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Extracting the time variable gravity field from satellite gravity data using a sawtooth filter

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Abstract

The Grace satellite pair has been in operation since March 2002 providing monthly gravity potential solutions. This data set contains the variation of the gravity potential as a function of time however its use is limited by the presence of vertical striping noise which overwhelms the time variable signal. Several sophisticated filters exist to extract the time variable signal from the noise however they are seldom used as these filters are complex and difficult to implement. Consequently a large proportion of users of time variable Grace data use a conventional Spherical Gaussian Filter with a large smoothing radius of 600–1000 km which greatly attenuates the vertical striping noise however it also attenuates the remaining signal significantly. The difficulty in removing the noise is that the vertical striping noise is not band limited. We have studied the nature of the vertical striping noise and have found that it occurs over all harmonic degrees however it is associated only with the high harmonic orders. We also find that it occurs only in the east–west and radial components of the gravity field and that the noise is much greater than the signal in these two components. Further we observe that these two components are very similar at all geographic latitudes and that by performing a phase shift and subtracting one component from the other, one obtains a noise free signal. We use this procedure to define a new filter which we call the Sawtooth Filter and find that this filter offers three interesting properties: (i) it subtracts the vertical striping noise from the time variable signal (ii) it amplifies the higher degree harmonics thus improving the spatial resolution (iii) it is simpler to implement and use than the Spherical Gaussian Filter.

1 Introduction

The use of Grace gravity data to study variations in the gravity field as a function of time, are severely limited by noise in the form of vertical stripes. This vertical striping noise is believed to be a consequence of the geometry of the data acquisition. The

Grace satellite pair travel along a polar orbit and the resulting satellite tracks traverse the globe vertically. This results in data that is very densely sampled in the satellite track direction (north–south) but less densely sampled in the east–west direction where the sampling corresponds to adjacent satellite tracks. The difference in the sampling between the north–south and east–west directions results in a Harmonic Coefficient data set which contains noise in the form of broad vertical stripes. The noise level of these vertical stripes is negligible when considering the static gravity field however when considering the variations of the gravity field as a function of time, then the amplitude of the vertical striping noise is far greater than the gravity field changes over time. The Grace mission has been in operation since March 2002 and thus offers the opportunity of monitoring time variations of the gravity field since that date to the present time, however the vertical striping noise severely handicaps these studies. Several filters have been published that attenuate the noise however since the noise is not band-limited these filters are usually complex and difficult to use. In what follows we mention some of the more recent attempts at filtering the noise.

Chen et al. (2006) develop an asymmetrical filter defined by the data variance as a function of degree and order. The filter is optimized using two variables such that the data variance over land is maximized with the respect to the data variance over oceanic areas. The two parameters are determined by trial and error. Wouters and Schrama (2007) transform the harmonic coefficient data set to a new set of basis functions using Principal Component Analysis. The new basis functions are used or excluded using a statistical test of the noise level. Davis et al. (2008) propose a filter that is defined as a function of the error in the data for each degree and order. The error is quantified and the harmonic coefficients are either used or excluded on the basis of a statistical *F* test. Bruinsma et al. (2010) construct a filter function which is a product of three functions multiplied by a fourth term which is a function of the error. A total of 5 parameters are required to define this function. These parameters have to be chosen by the user by performing a search in the five dimensional parameter space.

These sophisticated filters reduce the vertical striping noise however they also attenuate or modify the signal and have the drawback that they are difficult to implement and use. Consequently the preferred filters used by the majority of users of Grace data have been the Global or Spherical Cap Gaussian filters (Jekeli, 1981; Swenson and Wahr, 2006). The Spherical Gaussian filter attenuates both the noise and the signal however it does not remove the noise completely. We have developed a new filter which is simpler to implement and use than the Gaussian filter and which offers two advantages over the Spherical Gaussian Filter: (i) it removes the vertical striping noise and (ii) it amplifies the high degree harmonics thus improving the spatial resolution of the data set. We call this filter the Sawtooth Filter.

2 Method

We have used the University of Texas Centre for Space Research (UTCSR) monthly Grace Gravity Potential Spherical Harmonic Coefficients corresponding to Harmonic Degree $n = 60$ release = 04 (GM60RL04). When considering the variation of the gravity potential with time, a static potential is subtracted from the monthly gravity potential solutions.

$$W3 = W2 - W1$$

where:
$W1$ = static gravity potential
$W2$ = monthly gravity potential
$W3$ = dynamic gravity potential which is the variation of the monthly potential with respect to the static potential.

The dynamic potential contains both signal and noise however the noise $\gg$ signal. The noise is present at all latitudes and longitudes in the form of long vertical stripes which completely overwhelm the dynamic signal. Closer inspection of the characteristics of the noise reveal that it occurs in the $\partial W3/\partial Y$ and $\partial W3/\partial R$ components of the

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gravity potential $W3$ and that the nature of the noise is very similar if not identical in both these components. The vertical striping noise is not apparent in the $\partial W3/\partial X$ component of the gravity potential $W3$. Figure 1a and b shows the east–west ($\partial W3/\partial Y$) and radial ($\partial W3/\partial R$) components of the gravity field along two parallels (latitude = 25° N and latitude = 35° N) between longitudes 0° E and 90° E. If the east–west ($\partial W3/\partial Y$) and radial ($\partial W3/\partial R$) components are aligned in phase, we observe that these two components are very similar at all latitudes. When comparing the magnitude of the north–south ($\partial W3/\partial X$) component which can be considered noise free, with the east–west and radial components which contain the noise, we conclude that the magnitude of the noise signal is much greater than the magnitude of the dynamic gravity signal and thus that the $\partial W3/\partial Y$ and $\partial W3/\partial R$ components represent (noise + signal) with noise $\gg$ signal. For convenience from now on $W = W3$.

As a consequence of the previous observations we conclude the following:

i. The $\partial W/\partial X$ component contains very little if any vertical striping noise.

ii. The $\partial W/\partial Y$ and $\partial W/\partial R$ components contain all or most of the vertical striping noise and the noise $\gg$ signal.

iii. The $\partial W/\partial Y$ and $\partial W/\partial R$ components are observed to be very similar at all latitudes when aligned in phase and hence the same noise appears to be common to both components. Shifting one component say $\partial W/\partial R$ such that it coincides in phase with the other component ($\partial W/\partial Y$) and then subtracting one component from the other results in a signal with little or no vertical striping noise.

We exploit these characteristics to remove the noise. Consider the ($\partial W/\partial Y$) and ($\partial W/\partial R$) components of the gravity potential W:

$$\partial W/\partial Y = -(GM/(ra\cos\phi))\sum_n (a/r)^{n+1}\sum_m(-mC_{nm}\sin m\lambda + mS_{nm}\cos m\lambda)P_{nm} \tag{1}$$

$$\partial W/\partial R = -(GM/(ra))\sum_n (n+1)(a/r)^{n+1}\sum_m(C_{nm}\cos m\lambda + S_{nm}\sin m\lambda)P_{nm} \tag{2}$$

Where:
G = Gravitational constant.
M = Total Mass of the Earth System.
r = Radius from the centre of the earth to the computation point.
a = Equatorial radius of the earth ellipsoid.
n = Index used to indicate the degree of the harmonic expansion term.
m = Index used to indicate the order of the harmonic expansion term.
C_{nm}, S_{nm} = Cosine and Sine Harmonic Coefficients respectively.
ϕ = geographic latitude in radians.
λ = geographic longitude in radians.
$\sum_n$ = Summation over all degrees from $n = 0$ to n = highest.
$\sum_m$ = Summation over all orders from $m = 0$ to $m = n$.
P_{nm} = Normalized Associated Legendre Polynomial for degree = n and order = m.

Define $\partial W/\partial R'$ equal to $\partial W/\partial R$ but shifted in phase such that it coincides with the phase of the $\partial W/\partial Y$ component. This simply requires a phase shift = $(m\lambda/4)$ to each wavelength = $(m\lambda)$ of the sine and cosine functions in $\partial W/\partial R$:

$$\partial W/\partial R' = -(GM/(ra))\sum_n (n+1)(a/r)^{n+1} \sum_m (C_{nm}\cos(m\lambda + m\lambda/4) + S_{nm}\sin(m\lambda + m\lambda/4))P_{nm}$$

$$\partial W/\partial R' = -(GM/(ra))\sum_n (n+1)(a/r)^{n+1} \sum_m (-C_{nm}\sin m\lambda + S_{nm}\cos m\lambda)P_{nm} \tag{3}$$

since:
$\cos(m\lambda + m\lambda/4) = -\sin m\lambda$
$\sin(m\lambda + m\lambda/4) = \cos m\lambda$.

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Now consider the difference between $\partial W/\partial R'$ and $\partial W/\partial Y$:

$$D = (\partial W/\partial R' - \partial W/\partial Y)$$

$$D = -(GM/(ra))\sum_n (a/r)^{n+1}\sum_m [(n+1)-(m/\cos(\phi))](-C_{nm}\sin m\lambda + S_{nm}\cos m\lambda)P_{nm}$$

Let $f = [(n+1)-(m/\cos(\phi))]$ then:

$$D = -(GM/(ra))\sum_n (a/r)^{n+1}\sum_m (-fC_{nm}\sin m\lambda + fS_{nm}\cos m\lambda)P_{nm} \quad (4)$$

The above Eq. (4) is a new signal which is in phase with the $\partial W/\partial Y$ component. The Harmonic Coefficients (fC_{nm}) and (fS_{nm}) are a new set of noise-free harmonic coefficients obtained by the action of the factor f:

$$f = [(n+1)-(m/\cos(\phi))]$$

Where:
n = harmonic degree
m = harmonic order
ϕ = geographical latitude in radians.

In Fig. 2 we represent the function $f = [(n+1)-(m/\cos(\phi))]$ as a function of degree and order for latitude = 30° N. The factor f acts as a filter which we will denote a "Saw-tooth" filter. For representation purposes, the filter function is expressed as a function of degree = n^* with order = m sequenced between adjacent values of degree = n using the expression

$$n^* = n + (m/(n+1))$$

In a similar fashion we could have shifted the $\partial W/\partial Y$ component to coincide in phase with the $\partial W/\partial R$ component. The resulting filter function f is the same. We observe that the filter function acts on the harmonic coefficients in two ways:

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i. Attenuating the high order = m coefficients (sectorial and near sectorial harmonics).

ii. Amplifying the harmonic coefficients as a function of degree = n.

The benefits of the filter are thus also twofold as firstly it attenuates the vertical striping noise which is contained in the high order = m harmonics and secondly it amplifies the higher degree harmonics relative to the lower degree harmonics thus improving the resolving capability of the data.

3 Characterising the noise

In what follows we identify the harmonic coefficients which contain the noise and compare the result of applying different filters to the data. To this end we consider the dispersion and the standard deviation of the monthly Harmonic Coefficient solutions collected over 12 months (January to December 2011).

$$\text{Dispersion}\,(C_{nmi}) = (C_{nmi} - AvC_{nmi})$$

$$\text{Standard Deviation}\,(C_{nmi}) = \left[(1/11)\cdot \sum_i (C_{nmi} - AvC_{nmi})^2\right]^{0.5}$$

Where:
C_{nmi} = harmonic coefficients of the monthly solutions of the potential for degree = n, order = m, and month = i. These coefficients generate the monthly potentials $W2$.
$AvC_{nmi} = (1/12)\cdot(\sum_i C_{nmi})$. This corresponds to a static potential $W1$.
$\sum_i$ = summation over the monthly index i from $i = 1$ to $i = 12$.

We compare the standard deviation of the unfiltered C_{nm} coefficients with the Spherical Cap Gaussian Filtered C_{nm} Coefficients in Fig. 3a. We observe that the standard deviation of the filtered data has been attenuated for all degrees and orders however

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the standard deviation continues to increase as a function of order with maxima at high orders = m which correspond to the sectorial and near sectorial harmonics which cause the vertical striping noise. Thus the overall signal strength is severely attenuated by the Spherical Cap Gaussian Filter but the vertical striping noise persists.

In Fig. 3b we compare the unfiltered C_{nm} coefficients and the Sawtooth Filtered C_{nm} Coefficients. In the Sawtooth filtered data we observe that the standard deviation is similar for all degrees and orders and that the highest orders have been strongly attenuated. The peaks now correspond to zonal and near zonal coefficients (low order = m) and not the sectorial and near sectorial coefficients (high order = m) as was the case in the unfiltered and Gaussian filtered data. The result is that the vertical striping noise is greatly attenuated while the overall signal strength is amplified. Since the amplifying action of the filter increases with increasing degree=n, the Sawtooth filter enhances the high degree harmonics and thus improves the spatial resolution of the result.

We also represent the dispersion for six sets of monthly coefficients identified as 10 152 181, ..., 10 001 031. This dispersion offers a visual estimate of the error in the coefficients of the $W3$ potential. In Fig. 4a we represent the scatter in the coefficient values for the range of harmonics with degree $n = 50$ to degree $n = 60$. We observe that between adjacent values of degree = n^* the scatter increases exponentially. The maximum scatter is observed at high orders = m. Figure 4b represents the scatter in the same data considered in Fig. 4a after the use of the sawtooth filter. We observe that now the scatter is similar at all degrees = n and orders = m and that the high orders = m have been strongly attenuated. The difference in the absolute values of the unfiltered and filtered coefficients is due to the action of the filter. In Fig. 4c we represent the dispersion of the same coefficients in Fig. 4a after use of a Spherical Cap Gaussian Filter with smoothing radius $r = 600\,\text{km} = 3\sigma$ (a-parameter = 1011.186). The dispersion is attenuated however the scatter increases with increasing order = m as observed in the unfiltered data. Maximum scatter occurs at high order = m harmonics corresponding to the sectorial and near sectorial harmonics, thus the vertical striping noise persists.

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4 Results

The filtered $\partial W/\partial X$, $\partial W/\partial Y$ and $\partial W/\partial R$ components are expressed using the filtered harmonic coefficients fC_{nm} and fS_{nm}:

$$\partial W/\partial X^{\#} = -(GM/(ra))\sum_n (a/r)^{n+1}\sum_m (fC_{nm}\cos m\lambda + fS_{nm}\sin m\lambda)(\partial P_{nm}/\partial\theta)$$

$$\partial W/\partial Y^{\#} = -(GM/(ra\cos\phi))\sum_n (a/r)^{n+1}\sum_m (-mfC_{nm}\sin m\lambda + mfS_{nm}\cos m\lambda)P_{nm}$$

$$\partial W/\partial R^{\#} = -(GM/(ra))\sum_n (n+1)(a/r)^{n+1}\sum_m (fC_{nm}\cos m\lambda + fS_{nm}\sin m\lambda)P_{nm}$$

where $(\partial W/\partial X)^{\#}$, $(\partial W/\partial Y)^{\#}$ and $(\partial W/\partial R)^{\#}$ denote the sawtooth filtered components of the gravity potential W. We express the gravity field components without the centripetal acceleration due to the rotating ellipsoidal earth.

Figure 5a–d compares the result of applying the Spherical Cap Gaussian filters with the Sawtooth filter on the vertical component of the Gravity Field Vector ($\partial W/\partial R$).

5 Discussion

In Fig. 5a–d we have considered the action of the Spherical Cap Gaussian filter and the Sawtooth filter on the field due to the potential $W3 = W2 - W1$. The $W3$ potential represents the small monthly variations with respect to the static potential which in our case is the 12 month average potential. The vertical striping noise inherent in the data was filtered using the Gaussian and Sawtooth filters. The Gaussian filter is not able to remove the vertical striping noise and thus the resulting data is of limited use for the study of the time variable gravity field. The Sawtooth filter however does remove the vertical striping noise completely or almost completely, by attenuating high order $= m$ harmonic coefficients. The Sawtooth filter also amplifies the higher degree $= n$ harmonic coefficients relative to the lower degree harmonic coefficients, thus highlighting

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the high degree data and improving the spatial resolution. From the above results we conclude that the Sawtooth filter extracts a time variable gravity field with improved spatial resolution from the original noise swamped time variable signal. The question that remains is to ascertain the distorting effect of the Sawtooth filter on the data. To this end we consider a benchmark data set with negligible noise: the static potential $W1$ potential which is the 12 month average Potential for the year 2009. The signal to noise ratio of this potential is so high (Signal/Noise > 500) that it can be considered noise free. We apply the Spherical Cap Gaussian filter and the Sawtooth filter to the $W1$ harmonic coefficients and compare the resulting gravity field with the unfiltered field. Figure 6a–d presents the results. The Spherical Cap Gaussian filter conserves all of the features observable in the unfiltered data set and the result of the filtering action is to smooth and attenuate the signal. Thus this filter results in smoothed and attenuated features of the original data however the main features are conserved. The Sawtooth filter has a greater effect on the data. It amplifies the high degree = n harmonics while at the same time attenuating the high order = m harmonics. This results in attenuation of the sectorial and near sectorial harmonics which is manifest in Fig. 6d as a loss of resolution in the east–west direction. Two distinct features (one over the North of Africa and the other over the Iberian Peninsula) are amplified by the action of the sawtooth filter . Another feature in the North–West corner of the study region is filtered out and one is led to conclude that this feature must be related to the high order = m harmonics (sectorial and near sectorial harmonics). This appears to contradict our claim that the Sawtooth filter improves the spatial resolution. One must remember however that we are considering different fields: (i) the dynamic gravity field (ii) a static gravity field. When considering (i) the dynamic field, the signal is overwhelmed by the vertical striping noise and the filter removes mainly noise and enhances the remaining signal. When considering (ii) a static field with negligible noise, the filter removes high order = m signal with no noise thus reducing the spatial resolution in the east–west direction of the static field however all other features are amplified. When considering the time variable field the Sawtooth filter offers the opportunity to subtract the vertical striping noise and obtain a time-variable gravity field with amplified high degree harmonics and thus improved spatial resolution. The drawback is that the resultant gravity field is modified by the loss of the sectorial and near sectorial signal and hence loss of resolution in the east–west direction. Regardless of this drawback, when considering the variation as a function of time of the sawtooth filtered data one will be comparing fields that have been modified in an identical fashion by the same filter and they are thus informative of the time variations of the field.

6 Conclusions

Grace data contain correlated noise associated with the high order = m harmonics which is called vertical striping noise. Studies of the variation of the gravity field with time are seriously limited by this vertical striping noise which overwhelms the desired time variable signal. Attempts have been made to remove this noise but conventional filters are not adequate as the noise is present at all degrees = n. In this study we identify that the vertical striping noise is associated with high order = m harmonics for all degrees = n. Further we find that most if not all the vertical striping noise occurs in the radial and east–west components of the gravity field. We make use of this characteristic to design a filter which removes the vertical striping noise from all three gravity field components. We call this filter the Sawtooth filter and compare it with the Gaussian Filter which is the filter most commonly used with Grace data. The Sawtooth filter attenuates high order = m harmonics at all degrees = n and hence attenuates the sectorial and near sectorial harmonic coefficients associated with the vertical striping noise. The advantages offered by the Sawtooth Filter are: (i) the vertical striping noise is completely or almost completely removed (ii) higher degree = n harmonics are amplified thus improving the spatial resolution of the data. (iii) It is simpler and easier to use than the Spherical Gaussian Filter. The sawtooth filter alters the gravity field signal, however it affects all data in identical manner and thus the dynamic behavior of the resultant field can be studied.

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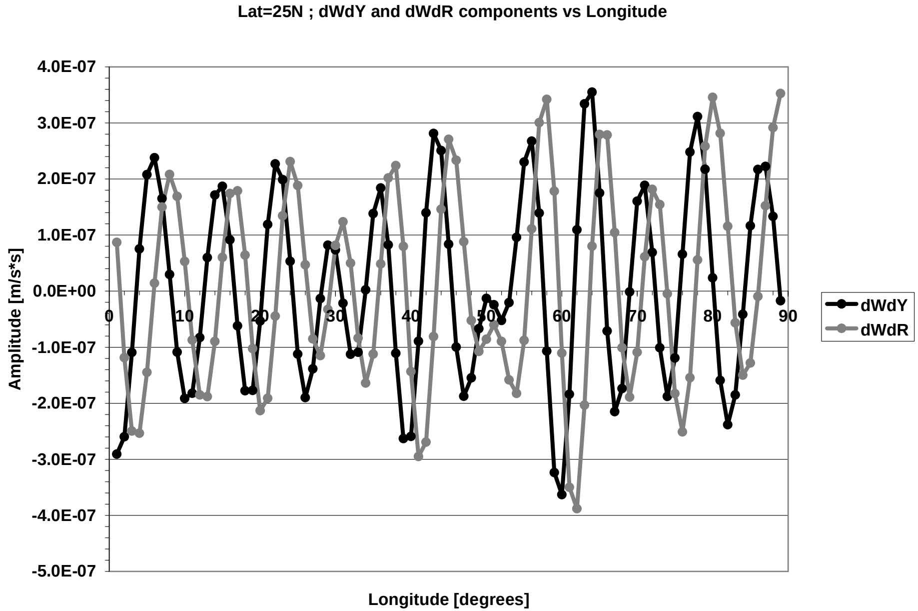

Fig. 1a. Dynamic Gravity field in the east–west ($\partial W/\partial Y$) and radial ($\partial W/\partial R$) components along the parallel with latitude = 25° N between longitudes 1° E and 89° E.

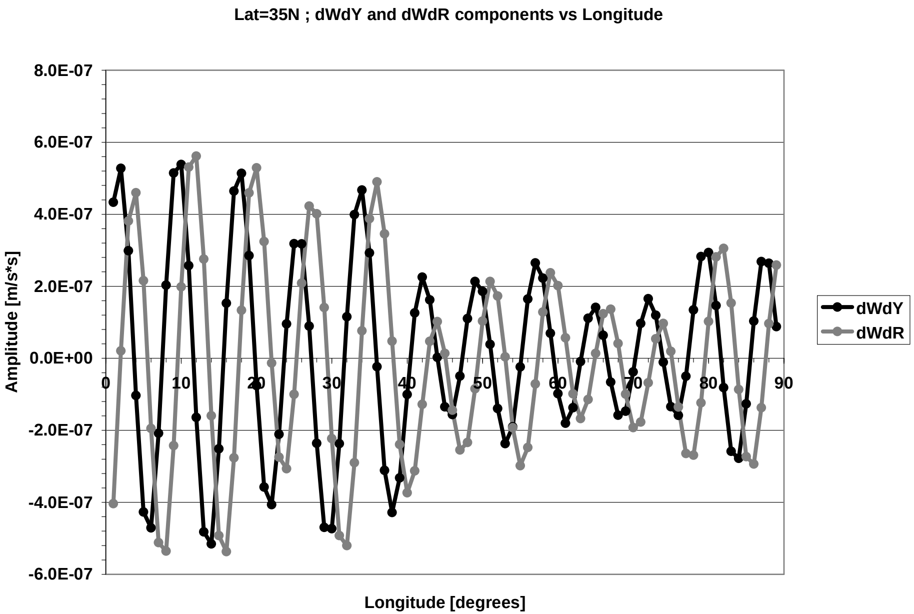

Fig. 1b. Dynamic Gravity field in the east–west ($\partial W/\partial Y$) and radial ($\partial W/\partial R$) components along the parallel with latitude = 35° N between longitudes 1° E and 89° E.

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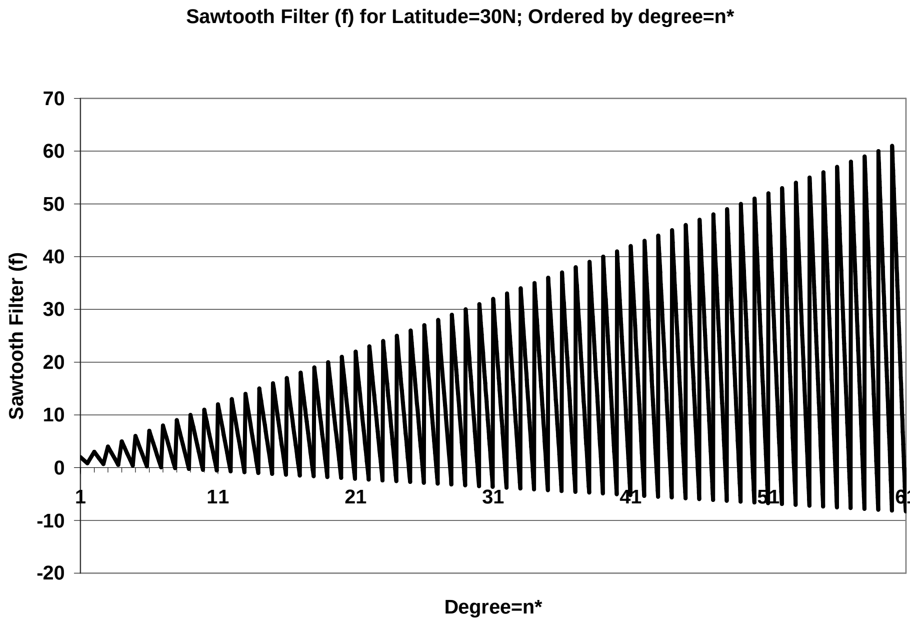

Fig. 2. Sawtooth Filter (f) along the parallel = 30° N as a function of degree = n^* where $n^* = n+(m/(n+1))$. We observe that the action of the filter is twofold: (i) attenuation of high order = m harmonics and (ii) amplification of high degree = n harmonics.

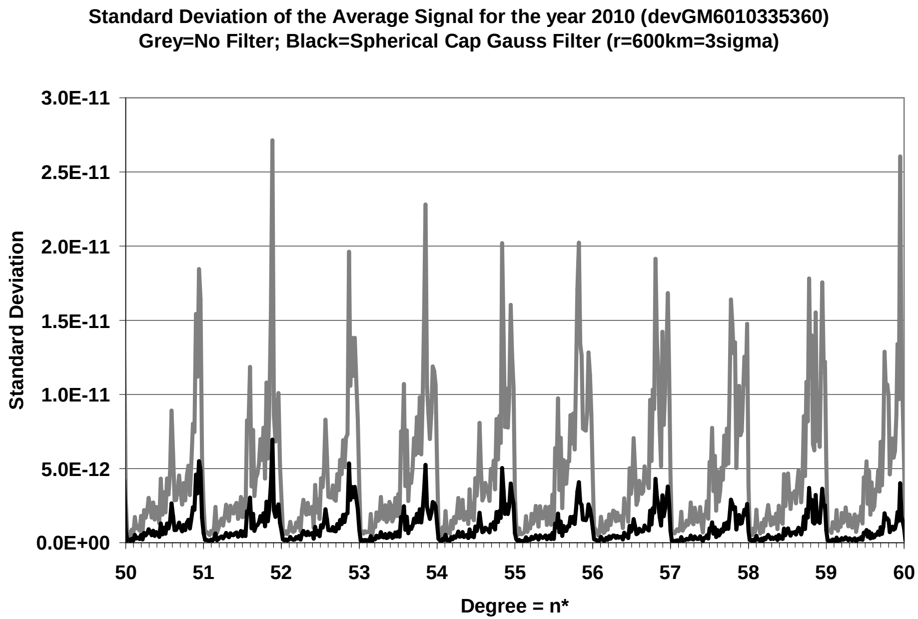

Fig. 3a. Spherical Cap Gaussian Filter. The grey line corresponds to the Standard deviation of the unfiltered harmonic coefficients for the year 2010. Standard Deviation = $((1/11)\cdot(\sum C_{nmi} - AvC_{nmi})^2)^{0.5}$, $i = 1,..,12$. The black line corresponds to the standard deviation of the same set of harmonic coefficients after filtering with a Spherical Cap Gaussian Filter with smoothing radius $r = 600\,\mathrm{km} = 3\sigma$ (a-parameter = 1011.186). The effect of the Global and Spherical Cap Gaussian filters is almost identical. Here we consider the range of degrees $n = 50$ to $n = 60$. We observe that the standard deviation of the filtered data has been attenuated for all degrees and orders however the standard deviation continues to increase as a function of order with maxima at high orders = m which correspond to the sectorial and near sectorial harmonics which cause the vertical striping noise. Thus the overall signal strength is severely attenuated by the Spherical Cap Gaussian Filter but the vertical striping noise persists.

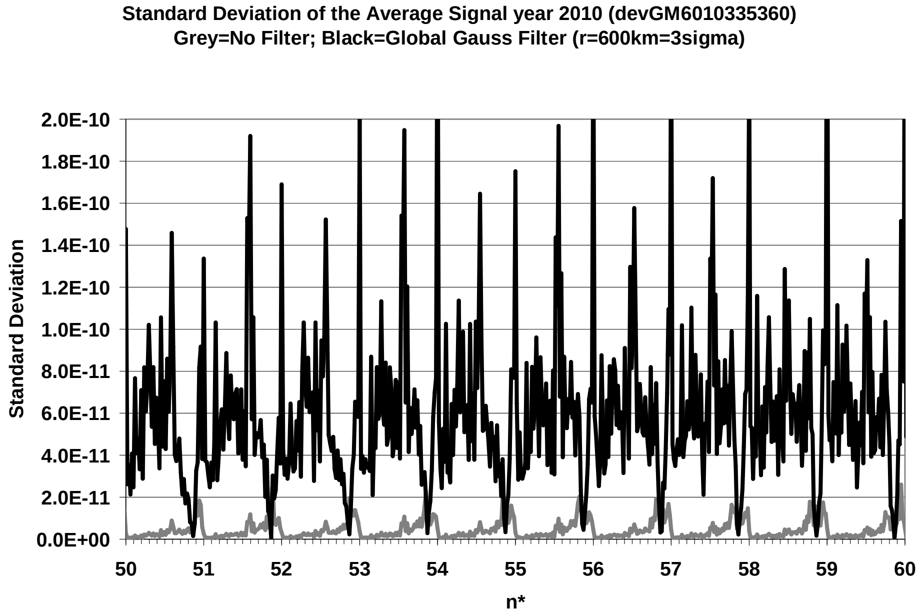

Fig. 3b. Sawtooth Filter. The black line is the standard deviation of the same harmonic coefficients considered in Fig. 3a after filtering with the Sawtooth filter. The grey line is the standard deviation of the unfiltered coefficients. The difference in scale of the filtered and unfiltered data is due to the amplifying action of the filter which increases with increasing degree = n. Here we consider the range of degrees $n = 50$ to $n = 60$. In the Sawtooth filtered data we observe that the standard deviation is similar for all degrees and orders and that the highest orders have been strongly attenuated. The peaks now correspond to zonal and near zonal coefficients (low order = m) and not the sectorial and near sectorial coefficients (high order = m) as was the case in the unfiltered and Gaussian filtered data. The result is that the vertical striping noise is greatly attenuated while the overall signal strength is amplified. Since the amplifying action of the filter increases with increasing degree = n, the Sawtooth filter enhances the high degree harmonics and thus improves the spatial resolution of the result.

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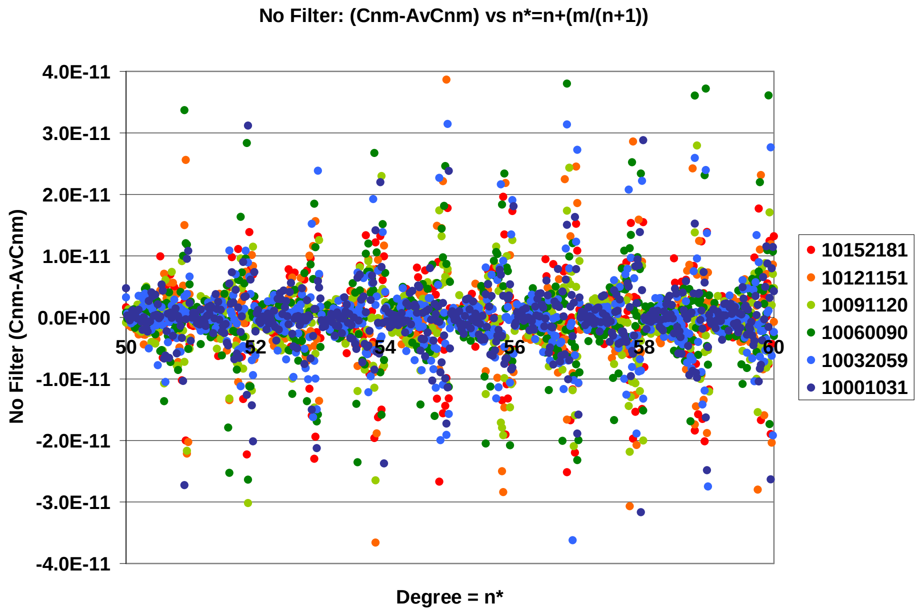

Fig. 4a. Unfiltered data. Dispersion of the C_{nm} coefficients relative to the 12 month average of C_{nm} coefficients over the year 2011. Dispersion = $(C_{nmi} - AvC_{nmi})$, $i = 1, .., 12$. We represent the range of degrees $n = 50$ to $n = 60$. We observe that the scatter increases with increasing order = m for each degree = n^* with the greatest scatter occurring at high order = m values. The high order = m coefficients correspond to the sectorial and near sectorial harmonics and are responsible for the vertical striping noise.

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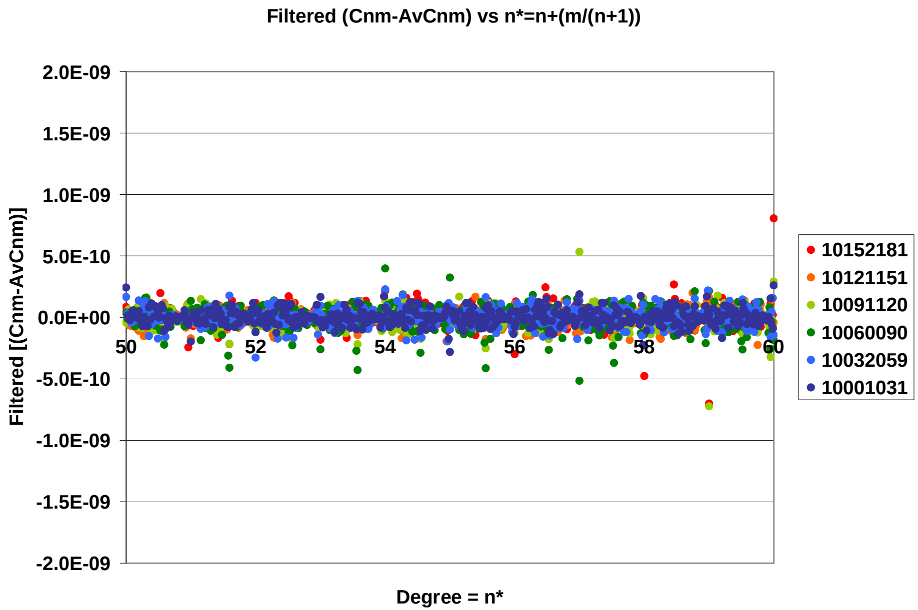

Fig. 4b. Sawtooth Filtered Data. We represent the range of degrees $n = 50$ to $n = 60$. Dispersion of the same coefficients considered in Fig. 4a after use of the Sawtooth Filter. We observe that the scatter is similar at all degrees = n and orders = m. The high order = m coefficients have been greatly attenuated thus reducing the vertical striping noise which is expressed by the sectorial and near sectorial coefficients. The difference in scale of the two figures is a consequence of the amplification of the higher degrees by the filter which results in an enhancement of the high frequency information and hence an enhancement of the spatial resolution of the data.

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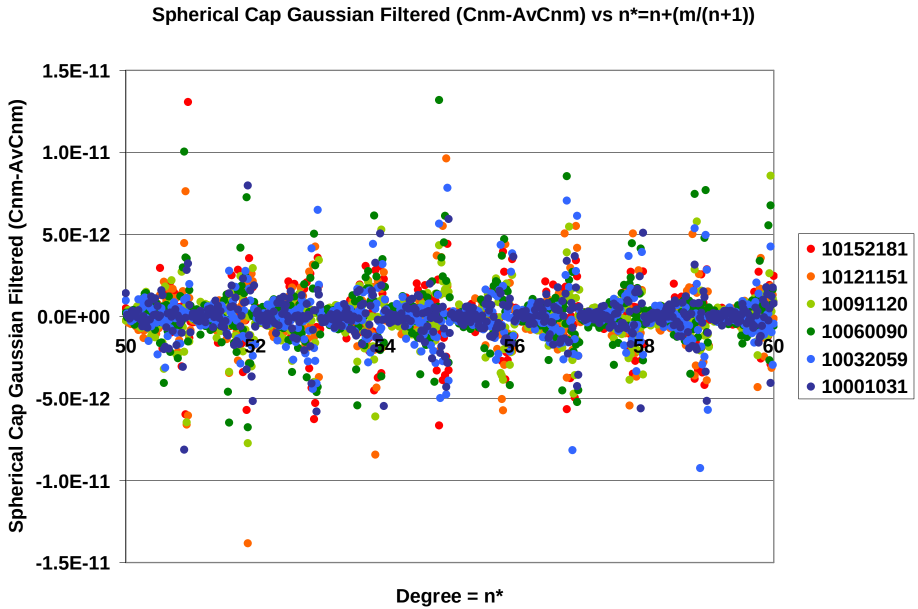

Fig. 4c. Spherical Cap Gaussian Filter. We represent the range of degrees $n = 50$ to $n = 60$. The dispersion of the same coefficients in Fig. 4a after use of a Spherical Cap Gaussian Filter with smoothing radius $r = 600\,\text{km} = 3\sigma$ (a-parameter = 1011.186). The dispersion is attenuated (scale maximum is 1.5×10^{-11}) however the scatter increases with increasing order = m as observed in the unfiltered data. Maximum scatter occurs at high order = m harmonics corresponding to the sectorial and near sectorial harmonics, thus the vertical striping noise persists.

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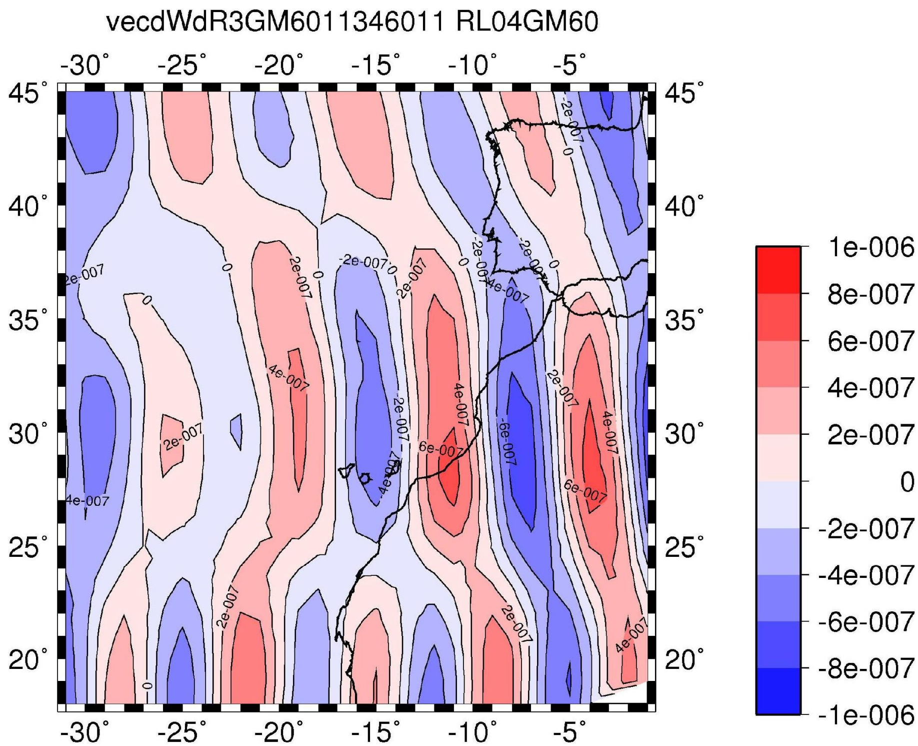

Fig. 5a. Unfiltered radial Component of the Dynamic Gravity Field ($\partial W/\partial R$) for the month of December 2011. Data set used is GM6011346011RL04-UTCSR. Static field was the 12 month average field for the year 2009. Scale ranges between -1×10^{-6} and $+1\times10^{-6}$ [$\mathrm{m\,s^{-2}}$]. We observe that the vertical striping noise prevails.

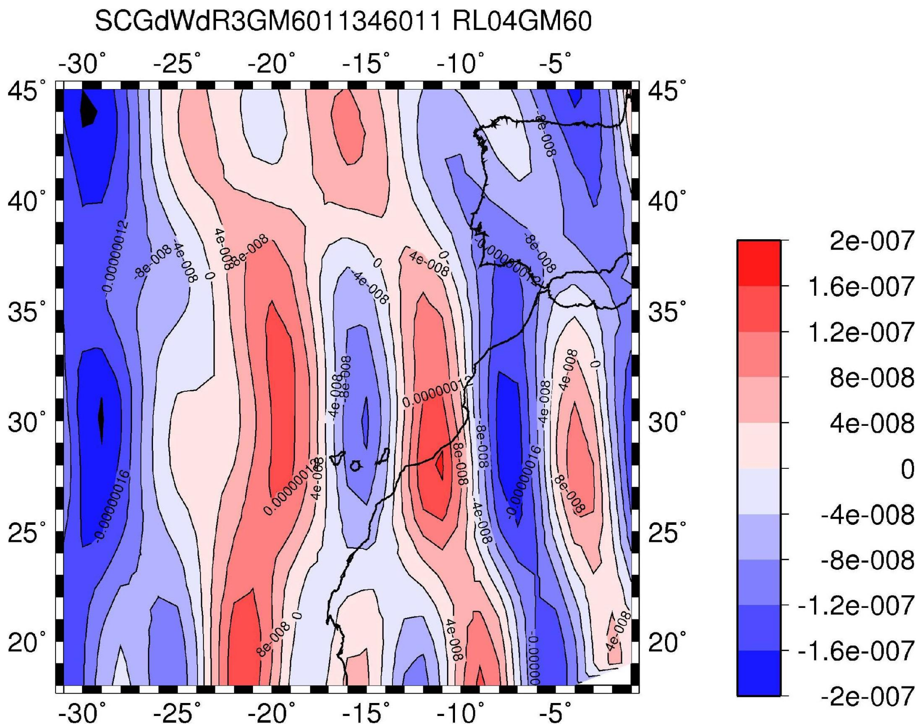

Fig. 5b. Gaussian Filtered radial Component of the Dynamic Gravity Field for the month of December 2011. The filter is a Spherical Cap Gaussian filter with smoothing radius $r = 600\,\mathrm{km} = 3\sigma$. Data set used is GM6011346011RL04-UTCSR. Static field was the 12 month average field for the year 2009. Scale ranges between -2×10^{-7} and $+2\times10^{-7}$ [$\mathrm{m\,s^{-2}}$]. The amplitude of the result is attenuated by the action of the filter however the vertical striping noise persists.

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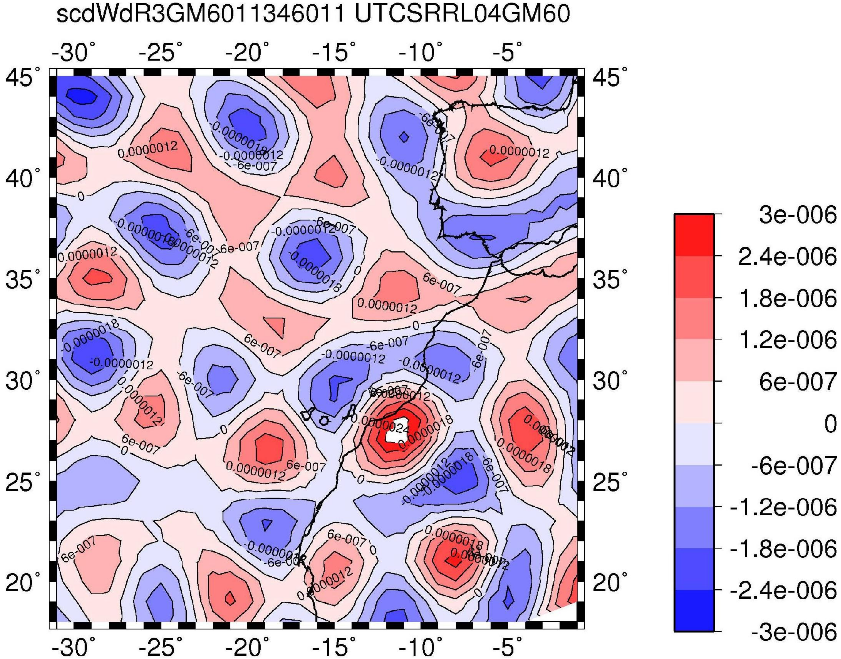

Fig. 5c. Sawtooth Filtered radial Component of the Dynamic Gravity Field for the month of December 2011. The filter is the Sawtooth filter. Data set used is GM6011346011RL04-UTCSR. Static Field was the 12 month average field for the year 2009. Scale ranges between -3×10^{-6} and $+3 \times 10^{-6}$ [m s^{-2}]. The filter amplifies the higher degree harmonic coefficients relative to the lower degree harmonic coefficients and removes the vertical striping noise. The following figure is the standard deviation of the sawtooth filtered data and we observe that most of the data features are smaller than their corresponding error. Only one data feature with an amplitude greater than 3.0×10^{-6} [m s^{-2}] is greater than its error. This lies on the African Coast just east of the Canary Islands. At this stage we do not know the cause of this feature however an advantage of the Sawtooth filter is that the salient features of the field that remain after filtering can be ascribed to real features and not to artifacts caused by the vertical striping noise.

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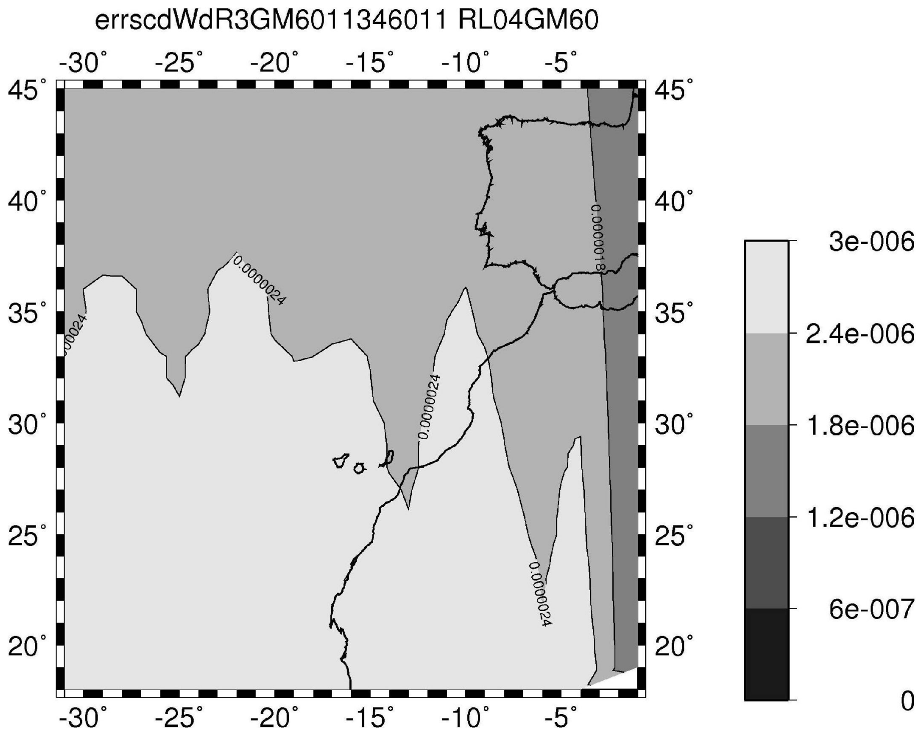

Fig. 5d. Standard Deviation of the Sawtooth Filtered radial Component of the Dynamic Gravity Field for the month of December 2011. The filter is the Sawtooth filter. Data set used is GM6011346011RL04-UTCSR. Static field was the 12 month average field for the year 2009. Scale ranges between 0×10^{-6} and $+3 \times 10^{-6}$ [$\mathrm{m\,s^{-2}}$]. The amplitude of the sawtooth filtered data in Fig. 5c is smaller than its standard deviation over most of the region, however just to the east of the Canary Islands we observe a circular feature which has an amplitude $> 3.0 \times 10^{-6}$ [$\mathrm{m\,s^{-2}}$].

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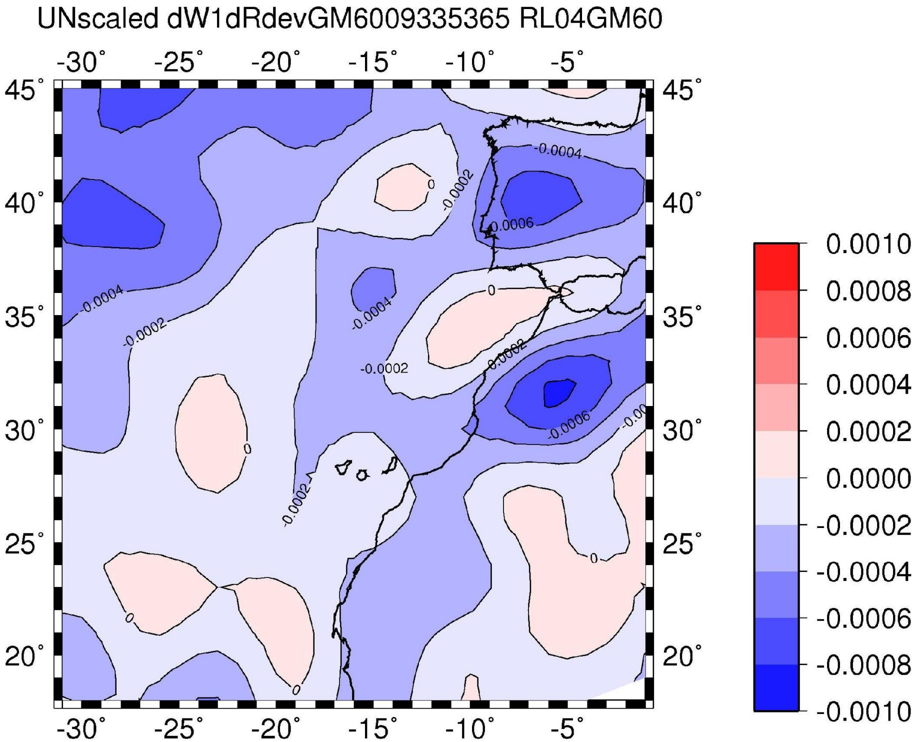

Fig. 6a. Unfiltered radial Component of the Gravity Field due to the $W1$ potential ($\partial W1/\partial R$). The $W1$ potential corresponds to the 12 month average over the year 2009 (devGM6009335365) and thus represents the Static potential with negligible noise levels. We use this gravity field as a benchmark to compare the action of the different filters on the signal as the noise levels for this field are negligible. Units = [ms^{-2}].

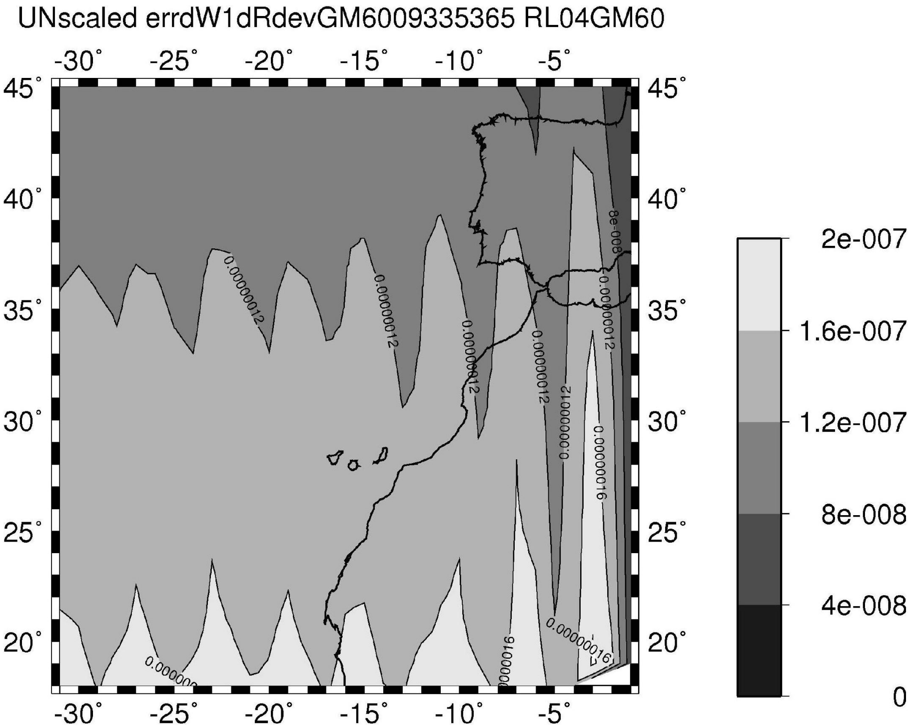

Fig. 6b. Standard Deviation of the radial Component of the Unfiltered Gravity Field due to the W1 potential ($\partial W1/\partial R$). The $W1$ potential corresponds to the 12 month average over the year 2009 (devGM6009335365) and thus represents the static potential. The standard deviation values are all below 2×10^{-7} [$\mathrm{m\,s^{-2}}$] while the signal in Fig. 6a is greater than 1.0×10^{-4} [$\mathrm{m\,s^{-2}}$] resulting in a signal to noise ratio > 500. We conclude that the noise levels are negligible and use the gravity field of the $W1$ potential as a benchmark to compare the action of the different filters on the signal. Units = [$\mathrm{ms^{-2}}$].

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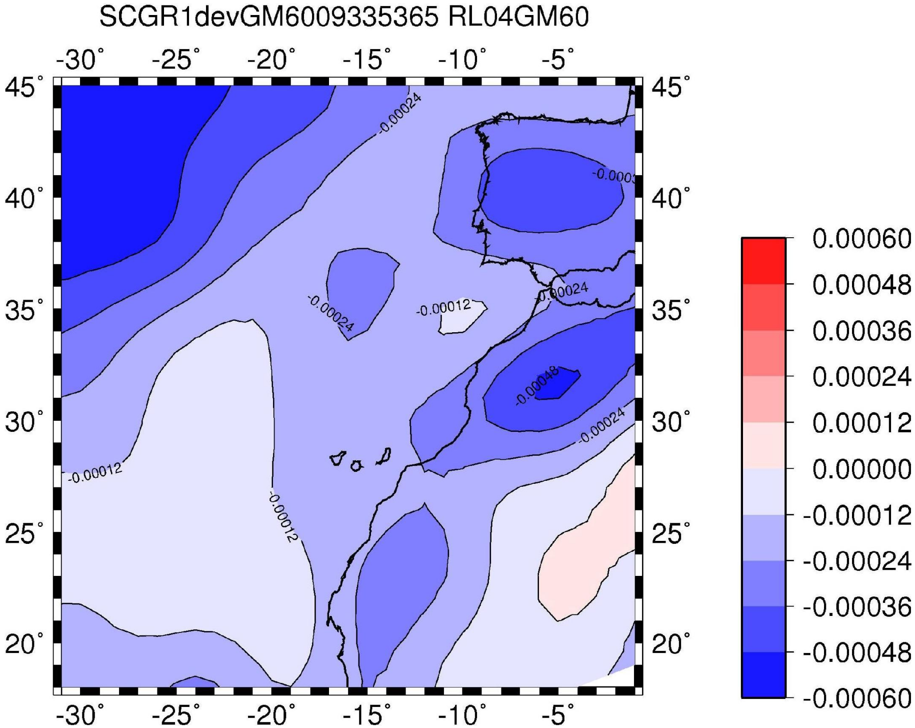

Fig. 6c. Spherical Cap Gauss Filter with smoothing radius $r = 600\,\text{km} = 3\sigma$. Filtered radial Component of the Gravity Field due to the $W1$ potential. The $W1$ potential corresponds to the 12 month average over the year 2009 (devGM6009335365). We compare this Spherical Cap Gauss filtered radial component of the Gravity Field with the unfiltered radial component of the Gravity Field in Fig. 6a in order to asses the filter action on the data. We observe smoothing of the data and approximately a 40 % decrease in signal strength. Units = [ms^{-2}].

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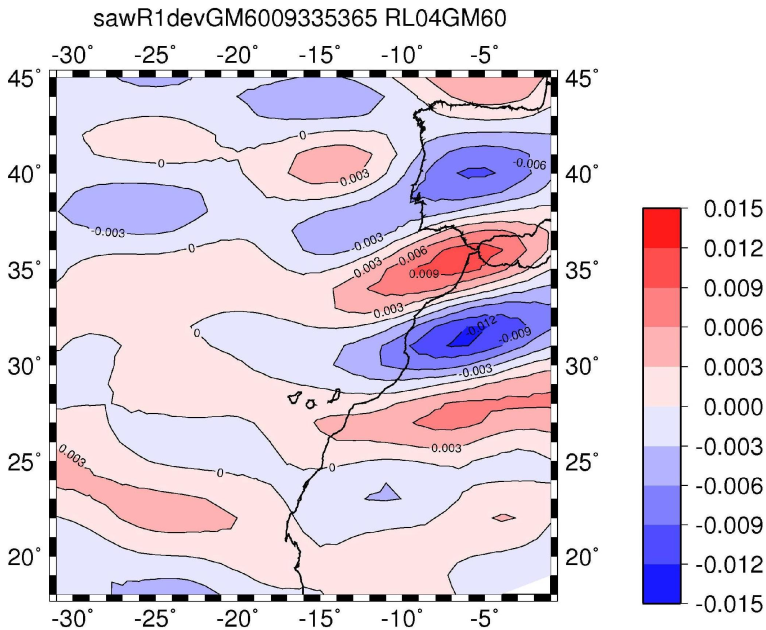

Fig. 6d. Sawtooth Filter. Filtered radial Component of the Gravity Field due to the *W*1 potential. The *W*1 potential corresponds to the 12 month average over the year 2009 (devGM6009335365). We compare this Sawtooth filtered field with the unfiltered field in Fig. 6a in order to asses the filter action on the data. We observe a strong increase in signal strength. This is expected due to the characteristics of the Sawtooth filter which amplifies the high degree = n harmonic coefficients while at the same time attenuating the high order = m harmonic coefficients. The attenuation of the high order = m harmonic coefficients results in the attenuation of the sectorial and near sectorial harmonics and thus some loss in resolution in the east–west direction. We observe that the feature in the north–west corner of the unfiltered data has been completely attenuated by the sawtooth filter thus indicating that it is a north–south oriented linear feature associated with sectorial and near sectorial harmonics. Units = [ms^{-2}].

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