NWP SAF

Annex to AAPP scientific documentation:

Pre-processing of ATMS and CrIS

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This documentation was developed within the context of the EUMETSAT Satellite Application Facility on Numerical Weather Prediction (NWP SAF), under the Cooperation Agreement dated 1st December 2006, between EUMETSAT and the Met Office, UK, by one or more partners within the NWP SAF. The partners in the NWP SAF are the Met Office, ECMWF, KNMI and Météo France.

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1. INTRODUCTION

This document details the scientific and technical issues that are related to pre-processing within AAPP of the data from the sounder instruments on NPP and the follow-on JPSS satellites. The document provides a basis for the design choices made during the development of AAPP v7, and is intended to provide the users with insight into the software functionality.

On NPP and JPSS, the microwave sounder is ATMS (Advanced Technology Microwave Sounder), and the infrared sounder is CrIS (Crosstrack Infrared Sounder). Their main characteristics (see [1]) are summarised below:

ATMS:

- 22 channels (similar to AMSU+MHS combined)
- Scan time 8/3 sec for all channels
- Dwell time 18 ms for all channels (continuous scan)
- 96 samples per scan, separated by 1.11°
- Footprint 5.2° at 23.8 and 31.4 GHz, 2.2° at 50-57 GHz and 89GHz, 1.1° at 166 GHz and 5 channels around 183 GHz.

CrIS:

- Michelson interferometer
- 3 spectral bands covering nominally 650-1095 cm^{-1} (713 channels, sampling 0.625 cm^{-1}), 1210-1750 cm^{-1} (433 channels, sampling 1.25 cm^{-1}) and 2155-2550 cm^{-1} (159 channels, sampling 2.5 cm^{-1}). Total 1305 channels.
- The number of channels available in the Sensor Data Records is 1317, since 2 extra samples are included at the edge of each band.
- Scan time 8 seconds
- Dwell time 167 ms (step scan)
- 30 steps per scan, separated by 3.333° (field-of-regard – FOR)
- Each FOR has 9 fields-of-view (FOV) arranged in a box pattern with 1.1° separation cross-track and 1.024° separation along-track
- The orientation of the 9 FOVs rotates across the scan by an angle equal to the scan angle

The pre-processing step of AAPP is required to perform the following functions

1. Manipulate the beam shape of ATMS. The raw data are over-sampled at all except the high frequencies – hence the raw NEΔT is high. Users typically require noise levels and beam widths comparable with AMSU-A.
2. Map ATMS to CrIS
3. Channel selection, Principal Components and spatial thinning options for CrIS – similar to what is done for IASI

These functions are discussed in the following sections.

2. PREVIOUS WORK

In [2], Bell describes the scheme used in the NWP-SAF pre-processor for SSMIS. The approach taken is

1. Re-map all SSMIS channels to a common grid (in this case the Lower Atmospheric Sounding channels). The four nearest neighbours are used, weighted by the inverse distance to the destination point.
2. Perform data averaging using a Gaussian weighting function with user-defined width

Bell points out that Fourier techniques could be used to do the averaging, but in the end the decision was taken to use a simpler technique.

The present case of ATMS and CrIS is somewhat different from the case of SSMIS: (i) all ATMS channels are co-located, (ii) we do not have the complication of a conical scan to consider, (iii) not all users will want to re-map to the CrIS grid, and (iv) the ATMS swath extends substantially beyond the CrIS swath, so there will be no problems with edge effects.

The following approach is implemented in AAPP v7:

1. Use Fourier techniques to manipulate the ATMS beam width and reduce noise, retaining the original high sampling density
2. Map the modified ATMS to CrIS, using interpolation
3. Users who do not require mapping to CrIS may simply re-sample the output of step 1 at a more appropriate lower sampling density (e.g. same as AMSU-A).

A simple *n*×*n* averaging (e.g. 3×3) is also provided in AAPP as an alternative to Fourier manipulation.

3. ATMS BEAM WIDTH MANIPULATION

For simplicity we assume ATMS has a Gaussian beam, and that the scan-motion-smearing (due to continuous scan) may be neglected. The latter is a reasonable assumption for channels whose beam width is broad compared with the sampling distance. It is well known that the Fourier Transform (FT) of a Gaussian is a Gaussian. For example, if we have a function of time $F(t)$ that is Gaussian in form, then the equivalent function of angular frequency, $F(\omega)$, is given by:

$$F(t)=\exp\left(-at^2\right) \qquad F(\omega)=C\exp\left(-\frac{\omega^2}{4a}\right);\quad C=\sqrt{\frac{\pi}{a}}$$

If x is distance in units of the radiometer sampling distance, f is spatial frequency in units of the reciprocal of the sampling distance, *PSF* is the point spread function (beam shape), *MTF* is the modulation transfer function (spatial frequency response) and w is the 3dB full-width, in samples, then the FT pair becomes:

$$PSF=\exp\left(-\left(\frac{x}{w/2}\right)^2\ln 2\right) \qquad MTF=\exp\left(-\frac{(\pi f w/2)^2}{\ln 2}\right)$$

In the spatial frequency domain we can easily compute the manipulation required in order to convert from one beam width to another – it is the new MTF divided by the old MTF.

For example, if the sampling distance is 1.11°, and we wish to convert a 2.2° beam width to a 3.3° effective width, the two MTFs and the MTF amplification factor are shown in Figure 1. (These are actually sections through a 2D function). The corresponding PSFs are shown on the right.

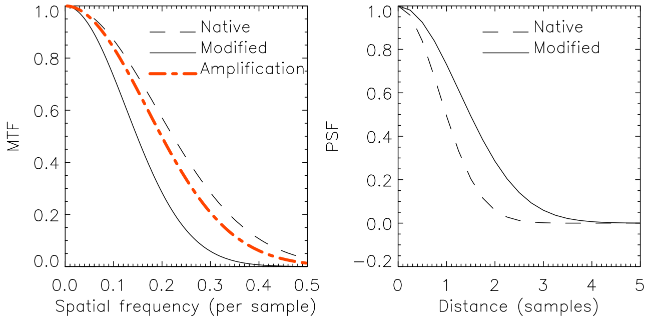


Figure 1: Conversion of 2.2° beam width to 3.3°. The sampling distance is 1.11°

If we assume the instrument has white noise characteristics then the noise reduction factor is the RMS value of MTF. In the above example, the noise reduction factor is 0.30. If we convert from 1.1° (i.e. MHS-like channels) to 3.3° then the noise reduction factor is 0.23. These noise reduction factors are surprisingly good. Simple averaging of 3×3 samples would only give a noise reduction of 0.33. The explanation seems to be that a simple 3×3 averaging of MHS-like channels does not result in a Gaussian function – it is more like a top hat – so the two are not strictly comparable.

What about the two low-frequency channels with 5.2° beam width? In principle one could synthesise a narrower beam by amplifying all except the lowest spatial frequencies. However this must be done with care otherwise there will be a very large noise penalty. In our favour is the fact that these channels are initially heavily over-sampled: the scene energy beyond about 0.5×nyquist is negligible. So if we amplify the low spatial frequencies but cut off the amplification function at a pre-defined spatial frequency then we will reduce the beam width but still eliminate much of the noise.

Experiments have shown that smoothly attenuating the amplification function gives an improved result compared with a sharp cut-off – with narrower 3dB beam width and less “ringing” in the modified imagery. Figure 2 shows an example of such a manipulation.

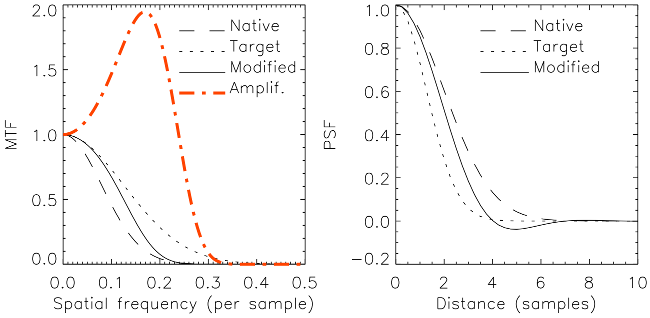


Figure 2: Attempt to synthesise an AMSU-A-like beam width (3.3°) from an ATMS channel with width 5.2°

The resulting modified PSF has a 3dB width of 4.8° and the noise factor is 0.72. Although the beam width is only 7% narrower than the native beam width, the MTF at low spatial frequencies is very close to the “target” MTF – so for large and medium-scale structures (e.g. coastlines) the imagery will correlate well with imagery from the higher frequency channels manipulated to 3.3°.

The modified MTF in Figure 2 (solid curve on left hand plot) has the following form:

$$MTF' = \exp\left(-Af^2 - Bf^4\right) \tag{1}$$

If MTF_{Target} represents the ideal Gaussian (i.e. $MTF_{Target} = \exp(-Af^2)$) then the equation may be conveniently reformulated:

$$MTF' = MTF_{Target} \times \exp\left(-\frac{\left(\ln MTF_{Target}\right)^2 \ln 2}{(\ln c)^2}\right) \tag{2}$$

where c is a cutoff defined as the value of MTF_{Target} at which $MTF' = 0.5 \times MTF_{Target}$. In Figure 2, $c = 0.4$. A lower value of c will result in a narrower beam width but higher noise, e.g. if $c = 0.3$ then the noise factor is increased to 1.3. Note that MTF' has circular symmetry.

The curve in Equation 1 is of course just one of many possibilities for the MTF manipulation function. But the formulation shown does appear to have suitable properties for many users, i.e. it smoothly attenuates the modified MTF, having little effect at low spatial frequencies but effectively filtering instrument noise at the high spatial frequencies. This function in provided in AAPP v7. An alternative approach would be to use an adaptive technique such as the Wiener Filter, but this is unsuitable for NWP applications because the noise and effective beamwidth would be scene-dependent.

Thus for performing Fourier manipulations on a given ATMS channel, the user should be able to specify the following two numbers:

1. Target beam width (e.g. 3.3°)
2. The value of *c* (e.g. 0.4 for channels 1-2).

The manipulation is illustrated in Figure 3, in which brightness temperature fields with the ATMS sampling characteristics have been simulated from NOAA-18 MHS channel 1. Looking at the difference fields, it can be seen that the enhanced 5.2° scene (with target beam width 3.3° and cutoff 0.4) is much closer to the nominal 3.3° field than is the raw 5.2° scene. The raw scene (labelled (c) – (b)) displays large differences close to coast lines and strong cloud features, that are much reduced in the enhanced scene.

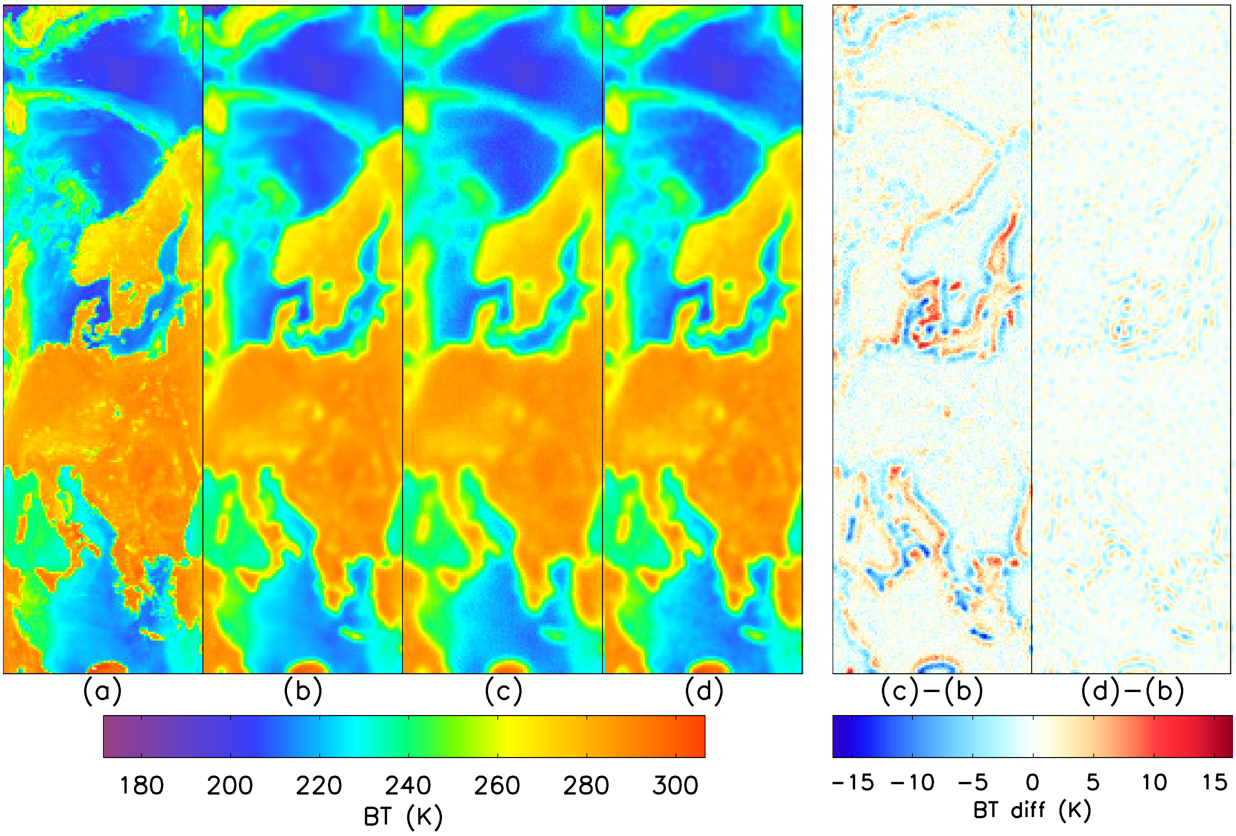


Figure 3: Simulated ATMS imagery and difference fields. Left: (a) MHS 89 GHz image; (b) as seen by a channel with 3.3° beamwidth; (c) as seen by a channel with 5.2° beamwidth; (d) enhancement of the 5.2° image using the manipulation of Figure 2. Right: Difference fields (c) – (b) and (d) – (b).

4. MAPPING ATMS TO CRIS

The footprint pattern for two successive scans of CrIS is shown in Figure 4. It is shown as a function of scan angle (cross-track) and time (along-track), assuming a a nominal height of 833 km and an orbital period of 101 minutes. Strictly speaking the along-track separation of the 9 samples in a FOR will depend on the satellite height and velocity – since they are fixed in angle.

Close to nadir, the pattern is approximately rectangular, with a small gap between scans. As the scan angle increases the box pattern of the FOR rotates, such that they are diamond shaped at the swath edges. The diamonds are elongated in the along-track direction towards the edges of the scan due to two factors: (i) increased distance from the satellite to the surface, and (ii) curvature of the Earth results in successive scan lines being slightly closer together than they are at nadir.

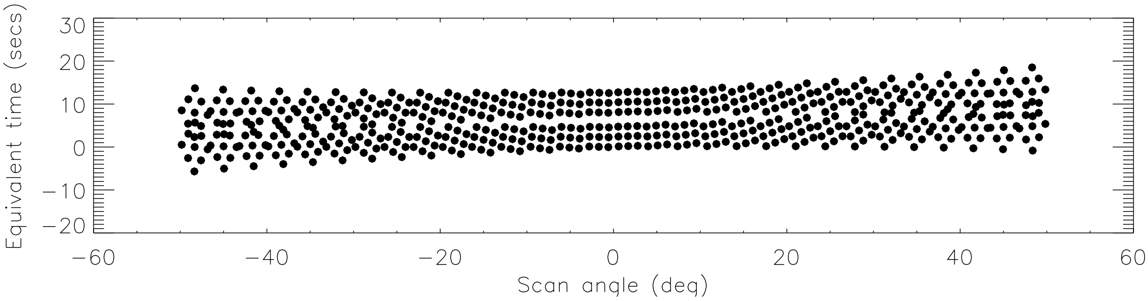


Figure 4: Footprint pattern for CrIS

The specification for the CrIMSS EDRs states that ATMS will be mapped to the centre of each FOR, see [4] and [5]. In this case mapping of ATMS to CrIS is similar in principle to the other mappings performed in AAPP (e.g. AMSU-A to HIRS). AAPP normally uses a bilinear interpolation for such mappings.

The sampling density of ATMS is 9 times that of AMSU. This effectively eliminates aliasing errors in the re-mapping. It is assumed that ATMS has already been noise-filtered using the techniques of Section 3.

Whilst one ATMS spot per FOR may be adequate for some users, others may require ATMS to be mapped to each of the 9 FOVS. The re-mapping software must therefore take account of the rotation of the FOR box pattern. There are two ways in which this could be done:

1. Compute a look-up table of duration 8 seconds that specifies which ATMS samples should be used for each CrIS FOV, using nominal scan geometry. Apply this to all the CrIS scans within a granule.
2. Use the supplied latitude/longitude values for each instrument to identify the neighbouring ATMS samples for each CrIS FOR. Then use bilinear interpolation for the individual CrIS FOVs.

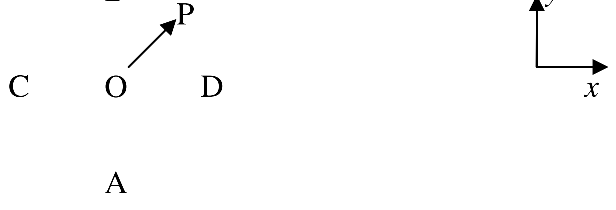
The AAPP mapping routines were originally developed to use look-up tables, since that is the most efficient computationally. However, experiments with prototype code suggest that method 2 is now feasible, and this method has the advantage that any navigation offsets used in SDR processing are automatically accounted for. It is also generic – could be used for other instruments.

Looking at method 2 in more detail, the method implemented in AAPP v7 is as follows:

a) Convert all latitude/longitude values to Cartesian X/Y/Z co-ordinates

b) For each CrIS scan line, find the three ATMS scan lines that are nearest in time.

c) Let A, O, B denote points in successive ATMS scans and C, O, D denote successive ATMS scan positions. P is the CrIS point to be located:



The displacement of point P from point O, in units of the ATMS grid (x, y) is given by

$$\Delta y = 2(\mathbf{OP}\times\mathbf{CD}).(\mathbf{AB}\times\mathbf{CD}) \big/ |\mathbf{AB}\times\mathbf{CD}|^2$$

$$\Delta x = -2(\mathbf{OP}\times\mathbf{AB}).(\mathbf{AB}\times\mathbf{CD}) \big/ |\mathbf{AB}\times\mathbf{CD}|^2$$

where **OP**, **AB** and **CD** are vectors, × denotes vector product and the dot denotes scalar product.

d) Interpolate each ATMS channel to the CrIS spots using bilinear interpolation.

5. CRIS PRE-PROCESSING

For the CrIS Sensor Data Records, Ref [1] and [7] show that the interferograms will have been transformed into calibrated, geolocated radiances. They will have been spectrally corrected to allow for differences between the 9 FOVs – i.e. similar to the IASI level 1C radiance product. Like IASI, CrIS has 3 spectral bands. Unlike IASI, there will be gaps between the 3 bands (1095-1210 cm^{-1}, 1750-2155 cm^{-1}).

Ref. [4] states that the CrIS SDR processing will produce unapodized spectra. Such spectra are difficult to handle in the radiative transfer modelling, and therefore the CrIMSS algorithm converts the spectra to either Hamming apodization or Blackman-Harris apodization. Furthermore, the BUFR format data that will be distributed by NOAA will have Hamming apodization [T. King, pers. comm.]. These apodization functions are illustrated in Figures 4 and 5, together with the Gaussian apodization[1] that is used for IASI.

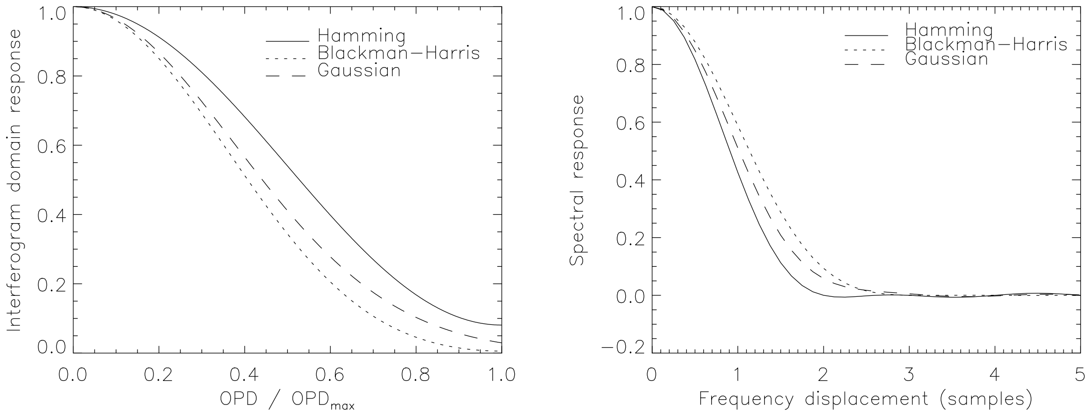


Figure 5: Comparison of apodization functions in the interferogram domain (optical path difference – OPD) and the spectral domain

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[1] The Gaussian apodization function is the Fourier transform of a Gaussian line shape having 3dB half-width equal to the wavenumber sampling interval. It is truncated at OPD_{max}.

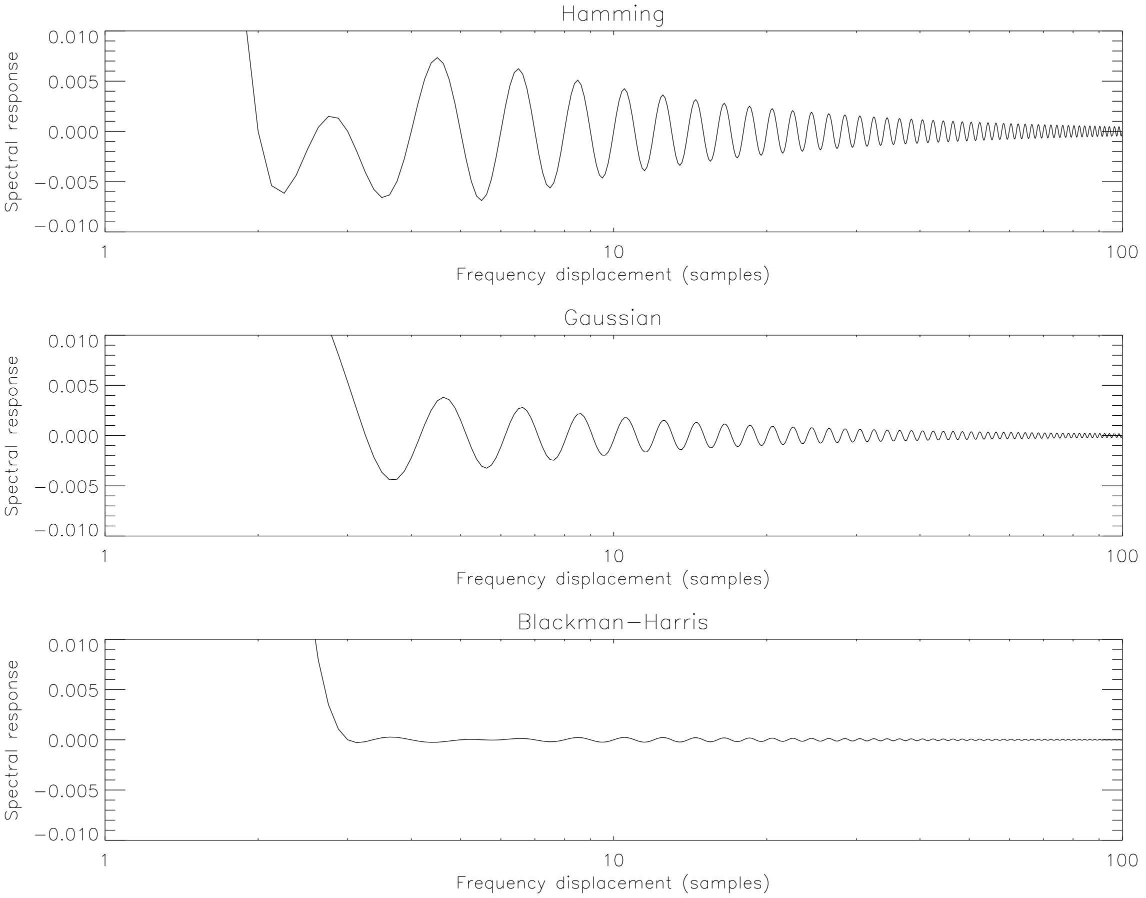

Figure 6: Comparisons of apodization function ripple in the spectral domain

Apodized spectra, x, are easily generated from unapodized data, y, for the Hamming and Blackman Harris apodizations [4]:

$$x_{i-2} = A_2\, y_{i-2} + A_1\, y_{i-1} + A_0\, y_i + A_1\, y_{i+1} + A_2\, y_{i+2}$$

Hamming: $[A_0, A_1, A_2] = [0.54, 0.23, 0]$
Blackman-Harris: $[A_0, A_1, A_2] = [0.42323, 0.248775, 0.03961]$

where two samples have been discarded from each end of the spectrum.

Referring to Figure 4, it can be seen that to accurately reverse the apodization process is impossible for Blackman-Harris because the interferogram-domain response falls almost to zero at maximum optical path difference. The Hamming apodization can be reversed, to a good approximation, but note that

- If only 1305 channels are available (which will be the case for the BUFR products) then there will be errors at the band edges for de-apodized spectra.
- If the apodized spectra are quantized for data transmission purposes then that could degrade any de-apodization.

The reason for considering de-apodization is that if PC scores are required, they should be generated from noise-normalised data – which ideally means from self-apodized CrIS spectra, for which noise does not vary with OPD. We do not have access to self-apodized spectra but we can assume that self-apodized spectra are not that different from unapodized spectra. This is because the spectral sampling is very coarse for band 3 (ten times that of IASI), which is where beam divergence would be expected to produce the strongest attenuation of the interferogram response.

Despite a theoretical preference for generating PC scores from unapodized data, experience with IASI suggests that satisfactory reconstruction scores can in fact be generated from PC scores from apodized spectra. Of course, because the three bands have different spectral sampling and do not overlap, PC scores would have to be computed for each band separately.

Some users will prefer a channel selection to PC scores. This should be straightforward as we can use the same method (possibly the same channels) as for IASI.

Similarly, for spatial thinning, there will be a requirement to implement a "1 in 9" thinning option, e.g. "warmest field of view" as is commonly used for AIRS. Other users may prefer fixed FOVs (e.g. the central FOV). Intermediate thinning options may also be required (e.g. "4 in 9" is a good compromise).

Note that according to [8] "CrIS SDRs contain 2 QC words (the imaginary part of the signal and a noise estimate) for every 1 measurement word (the real part of signal)". This could be a useful handle on the noise if a reference noise profile is not available. However, this information is not available in the BUFR files to be distributed by NOAA.

6. ATMS DERIVED CLOUD PRODUCTS

The ATMS pre-processing will include generation of derived cloud and surface products in the same way as is done for AMSU/MHS. Specifically:

- Surface type estimation
- Scattering indices
- Precipitation probabilities
- Surface cost function (which can be used over sea as a cloud liquid water index)

In generating these products it will be necessary to update the coefficient files in order to take account of spectral differences between ATMS and AMSU, namely:

- Channel 3 of ATMS (51.76 GHz) is a new channel not present in AMSU-A. This may be useful for assessing surface type.
- Channels 19 (183.31±4.5) and 21 (183.31±1.8) are also new.
- ATMS uses horizontal polarisation (at nadir) for all the sounding channels (i.e. only channels 1, 2 and 16 are vertical). AMSU-A has vertical polarisation for the channels at 50.3, 52.8 and 54.9 GHz.

7. DATASETS

AAPP needs to accept both HDF-5 and BUFR formats. The method of handling this is to have a flat binary "level 1c" intermediate format – as for MetOp – with separate front-ends for HDF-5 and BUFR.

For the "level 1d" outputs, we require the ability to produce:

- ATMS level 1d, on original grid (1.1° scan angle, 8/3 sec scans). Keep relatively narrow beam widths.
- ATMS level 1d, on AMSU-A-like grid (3.3° scan angle, 8 sec scans). Beam widths all 3.3° (except at 23 and 31 GHz).
- CrIS level 1d, thinned spatially, 1 FOV per FOR, with mapped ATMS.
- CrIS level 1d, full resolution, with mapped ATMS.

Two ATMS 1d formats are implemented, one with 32 spots per record (1 scan in 3) and the other with 96 spots per record (every scan). For CrIS, we adopt a similar approach to IASI: 1 record per detector, each with 30 spots.

Both ATMS and CrIS level 1d products would include the derived products mentioned in section 6.

As a "day 2" product, it is also planned (by Météo-France) to introduce a MAIA upgrade, to map VIIRS to CrIS. So the CrIS level 1d format will need to accommodate VIIRS and its derived products. VIIRS has 22 spectral bands.

8. IMPLEMENTATION ASPECTS

7.1 Missing data

Missing or corrupt ATMS data will cause problems. This could affect either whole scans or isolated spots within a scan. A proposed approach is to use linear interpolation in the along-track direction in order to fill in missing points prior to manipulating the beam width. Having done the manipulations, the points can be set to missing again prior to re-mapping, in order to ensure that only trustworthy data are used.

7.2 Fourier transforms

Fourier transforms work most efficiently when the number of points in each dimension is a power of 2. ATMS has 96 samples per scan line. It is proposed to pad this out to 128 by reversing the outermost 16 points on each side of the swath. Similarly, in the along-track direction we can pad out to the next power of 2.

A complete orbit has typically 2300 scans. So to process all channels for one orbit we would require 22 forward and 22 inverse FTs, each of 128×4096 points. On a medium spec PC (2.4GHz P4, 512Mb RAM, single core) this takes about 10 seconds. This is acceptable – and for comparison it is 1-2 orders of magnitude less than is required for computing Principal Component scores for IASI. In practice, granules of ~6 minutes, or shorter, are likely to be used rather than whole orbits.

9. REFERENCES

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