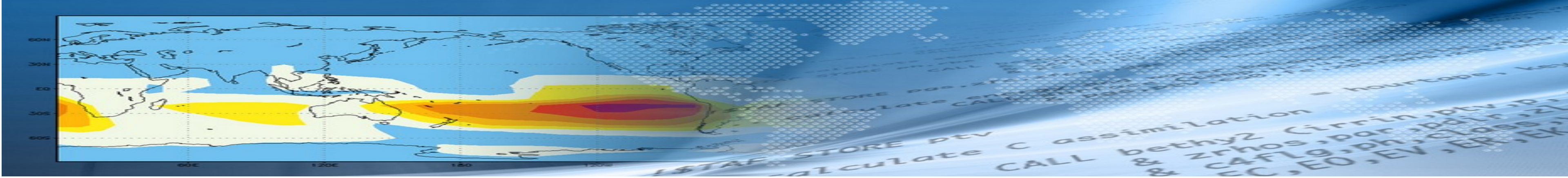

Harmonisation of microwave humidity sounder time series for climate applications

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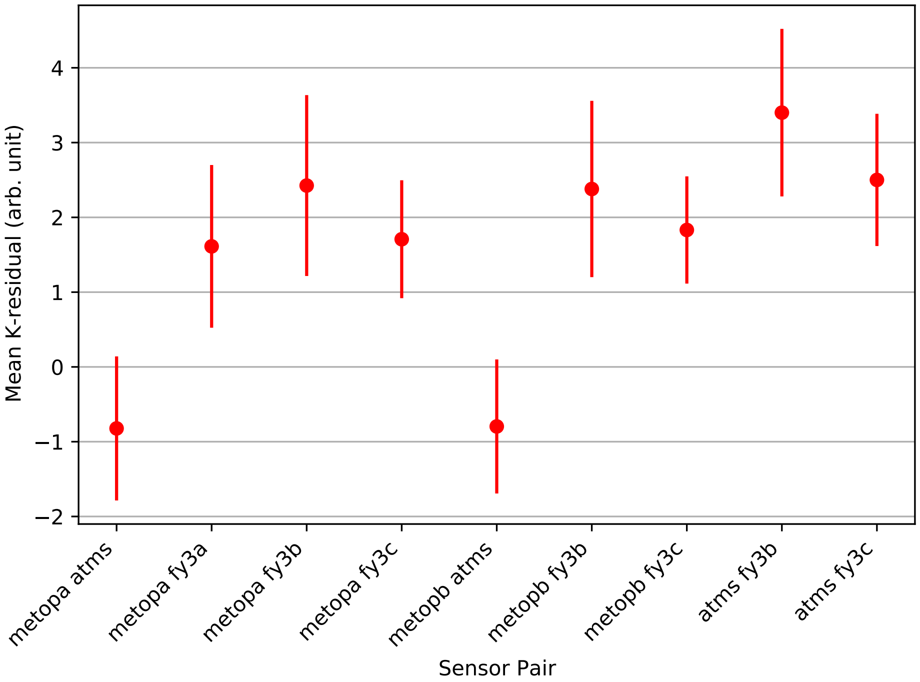
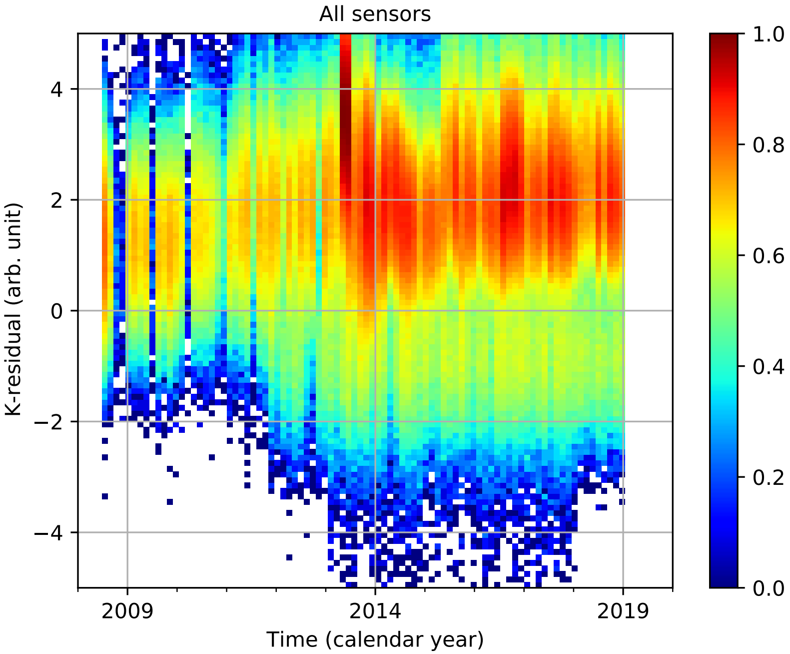
1) FastOpt, Hamburg, Germany

2) EUMETSAT

Motivation: microwave sensor differences

Channel 183.31 ±1 GHz





- Large offsets
- Some differences change with time

Inter-satellite re-calibration

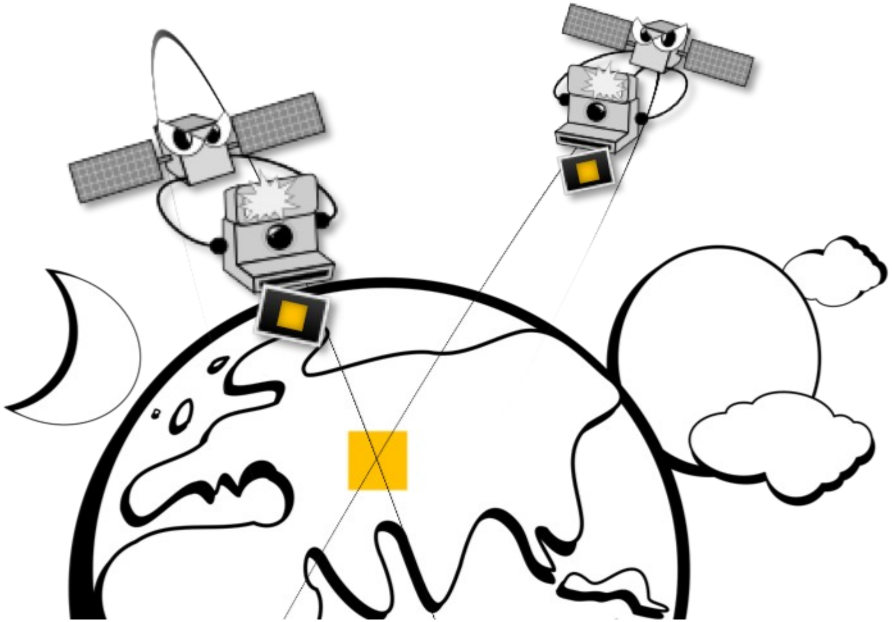
Motivation:

- long term Climate Data Records (CDR’s) need to combine observations from several sensors
- **but** there are unexpected **sensor to sensor differences** even after careful calibration

Methods:

- bias and trend correction is applied after calibration on >Level-1b data
- homogenisation does not take differences in Spectral Response Function (SRF) into account
- harmonisation (inter-satellite re-calibration)
  - based on measurement equations
  - given SRF differences are taken into account
  - uses fundamental measurements, i.e. counts in level-1a data
  - considers all uncertainties, **metrological** based approach
  - uses simultaneous overpasses or **match-ups**

Match-ups



Sensors on satellites looking

- at the same **area** on earth
- at the same **time**
- from the same **distance**
- with the same **viewing angle**
- with the same photon **sensitivity**

shall measure the same radiance

Here we assume

- largely overlapping **area**
- small **time** difference
- small **viewing angle** differences
- differences in Spectral Response Functions (SRF)

Due to the spatial and temporal variability of the radiances these intervalls add a match-up uncertainty

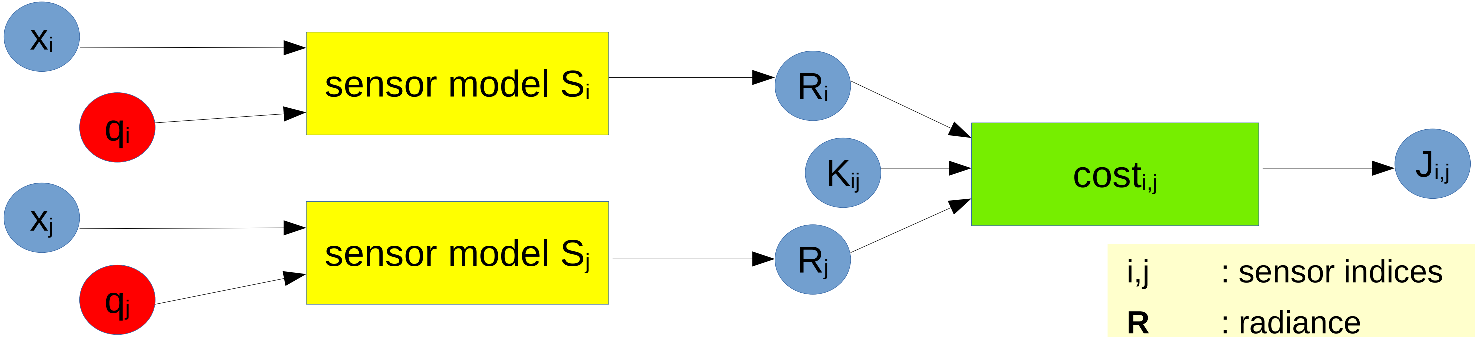
Harmonisation

Solution:

- From simultaneous overpasses of satellites match-up data sets are derived.
- Additional ‘warm’ match-ups of targets varying slowly based on geostationary satellites are used.
- Uncertainty of each fundamental datum is assessed.
- Expected differences in radiance due to different SRF are calculated.
  Uncertainty of expected differences is assessed.
- Uncertainty in radiance difference due to match-up is assessed. Zero mean difference is assumed.
- A Bayesian based cost function (J) is defined to quantify the sensor to sensor misfit.
- The cost function is minimized by changing parameters of the sensors measurement equation.
- Parameters (x) can be polynomial coefficients and/or calibration coefficients determined pre-launch or in-orbit.
- Certain other parameters (**sensor state variables** q) of the measurement equation have uncertainties to be considered
- All derivative code generated by Automatic Differentiation (AD)

- **M**arginalised **E**rror **I**n **V**ariables (MEIV) method:
  - does not optimize sensor state variables (q)
  - substabtially reduced memory and computing time resources
  - takes all uncertainties into account (including correlation)

Harmonisation Framework



$$J = \sum_{i,j,i<j} J_{i,j}$$

$$J_{i,j} = \frac{1}{2}(R_i - R_j - K_{ij})^t \, (C_i + C_j + C_{kij})^{-1} \, (R_i - R_j - K_{ij})$$

$$\boxed{R_i = S_i(x_i, q_i)}$$

$$C_i = \left(\frac{\partial S_i}{\partial q_i}\right) W \; C_q \; W^t \left(\frac{\partial S_i}{\partial q_i}\right)^t$$

i,j : sensor indices

R : radiance

K : expected difference in radiance

J : cost function

X : calibration parameters of sensor model

q : sensor state variables

C : error covariance matrix

C_{kij} : uncertainty of match and expected difference in radiance

C_i : uncertainty of sensor radiance

W : averaging matrix

C_q : uncertainty of sensor state variables

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Harmonisation Framework MEIV

C_i is **huge**, handling and inverting a huge matrix is expensive
==> using matrix free algorithms

$$J_{i,j} = \frac{1}{2}(R_i - R_j - K_{ij})^t \, (C_i + C_j + C_{kij})^{-1} \, (R_i - R_j - K_{ij})$$

$(C_i + C_j + C_{kij})^{-1} \, (R_i - R_j - K_{ij})$ by solving $(C_i + C_j + C_{kij}) \; x = (R_i - R_j - K_{ij})$ using conjugate gradient solver

$$C_i \; x = \left(\frac{\partial S_i}{\partial q_i}\right) \; W \; C_q \; W^t \; \left(\frac{\partial S_i}{\partial q_i}\right)^t x$$

$\left(\frac{\partial S_i}{\partial q_i}\right)^t x$ matrix free by <u>reverse/adjoint</u> mode Automatic Differentiation

$\frac{\partial S_i}{\partial q_i} v$ matrix free by <u>forward/tangent</u> mode AD

minimization of **J** by limited memory quasi Newton BFGS algorithm using:

$\frac{\partial J}{\partial x}$ gradient by <u>reverse/adjoint</u> mode AD

measurement equations METOP-A,B (MHS)

Antenna temperature by Planck law

$$R_{OBCT} = Planck\left(T_{OBCT}\right)$$

$$R_{DSV} = Planck\left(T_{DSV}\right)$$

Two-point calibration

$$a = \frac{R_{OBCT} - R_{DSV}}{C_{OBCT} - C_{DSV}}$$

$$R_{ME} = R_{OBCT} + a * \left(C_E - C_{OBCT}\right) + u * a^2 * \left(C_E - C_{DSV}\right) * \left(C_E - C_{OBCT}\right)$$

Antenna Pattern Correction (APC)

$$R = \frac{1}{g_E} * \left[R_{ME} - \left(1 - g_E\right) * R_{DSV}\right]$$

Brightness temperature by inverse Planck law

$$T = Planck^{-1}(R)$$

R : radiance
T : brightness temperature
ν : frequence

<u>sensor state variables:</u>
C_{DSV} : Deep Space View counts
C_E : Earth counts
C_{OBCT} : On Board Calibration Target counts
u : non-linearity factor
g_E : portion from Earth (APC)

🟩 3 varied parameters

Planck law

$$R = \frac{\left(2hc^2 * \nu^3\right)}{\left(e^{\left(\left(hc/k_b * \nu\right)/T\right)} - 1\right)}$$

inverse Planck law

$$T = \frac{hc/k_b * \nu}{\log\left(\frac{2hc^2\nu^3}{R} + 1\right)}$$

measurement equations Fengyun-3A (MWHS)

Antenna temperature by Planck law

$$R_{OBCT} = Planck\left(T_{OBCT}\right)$$

$$R_{DSV} = Planck\left(T_{DSV}\right)$$

sensor state variables:

C_{DSV} : Deep Space View counts
C_E : Earth counts
C_{OBCT} : On Board Calibration Target counts
R_{OBCT} : On Board Calibration Target radiance
u_i : coefficients of APC
APC_1 : pixel dependent Antenna Pattern Correction

Two-point calibration

$$a = \frac{R_{OBCT} - R_{DSV}}{C_{OBCT} - C_{DSV}}$$

$$R_{ME} = R_{OBCT} + a * \left(C_E - C_{OBCT}\right)$$

🟩 3 varied parameters

Brightness temperature by inverse Planck law

$$T_{ME} = Planck^{-1}\left(R_{ME}\right)$$

Non linear correction

$$T_{nl} = \boxed{u}_1 + \boxed{u}_2 * T_{ME} + \boxed{u}_3 * T_{ME}^2$$

Antenna Pattern Correction

$$T = APC_1 + APC_2 * T_{nl}$$

measurement equations Fengyun-3B/C (MWHS/MWHS2)

Antenna temperature by Planck law

$$R_{OBCT} = Planck\left(\boxed{T_{OBCT}}\right)$$

$$R_{DSV} = Planck\left(\boxed{T_{DSV}}\right)$$

Two-point calibration

$$a = \frac{R_{OBCT} - R_{DSV}}{C_{OBCT} - C_{DSV}}$$

$$R_{ME} = R_{OBCT} + a * \left(C_E - C_{OBCT}\right) + \boxed{u} * a^2 * \left(C_E - C_{DSV}\right) * \left(C_E - C_{OBCT}\right)$$

Brightness temperature by inverse Planck law

$$T_{ME} = Planck^{-1}\left(R_{ME}\right)$$

Antenna Pattern Correction

$$T = APC_1 + APC_2 * T_{ME}$$

<u>sensor state variables:</u>

C_{DSV} : Deep Space View counts

C_E : Earth counts

C_{OBCT} : On Board Calibration Target counts

R_{OBCT} : On Board Calibration Target radiance

u : non-linearity factor

APC_1 : pixel dependent Antenna Pattern Correction

🟩 3 varied parameters

measurement equations SNPP (ATMS)

Cold and warm target temperatures

$$T_C = A + B\left(T_{COSMIC} + \boxed{dT_C}\right)$$
$$T_W = A + B\left(T_{OBCT} + \boxed{dT_W}\right)$$

Antenna temperature

$$T_{lin} = T_W + \left(C_E - C_{OBCT}\right) * \frac{T_W - T_C}{C_{OBCT} - C_{DSV}}$$

Non-linear correction

$$T_{nonlin} = T_{lin} + \boxed{u} * \left(1 - 4\left(\frac{T_{lin} - T_E}{T_W - T_C} - 0.5\right)^2\right)$$

Antenna Pattern Correction

$$T = T_{nonlin} - APC$$

<u>sensor state variables:</u>

C_{DSV} : Deep Space View counts
C_E : Earth counts
C_{OBCT} : On Board Calibration Target counts
u : non-linearity factor
APC : pixel dependent Antenna Pattern Correction

🟩 3 varied parameters

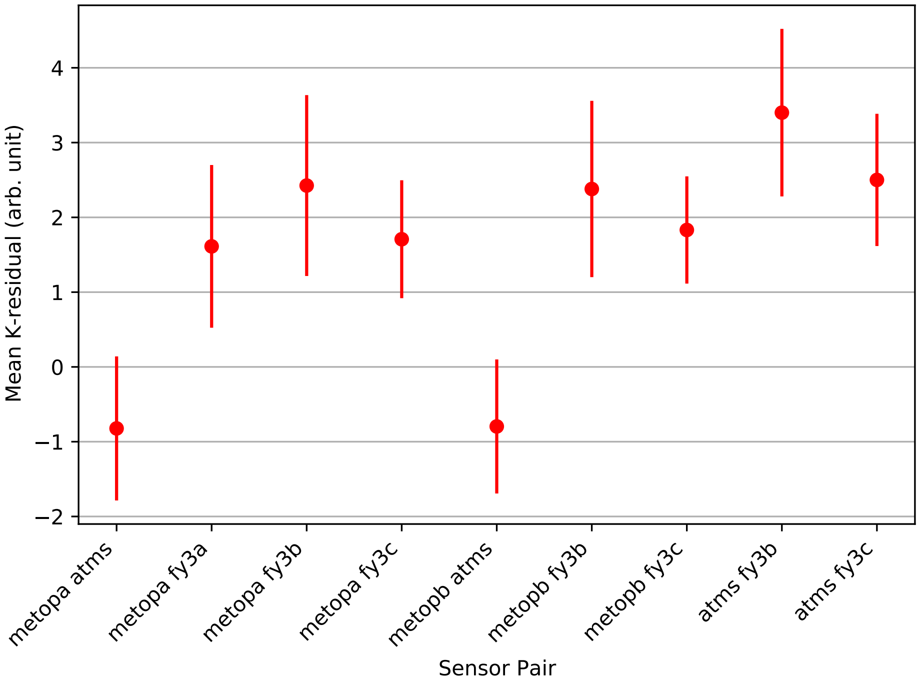
Harmonisation setup for microwave

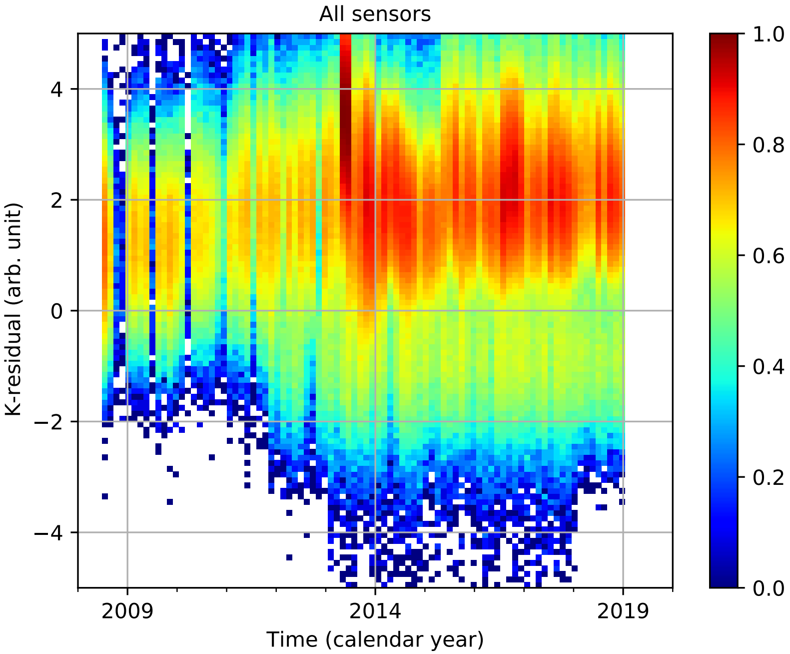
Sensors: **MetOp-A**, MetOp-B, ATMS, Fengyun-3A, -3B, -3C

- Cold match-ups:
  - difference in space: 10 km
  - difference in time: **5 min**
  - difference in viewing angle: ratio of path length < 0.05
- Intermediate warm match-ups, LEO-GEO:
  - MVIRI homogene 3x3pixel scene, std.dev. < 1 K
  - MVIRI ΔT < 1 K
  - difference in space: 4 km
  - difference in time: 5 min
  - difference in viewing angle: ratio of path length < 0.05
- Warm match-ups, LEO-LEO:
  - difference in space: 10 km
  - difference in time: **6 hours**
  - difference in viewing angle: ratio of path length < 0.05
- 1.5 million match-ups by 9 sensor pairs
- Channel 183.31 ±1 GHz, also available are ±3 GHz, and ±7 GHz
- 15 parameters to optimise: 5 sensors a 3 parameters
- one sensor serves as **reference**, i.e. only radiances with uncertainties are used
  (not necessary, can be replaced by additional constraint on parameters)

Microwave sensor differences

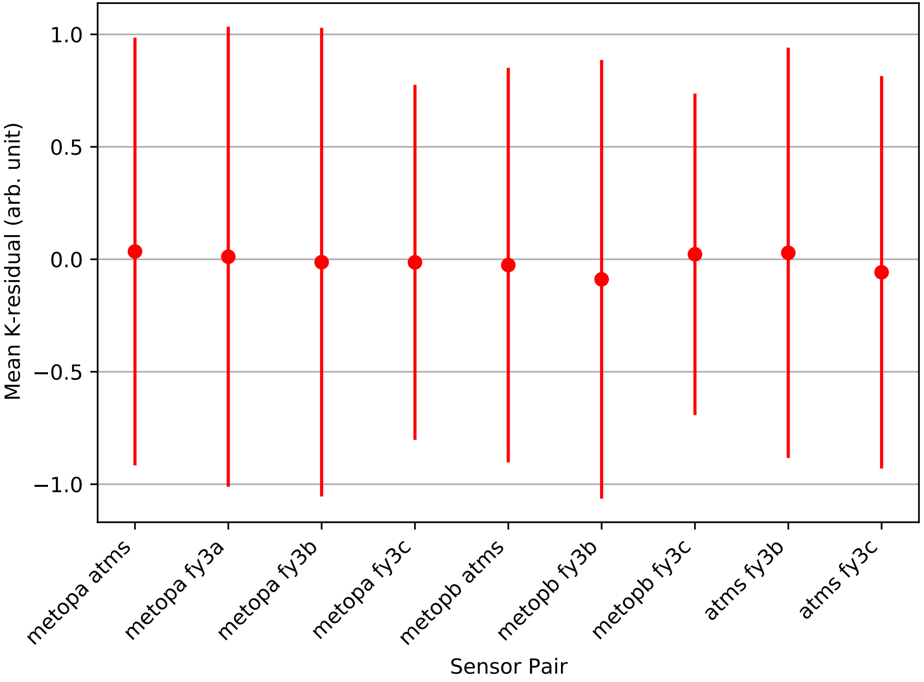
Channel 183.31 ±1 GHz

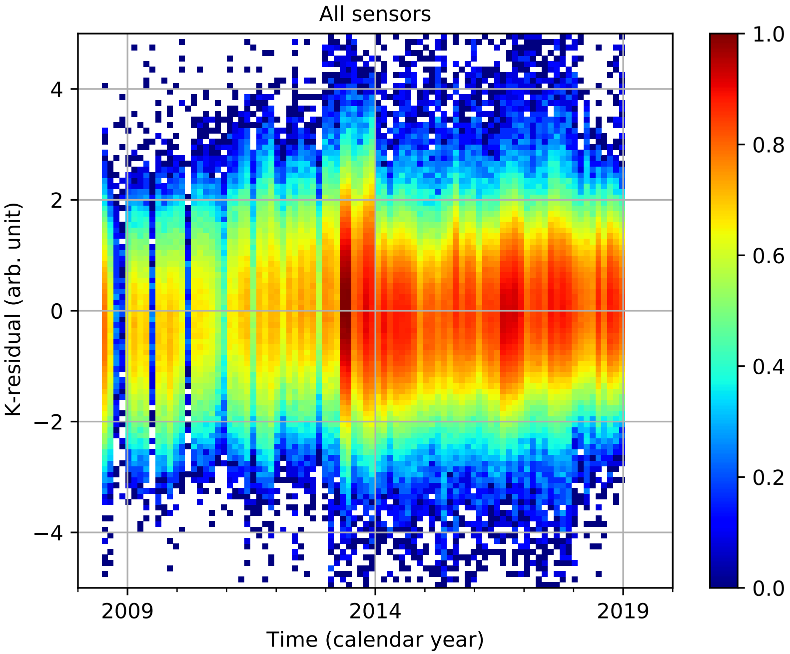




Residuals after harmonisation

Channel 183.31 ±1 GHz





- mean residuals are close to zero
- distribution is similar for all pairs
- a problematic sensor would stand out

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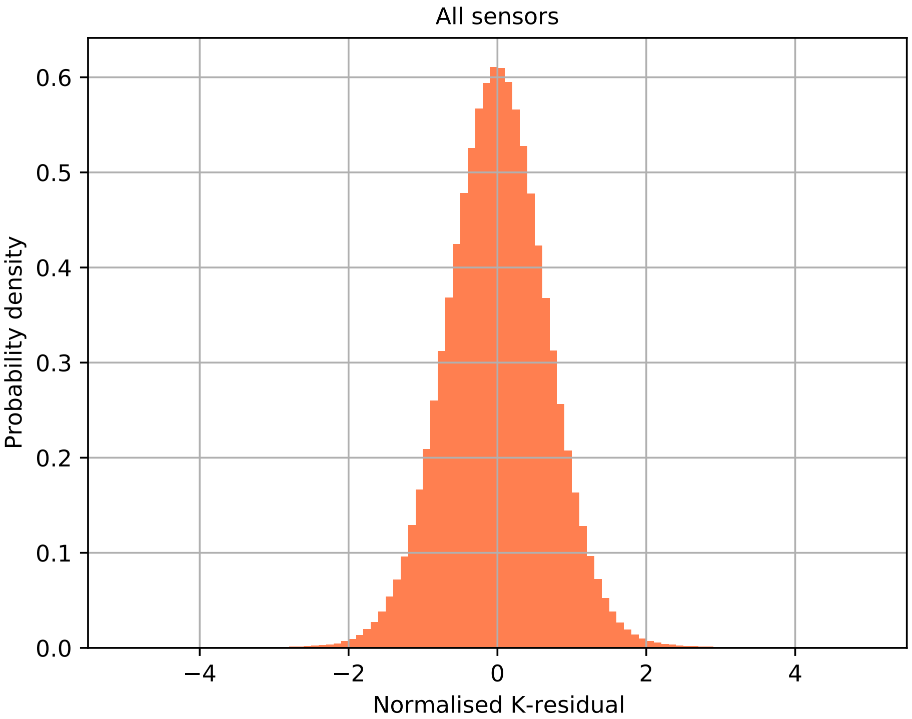
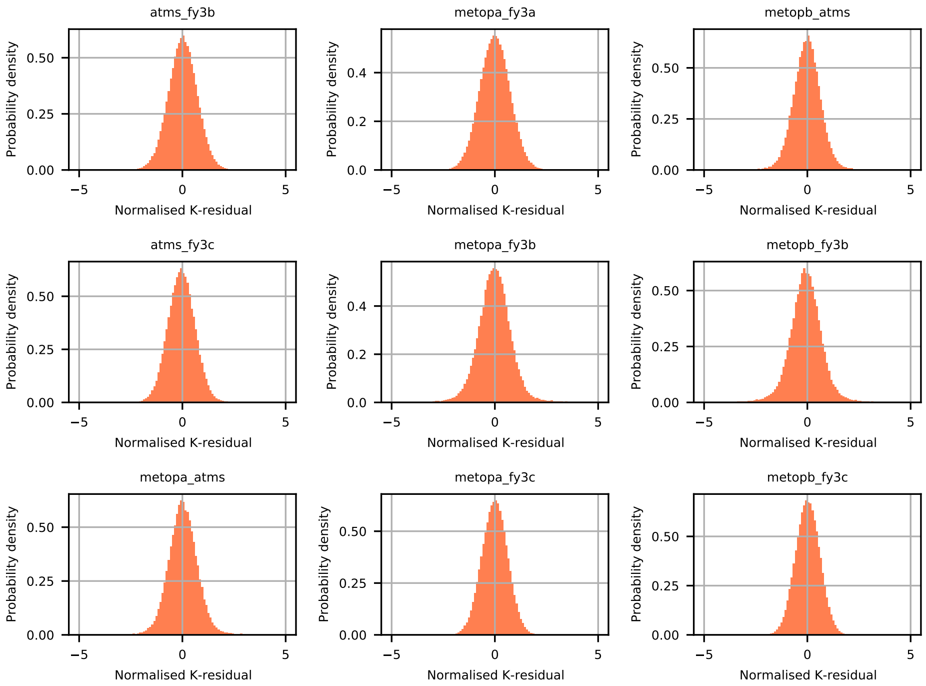
Distribution of residuals





Final residuals are
allmost Gaussian distributed.

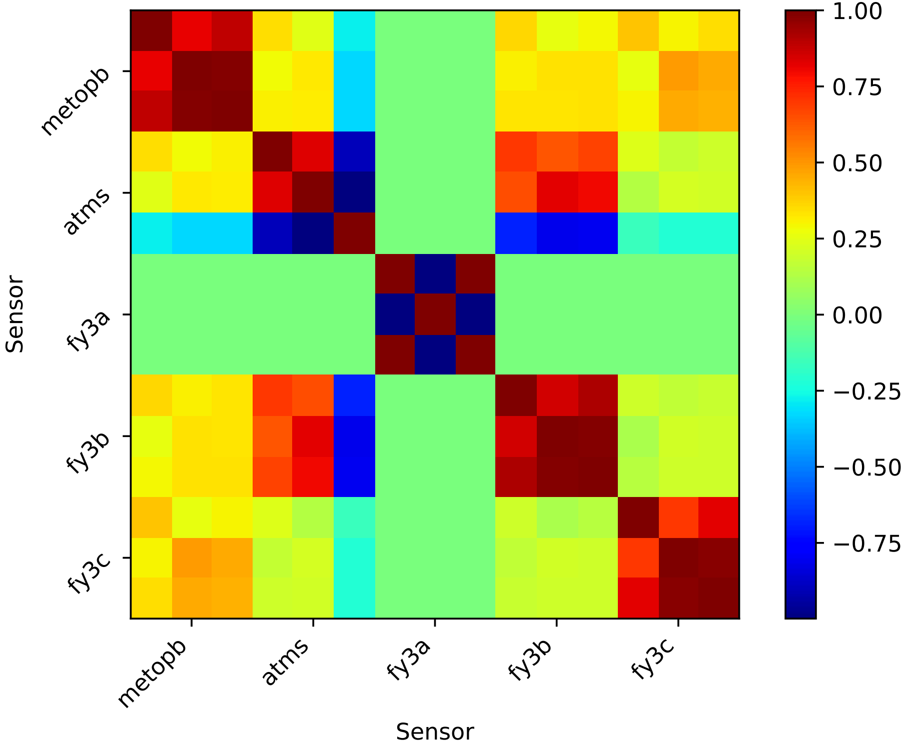
Posterior uncertainty covariance matrix

$$C_i = \left(\frac{\partial J^2}{\partial x^2}\right)^{-1}$$

posterior uncertainty covariance is inverse Hessian

$$\frac{\partial J^2}{\partial x^2}$$

Full Hessian by vector forward over scalar reverse mode AD



correlation matrix

Please note, correlation is covariance divided by variance

Conclusions

- Harmonisation of Microwave sensors based on MEIV successful
  - misfit is reduced substantially
  - posterior statistics are consistent with assumptions
  - full range coverage by including ‘warm’ match-ups from targets changing slowly
- For good results, estimation and propagation of uncertainties is important
- Automatic Differentiation (AD) with TAF (Transformation of Algorithm in Fortran) greatly helped
  - only function code must be written
  - efficient derivative codes generated ‘on the fly’
  - can operate in scalar mode for matrix free uncertainty propagation
    or vector mode for full Jacobian/Hessian computation
- Optimal parameters are used to produce new FCDR’s with uncertainties
- Algorithm published in remote sensing 2019, 11(9), 1002; https://doi.org/10.3390/rs11091002

Outlook

- Analysis of remaining misfit
  - revisit measurement equation formulation
  - introduce new parameter in measurement equation
- Simultaneous harmonisation of several channels if the misfit is correlated (eg. HIRS)
- MEIV Harmonisation can be extended to use other sources of information
  - simulated radiances
  - known targets