Simulations of Deep Extra-galactic Surveys with Herschel-SPIRE

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Abstract.

The SPIRE Photometer Simulator reproduces the entire Herschel-SPIRE system in a modular IDL program. Almost every aspect of the operation of SPIRE can be investigated in a systematic way to ensure that observations are performed in the most efficient way possible when Herschel flies. This paper describes some of the work done with the Simulator to help prepare for large observing programs such as deep extra-galactic, high-redshift surveys.

1. Introduction

Expensive space missions with limited operating lifetimes, such as Herschel (Pilbratt 2006), require efficient operation in order to obtain the best possible value for money in terms of the quantity and quality of astronomical data obtained. Careful preparation of every aspect of the mission needs to be undertaken, including how the various instruments on board the spacecraft are operated to achieve optimum performance. SPIRE (Griffin et al. 2006) is one of three scientific instruments on board the Herschel spacecraft and covers the longer wavelength range from $\sim 200 - 600 \, \mu m$ with both a photometer and an imaging Fourier Transform Spectrometer (FTS). This paper describes how the operation of the photometer half of the SPIRE instrument has been optimised through the use of an instrument Simulator, and how the same Simulator can be used to prepare for large observing programmes.

1.1. The SPIRE Photometer Simulator

The Simulator is an IDL coded virtual version of the photometer half of the Herschel-SPIRE system. It incorporates as many of the physical instrumental and telescope characteristics as it is possible to include in a computationally practical and user-friendly program. Full details of the individual modules and their interaction with each other are given in Sibthorpe et al. (2004).

Briefly, the user creates a suitable input sky – as realistic or fantastic as desired – for each of the three SPIRE bands. These are fed into the Simulator where they are convolved with a representative beam profile and then 'observed' with the bolometer detector arrays. Parameters for the observation are predefined by the user in the same way that a real observation would be planned. The astronomical power from the sky and the background radiation from the telescope and internal instrument components are all passed into a module containing a model of the individual detectors, which calculates their response to
the incident radiation. This bolometer model also calculates and superimposes realistic noise on the output detector time-lines. The detector time-lines are then low-pass filtered and sampled, in the same way as done by the on-board electronics, to produce output voltage time-lines. Additionally, a pointing time-line is generated based on the observation parameters.

2. Optimisation of Observing Modes

SPIRE has several modes of operation (Griffin et al. 2006), but the primary mapping modes are scan and jiggle. The SPIRE arrays are hexagonally close-packed, feedhorn coupled bolometers, with a detector spacing of twice the beam full width half maximum (FWHM), so they do not fully sample the sky in a single pointing. The two mapping modes account for this in different ways. Jiggle map mode is used to observe individual \(4' \times 4'\) fields by pointing the telescope in one direction and 'jiggling' the instrument’s internal beam steering mirror to fill the whole field area with data. While large maps can be created by tiling together individual jiggle map fields it is more observationally efficient to use scan map mode, which involves scanning the telescope across the sky at a constant rate to create a strip of data. By decelerating the telescope at the end of one strip, slewing perpendicular to the scan direction and accelerating back up to scanning speed in the opposite direction, a large map can be built up with successive, adjacent scan strips. The detector arrays are rotated slightly, relative to the scan direction, so that the gaps between adjacent detectors are filled by other detectors following on behind.

Because of the nature of the bolometer detectors scan map data time-lines are subject to \(1/f\) noise – excess noise at low frequencies, or drifts on long time-scales – that cause 'stripes' in the resultant maps (see left hand panel of Figure 1). Jiggle map mode is immune to \(1/f\) noise because the signal is 'chopped', so the map is the difference between on- and off-source signals. Sibthorpe et al. (2006) describe how the Simulator has been used to determine the optimum parameters for operating SPIRE in scan map mode, principally how the competing effects of the low-pass electronics filter and \(1/f\) noise lead to an optimum scan speed around \(30''\,\text{s}^{-1}\). Additionally, the angle of rotation between the scan direction and the array orientation, and the spacing between successive scan strips have been optimised to produce highly uniform sky coverage.

3. Preparation for Deep Extra-Galactic Surveys

With the scan map mode parameters optimised we can investigate how instrumental characteristics will affect actual observations. Part of the SPIRE Guaranteed Time (GT) programme will involve deep extra-galactic, high-redshift surveys that cover large areas of sky down to, and even below, the confusion limit. To see how \(1/f\) noise is likely to affect the sensitivity of such surveys to faint point sources we designed a series of 'observations' to be carried out with the Simulator. We used the GALICS model of galaxy evolution (Hatton et al. 2003) to produce input skies of a suitably realistic extra-galactic cosmological field covering 1 sq. deg. The field was populated with 58590 sources down to a 250 \(\mu\text{m}\) band flux limit of 2 mJy (a confusion limit of 40 beams per source is
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\(\sim 1000\) sources per sq. deg.) Since the GALICS model is based on a hierarchical galaxy formation model the clustering of the sources is more realistic than a simple Poisson distribution, and so the confusion noise should be closer to what will be experienced by SPIRE in flight.

Two sets of simulated observations were performed, one with the \(1/f\) noise switched off, leaving simply white noise in the detector time-lines, and the other with the \(1/f\) noise switched on and at a level that matches the design requirement of the SPIRE bolometers (a knee frequency of 100 mHz.) This is a worst case scenario for the real instrument as the majority of the detectors exhibit less \(1/f\) noise than the requirement. The final sensitivity of the combined simulations (for each noise test) was designed to approximate a confusion limited observation.

A source detection routine was run on naive maps created from each noise test to compare the relative sensitivity of the observations with and without \(1/f\) noise. The extracted source list was then cross-referenced with the input source catalogue. As expected, the map with the \(1/f\) noise showed a significantly higher detection threshold (\(\sim 30\%\)) and with a higher fraction of spurious source detections. Therefore, if left untreated, \(1/f\) noise could seriously affect such a survey. Integration times would need to be \(\sim 70\%\) longer to reach the desired detection threshold than expected from the sensitivity estimates, which currently assume no contribution from \(1/f\) noise.

However, there is much that can be done to alleviate \(1/f\) noise, for example iterative map making methods borrowed from CMB analysis, or filtering schemes. High-pass filtering involves removing all the low frequency modes from a Fourier transform of the time-line data from each detector. This eliminates the long period drifts associated with \(1/f\) noise, effectively removing the stripes in scan maps. Some point source flux is also lost in this process however, so the cut-off frequency must be a compromise between this and removing as much \(1/f\) noise as possible.

We devised the following scheme to filter the data, based on common cleaning routines used in radio astronomy: first construct a map from the unfiltered data; detect the brightest sources and subtract a point source model for each source from the time-series data; Fourier transform and high-pass filter the data, using a cut-off frequency of half the \(1/f\) knee frequency (50 mHz in this case); inverse Fourier transform the data back into time-series and add the bright point sources back on; finally, re-create a map from this filtered data. Removing the bright point sources before filtering prevents negative dips appearing in the map either side of the sources in the scan direction. This reduces the likelihood of the filtering process adversely affecting fainter source flux recovery.

Having made a new map we ran the source detection routine again. The situation was much improved with the detection threshold now only slightly higher than the white noise case. The number of spurious source detections was also much reduced, although still higher than the white noise case. Based on this analysis we believe that the level of \(1/f\) noise expected for SPIRE will not cause a significant problem for these types of faint point source surveys. Simple filtering schemes can go a long way towards reducing \(1/f\) noise effects while more sophisticated methods may eliminate it entirely. See figure 1 for a comparison of pre- and post-filtered images.
Figure 1. The lower right corner of the 250 µm Simulator output map (covering $\sim 35' \times 28'$) showing the effect of $1/f$ noise (left) and how the simple filtering scheme improves the situation dramatically (right). Note how the SPIRE array has been scanned both horizontally and vertically in this simulation to allow more sophisticated techniques, requiring cross-linked data, to be tested. The first Airy ring is also visible around the brighter sources.

4. Summary and Future Work

The SPIRE photometer Simulator is a very powerful tool for investigating the consequences of instrumental effects on the quality of astronomical data to be obtained with SPIRE. Not only has it helped in the optimisation of the observing modes but it is also providing a head start in understanding the data and how it will be best processed when the real thing becomes available.

As well as simulating cosmological surveys the Simulator is also being used to simulate galactic (Sibthorpe, in preparation) and local Universe observations. Together, these simulations are central to the selection and development of the map making code to be delivered as part of the SPIRE pipeline processing package. This process is currently underway and as launch approaches the Simulator will be used to make further simulations to help refine the performance of the map making algorithm as well as helping to develop optimised source detection routines capable of fully exploiting the SPIRE data.

Finally, being a modular program the Simulator is fully customisable and can be modified to represent any other facility of a similar design to SPIRE, or even to help design the next generation of far-IR observatories.

References
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