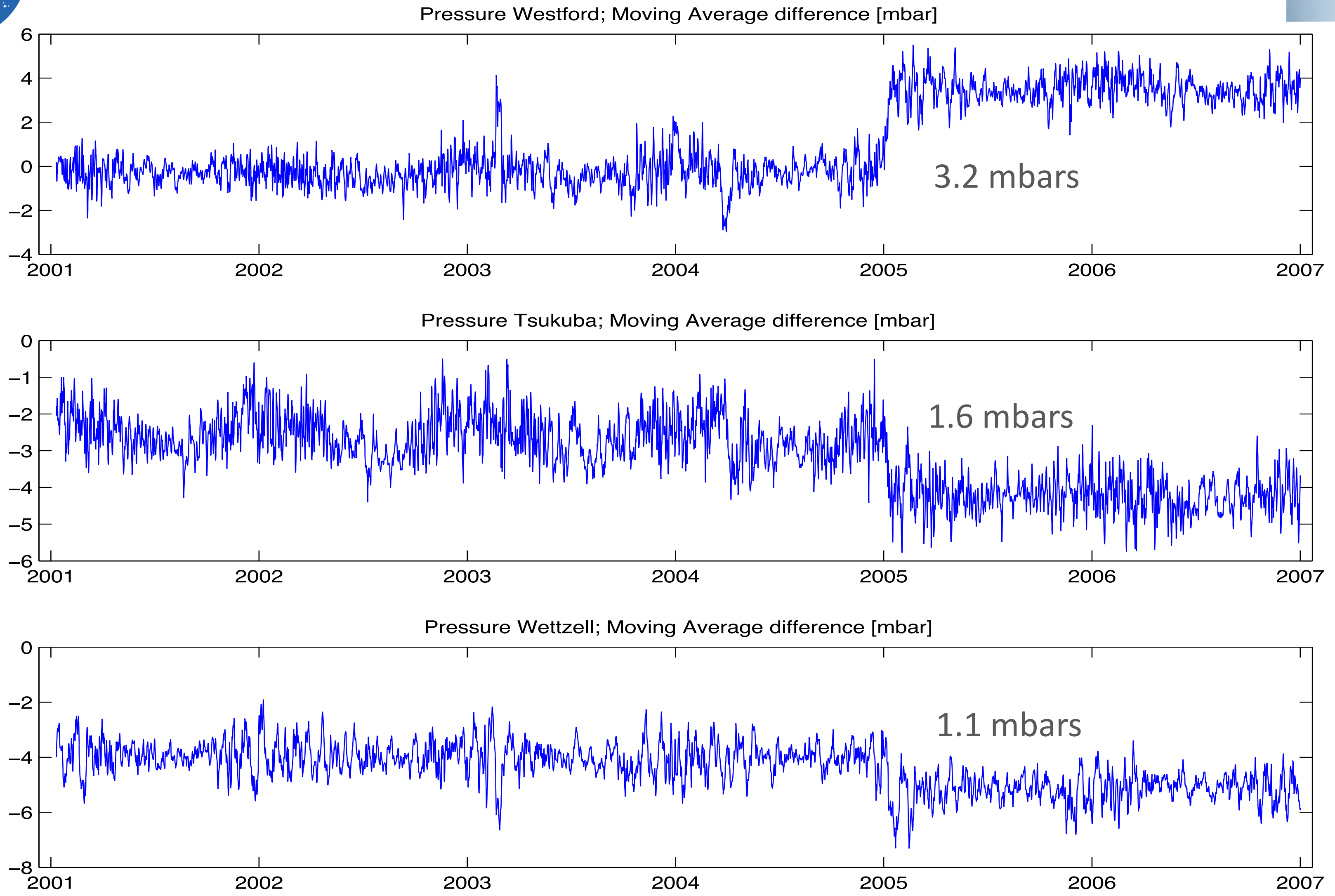


Systematic differences - Pressure

- When compared to other sources of met data, we found systematic differences between the pressure time series of the database and external sources (VMF, ECMWF, SA01).
- From 2006, the met data in the databases is the met data from the SA01 met sensor (+3.2mbar, cf. memo *A. Niell*).



Systematic Differences-Pressure



Graphs showing jumps for WESTFORD, TSUKUBA and WETTZELL.

Lack of homogeneity in the databases

- How to find bad data and in-homogeneities;
- To find **outliers** the time series were looped through searching for points that were significantly bigger or smaller than the mean.
- To find **missing data** points that had been filled with -999.999 were searched for.
- A method called SNHT (Standard Normal Homogeneity Test) were used to find **jumps** in the time series.

  - Developed by Alexandersson (1986) after the work of Hawkins (1977).

Lack of homogeneity in the databases

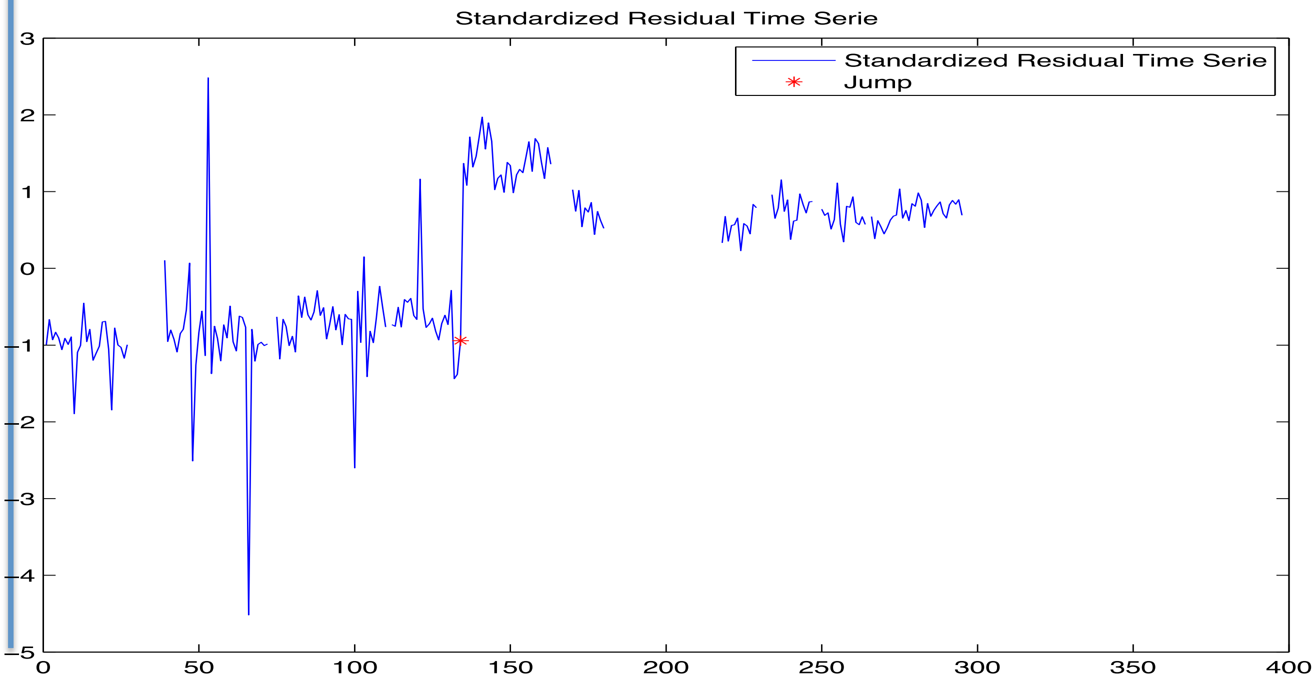
- Series of N elements, zero mean and unit variance.
- The a-value that maximize T_a is the MLE (Maximum Likelihood Estimate) of the point where the change in mean occurs. Therefore our jump point.
- Magnitude of the jump may be calculated as m1-m2.

$$H_0 = Z \sim N(0,1)$$

$$H_1 = \begin{cases} Z_t = z_{1t} \sim N(m_1, 1) & 1 < t < a \\ Z_t = z_{2t} \sim N(m_2, 1) & a < t < N \end{cases}$$

$$T_{SNH} = max_{1 \leq a \leq N-1}\{T_a\}$$

$$max_{1 \leq a \leq N-1}\{T_a\} = max_{1 \leq a \leq N-1}\{|\sum_{i=1}^{a} Z_i|\sqrt{\frac{N}{a(N-a)}}\}$$



WESTFORD, pressure
2002-2010

Alternative sources of met data

- For WESTFORD we have 3 sources of data;
  - **Database** (met sensor on site till 2006 when it was filled with SA01 data).
  - **VMF**, met data from the ECMWF model interpolated to the VLBI station positions (*J. Boehm*).
  - **SA01**, the GPS sensor in the Suominet network, from 2006 (*A.Niell*).
- But for the other stations we just have the database and VMF-data.
- Alternative sources of met data:

  - ECMWF (1.5*1.5 grid) www.ecmwf.int

  - NCEP (2.5*2.5 grid) www.esrl.noaa.gov
- Data of this sort is given on grid points, where you have time, latitude, longitude, data of interest such as temperature, pressure and humidity. This can be downloaded in netCDF format.
- We need pressure and temperature for the VLBI station.

  => The data needs to be extrapolated and interpolated to telescope site.

- **Pressure**;
  - 6 hour pressure series.
  - Grid point heights, these heights are given as geopotential height.
- The relationship between the geometric height, h and the geopotential height, z, is:

$$z(h,\phi) = \frac{\gamma_s(\phi)}{\gamma_{45}} \frac{R(\phi) \times h}{R(\phi) + h}$$

- Where: $\phi = latitude$

$$\gamma_{45} = 9.89665 \frac{m}{s^2}$$

- Radius of the ellipsoid:

$$R(\phi) = (\frac{\cos^2(\phi)}{a^2} + \frac{\sin^2(\phi)}{b^2})^{-\frac{1}{2}}$$

- The value of gravity on the ellipsoid:

$$\gamma_s(\phi) = \gamma_e \frac{1 + k_s \sin^2(\phi)}{\sqrt{1 - e^2 \sin^2(\phi)}}$$

- Where:

$$e = 0.0066943800229$$

$$k_s = 1.931853 \times 10^{-3}$$

$$\gamma_e = 9.7803267714$$

- The barometric height formula (*Zdunkowski and Bott, 2004*):

p_0 – reference pressure
T_0 – reference temperature
Γ – lapse rate
g – acceleration due to gravity
R – gas constant
Δz – difference in geopotential height

$$p(z) = p_0 \left(\frac{T_0 - \Gamma \Delta z}{T_0}\right)^{\frac{g}{R\Gamma}}$$

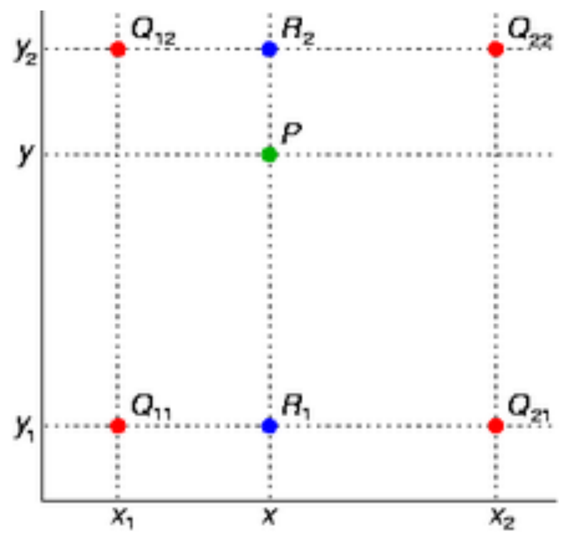
- **Temperature;**
  - 6 hour temperature series.
  - Grid point heights, these heights are given on the ellipsoid.
  - After calculating the geometric height difference we use the lapse rate of 0.006499° K/m to height adjust the temperature series.
- This formula could be improved by calculating the specific lapse rate for the telescope site, which also can be applied to the extrapolation of the pressure.

- Pressure and temperature series are obtained for the four grid points around the station at the antenna height.
- A bilinear interpolation to get the series at the telescope.
  - Linear interpolation in x-direction

    - Yielding R1 and R2

  - Linear interpolation in y-direction

    - Yielding P



ECMWF

- Time series of pressure and temperature were produced with ECMWF and NCEP.

  - ECMWF showed a better result, because of a big bias in pressure series for NCEP.

  - We proceeded with ECMWF data.

- From this extra source of data it became clear that the jump in the pressure data originated from the VMF data.

  - CALC/Solve runs, with new pressure series.

  - Fortran routines were made to make .trp files containing tropospheric parameters that are used in CALC/Solve based on the new source of data.

- Tropospheric parameters (parameters that gives the tropospheric path delay):

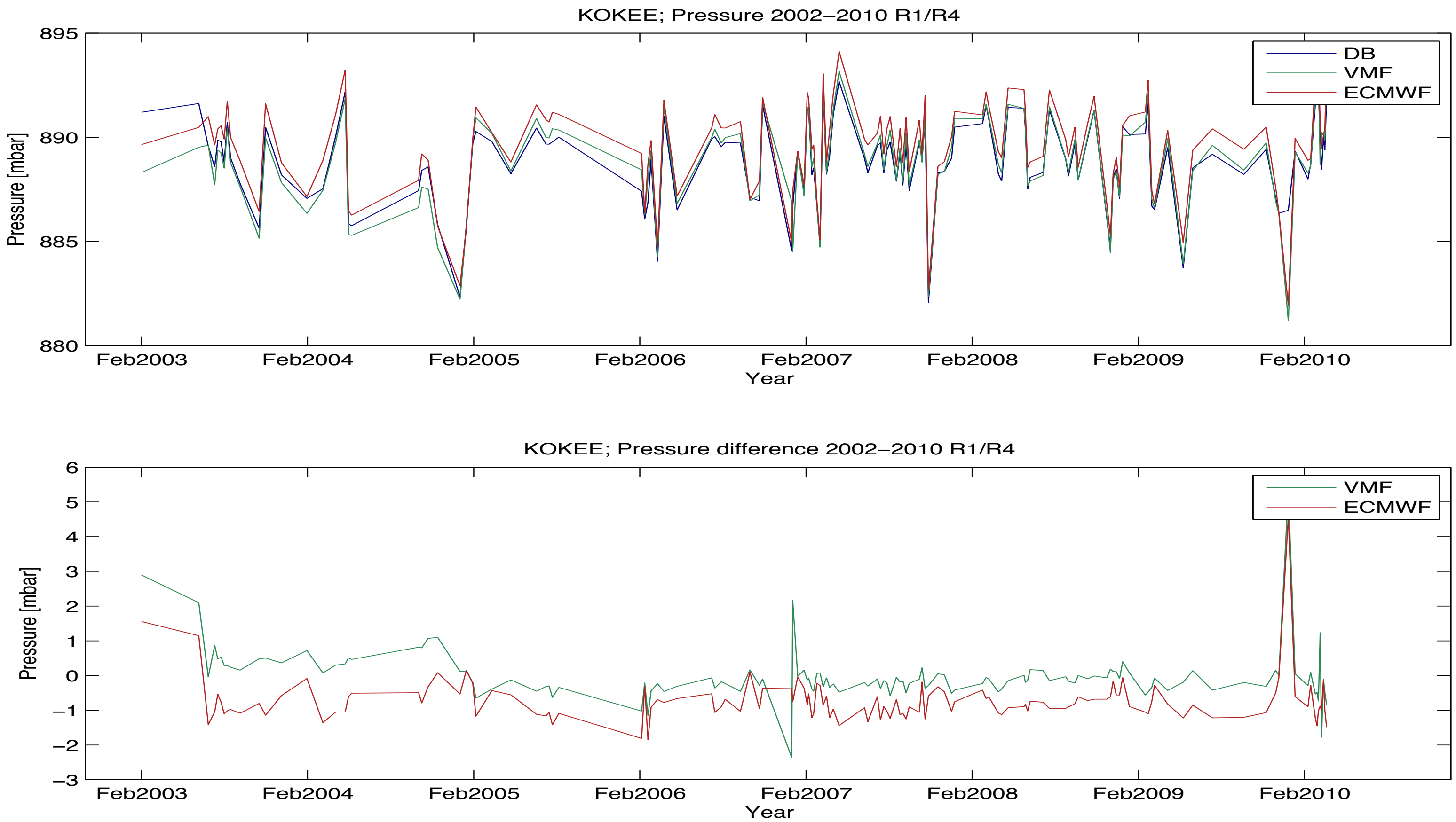
  - Atmospheric mapping functions

  - Pressure and temperature

  - Hydrostatic delay

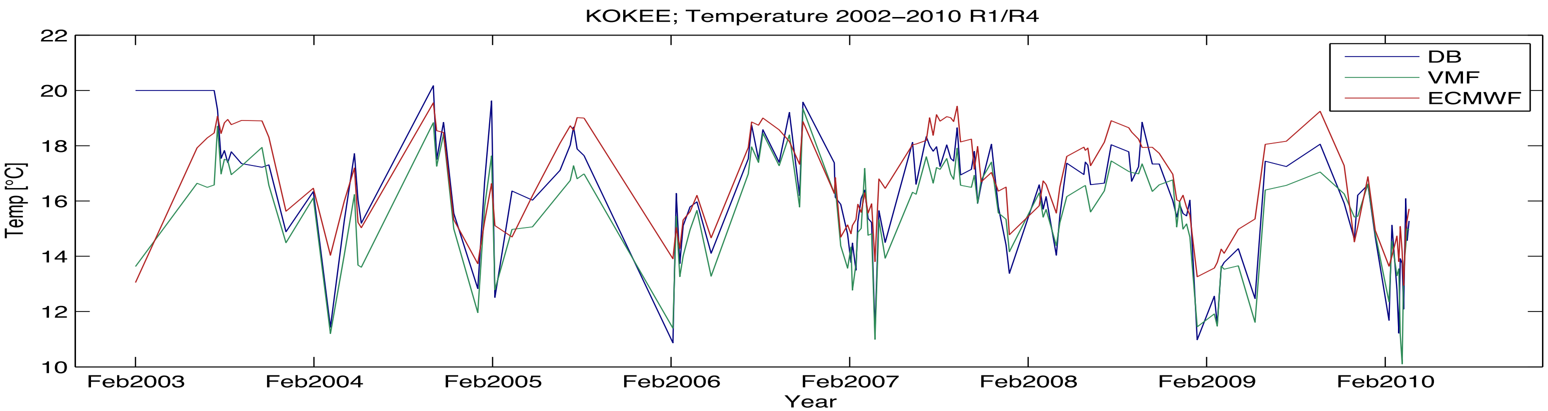
ECMWF

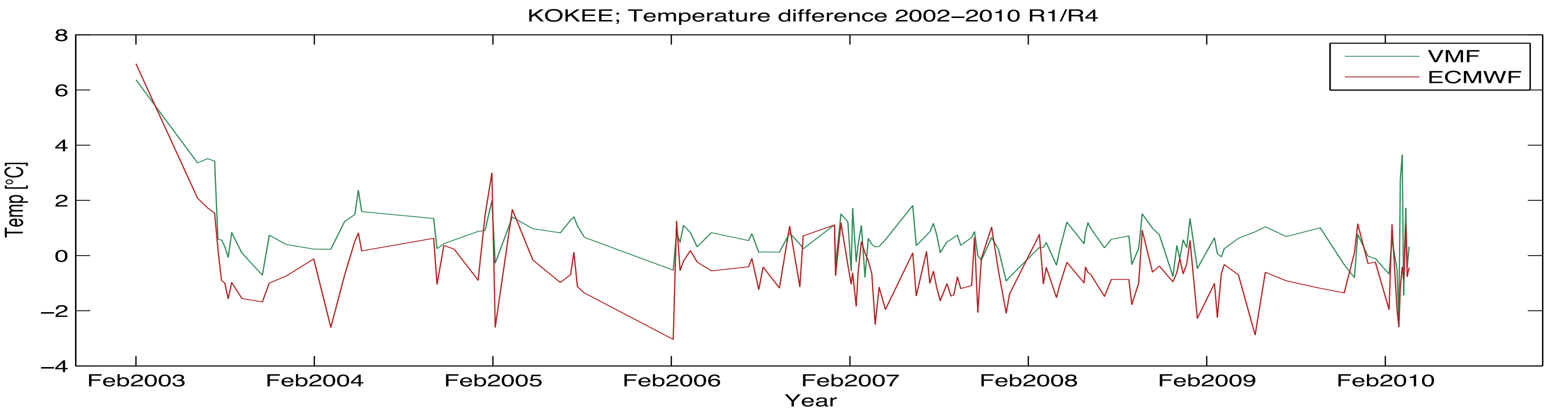
- Pressure series from ECMWF:
- Well correlated with what was in the database and VMF.
- ECMWF smoother than VMF.



ECMWF

- Temperature series from ECMWF:

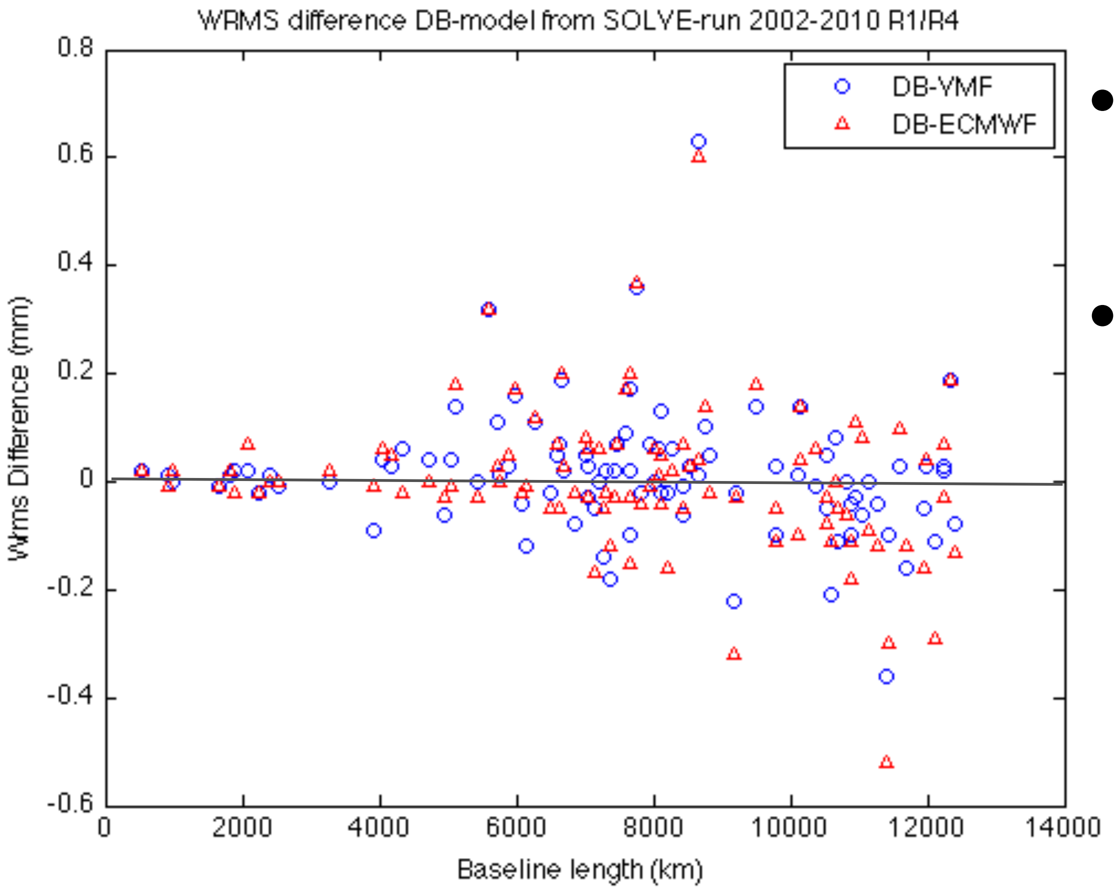




Systematic differences - Pressure

R1 and R4 sessions from 2002 to 2010

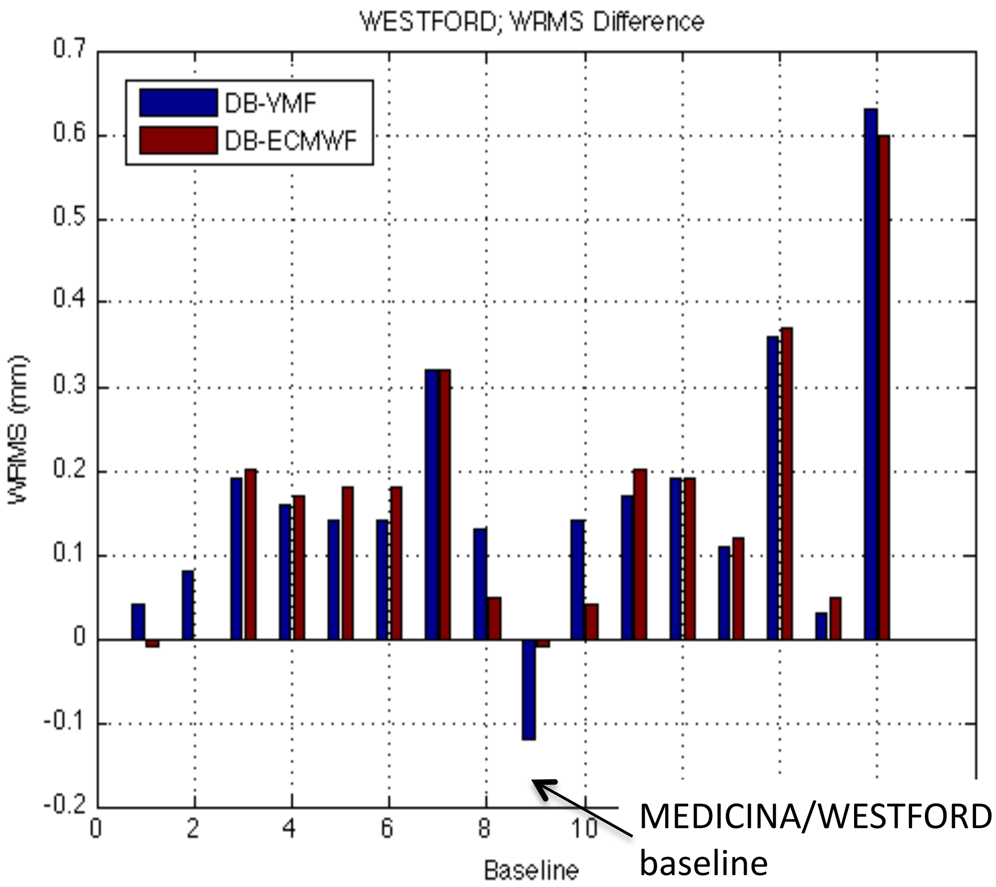
using the met data from either the DB, VMF or ECMWF



- Using ECMWF instead of DB shows no improvement.
- Using **VMF** instead of DB improves the WRMS of 61% of the baselines considered.

Systematic differences - Pressure

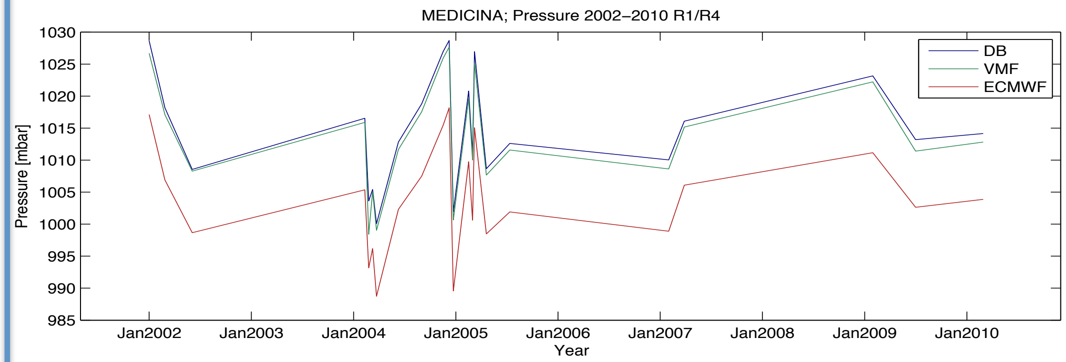
R1 and R4 sessions from 2002 to 2010

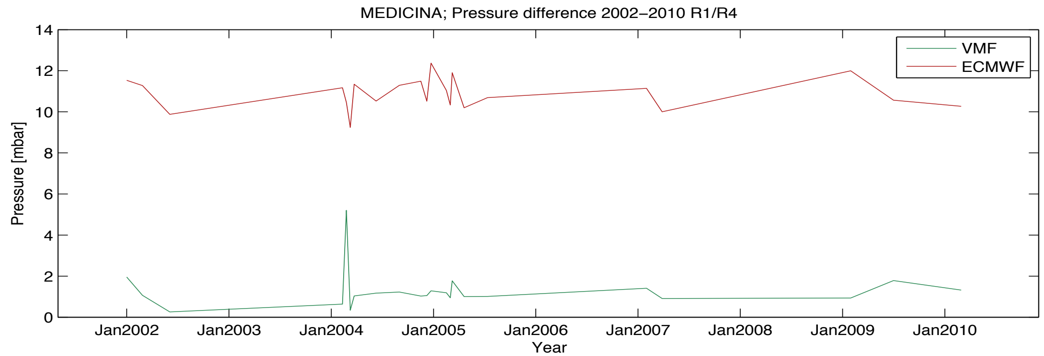


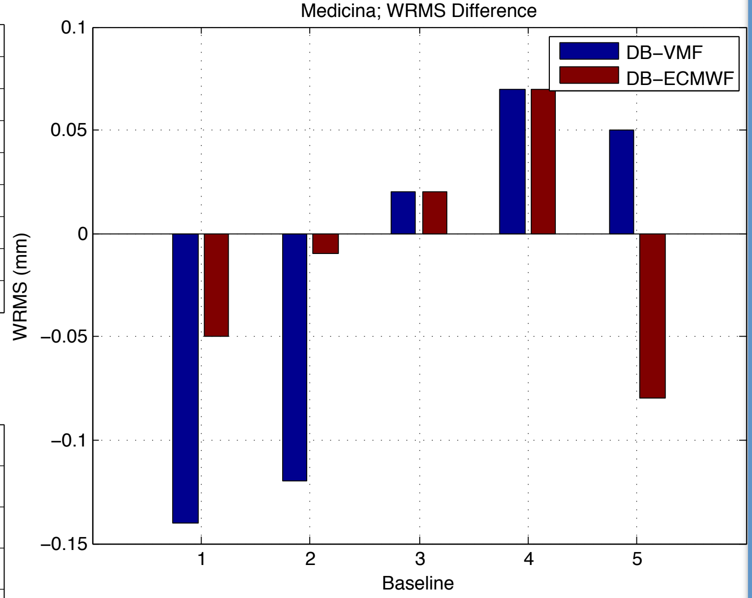
- For WESTFORD only, the WRMS differences show:
- An improvement when using either VMF or ECMWF rather than the met data from the DB.
- For 11 baselines out of 16 total, it is better to use **ECMWF** than VMF. This improvement may be explained by the homogeneity in the ECMWF met data, when the VMF data has a significant jump at the end of 2004.

Systematic Differences - Pressure

Medicina





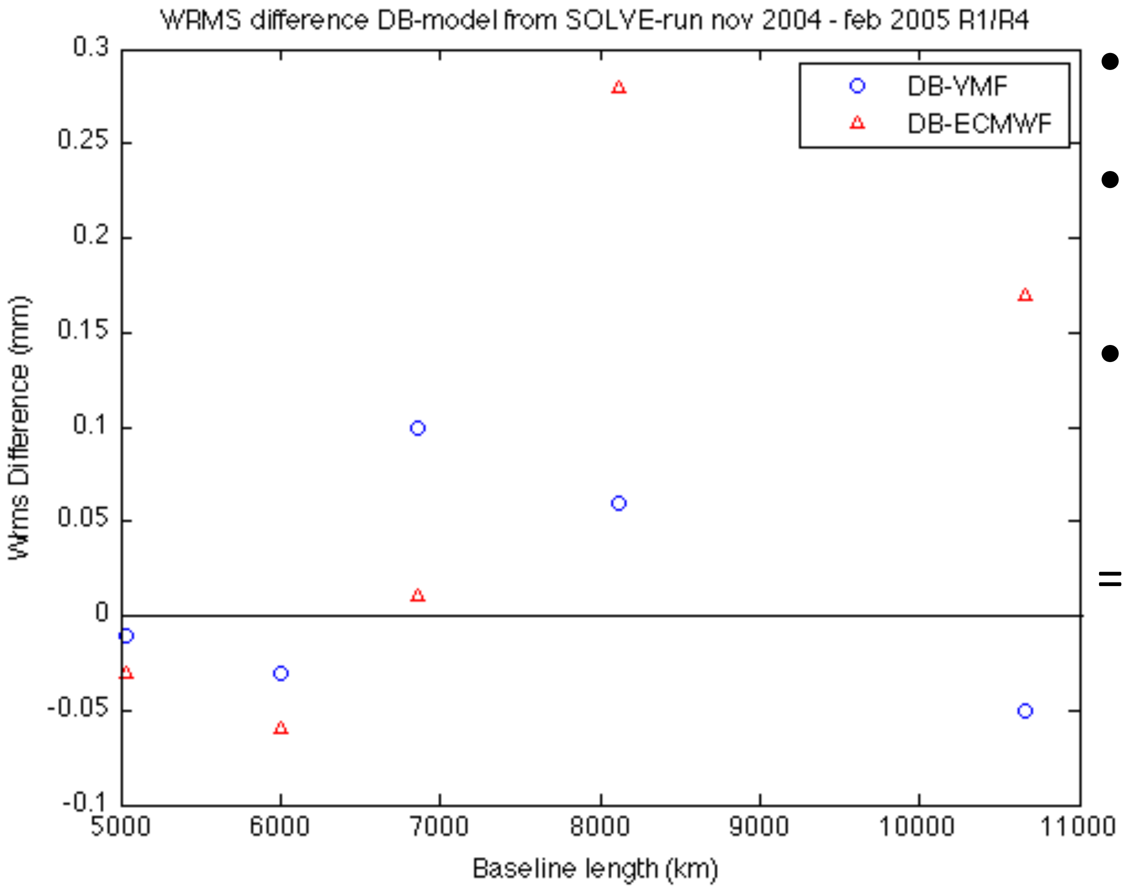


- Even though the VMF data and the data from the met sensor are close the WRMS is improved for 3 out of 5 baselines when using VMF.

Systematic differences - Pressure

R1 and R4 sessions from Nov 2004 to Feb 2005

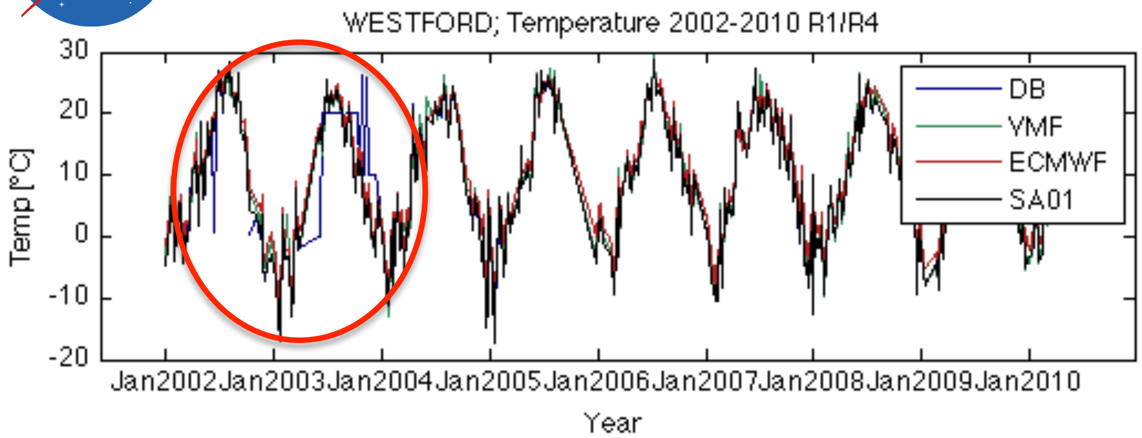
using the met data from either the DB, VMF or ECMWF

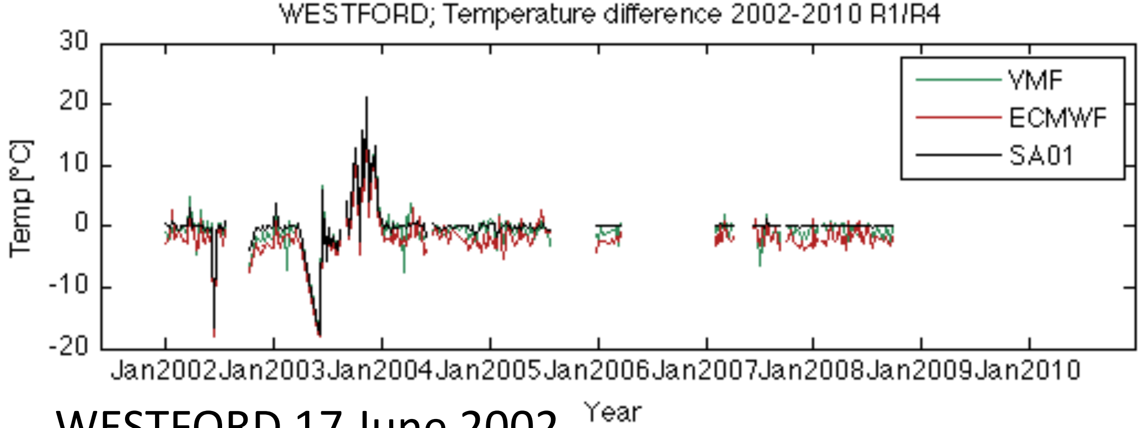


- There is met data in the DB.
- Using VMF instead of DB shows no improvement of the WRMS.
- Using **ECMWF** instead of DB the WRMS shows an improvement of 60% of the baselines considered.

=> The jump detected at the end of 2004 in the VMF data affects the quality of the solution when using the VMF met data.

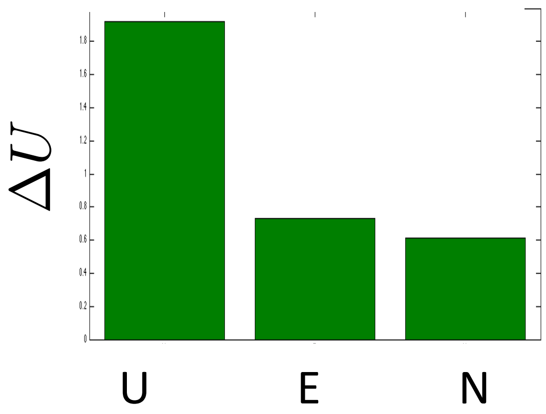
Abnormal behavior - Temperature

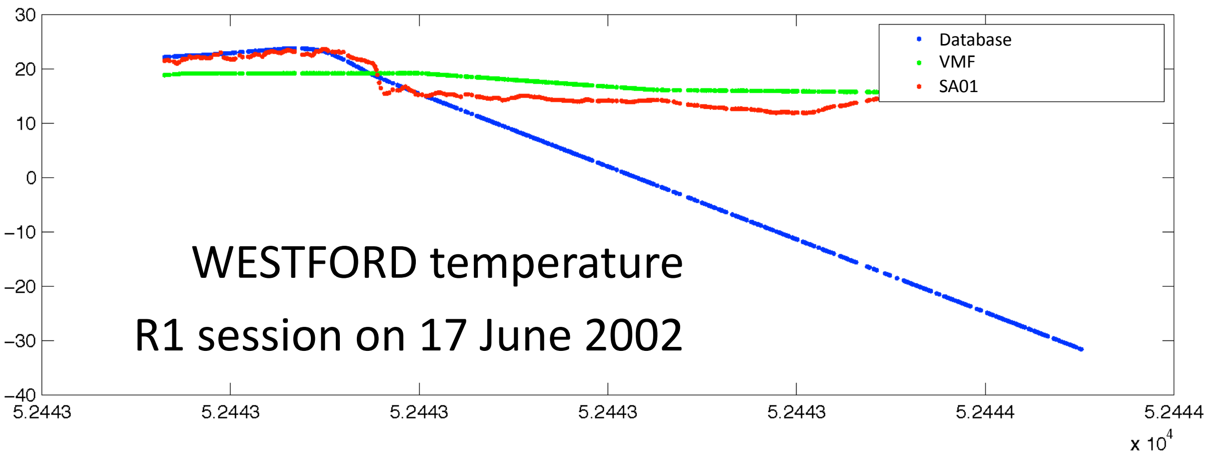




- Abnormal behavior in the temperature time series for WESTFORD. R1 and R4 sessions over the period 2002 to 2010.
- Daily means showing outliers of 10 °C.
- Sessions showing downs in temperature of -30 °C.

WESTFORD 17 June 2002





Thermal Deformation

- The annual cycle of thermal expansion may change the height of the VLBI reference point by as much as 20 mm (*A.Nothnagel 2008*).
- CALC/Solve uses a session based mean for the temperature where it calculates the thermal deformation of the telescope.
- It approximates the deformation as linear expansion.
- Assumes global expansion coefficients for steel and concrete parts.
- CALC/Solve will use session based mean temperature to calculate the axis offset variation and the line of sight variation.
- The partial derivatives are computed with respect to Up, East and North components.
- Finally the thermal displacement contribution is calculated.

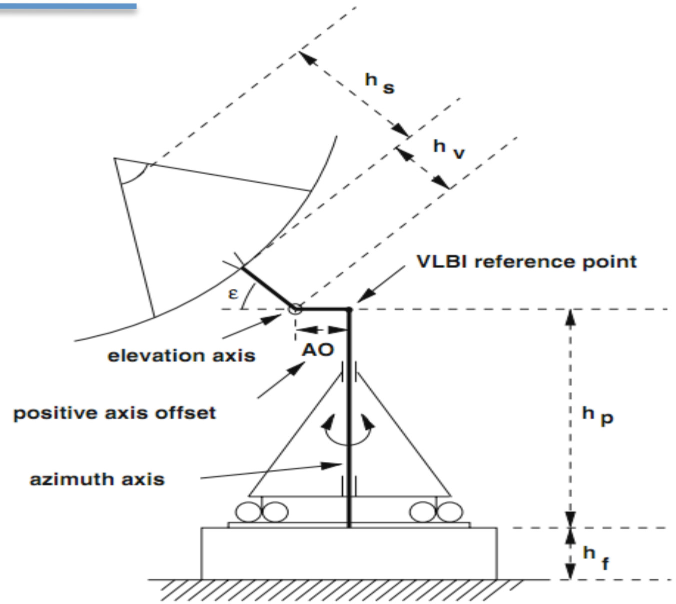
  - There is a time delay between the change in the surrounding air temperature and the expansion for the telescope, 2 hours for steel (*Nothnagel et al. 1995*) and 6 hours for concrete telescope structures (*Elgered and Carlsson 1995*).
- Use the temperature from VMF or ECMWF instead of a session based mean from the database – makes it possible to use the time delay.

Thermal Deformation

- Antenna offset brings antenna closer to the incoming wavefront.
- Wavefront arrives at the receiver by the axis offset contribution.
  - Depends on unit vector in source direction and unit vector in the direction of the fixed axis.
- Example: Alt-azimuth telescope mount with positive axis offset (*A.Nothnagel 2008*).
- The contribution of the thermal expansion effects on the time of arrival of a wavefront relative to the VLBI reference point, with respect to azimuth, elevation or declination:

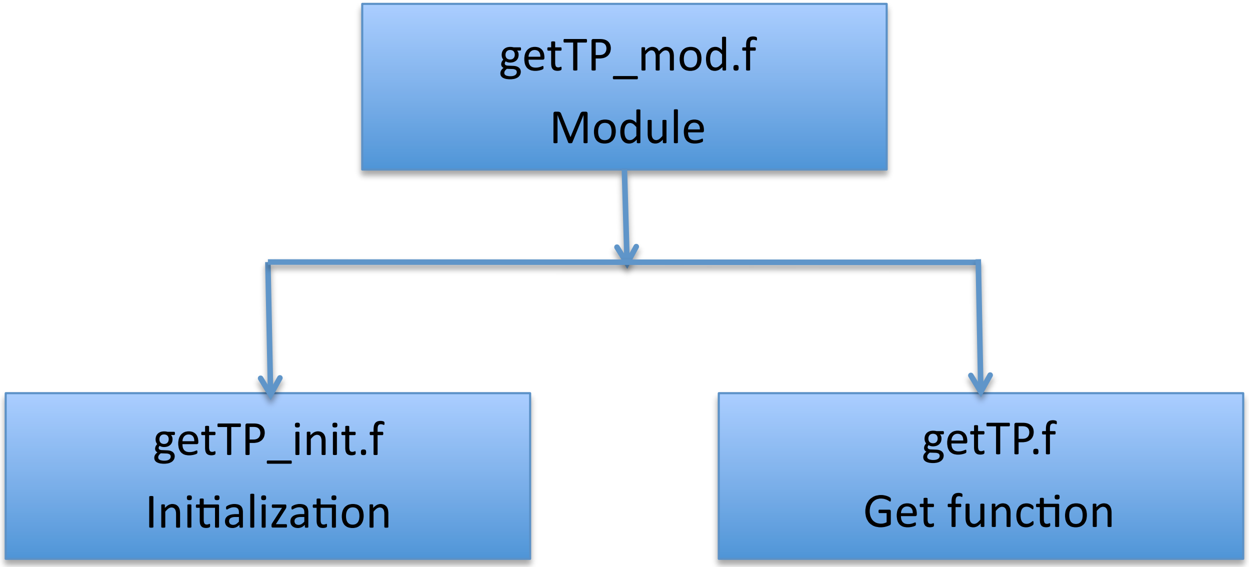
$$\Delta\tau_{therm.i} = \frac{1}{c}[\gamma_f(T(t-\Delta t_f)-T_0)(h_f\sin(\epsilon)) + \gamma_a(T(t-\Delta t_a)-T_0)(h_p\sin(\epsilon)+AO\cos(\epsilon)+h_v-F_a h_s)]$$

T – air temperature
γ_a, γ_f – expansion coefficients
h_f, h_p, hv, h_s – dimension of telescope [m]
AO – axis offset [m]
F_a – antenna focus factor
c – speed of light
t – observation epoch
$\Delta t_a, \Delta t_f$ – time lag



Thermal Deformation

Structure of read in-Fortran routines for temperature



Initialized before, and added in the routine that calculates the thermal displacement contribution that is dependent of the temperature.

Systematic Differences - Temperature

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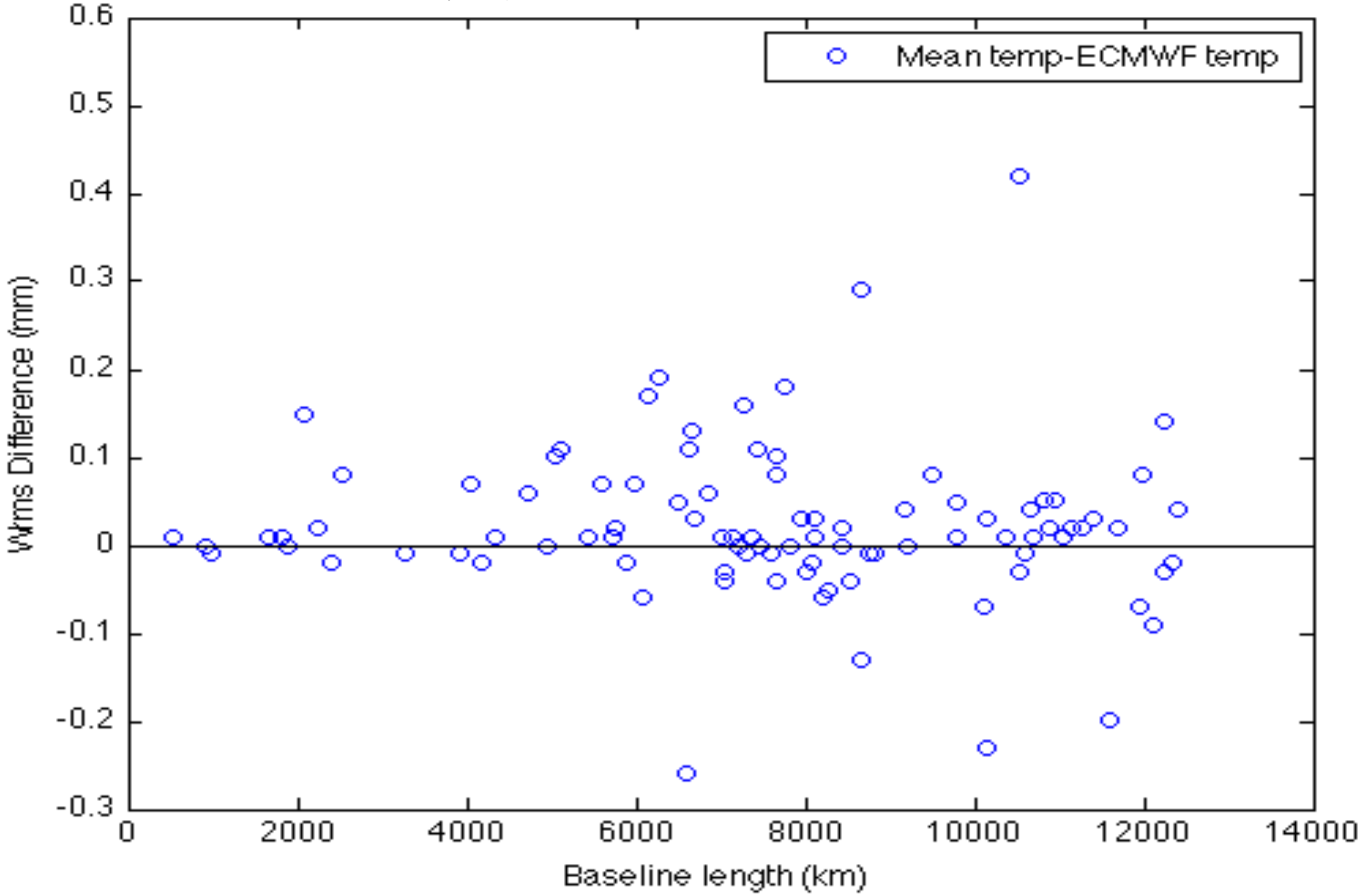
Baseline length repeatability

- VMF pressure and ECMWF temperature

WRMS difference, R1/R4 2002-2010

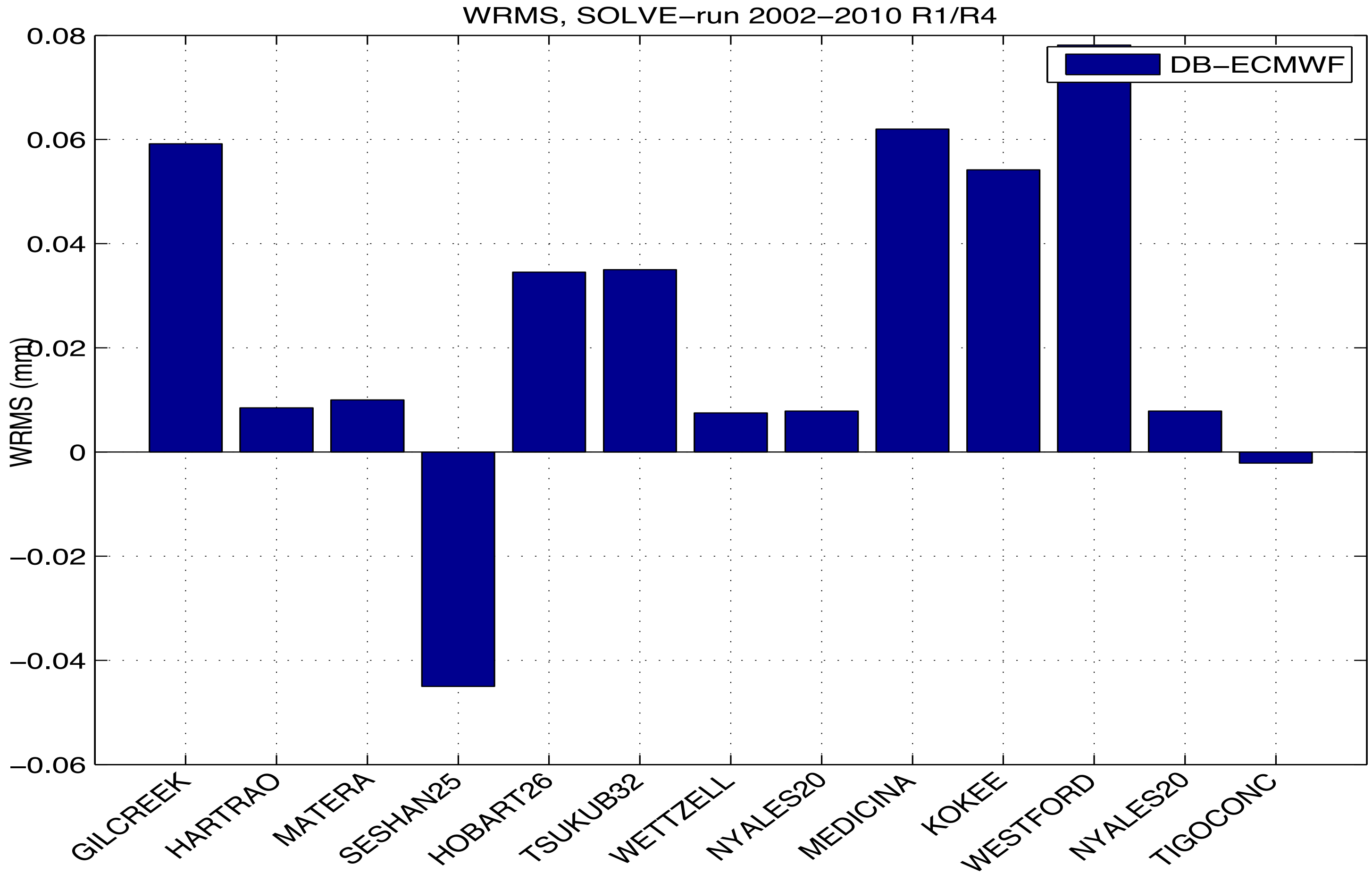


60% > 0
⇒Improvement for 60% of the baselines considered

Systematic Differences - Temperature

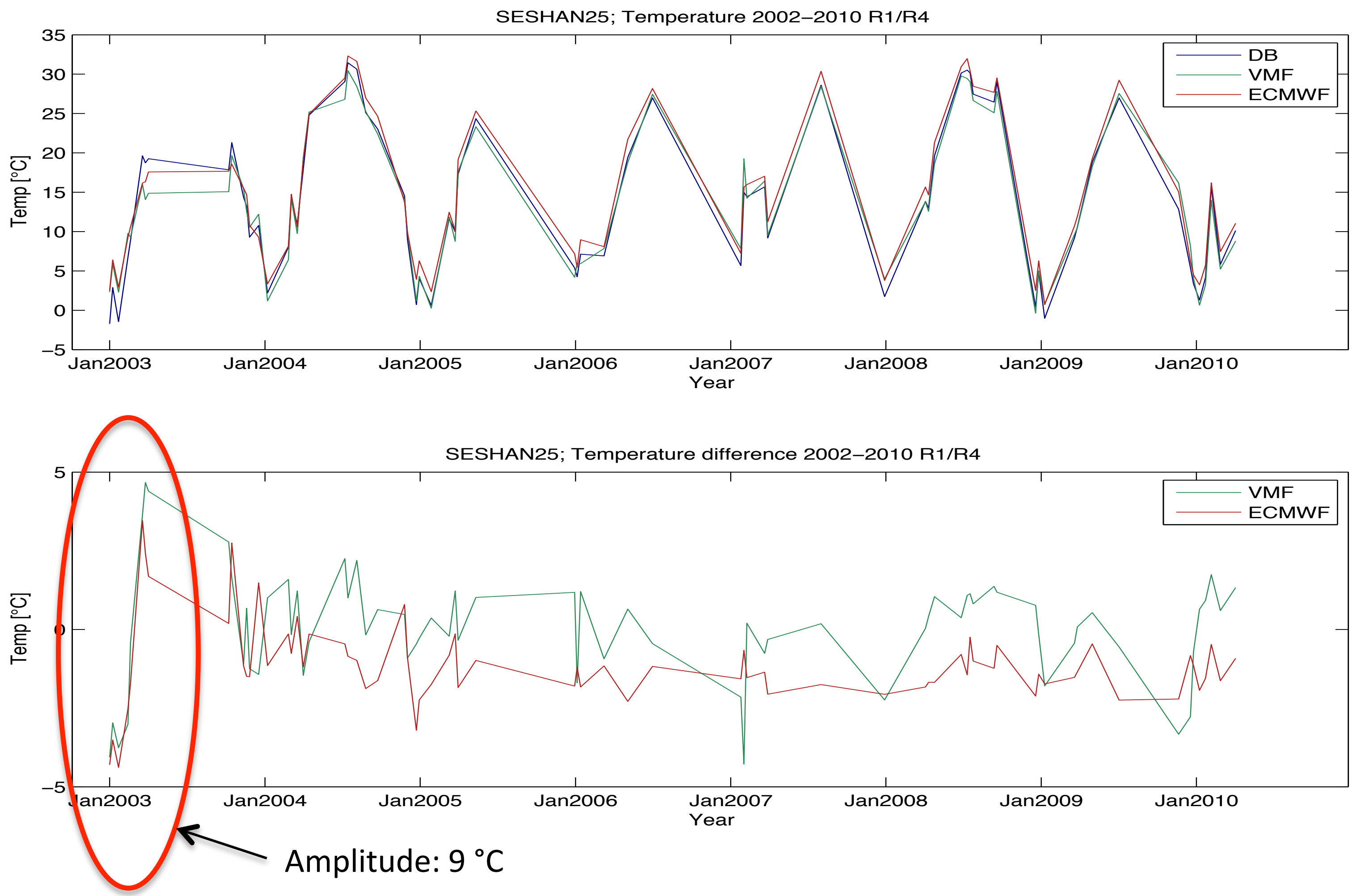
Baseline length repeatability, mean per baseline

- VMF pressure and ECMWF temperature



Systematic Differences - Temperature

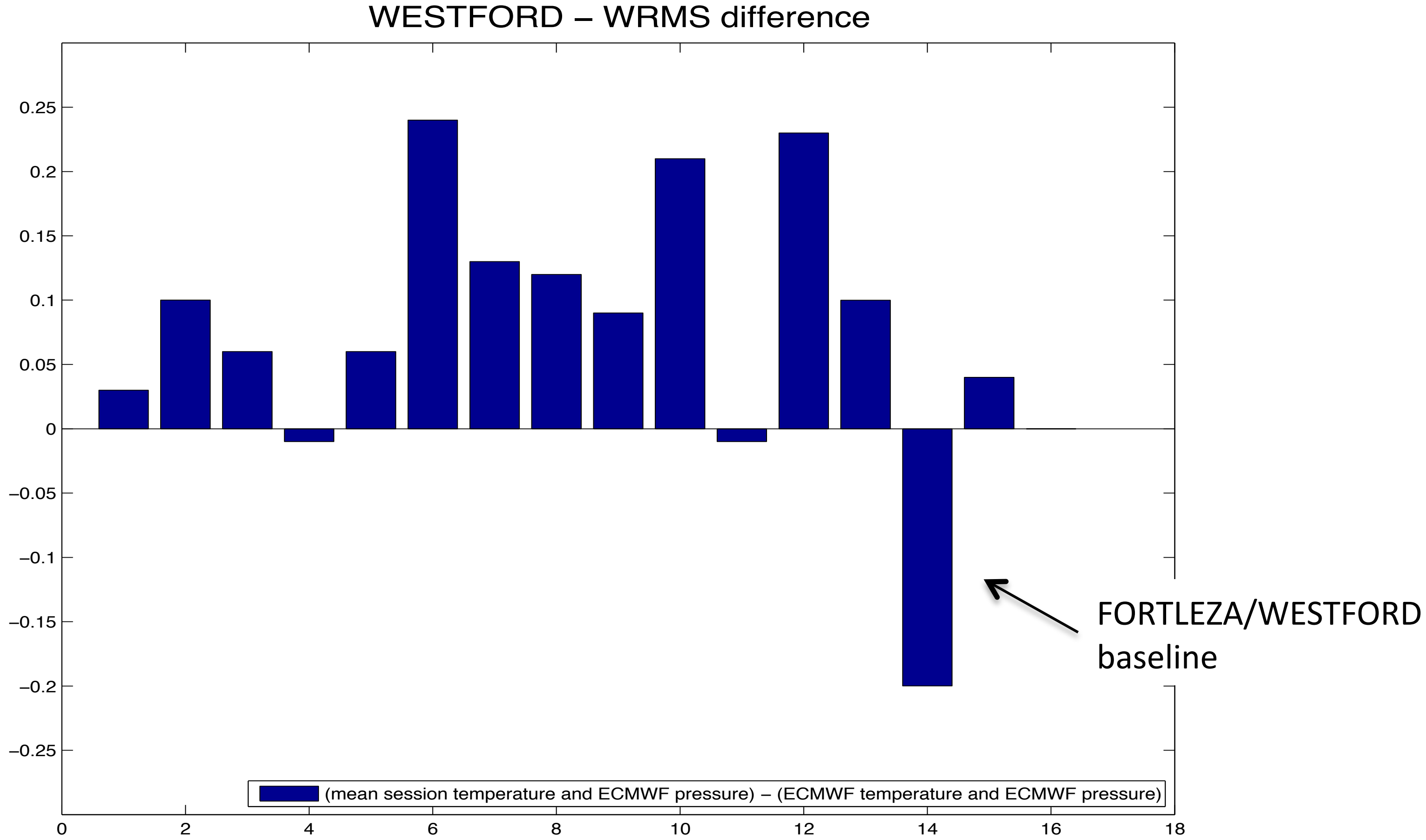
Temperature for SESHAN25:



Systematic Differences - Temperature

WESTFORD baseline, WRMS difference

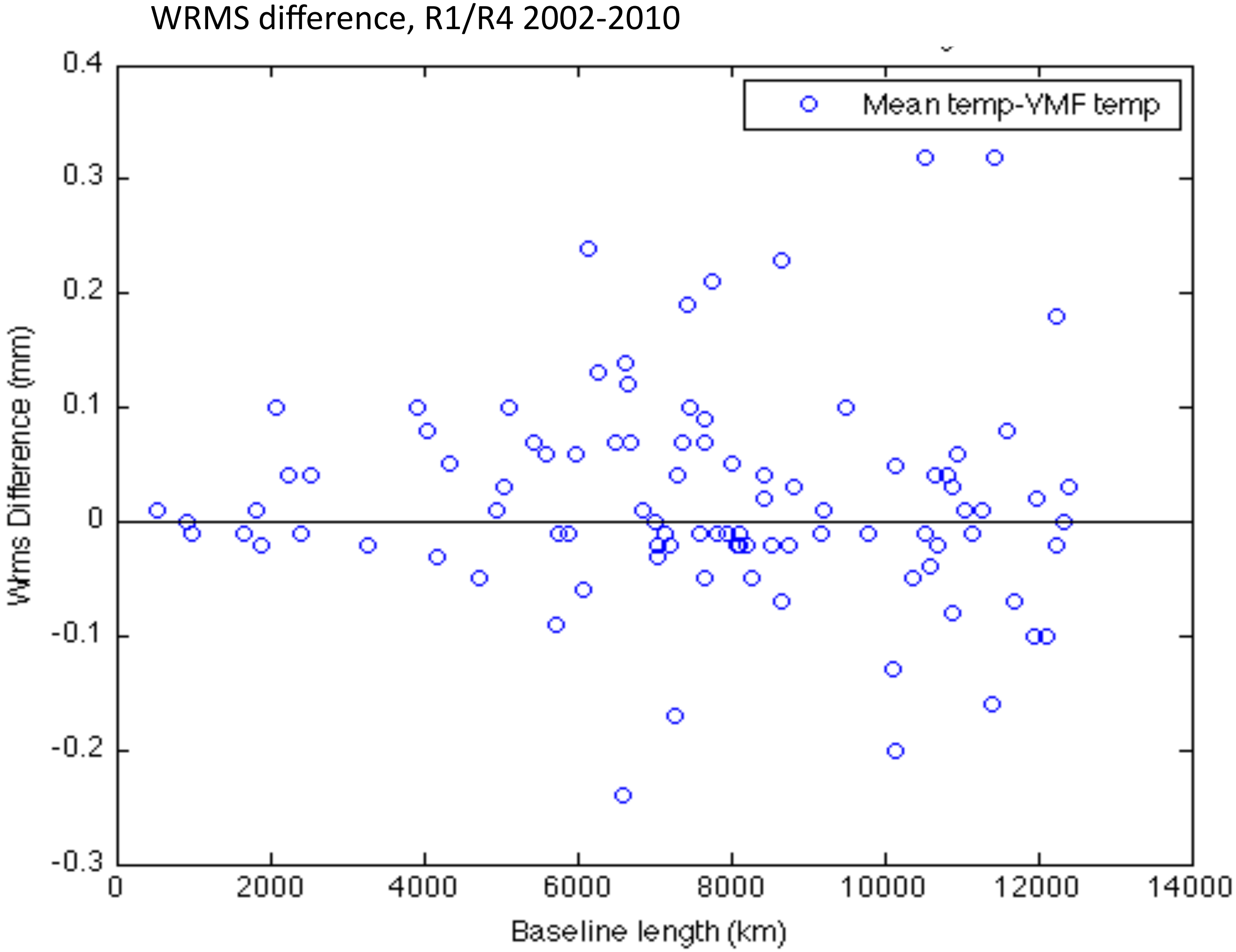
R1 and R4 sessions 2002-2010



Systematic Differences - Temperature

Baseline length repeatability

- VMF pressure and VMF temperature

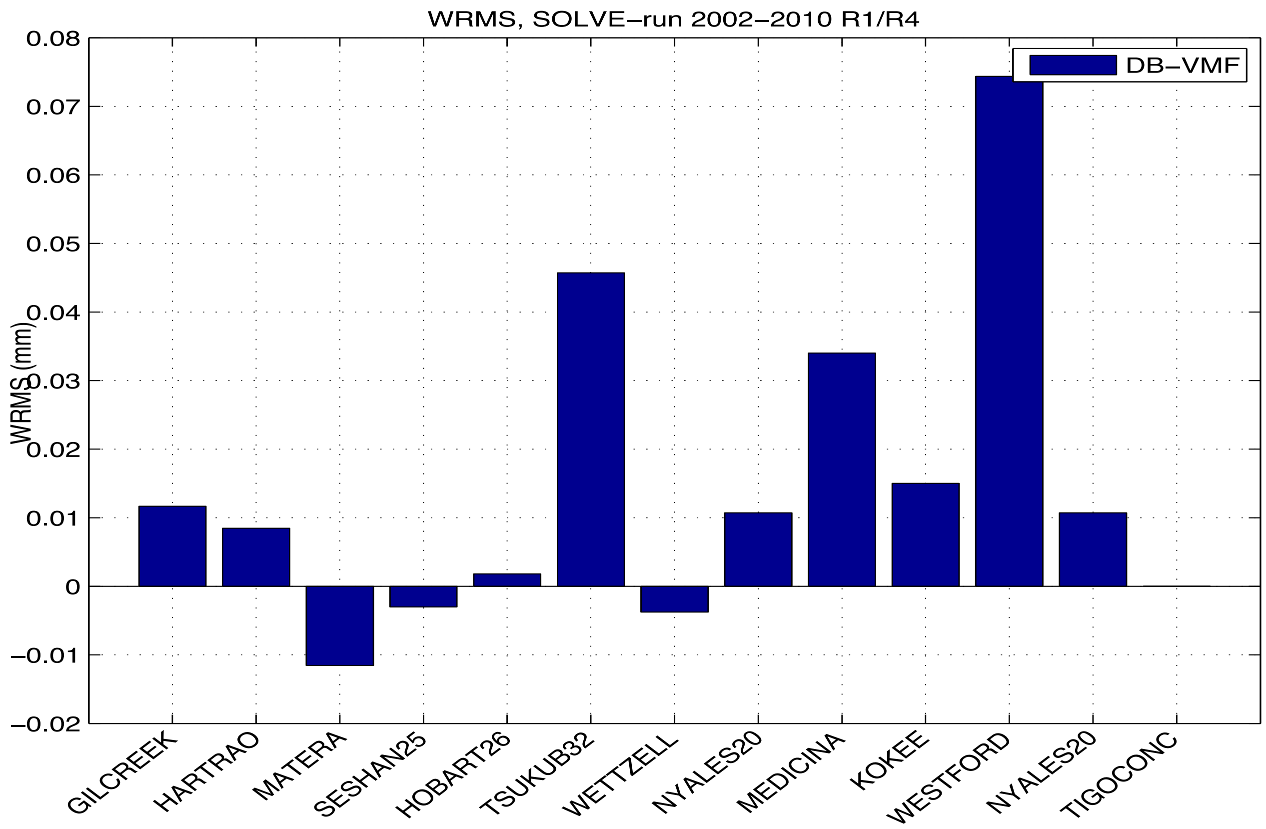


50% > 0

Systematic Differences - Temperature

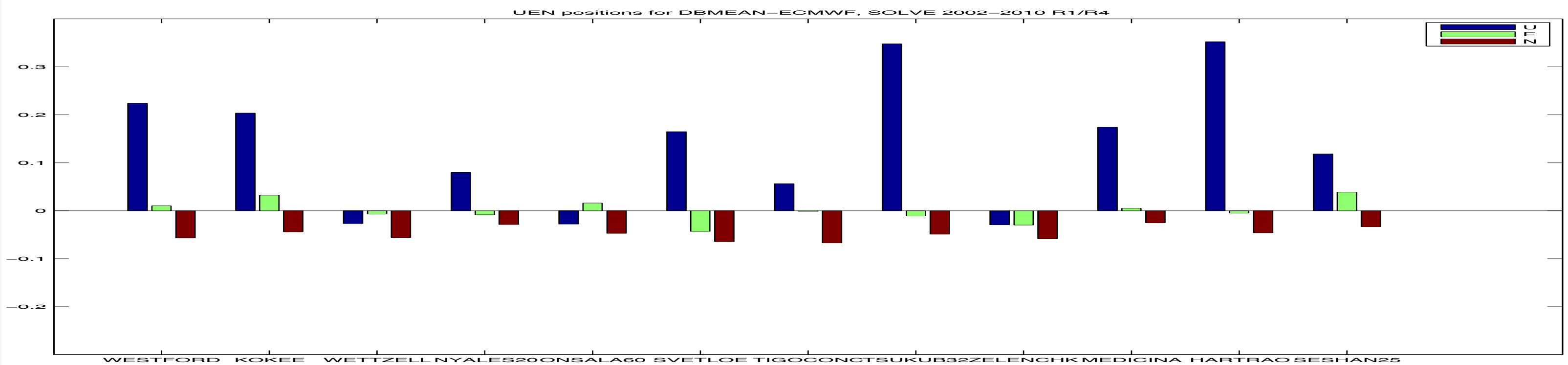
Baseline length repeatability, mean per baseline

- VMF pressure and VMF temperature

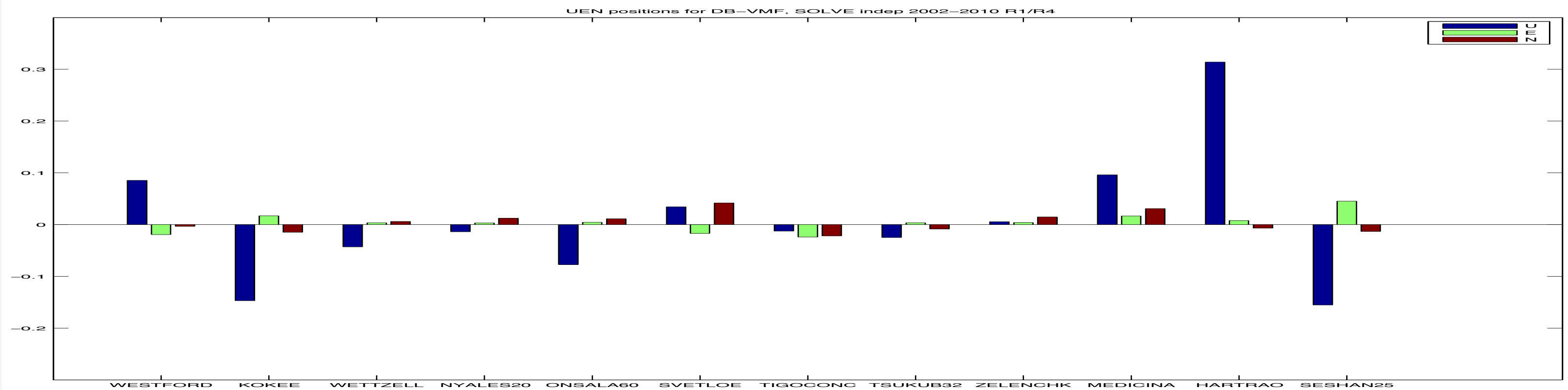


Systematic Differences - Temperature

- R1 and R4 sessions 2002-2010 looking at the UEN positions when comparing the use of temperature, ECMWF or VMF. The pressure used is from VMF.
- The U-component changes with the choice of temperature source, observing a change of up to 0.3 mm.



ECMWF

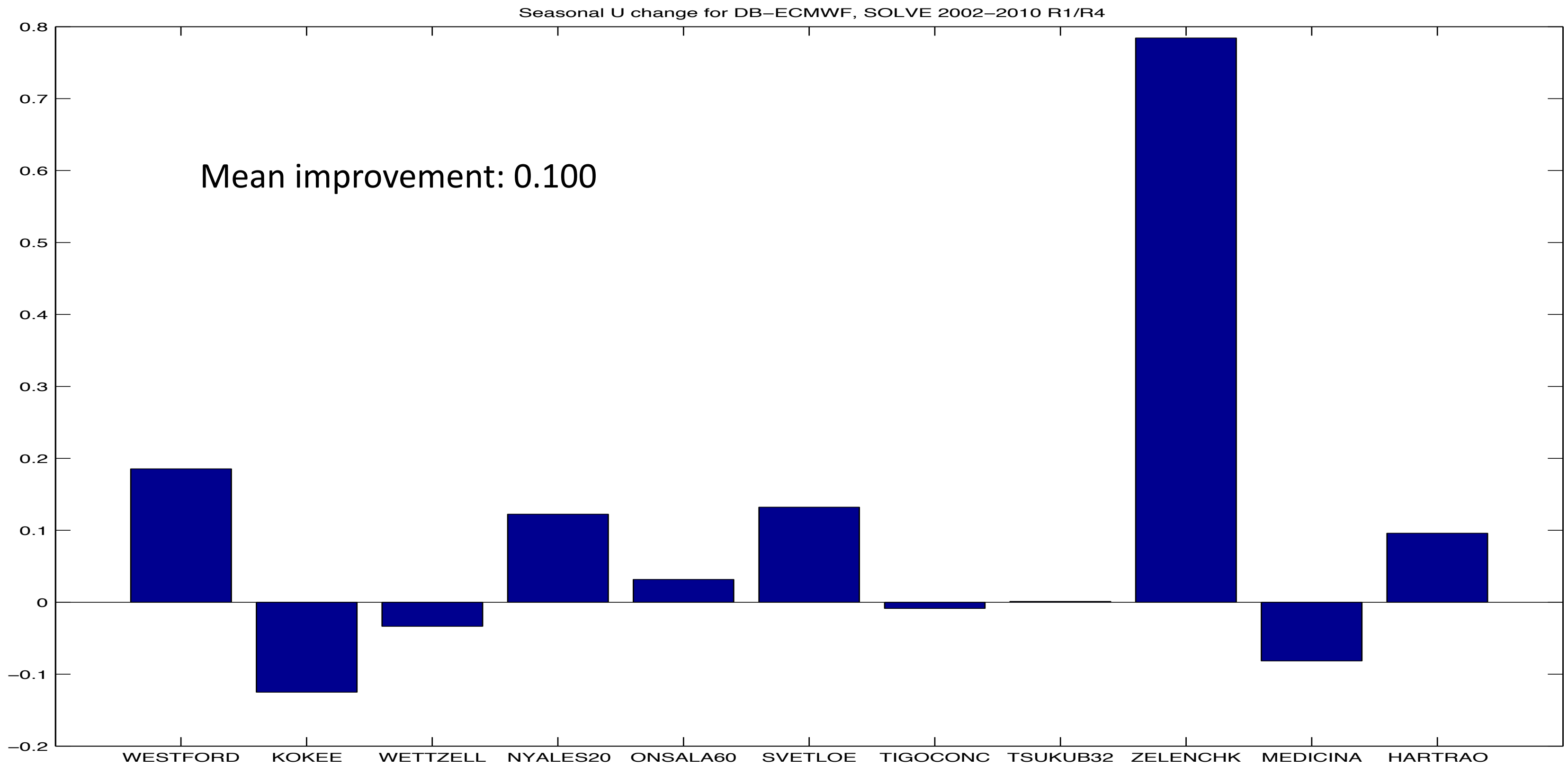


VMF

Systematic Differences - Temperature

Seasonal change

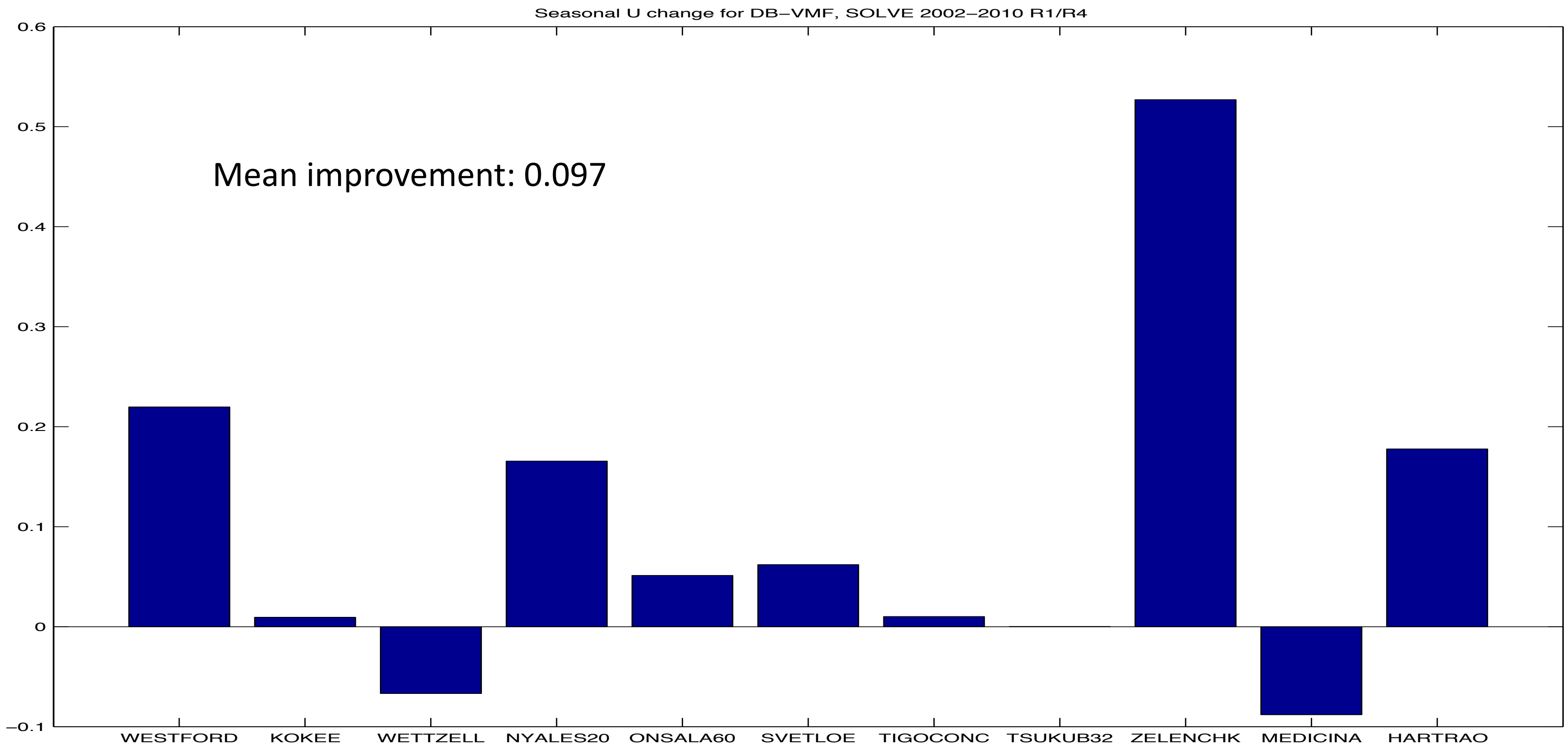
In annual amplitude for the U-component, using ECMWF temperature



Systematic Differences - Temperature

Seasonal change

In annual amplitude for the U-component, using VMF temperature



Conclusions

- Investigation of what we are using in CALC/Solve now.
  - Development of a tool that detects bad data (outliers, missing data, jumps)
- Computation of met data to be used for VLBI calculations.
  - Interpolate and extrapolate ECMWF and NCEP data.
  - Make this data useable in CALC/Solve by reformatting and arranging in databases.
- Investigation on how the use of different met data affects VLBI results when using CALC/Solve.
  - Development of software to read in ECMWF met data to make files containing the tropospheric parameters, where the pressure for the site is used.
  - Development of software that implements the use of instant temperature from a model instead of a session based mean to calculate the thermal deformation.
- Time series analysis to analyze the results of CALC/Solve runs.

Perspectives

- ***Ideal case:***

  A homogeneous network of meteorological sensors in the global network to be used by CALC/Solve.
- ***Improvements to be made now:***

  Use VMF model pressure data and ECMWF model temperature data.
- ***Further improvements:***
  - Improve temperature extrapolation for the ECMWF data by calculation of the lapse rate for each of the stations.
  - Investigate if further improvements can be done to the pressure extrapolation for the ECMWF data.
  - Add time lag in CALC/Solve for calculation of the thermal deformation.
  - Add a choice in CALC/Solve so user can choose what temperature settings should be used to calculate thermal deformation for the telescope.