CORRECTION OF ELECTRIC STANDING WAVES

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Abstract.

Electric Standing Waves (ESW) appear in some frequency bands of HIFI, a heterodyne spectrometer aboard the Herschel Space Observatory. ESWs consist of about 10 irregular ripples added to a continuum contribution. They distort the spectra and should be removed. ESWs change so rapidly that the standard ways to mitigate them, do not work.

We have built a catalog of thousands of spectra taken on empty sky that contain only the ESW contribution. All ESWs seem to belong to a limited number of multiplicative families. To find representative members of the families we modelled them as splines and chose one representative template model for each family based on Bayesian evidence. The resulting set of models is our catalog of possible ESW templates.

To correct a spectrum taken on an astronomical source, we select the template from the catalog that fits with the highest Bayesian evidence and subtract it. This has to be done in the possible presence of spectral lines and of a true astronomical continuuum. Both the true lines and continuum should be unaffected by the procedure. To exclude the lines we use a robustly weighted variety of the (gaussian) likelihood.

Ideally the correction should be part of the pipeline with which all HIFI observations have to be processed. This requires a procedure having no failures, no interaction, and limited CPU usage.

Keywords: Robust fitting, Instrumental correction

INTRODUCTION

Herschel is a large infrared and submm satellite that was launched by the European Space Agency (ESA) in 2009 and ended its mission when the He coolant ran out in 2013. Herschel had a 3.5m diameter mirror at a temperature of 80K. Given the fact that Herschel was built to observe the cool universe with temperatures in the range of 50 - 100K, the mirror must be considered as a hot background visible to the detectors.

HIFI[1] (Heterodyne Instrument for the Far Infrared) was one of 3 instruments in the payload of Herschel. Heterodyne instruments measure the difference frequency, or intermediate frequency (IF) by mixing the observed sky signal with a signal from a monochromatic source tuned close to the sky frequency, called the local oscillator (LO). By changing the LO frequency, the instrument can be tuned to the desired frequency.

HIFI could observe very high resolution spectra in one of 14 frequency bands (numbered 1 to 7, a and b). The spectrum was simultaneously measured in 2 orthogonal polarizations, "horizontal" (H) and "vertical" (V). Due to the (relatively) high temperature of the mirror all observations have the astronomical spectrum on top of the contribution of the mirror. The usual strategy to apply in such situations, is to subtract a spectrum of a nearby piece of empty sky which only contains the emissions of the mirror. Using this on-source minus off-source strategy allows to mitigate also other (additive) unwanted effects such as instrumental response and drift.

In the four highest frequency band, which uses Hot-Electron Bolometer (HEB) mixers, ESWs are present. These bands are labelled 6a, 6b, 7a and 7b, each in 2 polarizations, H and V. Unlike optical standing waves which are generated in the cavity between optical surfaces such as mirrors or feedhorns, Electric Standing Waves (ESW) are caused by reflections inside the transmission cable between the HEB mixer and the first signal amplifiers[2]. As such the ESW are created downstream of the mixing process and their shape does not depend on the LO tuning frequency. ESW are present in individual spectra and their amplitude changes rapidly from scan to scan which is why the differencing strategy (on-source/off-source) can not remove them. It should be noted that the ESW we are dealing with in the remainder of this paper are all residuals of the normal on-off differencing. i.e. they are differences themselves.

Traditional methods[3] consisting of the removal of sinusoidal features, fail because both the amplitude and the period of the waves change over the spectrum.
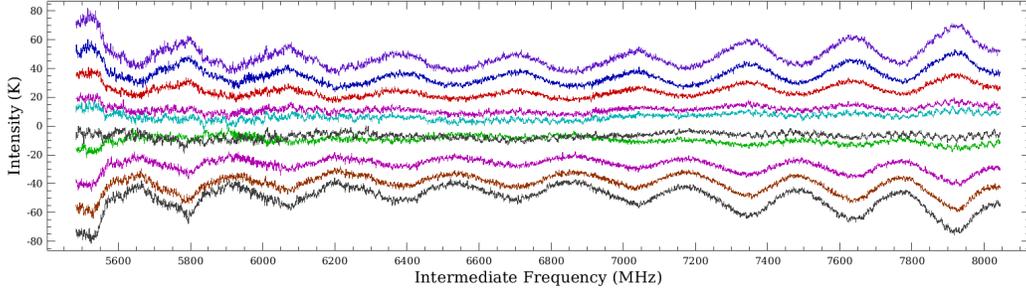
FIGURE 1. A fraction of all example ESW. Different colors indicate different ESW scans

DATABASE OF EXAMPLE ESW

In our observational database there are some very long calibration observations with numerous off-source spectra, i.e. taken on an empty patch of sky. Subtracting all these offs on the same sky position from each other gives even more example spectra of ESWs. As one spectrum on an off position is subtracted from another, the differences are clean of any flux that might originate at that sky position. The subtraction results in both positive and negative ESW features as the sign depends on which of the terms of the subtraction is largest. Thousands of example difference spectra were collected in a database.

In figure 1 a small number of example ESWs are shown. All other examples look very similar. Three things are obvious from inspection of the comprehensive database of ESW scans. Firstly, the ESW are very similar indeed, except for a multiplicative factor. Secondly, there are not only ripples in the ESW but also a continuum offset. Thirdly, the continuum offset scales with the modulation amplitude.

SPLINE MODELS

Selection

We want to model all examples in our database with a minimum set of cubic splines models. The minimum set will be our catalog of templates. Each template generates a family of possible ESWs by

$$F(\beta) = \beta \times T \tag{1}$$

where F is a family member, T is a template and β is a scaling factor. This way all ESWs can be explained as a member of a multiplicative family, each one fathered by a template.

To generate a catalogue of the templates we define 72 equidistantly spaced knots over the frequency axis and fit these models to all example ESWs. Subsequently we remove models that can be "better" explained by some fraction of another model, keeping the one with the larger amplitude as a template for the catalog. "Better" in this context means that the evidence for one model is higher than for another.

We write the evidence for the cubic splines model as

$$P(M_i|D_i) = \int P(D_i|\theta, M_i)P(\theta|M_i)d\theta \tag{2}$$

where M_i is a model with 75 spline parameters θ. There are always a few more parameters in a spline model than knots. D_i are the data of the example ESW. The priors for the θ parameters are all uniform with enough range to encompass their possible values. This evidence for M_i will be compared with the evidence for $F(\beta)$.

$$P(F|D_i) = \int P(D_i|\beta, F)P(\beta|F)d\beta \tag{3}$$

where β is a scalar multiplicative factor. The prior for β is also uniform between $[-2, 2]$. So we are comparing a 75-dimensional integral in θ with a 1-dimensional integral in β. Still the Ockham factor [4] is doing its job.

The model M_i will become a template in the catalogue only if the former evidence $P(M_i|D_i)$ is larger than $P(F|D_i)$ for all templates already in the catalogue. Otherwise it can be explained as a family member of some template already present.

The different bands and polarizations have quite different numbers of templates in their catalogues. Table 1 lists the number of unique templates that are found for each of the mixer bands.

TABLE 1.   Number of Templates

	6a	6b	7a	7b
H	28	14	62	13
V	5	12	162	89

Split Templates

For reasons that will become clear in the next section, we split all templates in our catalogue into two parts: a slowly changing spline with 4 knots, which represents the continuum of the ESW and a fast spline model with 72 knots which represents the wavy parts. The key element in the removal of all of the ESW, including the continua, is the (observed) fact that the slow parts and the fast parts scale in amplitude with the same factor. Once we know the scaling factor of the fast parts, the same factor applies to the slow parts.

We present the split templates for 2 bands: 6bV and 7bH. In the upper panel the slow continuum is displayed. In the lower panel the fast oscilatory parts.
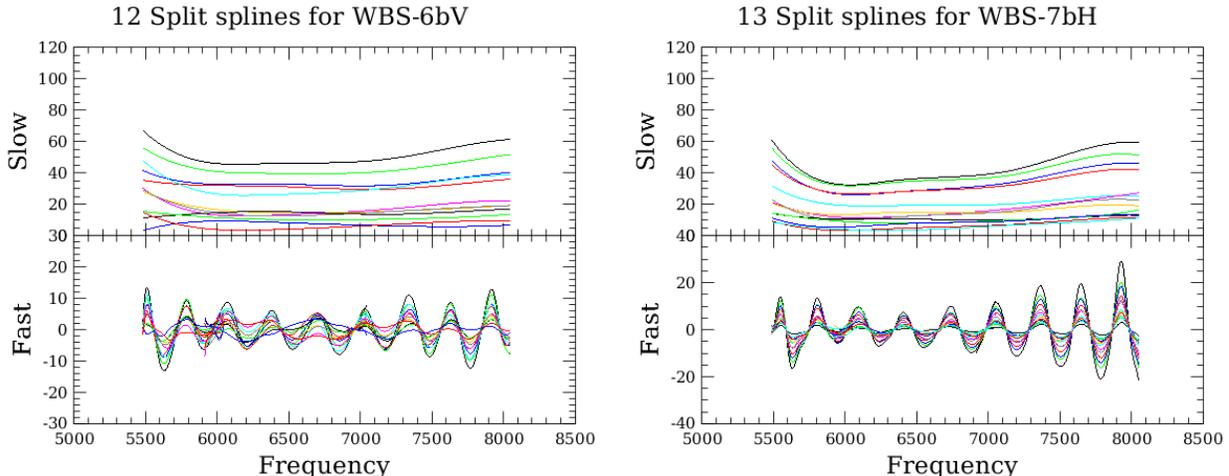
FIGURE 2.   Catalogue of spline templates for 6bV (left) and 7bH (right).

APPLICATION TO A HIFI SPECTRUM

A HIFI spectrum might be expected to contain a true sky continuum plus one or more emission or absorption lines and on top of that an unknown ESW contribution. To correct such a spectrum, we have to find out which family the ESW belongs to and what the amplitude β should be. This scaled template will be subtracted from the spectrum to remove the ESW contribution. The best template and the optimal scale factor is found as the one of which the fast (wavy) parts best fits the wavy part of the spectrum, disregarding the continuum and lines, if present.

However as a spectrum can contain a true continuum, which is independent of the slow (continuum) parts of the templates, we build a new model consisting of a total continuum contribution, B, and the fast part of a template, T^f.

$$M_j = B + \beta \times T_j^f \tag{4}$$

where j numbers the templates in the catalogue and B is another spline model with a few knots. It represents the summed continua of the source and the ESW.

As usual we determine which template produces the best fit by calculating the evidence similarly to equation 3.

$$P(M_j|D_i) = \int P(D_i|\beta,M_j)P(\beta|M_j)d\beta \tag{5}$$

All evidences in these procedures are calculated as Laplace approximations [5][6]. The parameters of the continuum model B are nuisance parameters. They are irrelevant and integrated out.

We also calculate the evidence for a model that consists of only the continuum, $M_0 = B$. If the last model yields the highest evidence then obviously there is no template which produces a better result and we subtract nothing from the spectrum. Otherwise we subtract from the spectrum $\beta \times (T^f + T^s)$, where T^f and T^s are the fast and slow parts of the best template and β is the optimal scale factor for this template.

Robust Fitting

To disregard any real astronomical emission (or absorption) lines in the fit we rewrite the gaussian likelihood in equation 5 as a weighted gaussian likelihood [7].

$$\log P(D_i|\beta,M_j) = \sum w_i \times (M_j - D_i)^2 \tag{6}$$

where the weights are defined as

$$w_i = \begin{array}{ll} (1-r_i^2)^2 & \text{if } |r_i| \leq 1 \\ 0 & \text{otherwise} \end{array} \tag{7}$$

and r are the scaled, normalized residuals.

$$r_i = (M_j - D_i)/(\alpha \times \sigma) \tag{8}$$

where σ is the noise scale of the fit and α is a positive constant determining at how many σ's the weight decreases to 0. We take $\alpha = 6$, meaning that residuals which are 6 times the noise scale are completely disregarded.

As the weights depend on the results of the fit, they cannot be calculated simultaneously. We need to set up an iterative scheme, where we start with all weights being 1 and subsequently calculate the weights using the fit results of the previous iteration. Such a scheme converges in about 5 iterations.

The robust procedure might seem a bit ad hoc, but it is just a computationally faster aternative to using a Laplace error distribution or a mixed Gausian error distribution. Pipeline processing requires economy in CPU usage.

Example

We present 2 independent spectra of the same object in figure 3, selected such that one (the lower) seems to be well calibrated, while the other is heavily affected by ESW. Obviously they should be the same as they are of the same astronomical source.
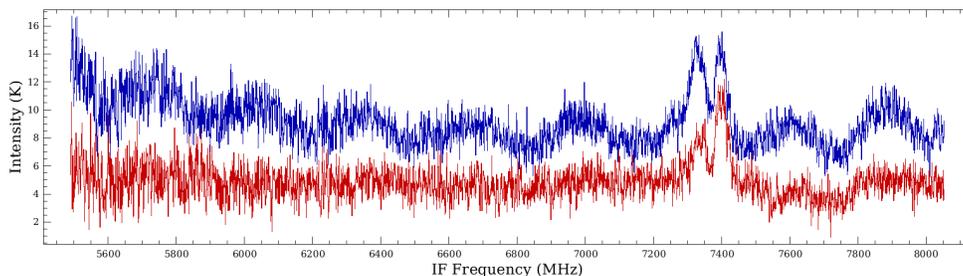
**FIGURE 3.** Two spectra on the same source

Before starting the processing we first filter the data through a 100 point boxcar filter. It helps to reduce the noise. Also, line features will stand out more clearly from the noise so the robust fitting will be able to better isolate them. As the resulting noise is now correlated over 100 points, we can reduce the number of points to be taken along in the calculations and improve processing speed.
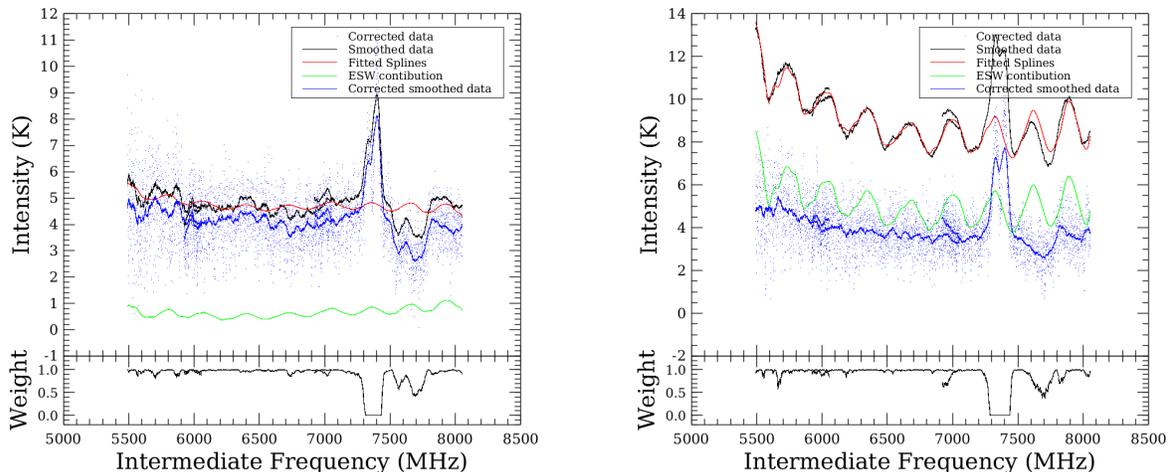
FIGURE 4. Correction Process. See text for explanation.

In figure 4 the same spectra as in figure 3 are displayed. The boxcar-filtered original data are in black. The best fit model of equation 4 is in red. The subtracted ESW is in green and finally in blue the filtered corrected spectrum. Blue dots are the corrected **un**filtered spectrum. In the lower panel the weights from the robust fitting are shown. It can be seen that the lines at frequencies around 7400 MHz are completely disregarded in the fit while the dips (absorption features) at around 7700 MHz have diminishing influence. At all other places the weights are (almost) 1.0, meaning that these points carry full weight in the fit.

Although the lower spectrum in figure 3 showed no visual ESW features, the procedure still found a small contribution. And indeed looking at the boxcar-filtered data we can see some ESW ripples.
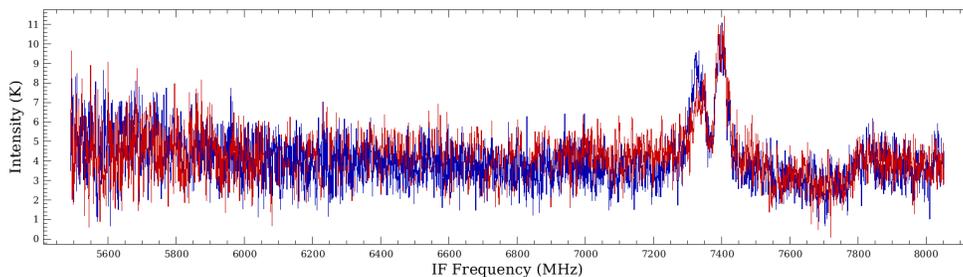
FIGURE 5. Corrected spectra

In figure 5 the corrected spectra are displayed. They fall nicely on top of each other. In itself this is no guarantee of correctness, but it points in the right direction.

Figure 6 shows the outcome of the correction technique applied to hundreds of spectra belonging to a spectral map exhibiting a wide range of ESW shapes. Here, the correction allows for the recovery of the brightness distribution of the intrinsic source continuum, as well as the complex velocity structure of the strong [CII] line present in the first half of the spectra.
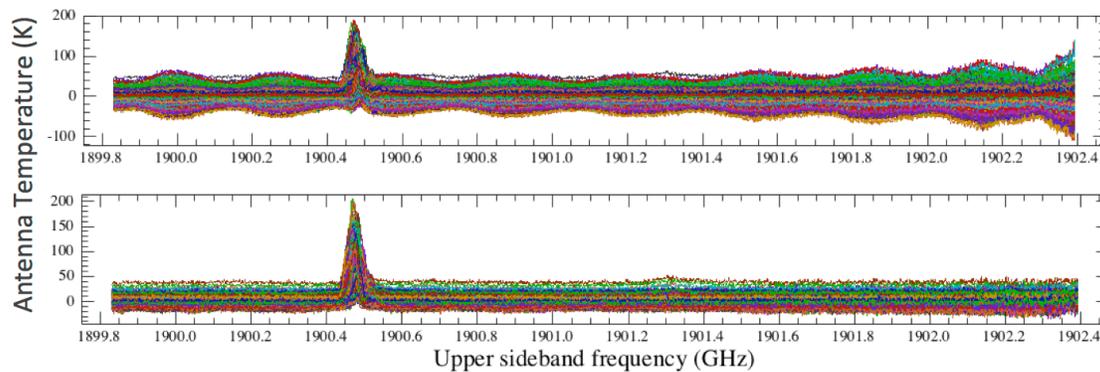
FIGURE 6. Illustration of the ESW correction on hundreds of spectra belonging to a spectral map (top: before correction, bottom: after correction). The width in the lower panel reflects the different amounts of continuum radiation as the instrument scans over the source to make a map. See text for further details.

CONCLUSION

The process is being tested and validated on all HEB observations in our database. A paper on these tests is in preparation. On each of the individual spectra the procedure was applied. In all cases the correction implied an improvement and a large fraction of the spectra could be considered ESW free after correction. At worst the spectrum is left untouched. There is a better agreement between the H and the V polarizations, both in means and in rms. The assumed relation between the amplitude of the continuum parts of the ESW and wavy parts can be confirmed.

After these succesfull tests the algorithm is being prepared for introduction into the HIFI pipeline.

ACKNOWLEDGMENTS

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