

# MEASURING THE SEVIRI MODULATION TRANSFER FUNCTION FOR ASSIMILATION INTO MET OFFICE MESOSCALE MODELS

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## Abstract

The variational assimilation method requires the observing process to be modelled for each observation type. Simulated radiances must be calculated from the model background for each satellite radiance observation. This poster compares a model of the SEVIRI Modulation-Transfer-Function (MTF) and Point-Spread-Function (PSF) based on pre-launch laboratory measurements with those calculated from images obtained during normal orbital observations. Although simulation of radiative transfer processes in the Earth's atmosphere has been investigated in detail for Met Office variational data assimilation, the simulation of the satellite instrument properties within assimilation schemes at the Met Office has generally been rather simplistic. We investigate here the observed PSF and MTF of the infrared channels of the SEVIRI instrument through comparison with 1km resolution MODIS images and also with the Met Office 1.5km resolution UKVD NWP model.

## INTRODUCTION

The variational data assimilation method used at the Met Office requires the observing process to be simulated for each observation type. For the case of geostationary satellite radiance observations, this means that simulated radiances must be calculated from the model background for each pixel of any satellite radiance images which are assimilated. Although simulation of radiative transfer processes in the Earth's atmosphere has been investigated in detail for Met Office data assimilation, the simulation of geostationary satellite instrument properties within assimilation schemes at the Met Office has generally been relatively simplistic.

The SEVIRI instruments on Meteosats 8 and 9 have 12 channels, but this work only address the 8 channels with the longest wavelengths (3.9 $\mu\text{m}$  to 13.4 $\mu\text{m}$ ). The operational SEVIRI instrument scans a 14-megapixel image of the Earth's disk every 15 minutes in each of these channels. Each observation pixel over the disk of the Earth is predominantly determined by the radiance from a small region (pixel footprint) on the Earth's surface and adjacent atmosphere – the dimensions of this footprint determine the blurring of the images. This paper investigates the extent of the footprint which gives a significant contribution to the observed flux in a given pixel. In the SEVIRI image plane, the footprint is described as the imaging Point-Spread-Function (PSF) of SEVIRI. We assume here that the SEVIRI channels used are linear in radiance, so that the observed radiance at a point in a SEVIRI image will be the convolution of an ideal (blur-free) image with the PSF at that location. We further assume that in the image plane the PSF is uniform across small regions of the Earth's disk, and is stable with time.

The Fourier transform of the PSF is the Modulation-Transfer-Function (MTF), describing the response of the instrument in the spatial-frequency domain. This paper compares models of the SEVIRI MTF and PSF based on pre-launch laboratory models with those calculated from images obtained during normal orbital observations. PSFs and MTFs of the infrared channels of the SEVIRI instrument are calculated by deconvolving SEVIRI images using 1km-resolution MODIS images and simulated images from the Met Office's UKVD NWP model. The UKVD model has a fixed 1.5km resolution grid over the UK, Ireland and North-West France, but has a gradually decreasing resolution away from this region. The model has 70 vertical levels extending up to a height of 40km, and the NWP system includes 3D-Var assimilation of surface, sonde, aircraft, Scatwind, atmospheric motion vectors, ground-based GPS, ATOVS and clear SEVIRI radiance observations.

## METHOD

We produce estimates of the SEVIRI MTF and PSF by deconvolving SEVIRI images with MODIS images taken very close in time, using similar wavelengths and geographical remapping of the images. The deconvolution is performed in the discrete Fourier domain using Fast Fourier Transforms (FFTs). Cases with predominantly clear sky were chosen in order to both maximise the amount of fine structure in the scene and minimise any changes which could occur between the times that the MODIS and SEVIRI images were obtained. A MODIS image  $m(x, y)$  and a SEVIRI image  $s(x, y)$  taken at the nearest possible time were selected. These images were then resampled to have the same pixel grid, selecting the nearest observation for each pixel in the resampled image. Both images were then transformed into radiances. The resampled images were blurred at the edges using a raised-cosine window function across repeating boundary conditions, so that there was a smooth gradient of radiance across the image boundaries (see e.g. the edges of Figures 1 and 2). The images  $s(x, y)$  and  $m(x, y)$  were then transformed using FFTs to give  $S(u, v)$  and  $M(u, v)$  respectively. An estimate of the MTF of SEVIRI (including the pixel sampling),  $P(u, v)$ , was then created by dividing the transform of the SEVIRI image by the transform of the MODIS image, using a 2D version of the filter described in Nahman & Guillaume (1981) to suppress noise:

$$P(u, v) = \frac{S(u, v)M^*(u, v)}{\left(|M(u, v)|^2 + (u^2 + v^2)r^2\right)} \quad \text{Equation 1}$$

where  $M^*(u, v)$  is the complex conjugate of  $M(u, v)$  at spatial frequencies  $u$  and  $v$ , and  $r$  is a constant chosen to filter out noise (but having a very much smaller size than the expected dimensions of the PSF).

$P(u, v)$  would only represent the true MTF of SEVIRI if the MODIS instrument provided a perfect representation of the radiances in the scene. Fortunately, the resolution of MODIS is high enough that its response will only have a small impact on the retrieved MTF for SEVIRI (see Figures 1 to 4). Note that a SEVIRI MTF calculated in this way includes the contribution from the rectangular pixel shape used for the SEVIRI 10.8 $\mu\text{m}$  image.

A similar deconvolution process was performed for SEVIRI images at other wavelengths. The process was also repeated using simulated images generated from the Met Office's 1.5km UKVD model at the SEVIRI wavelengths. In order to generate these simulated images, the model fields were interpolated to the footprint centre for each SEVIRI pixel, and the RTTOV v7 radiative-transfer code was used to calculate the radiance in each SEVIRI channel at the top of the atmospheric profile. The properties of the SEVIRI instrument were not modelled in the simulation, so the simulated images will include all high spatial-frequency structure which is captured by the 1.5km model.

The MTFs produced in this way are then compared with empirical models for the SEVIRI MTF based upon the work of Lee & Atkinson (2000).



**Figure 1:** SEVIRI 10.8 $\mu\text{m}$  image from 30/05/2009 showing clear sky over most of England and Wales. Part of this image is shown enlarged in Figure 3.



**Figure 2:** MODIS 11 $\mu\text{m}$  image taken at the same time as Figure 1. The part of the image around the city of Bath is shown enlarged in Figure 4.

## RESULTS

A model for the expected MTF of each SEVIRI channel was generated based on the semi-empirical modelling of Lee & Atkinson (2000). Cross-sections through the model (labelled “Model”) for the raw 10.8 $\mu\text{m}$  SEVIRI MTF are plotted alongside laboratory measurements made before launch (“Lab”) in Figure 7, and show good agreement in both East-West (“EW”) and North-South (“NS”) directions.

The MTF model was multiplied by the MTF response of a square SEVIRI pixel (i.e. multiplying by an appropriate sinc function). This gave the MTF for SEVIRI data when plotted on a pixel grid, as is the case for e.g. the images in Figures 1 and 3. East-West and North-South cross sections through this MTF are shown in Figure 8 labelled as “Model EW” and “Model NS” respectively.

Cross-sections through the calculated MTF  $P(u, v)$  for SEVIRI channel 10 derived using Equation 1 (using the image shown in Figure 1) are also plotted in Figure 8, labelled as “Image EW” and “Image NS”. At high spatial frequencies, this *in-orbit* MTF shows good agreement with the model MTF appropriate for SEVIRI data plotted on a square pixel grid. At low/intermediate spatial frequencies the *in-orbit* MTF shows a slightly higher response in the NS direction than the model.

A PSF was then generated from the derived *in-orbit* MTF (labelled “Image” in Figure 8). This PSF was generated using an FFT:  $p(x, y) = \text{FFT}[P(u, v)]$ , and is plotted in linear greyscale in Figure 5. The model MTF (“Model” in Figure 8) was transformed in the same way, and the resulting PSF is shown in Figure 6. PSFs were derived for six other SEVIRI channels in a similar way, and these are shown in Figure 9 alongside small sections of the images used in the deconvolution process.



Figure 3: Enlargement of Figure 1 around Bath.



Figure 4: Enlargement of same part of Figure 2.

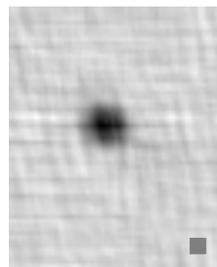


Figure 5: 10.8 $\mu\text{m}$  SEVIRI PSF derived from Figures 1 and 2. The SEVIRI pixel size is indicated by the grey square.

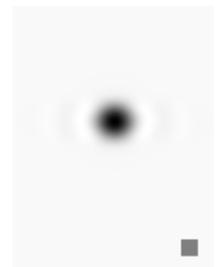


Figure 6: Theoretical model of expected PSF. The grey square shows the SEVIRI pixel size.

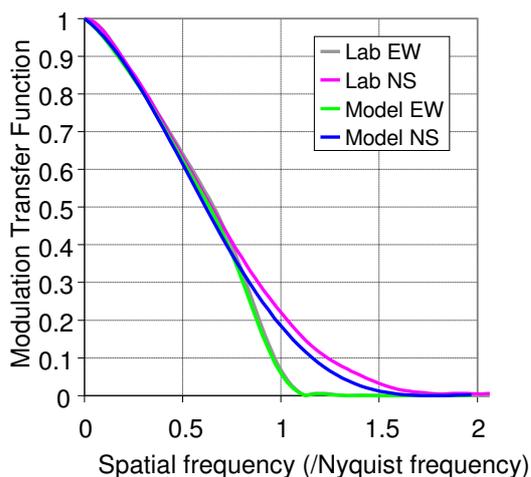


Figure 7: Theoretical model for the raw SEVIRI instrument MTF compared with pre-launch laboratory measurements.

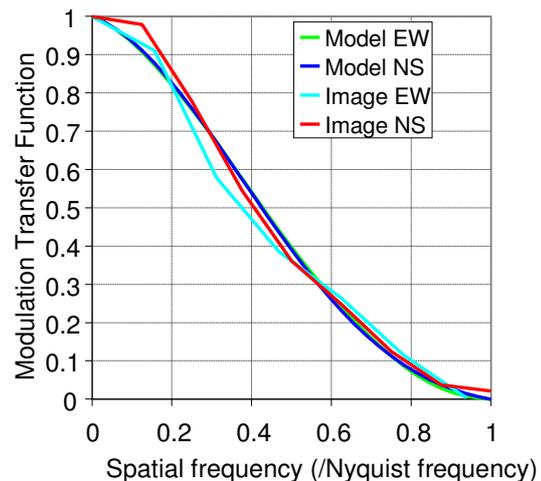


Figure 8: Theoretical model for the MTF including square pixel shape used in SEVIRI images, compared with MTF calculated through deconvolution of the SEVIRI image in Figure 1.

The PSFs retrieved in this way should be very slightly narrower than the true SEVIRI PSFs, as we have used a MODIS image for the deconvolution rather than a perfectly sharp representation of the scene. If the true SEVIRI and MODIS PSFs are nearly Gaussian in shape, then the width of the retrieved PSF  $d_R$  would differ from the true width of the SEVIRI PSF as follows:

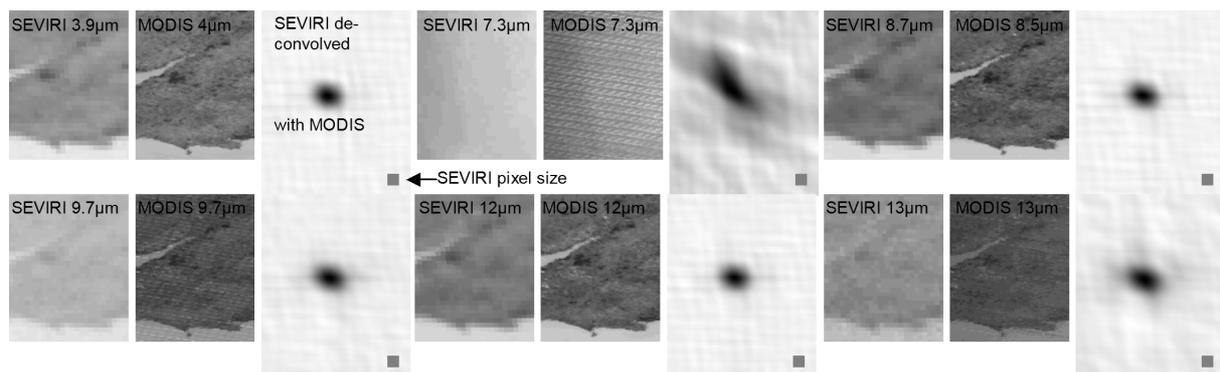
$$d_r = \sqrt{d_s^2 - d_M^2}$$

where  $d_M$  is the width of the MODIS PSF. This would be expected to produce an error of less than 10% in the width of the calculated SEVIRI PSF for the nominal resolution of MODIS.

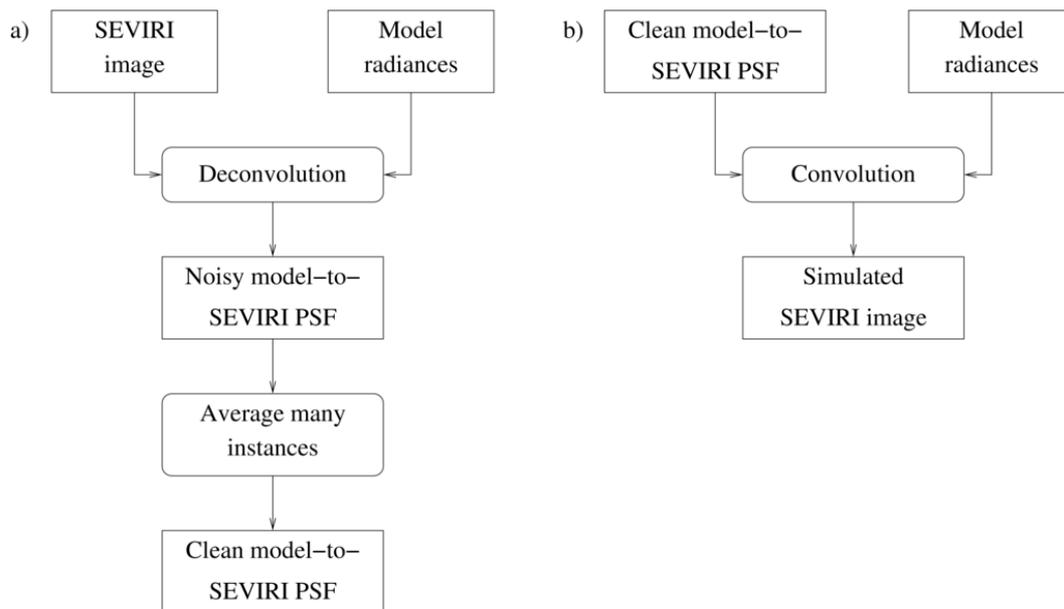
In order to produce simulated SEVIRI imagery from model background data, the model background must be sampled at the locations of the SEVIRI pixels, and top-of-the-atmosphere radiances must be calculated at each of these sample locations (e.g. using a radiative transfer model). The radiances must then be deconvolved with the PSF of the model background sampling function (typically linear interpolation), and then convolved with the PSF of SEVIRI. These two operations can be combined into one – convolving the radiances with one PSF; a “model-to-SEVIRI” PSF. This “model-to-SEVIRI” PSF can be generated by deconvolving the SEVIRI PSF with the model background interpolation function. The generation and use of this PSF is summarised in Figure 10. For very high-resolution NWP models and sensible interpolation between model gridpoints, this “model-to-SEVIRI” PSF will be very similar to the true SEVIRI instrument PSF (and to the PSFs calculated using MODIS above).

If NWP models perfectly represented the true state of the Earth system, then the “model-to-SEVIRI” PSF could be calculated directly, by deconvolving SEVIRI images using NWP model radiances calculated at each of the SEVIRI pixel locations. An experiment was performed to see whether the Met Office’s UKVD forecast model was sufficiently accurate and of sufficient resolution that such a “model-to-SEVIRI” PSF could be retrieved with good signal-to-noise. The UKVD model has 1.5km resolution over the UK, Ireland and North-West France, but has a gradually decreasing resolution away from this region.

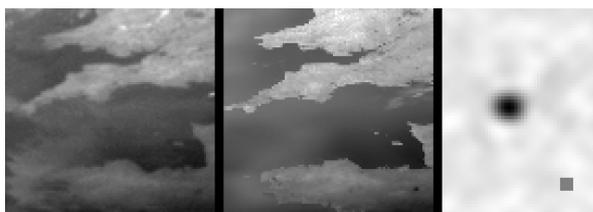
Cloud-free sections of three SEVIRI images from the evening of 10 September 2009 were deconvolved with NWP model backgrounds from the Met Office UKVD 1.5km resolution forecast model. The forecast model was sampled at the locations of the SEVIRI pixels (using linear interpolation of model fields between the model gridpoints). RTTOV 7 was used to generate brightness temperatures at each sampled location. The deconvolution process was performed in the same way as for Figures 5 and 9, and the resulting PSF was resampled to have four times the SEVIRI pixel density in each direction using sinc interpolation. The resulting PSFs and sections of the images used are shown in Figures 11 to 14 for four SEVIRI channels.



**Figure 9:** Enlargements of SEVIRI images in six other channels, along with the corresponding MODIS images, and the SEVIRI PSFs derived for these channels in the same way as for Figure 5. All show reasonably good agreement with modelled PSFs apart from the 7.3 µm channel (where there is a very low signal-to-noise ratio, partly due to MODIS noise). The PSF plots are on a different scale to the raw images; the grey box indicates the size of one SEVIRI pixel.



**Figure 10: Generating and using a "model-to-SEVIRI" PSF.** a) SEVIRI images are deconvolved using model radiances calculated at the SEVIRI pixel locations. The resulting PSFs are averaged to produce a "model-to-SEVIRI" PSF with good signal-to-noise ratio. b) At a later date, model radiances can then be convolved with the "model-to-SEVIRI" PSF in order to generate realistic simulated SEVIRI images.



**Figure 11: The 8.7µm SEVIRI image at the left was deconvolved with the model background (centre) to give an estimate of the SEVIRI PSF (right).**



**Figure 12: The 10.8µm SEVIRI image at the left was deconvolved with the model background (centre) to give an estimate of the SEVIRI PSF (right).**



**Figure 13: The 12.0µm SEVIRI image at the left was deconvolved with the model background (centre) to give an estimate of the SEVIRI PSF (right).**



**Figure 14: The 13.4µm SEVIRI image at the left was deconvolved with the model background (centre) to give an estimate of the SEVIRI PSF (right).**

## DISCUSSION AND FUTURE WORK

The MTFs and PSFs calculated using normal operational SEVIRI image data agree with a model for the SEVIRI MTF based upon work by Lee & Atkinson (2000) within the (relatively high) measurement noise. If a much larger image dataset was used, the statistical noise could be dramatically reduced providing much better measurements of the MTF and PSF. The PSFs deconvolved using MODIS images could be convolved with the nominal MODIS PSF in order to reduce the effect of the MODIS MTF. This work gives confidence that a PSF model could be reliably used when generating simulated SEVIRI imagery from high-resolution NWP model backgrounds. Differences in the locations of isolated small clouds at the top of the images are not sufficient to cause the deconvolution process to break down.

The PSFs derived in Figures 11 to 14 using NWP model backgrounds inspire confidence in the UKVD NWP model, as the presence of a distinct sharp peak at the origin indicates that the model is putting the correct radiances in the correct locations over a significant fraction of the scene. Given that only about 30 kilopixels of image data were used in generating these PSFs, they show remarkably high signal-to-noise. The fine structure evident over land in the NWP models may mean that the UKVD model is sufficiently high resolution that these PSFs are also good representations of the true SEVIRI instrument PSF.

Visual inspection of Figures 11 to 14 shows that fine structure in the sea-surface temperature is not reproduced in the NWP model. By selecting a region of the model domain which is dominated by land surface, and selecting a large number of cloud free scenes (difficult over the UK, but not impossible), we should be able to generate a much more accurate PSF for converting simulated model radiances into realistic simulated SEVIRI images. The signal-to-noise could almost certainly be further reduced using a better deconvolution algorithm, such as the CLEAN algorithm (Clark, 1980) or the maximum entropy method (Gull & Skilling, 1984).

## CONCLUSIONS

Estimates of the SEVIRI PSF and MTF in several infrared channels have been generated from a small set of SEVIRI operational images. Both MODIS images and NWP model backgrounds were tested as proxies for the true radiance distribution. The PSFs generated are consistent within the errors with both theoretical predictions of the SEVIRI instrument performance and with laboratory measurements made before launch. The PSFs generated from in-orbit operational images are noisy, but by averaging a larger dataset of PSFs generated in this way it should be possible to produce an accurate model of the instrument PSF.

We have also demonstrated an approach for generating a PSF-like function which can be convolved with radiances sampled from high-resolution NWP models in order to generate realistic simulated SEVIRI images directly from the model output. This will be extremely useful for qualitative assessment of model output, for monitoring, and potentially for variational assimilation techniques.

## REFERENCES

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