On the reprocessing of GOCE gravity gradients

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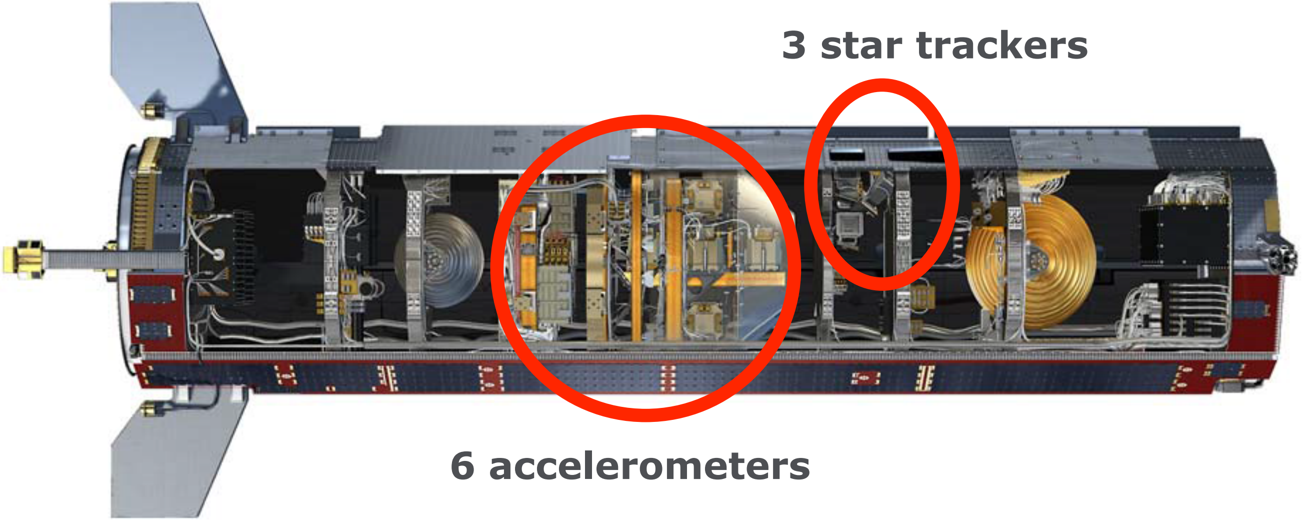
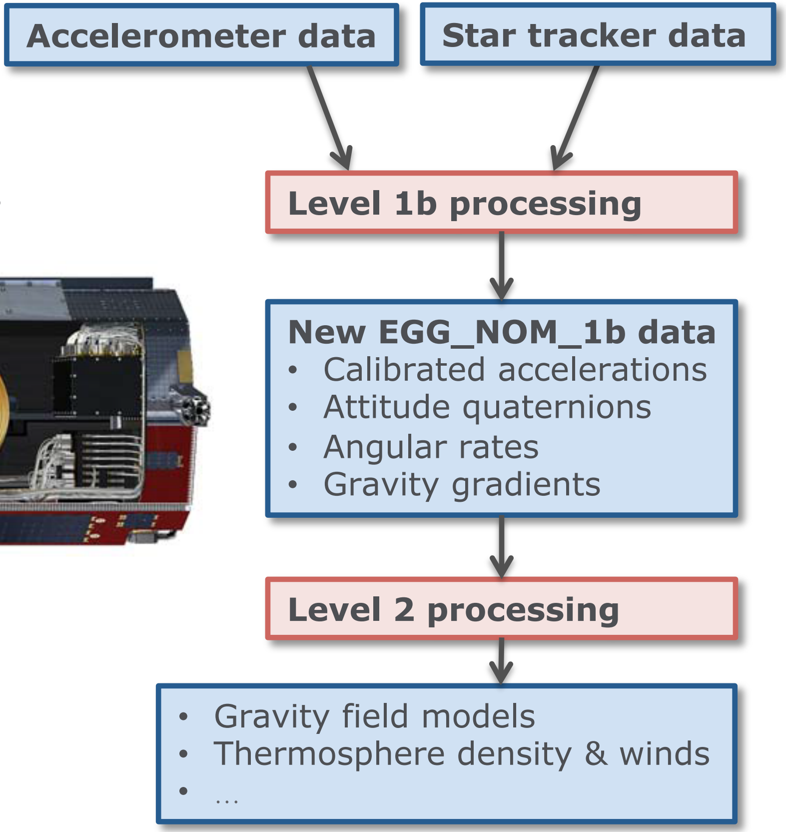
Roger Haagmans, Rune Floberghagen, Björn Frommknecht

13 April 2018

Introduction





Accelerometer data

Star tracker data

Level 1b processing

New EGG_NOM_1b data
- Calibrated accelerations
- Attitude quaternions
- Angular rates
- Gravity gradients

Level 2 processing

- Gravity field models
- Thermosphere density & winds
- …

GOCE gradiometer Level 1b processing

Each accelerometer measures in the rotating gradiometer frame

$$\boldsymbol{a}_i = -(\boldsymbol{V} - \boldsymbol{\Omega}^2 - \dot{\boldsymbol{\Omega}})\boldsymbol{r}_i + \boldsymbol{d}$$

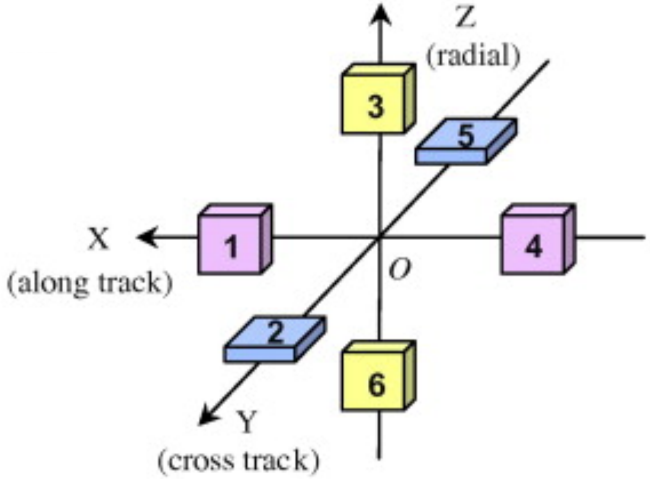
Non-gravitational

Gravity gradient

Centrifugal

Euler

Position with respect to center of mass



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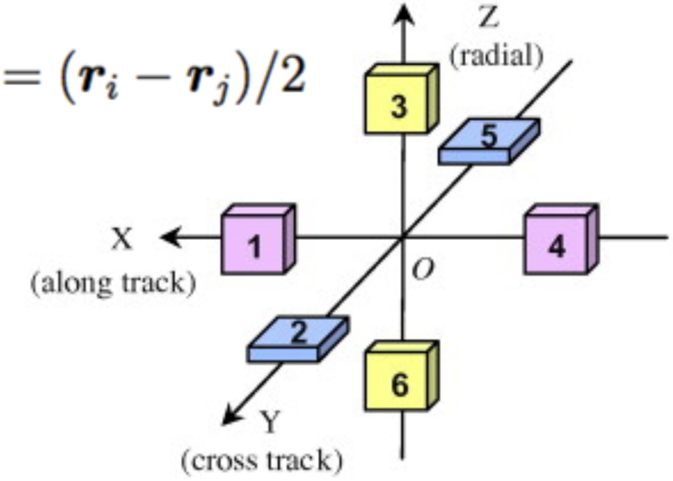
Position with respect to center of mass

Disaggregate (ij = 14, 25, 36)

$$\boldsymbol{a}_{cij} = (\boldsymbol{a}_i + \boldsymbol{a}_j)/2 = \boldsymbol{d}$$

$$\boldsymbol{a}_{dij} = (\boldsymbol{a}_i - \boldsymbol{a}_j)/2 = -(\boldsymbol{V} - \boldsymbol{\Omega}^2 - \dot{\boldsymbol{\Omega}})\boldsymbol{r}_{dij}$$

$$\boldsymbol{r}_{dij} = (\boldsymbol{r}_i - \boldsymbol{r}_j)/2$$



GOCE gradiometer Level 1b processing

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$$\boldsymbol{a}_i = -(\underbrace{\boldsymbol{V}}_{\text{Gravity gradient}} - \underbrace{\boldsymbol{\Omega}^2}_{\text{Centrifugal}} - \underbrace{\dot{\boldsymbol{\Omega}}}_{\text{Euler}})\underbrace{\boldsymbol{r}_i}_{\text{Position with respect to center of mass}} + \underbrace{\boldsymbol{d}}_{\text{Non-gravitational}}$$

Disaggregate (ij = 14, 25, 36)

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$$\boldsymbol{A}_d\boldsymbol{R}_d^{-1} + (\boldsymbol{A}_d\boldsymbol{R}_d^{-1})^T = -2\,(\boldsymbol{V} - \boldsymbol{\Omega}^2) \qquad \boldsymbol{A}_d = \begin{bmatrix}\boldsymbol{a}_{d14} & \boldsymbol{a}_{d25} & \boldsymbol{a}_{d36}\end{bmatrix}$$

$$\boldsymbol{A}_d\boldsymbol{R}_d^{-1} - (\boldsymbol{A}_d\boldsymbol{R}_d^{-1})^T = 2\,\dot{\boldsymbol{\Omega}} \qquad \boldsymbol{R}_d = \begin{bmatrix}\boldsymbol{r}_{d14} & \boldsymbol{r}_{d25} & \boldsymbol{r}_{d36}\end{bmatrix}$$

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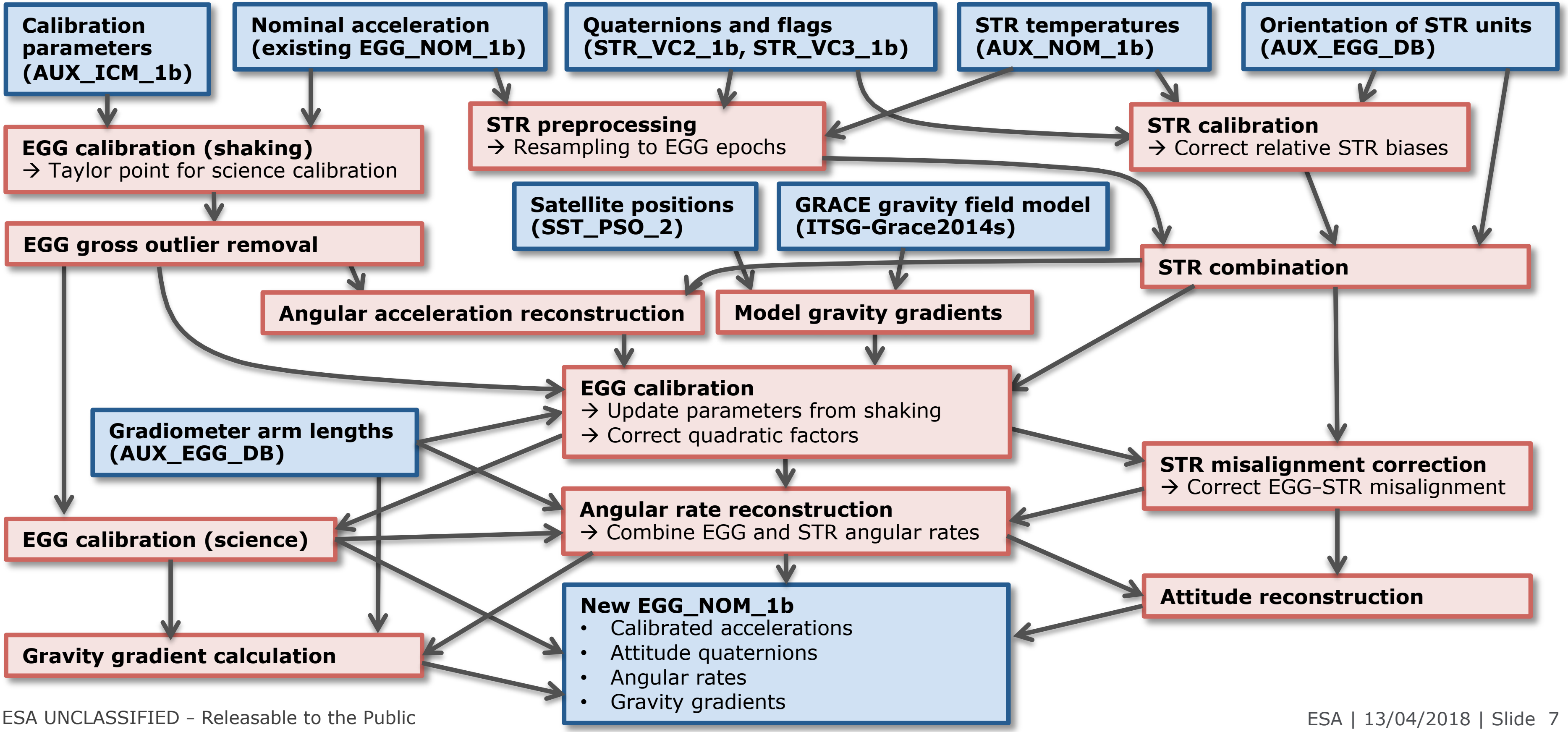
Combine with star tracker data

GOCE gradiometer Level 1b processing



Calibration parameters (AUX_ICM_1b)

Nominal acceleration (existing EGG_NOM_1b)

Quaternions and flags (STR_VC2_1b, STR_VC3_1b)

STR temperatures (AUX_NOM_1b)

Orientation of STR units (AUX_EGG_DB)

STR preprocessing
→ Resampling to EGG epochs

STR calibration
→ Correct relative STR biases

EGG calibration (shaking)
→ Taylor point for science calibration

Satellite positions (SST_PSO_2)

GRACE gravity field model (ITSG-Grace2014s)

EGG gross outlier removal

STR combination

Angular acceleration reconstruction

Model gravity gradients

EGG calibration
→ Update parameters from shaking
→ Correct quadratic factors

Gradiometer arm lengths (AUX_EGG_DB)

STR misalignment correction
→ Correct EGG-STR misalignment

Angular rate reconstruction
→ Combine EGG and STR angular rates

EGG calibration (science)

Attitude reconstruction

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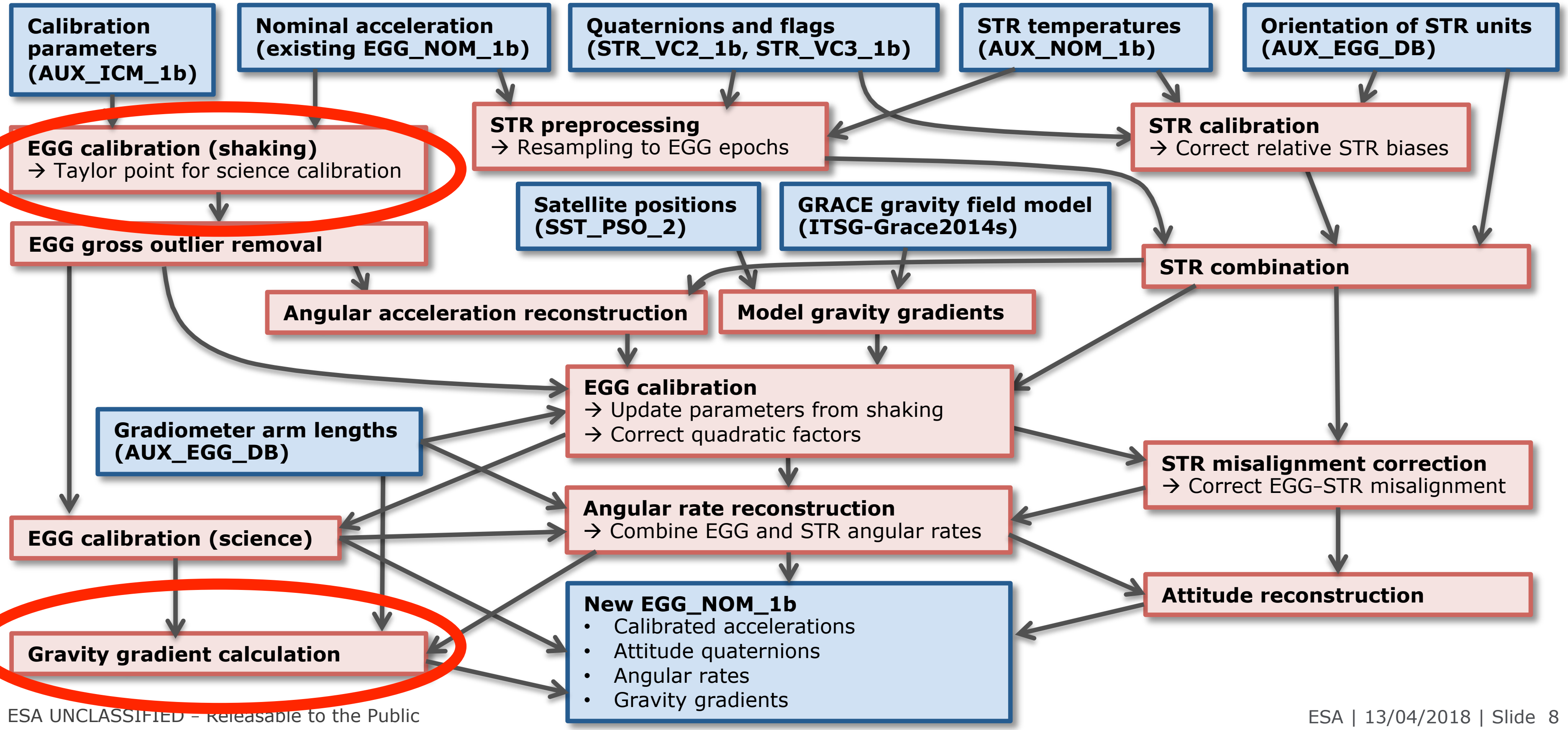
Gravity gradient calculation

GOCE gradiometer Level 1b processing



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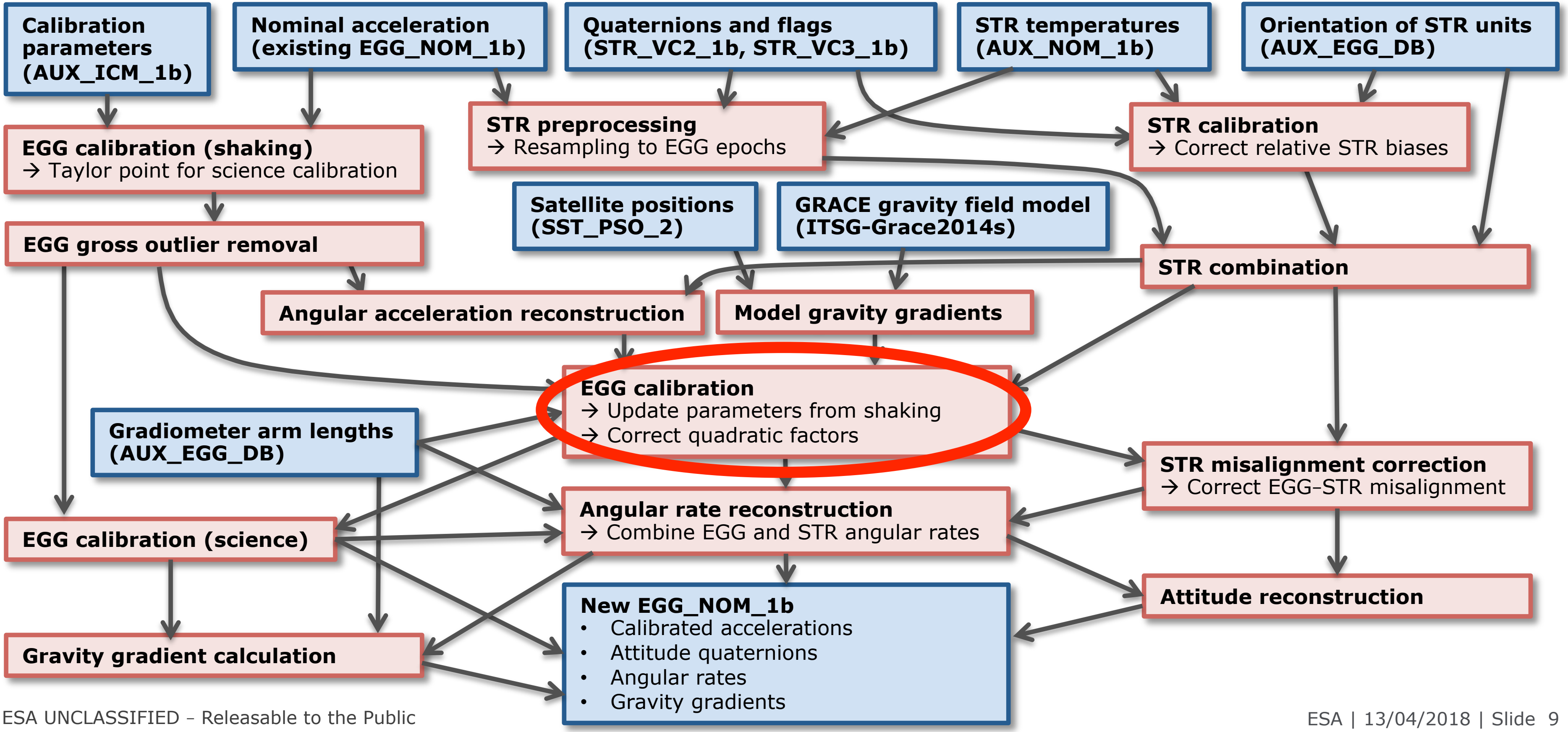

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Gravity gradient calculation

Gradiometer calibration: Observation equations

$$\boldsymbol{V}^{\text{GRACE model}} = -\frac{1}{2}(\boldsymbol{A}_d\boldsymbol{R}_d^{-1} + (\boldsymbol{A}_d\boldsymbol{R}_d^{-1})^T) + \boldsymbol{\Omega}^2$$

$$\boldsymbol{\Omega}^{\text{star trackers}} = \int \dot{\boldsymbol{\Omega}}\, dt = -\frac{1}{2}\int \boldsymbol{A}_d\boldsymbol{R}_d^{-1} - (\boldsymbol{A}_d\boldsymbol{R}_d^{-1})^T\, dt$$

$$\boldsymbol{a}_{cij} = \boldsymbol{a}_{ckl}$$

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Weakly non-linear through attitude

Non-linear via angular rates

$$\boldsymbol{\Omega}^{\text{star trackers}} = \int \dot{\boldsymbol{\Omega}}\,dt = -\frac{1}{2}\int \boldsymbol{A}_d\boldsymbol{R}_d^{-1} - (\boldsymbol{A}_d\boldsymbol{R}_d^{-1})^T\,dt$$

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$$\boldsymbol{a}_{cij} = \boldsymbol{a}_{ckl}$$

Use observations from science mode (as opposed to shaking mode)

Gradiometer calibration: Model parameters

For each gradiometer arm (ij = 14, 25, 36) per two months:

$$\begin{bmatrix}\boldsymbol{a}_{dij}\\ \boldsymbol{a}_{cij}\end{bmatrix} = \begin{bmatrix}\boldsymbol{C}_{ij} & \boldsymbol{D}_{ij}\\ \boldsymbol{D}_{ij} & \boldsymbol{C}_{ij}\end{bmatrix}\begin{bmatrix}\hat{\boldsymbol{a}}_{dij}\\ \hat{\boldsymbol{a}}_{cij}\end{bmatrix} + \begin{bmatrix}\boldsymbol{K}_i & \boldsymbol{K}_j\\ \boldsymbol{K}_i & -\boldsymbol{K}_j\end{bmatrix}\begin{bmatrix}\hat{\boldsymbol{a}}_i^2\\ \hat{\boldsymbol{a}}_j^2\end{bmatrix} + \begin{bmatrix}\boldsymbol{W}_{dij}\\ \boldsymbol{W}_{cij}\end{bmatrix}\dot{\boldsymbol{\omega}}$$

18 quadratic factors

Inverse calibration matrices (ICMs):
54 parameters + 54 parameter drifts

18 angular couplings

3 misalignments between
gradiometer and star trackers

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new

18 quadratic factors

Inverse calibration matrices (ICMs):
54 parameters + 54 parameter drifts

18 angular couplings

3 misalignments between
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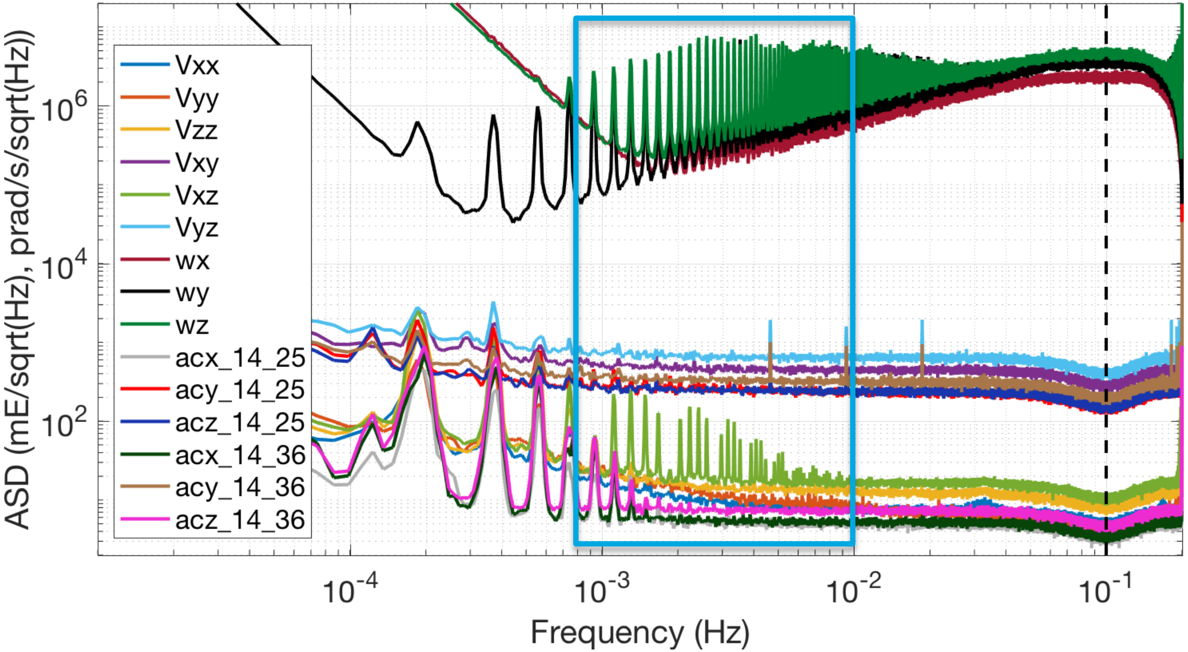
Gradiometer calibration: Stochastic model

Welch’s method for estimating the PSD where median replaces the average for robustness

Additional band-pass filter 0.8−10 mHz



Results

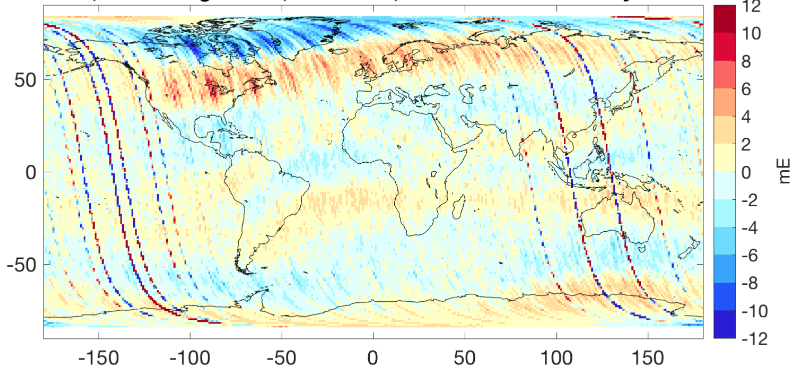
16 March – 22 May 2012

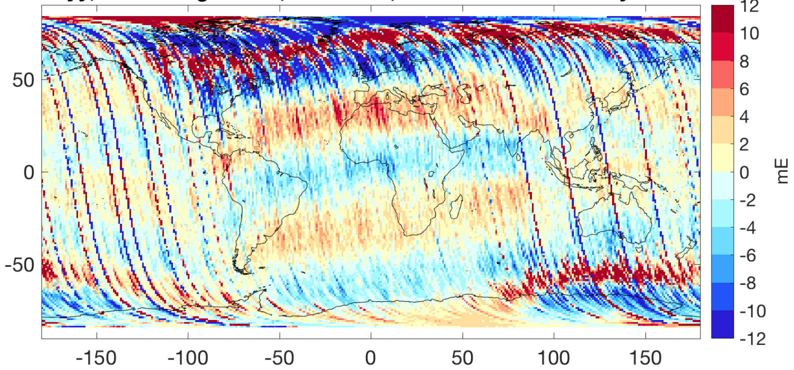
→ Towards the end of mission lifetime, but not yet at lower altitude

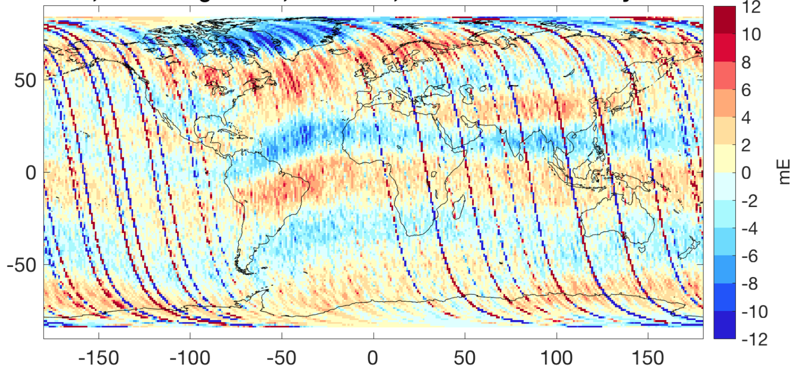
Compare GOCE gradients with GRACE model (ITGS-Grace2014k)

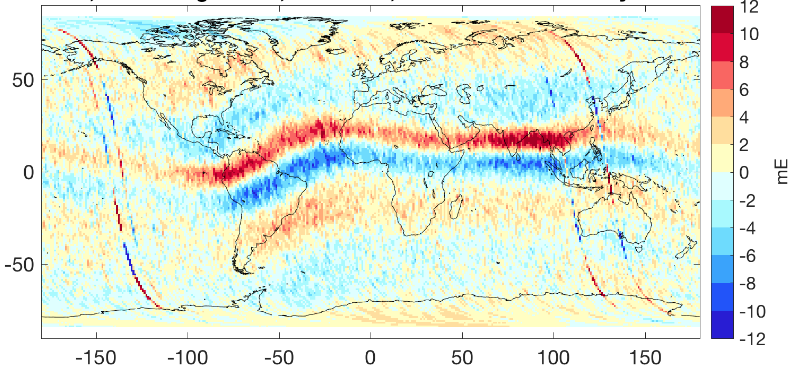
→ For maps: band-pass filter to 1-10 mHz, in which most systematic effects could be removed

Results

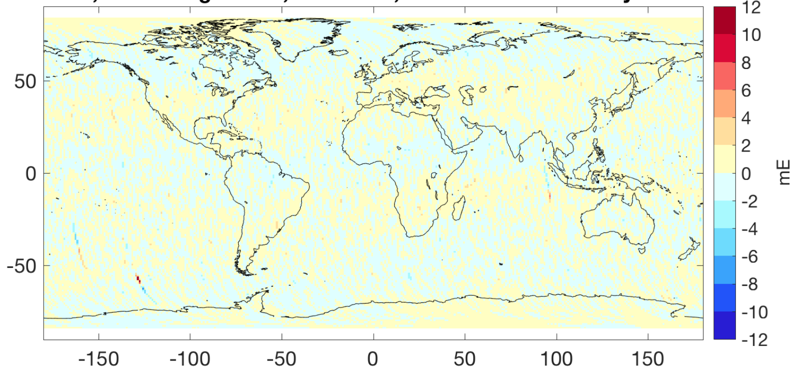

Vxx, ascending tracks, 1-10 mHz, 16-Mar-2012 - 22-May-2012


Vyy, ascending tracks, 1-10 mHz, 16-Mar-2012 - 22-May-2012


Vzz, ascending tracks, 1-10 mHz, 16-Mar-2012 - 22-May-2012


Vxz, ascending tracks, 1-10 mHz, 16-Mar-2012 - 22-May-2012

Results



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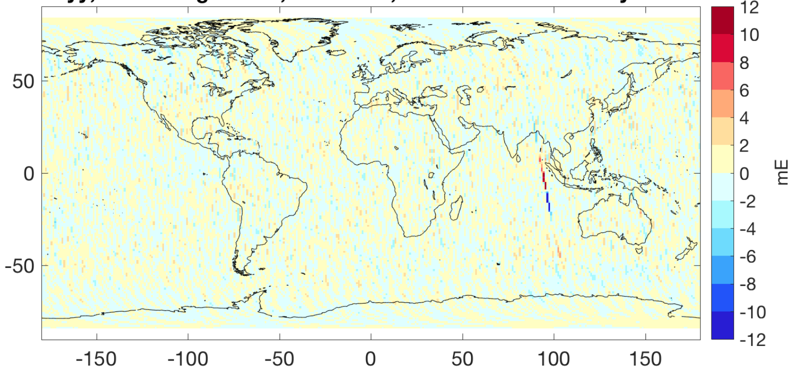
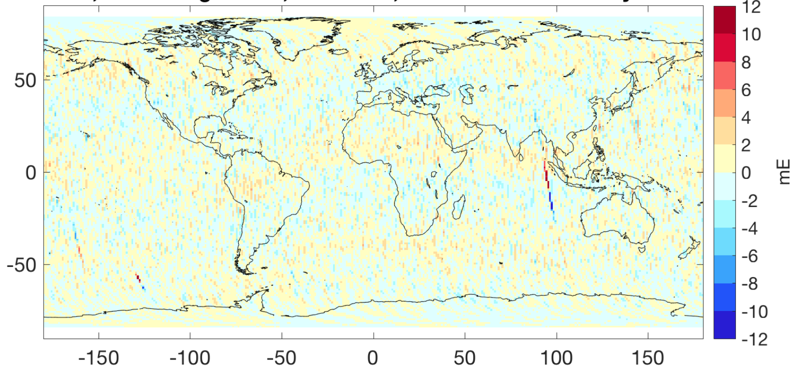
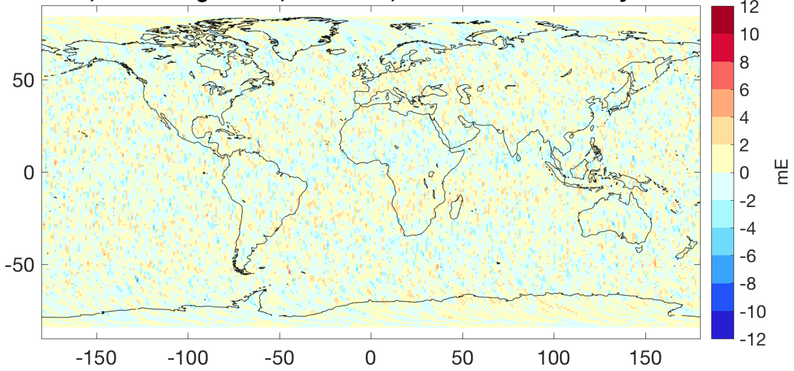


Vyy, ascending tracks, 1-10 mHz, 16-Mar-2012 - 22-May-2012

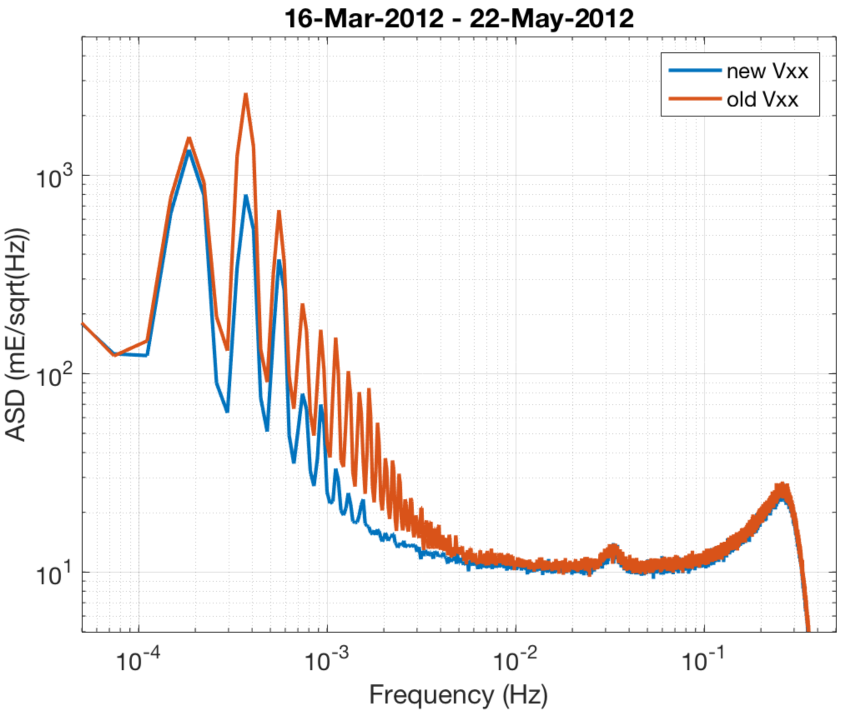


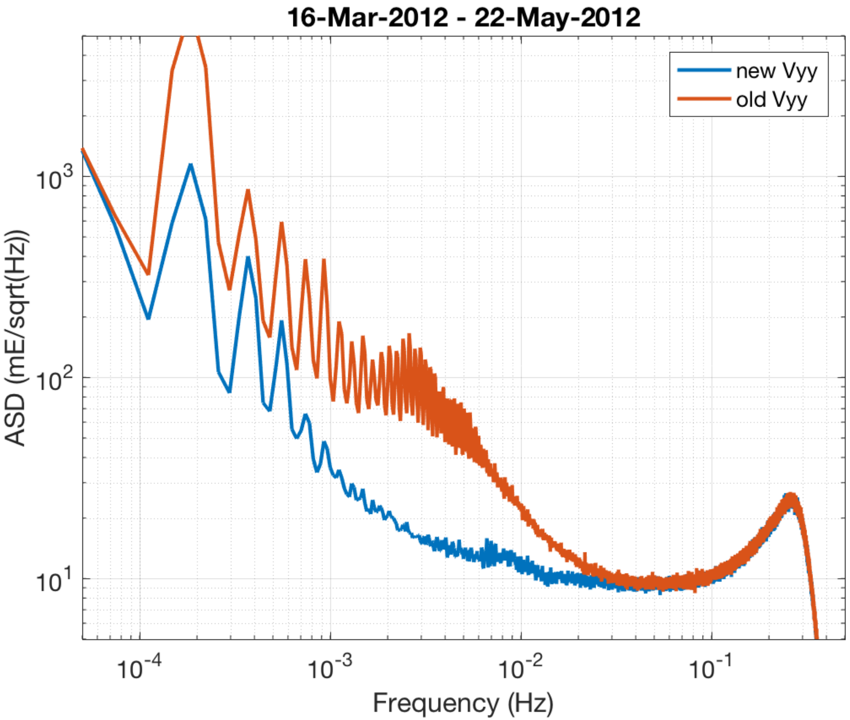
Vzz, ascending tracks, 1-10 mHz, 16-Mar-2012 - 22-May-2012



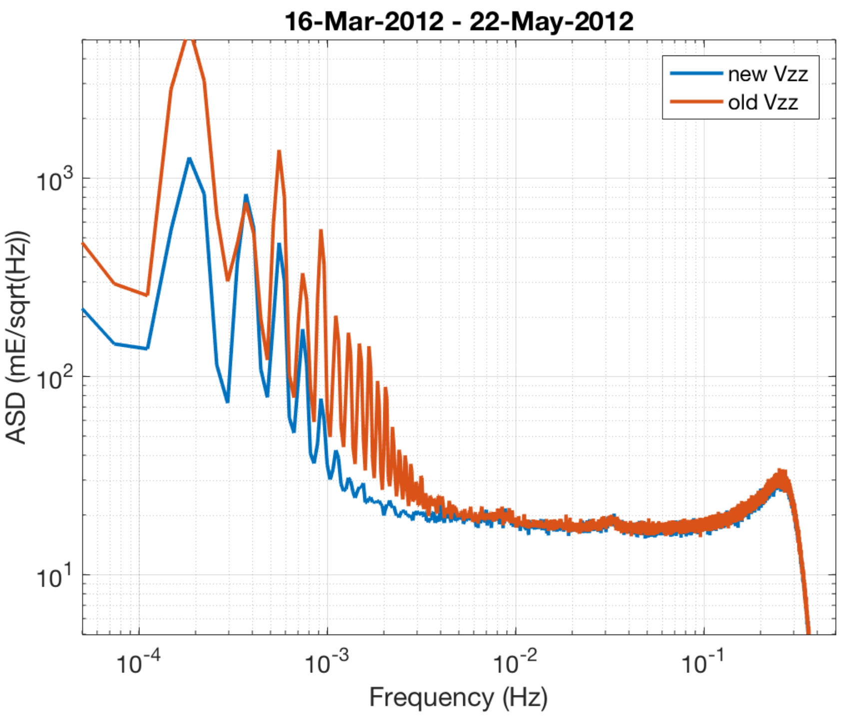
Vxz, ascending tracks, 1-10 mHz, 16-Mar-2012 - 22-May-2012

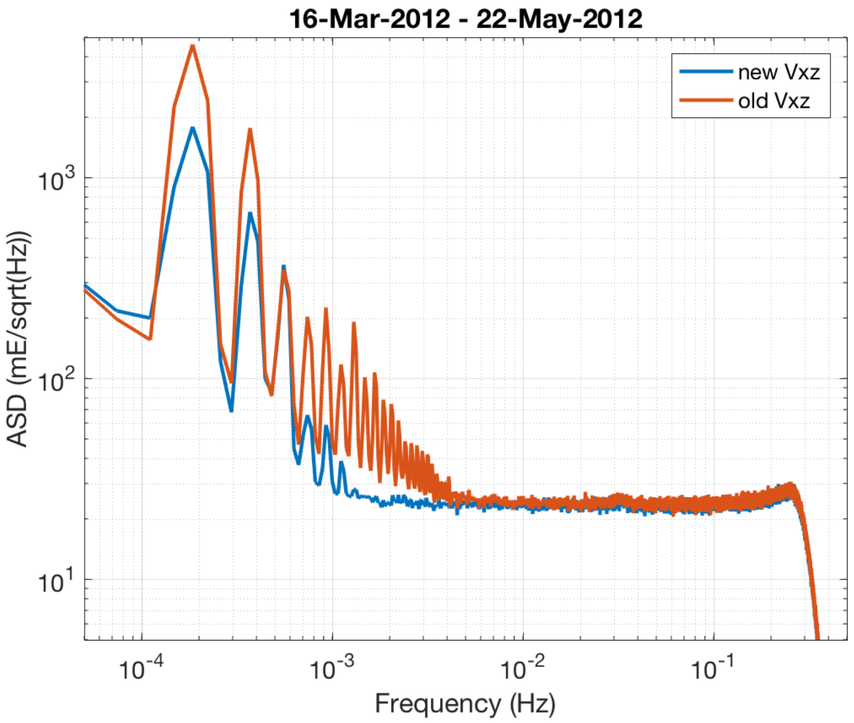
Results


16-Mar-2012 - 22-May-2012
new Vxx
old Vxx
ASD (mE/sqrt(Hz))
10^3
10^2
10^1
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Frequency (Hz)

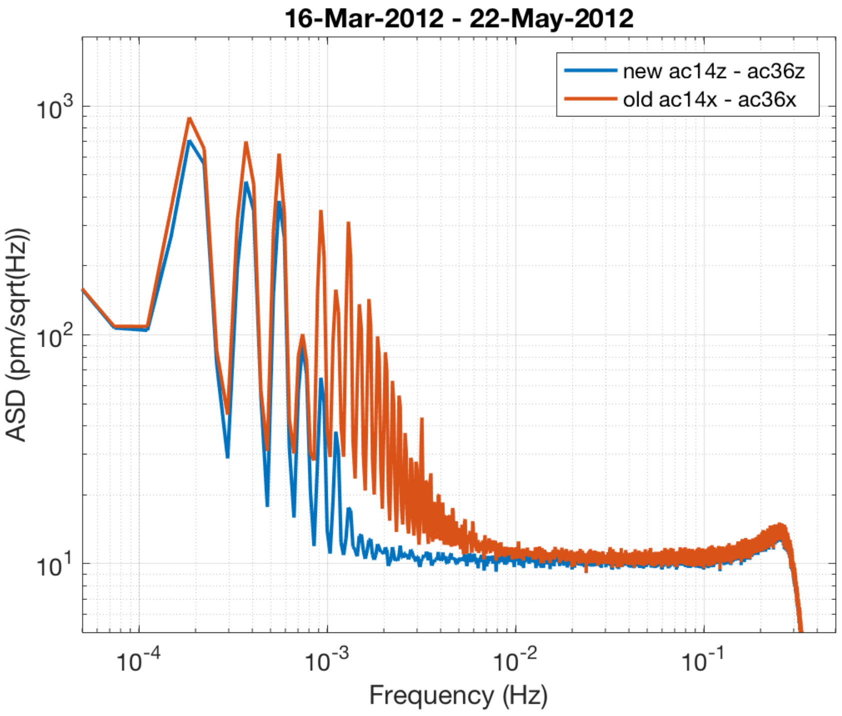

16-Mar-2012 - 22-May-2012
new Vyy
old Vyy
ASD (mE/sqrt(Hz))
10^3
10^2
10^1
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Frequency (Hz)

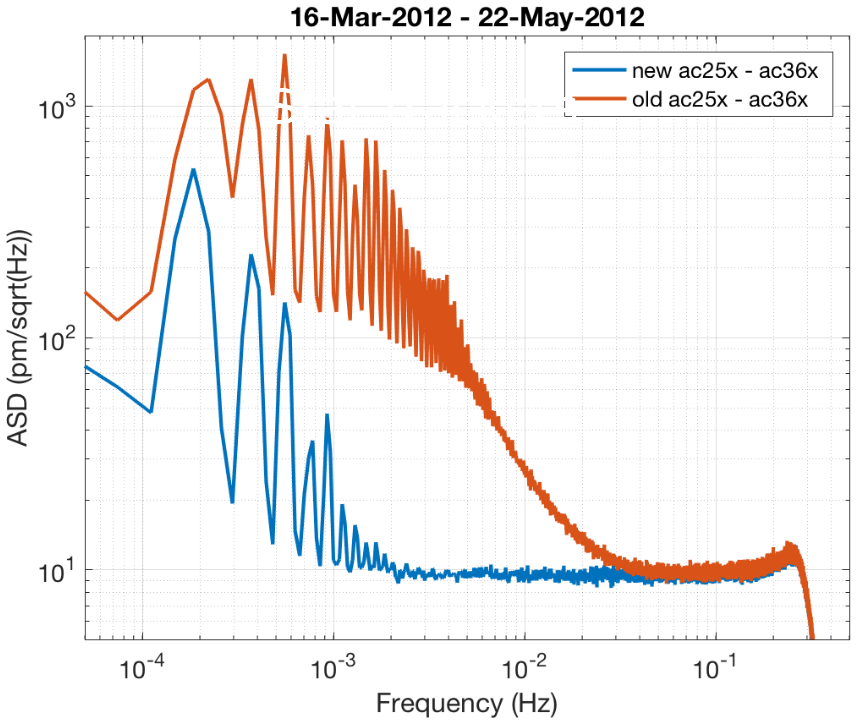
Results


16-Mar-2012 - 22-May-2012
new Vzz
old Vzz
ASD (mE/sqrt(Hz))
10^3
10^2
10^1
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Frequency (Hz)

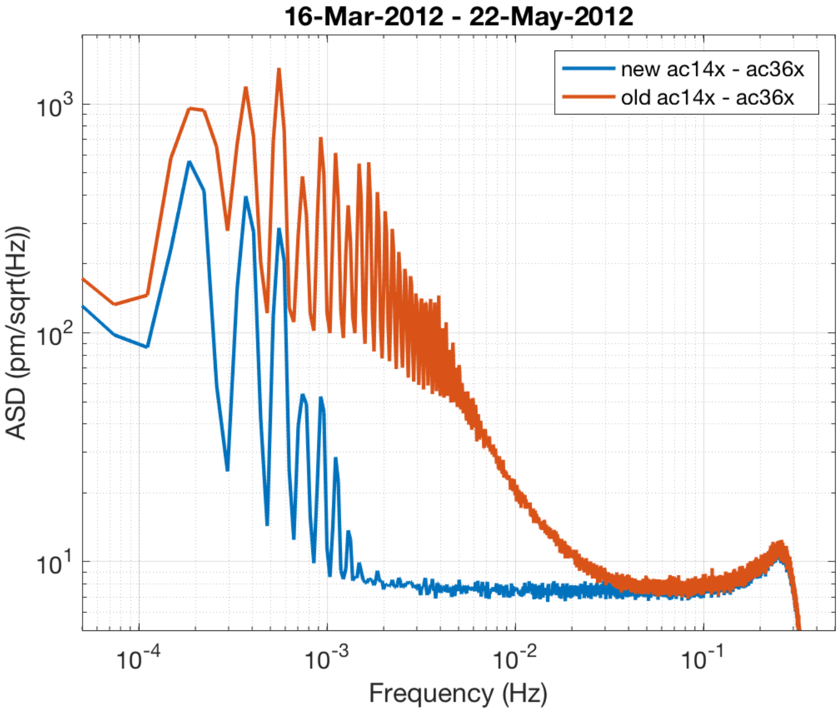

16-Mar-2012 - 22-May-2012
new Vxz
old Vxz
ASD (mE/sqrt(Hz))
10^3
10^2
10^1
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Frequency (Hz)

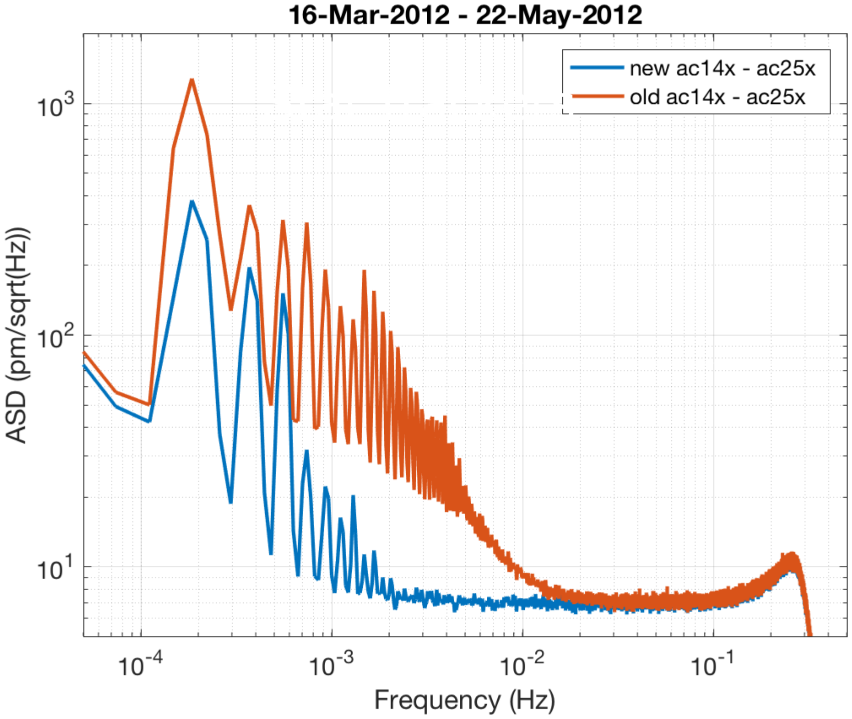
Results


16-Mar-2012 - 22-May-2012
new ac14z - ac36z
old ac14x - ac36x
ASD (pm/sqrt(Hz))
10^3
10^2
10^1
10^-4
10^-3
10^-2
10^-1
Frequency (Hz)


16-Mar-2012 - 22-May-2012
new ac25x - ac36x
old ac25x - ac36x
ASD (pm/sqrt(Hz))
10^3
10^2
10^1
10^-4
10^-3
10^-2
10^-1
Frequency (Hz)

Results


16-Mar-2012 - 22-May-2012
new ac14x - ac36x
old ac14x - ac36x
ASD (pm/sqrt(Hz))
10^3
10^2
10^1
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Frequency (Hz)


16-Mar-2012 - 22-May-2012
new ac14x - ac25x
old ac14x - ac25x
ASD (pm/sqrt(Hz))
10^3
10^2
10^1
10^{-4}
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10^{-2}
10^{-1}
Frequency (Hz)

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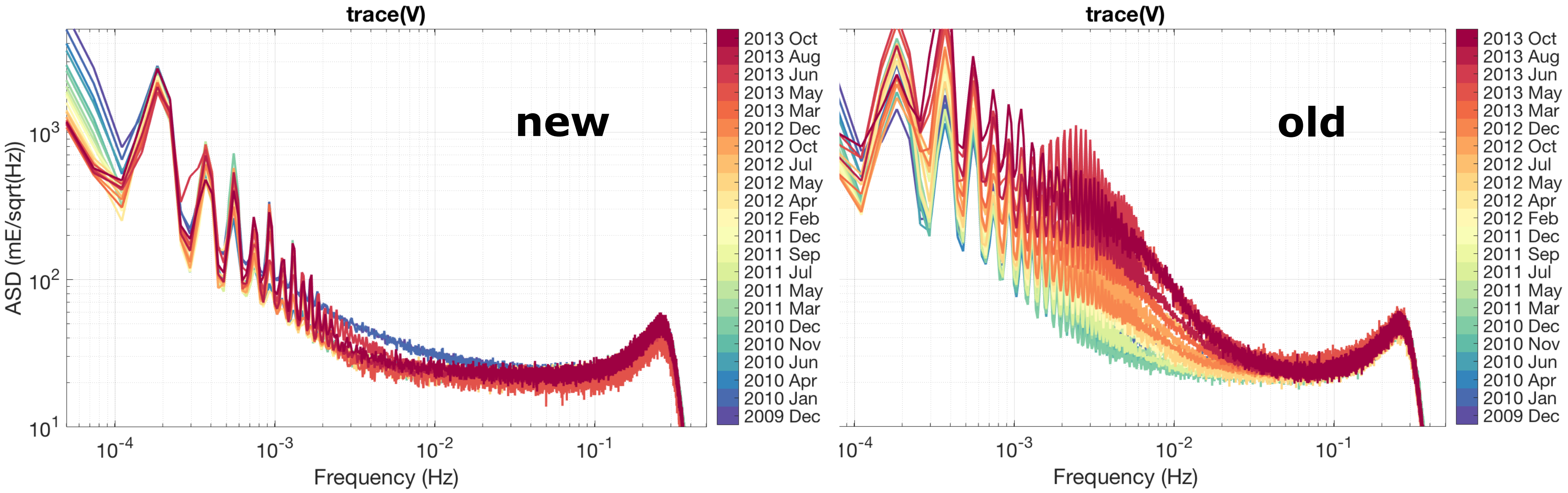

trace(V)
new
ASD (mE/sqrt(Hz))
10^3
10^2
10^1
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Frequency (Hz)
2013 Oct
2013 Aug
2013 Jun
2013 May
2013 Mar
2012 Dec
2012 Oct
2012 Jul
2012 May
2012 Apr
2012 Feb
2011 Dec
2011 Sep
2011 Jul
2011 May
2011 Mar
2010 Dec
2010 Nov
2010 Jun
2010 Apr
2010 Jan
2009 Dec
trace(V)
old
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Frequency (Hz)
2013 Oct
2013 Aug
2013 Jun
2013 May
2013 Mar
2012 Dec
2012 Oct
2012 Jul
2012 May
2012 Apr
2012 Feb
2011 Dec
2011 Sep
2011 Jul
2011 May
2011 Mar
2010 Dec
2010 Nov
2010 Jun
2010 Apr
2010 Jan
2009 Dec

Summary and Conclusions

Almost entirely **new L1b processing** implemented

Completely **new calibration** in science mode, including new parameters

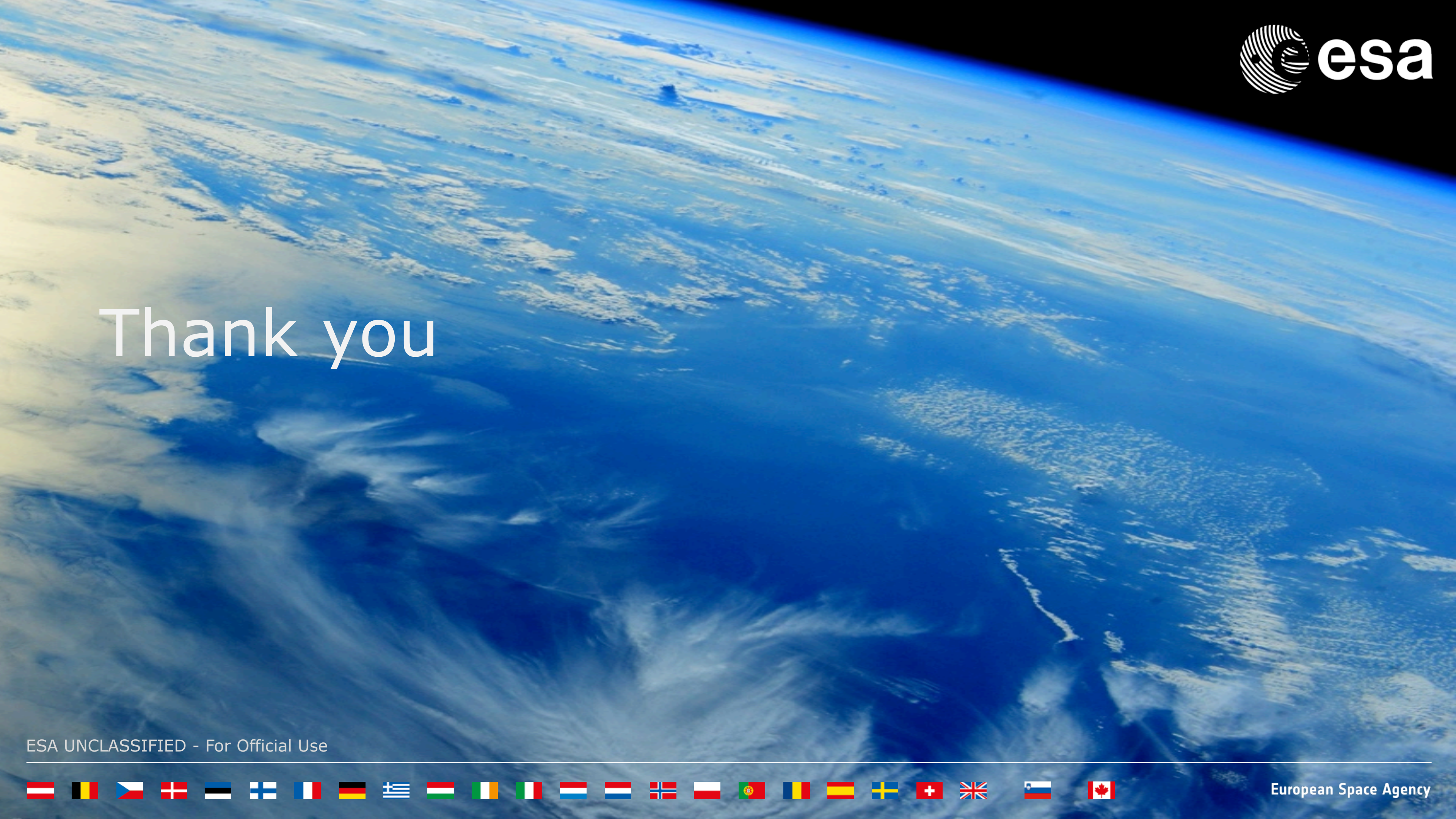
- Quadratic factors
- Angular couplings

Quadratic factors are very important to take into account

- Vyy drastically improved in regions around geomagnetic poles
- Vxx during first orbit lowering drastically improved

All gradients improved at low frequencies (smaller than 5 mHz)

Impact on GOCE gravity field models → presentation by Jan Martin Brockmann



Thank you