Map-making of Apex experiment for different scanning strategies

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1 Introduction

In this brief note, we look at the implications of the Apex scanning strategy on the performance of the map-making and on the properties of the reconstructed map. We put ourself in the context of observing the WFS (9h -4d), and covering a 6×6 degree field, some conclusion will not be specific to these field but are also relevant to the observations of any small patch on the sky. In the first section we describe the types of scanning strategy studied, the second part explains the simulations of the signal and noise, and the third part shows the reconstruct maps and their properties.

2 Scanning strategies used

We put ourselves on the Atacama observation site (longitude = $-67°45'18''$, latitude = $-23°1'23''$) and concentrate on the simplest scanning strategies, which we think will induce the less systematic effect :

- the first scanning strategy is a simple drift scanning, the telescope is pointed in the direction of the WFS field, then the earth rotation induces a movement on the sky along the RA axis. After a 24 minute drift (corresponding to the 6 degrees we want to cover), the telescope is repointed with a position 0.25 arcminutes (these number is chosen in order to avoid holes in the map) along the DEC axis above the one pointed at the beginning of the previous drift (we assume a 2 degrees/s speed of the telescope movement in azimuth and elevation during the repointing). We repeat this operation until we cover our 6x6 degrees field, meaning we need 1440 drifts. This should take 576 hours of observations (without time lost in repointing), and it would lead to 24 days of observations if we could observe 24 hours a day. However the WFS is at quite high declination and can not be seen all the day from the Atacama site, furthermore to reduce the atmospheric noise we prefer to observe at an elevation greater than 30 degrees. Taking that into account, the observation time of the WFS field if we start observing the 1^{st} January 2004 is about 8 hours a day (see figure 1 & 2), the observation duration should so be of 72 days (we simulated 90 days) ;

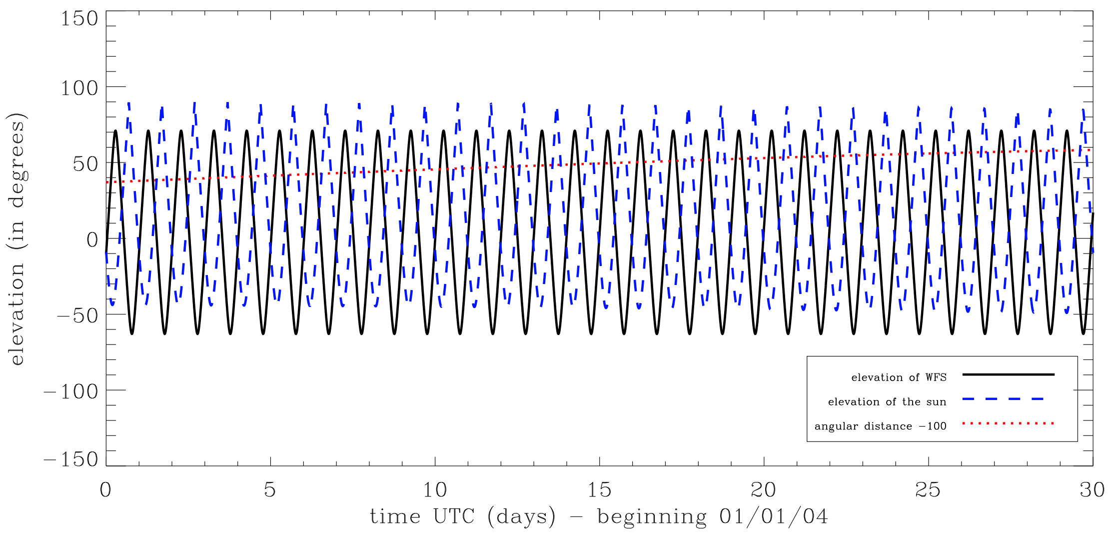

Figure 1: Elevation of the WFS during the beginning of January (in solid black), elevation of the sun (in dashed blue), and angular distance minus 100 degrees between the sun and the WFS position (in dotted red). This figure shows that during January, the WFS elevation is above 30 degrees for 8 hours a day and the sun is always 130 degrees away from WFS, furthermore the elevation of the sun is very low during the WFS observed time, this period is very good to observe the WFS field.

- the second scanning strategy make the same drift as the first one but at the same time the telescope chop in azimuth with an amplitude of 2 degrees (peak to peak) and with a frequency of 50 mHz (azimuth chopping follow a sinusoid). The maximum speed will be of 0.31 degrees/s and the maximum acceleration of 0.1 degrees/s^2

- The third scanning strategy make also the drift of the first scanning strategy and simultaneously the secondary mirror is chopping with an amplitude of 10 arcminutes (peak to peak) and with a frequency 0.5 Hz.

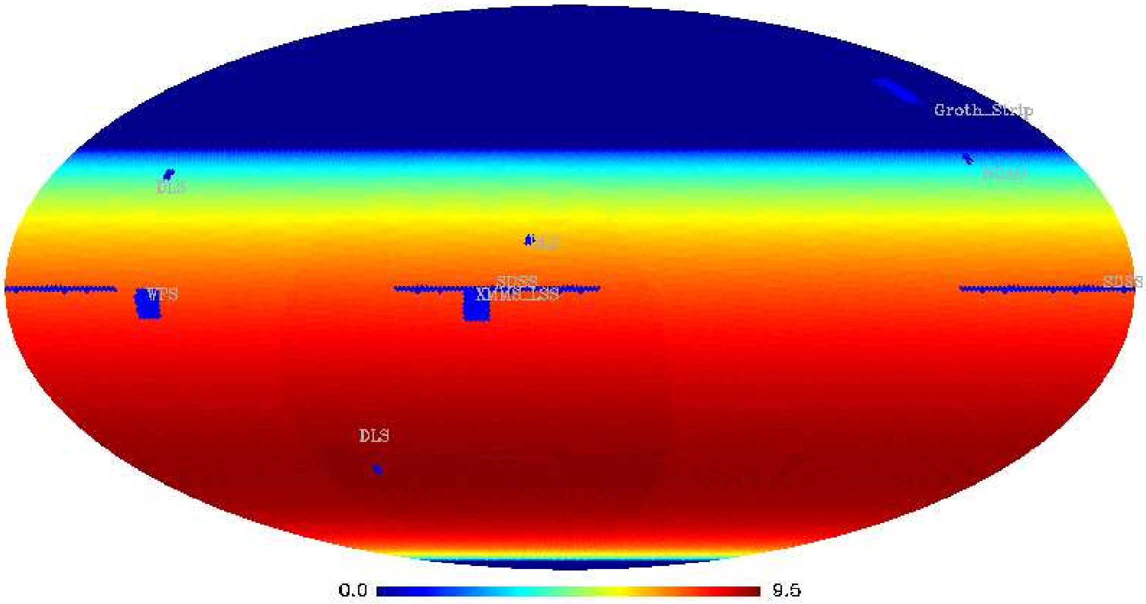

Figure 2: Map (in equatorial coordinates) of the observation duration from the Atacama site with an elevation above 30 degrees during a day. Some fields observed or that will be observed by other experiments are superimposed in blue.

2.1 Pure drift scanning

The pure drift scanning has the advantage that we always look at the same part of the sky, limiting the change in the far-side lobe contribution and in the airmass variation. With the pure drift scan it is also quite simple to cover the sky very homogenously, which will result in map with homogenous noise level. Following these scanning strategies around the WFS field we obtain the homogenous coverage shown in figure 3. These 1 arcminute pixel are covered on average 16 seconds, and with a very small dispersion of about 1% (see figure 3).

The *a priori* problems of this scan method is that we scan the sky very slowly 0.25 arcminute/s, that is why it takes so much time to cover the 6x6 degrees field. A consequence of this very slow drift is that the interesting signal will be at very low time frequency, for the SZ where we look at 0.25 arcminutes to 10 arcminutes the frequency range is 25 mHz to 1 Hz. As the noise will certainly not be white and will increase at low frequency (detector or atmospheric noise), if we use the 1/f noise model ($P_N(f) = \sigma^2 \left[1 + \left(\frac{f}{f_{knee}}\right)^{\alpha}\right]$), with these scanning strategy we need to have $f_{knee} \leq 25$ mHz. As an example of this effect, the figure 4 shows what happens to the SZ signal when highpass-filtered at 10 mHz and 100 mHz, in the first case the signal is almost intact, in the second case it is almost destroyed, that's why we also look at scan strategy which allowed to shift the SZ signal in frequency space.

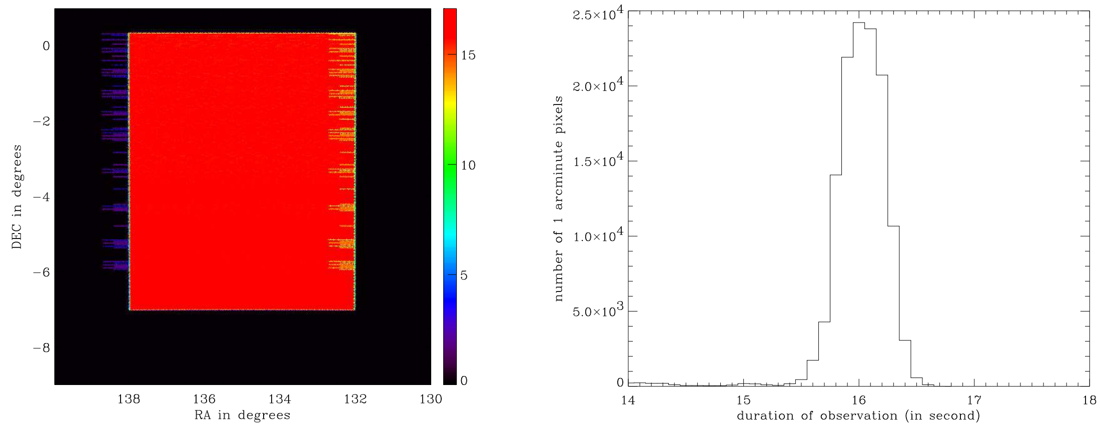

Figure 3: Map showing the duration of observation of each 1 arcminute pixels (left) and distribution of this duration (right), the drift scanning lead to an homogenous sky coverage.

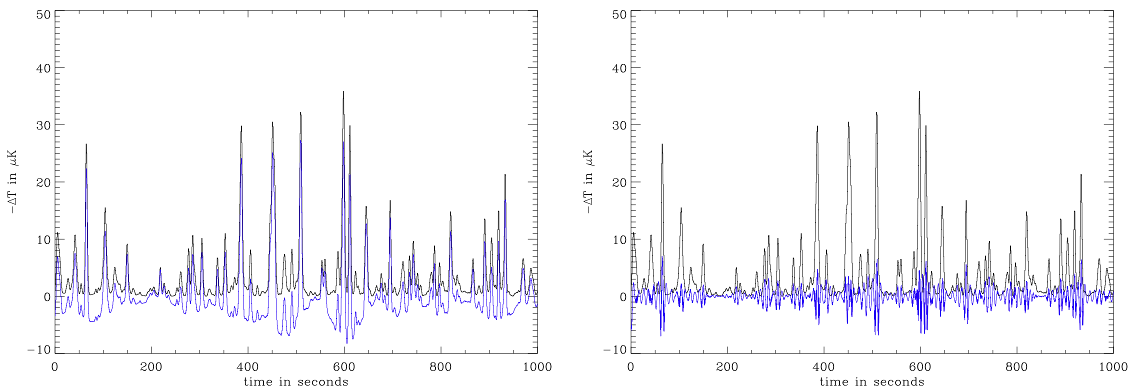

Figure 4: Both pictures show the original SZ timeline, build with a drift scanning startegy (in black) and the same timeline but highpass filtered (in blue) at 10 mHz (left) and 100 mHz (right).

2.2 Slow chopping of the telescope scanning

To increase the covering speed, we introduce a slow motion of the telescope in azimuth to avoid the airmass change, the small amplitude have been chosen to get a comparable sensitivity per pixel as the drift scanning. The average observed time per pixel (1 arcminute) is 15 seconds (less because the cover is still bigger), the coverage is less homogenous as shown in figure 5, and the dispersion about 10% (10 times bigger than the drift scan).

The homogeneity of the coverage may be recovered using a different chopping direction (meaning movement simultaneously in azimuth and elevation), but to the

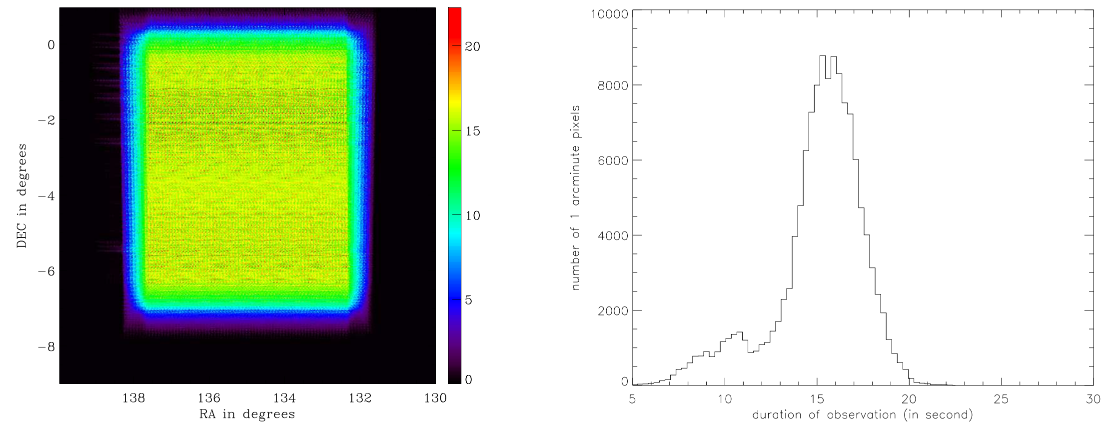

Figure 5: Map showing the duration of observation of each 1 arcminute pixels (left) and distribution of this duration (right), the slow chopped scanning lead to a less homogenous coverage than the simple drift one.

price of introducing airmass variation. Finally the figure 6 shows that the signal is less sensitive to highpass filter, both 10 mHz and 100 mHz do not destroy the SZ signal.

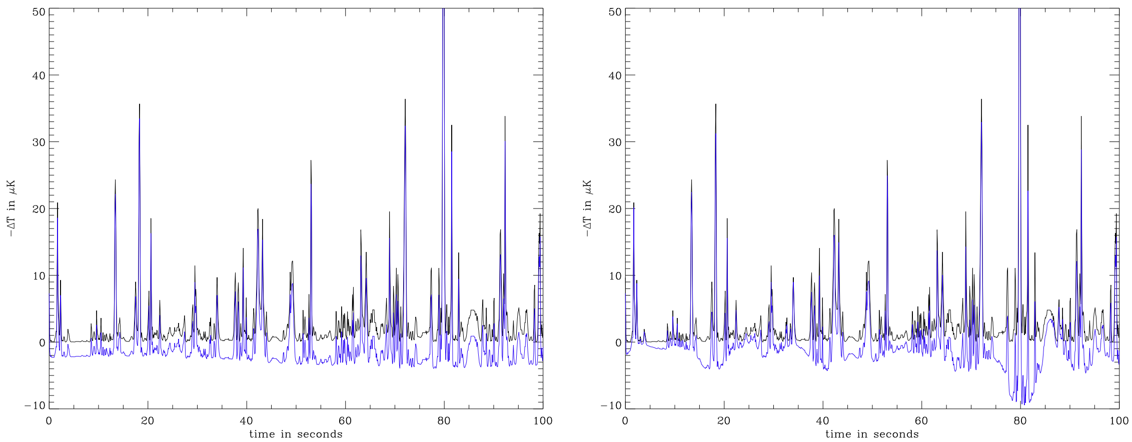

Figure 6: Both pictures show the original SZ timeline, build with a telescope chopping scanning startegy (in black) and the same timeline but highpass filtered (in blue) at 10 mHz (left) and 100 mHz (right).

2.3 Fast secondary mirror chopping scan

Another possibility to make a faster scan is to make the secondary mirror chop, the average observed time per pixel (1 arcminute) is almost 16 seconds like for the simple drift scan due to the small amplitude of the chopping. The coverage as described in figure 7 has lost its homogeneity, with a dispersion of 40%, however this inhomogeneity can be due to the chopping scheme (sinusoidal).

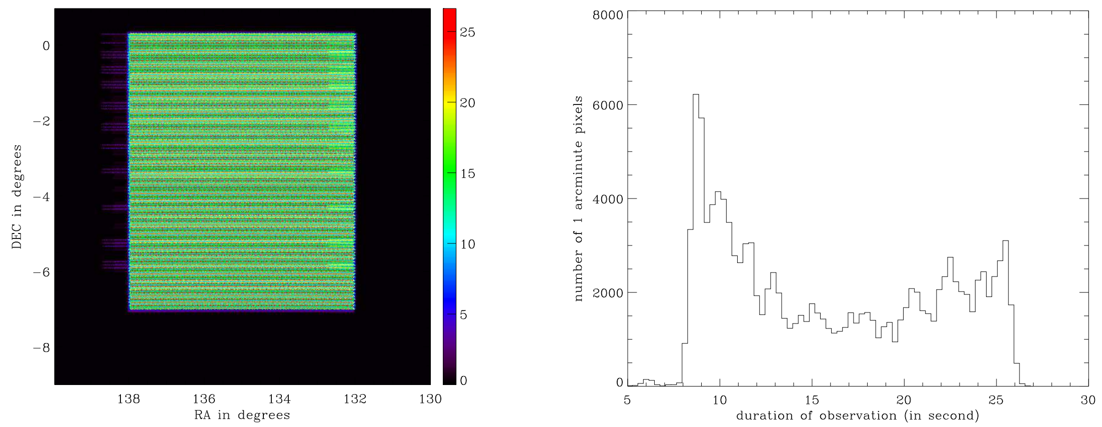

Figure 7: Map showing the duration of observation of each 1 arcminute pixels (left) and distribution of this duration (right), the fast chopped scanning seems to destroy the homogeneity of the coverage.

The figure 8 shows the small effect of highpass filtering at 10 mHz or even 100 mHz like with the previous scan strategy.

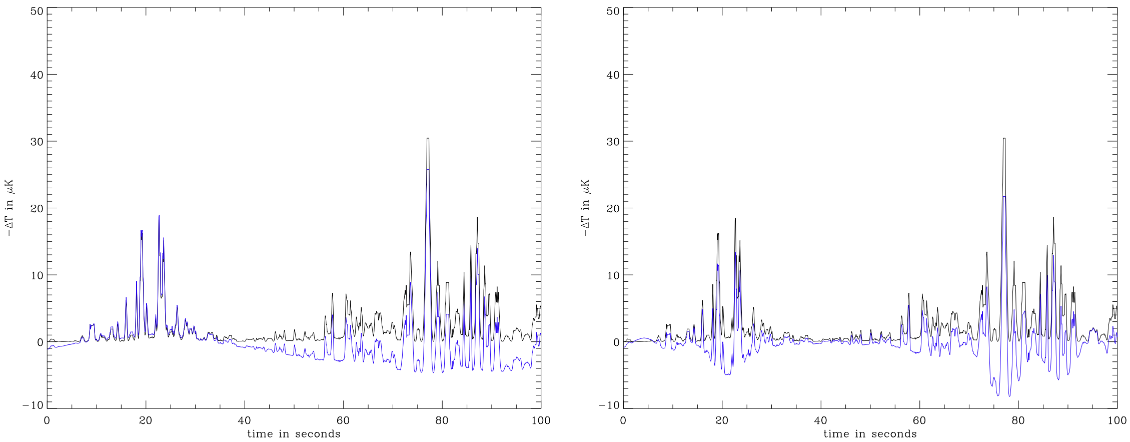

Figure 8: Both pictures show the original SZ timeline, build with a telescope chopping scanning startegy (in black) and the same timeline but highpass filtered (in blue) at 10 mHz (left) and 100 mHz (right).

3 Simulations

The next step is to look how the scanning strategy influence the reconstruction of the SZ map, for that we simulated :

- a SZ timeline built reading a 2048×2048 pixels (size of 0.2 arcminutes) map (figure 9), convolved by 0.8 arcminutes gaussian beam, provided by Martin White (see figures 4, 6, and 8 for a sample of these timelines);

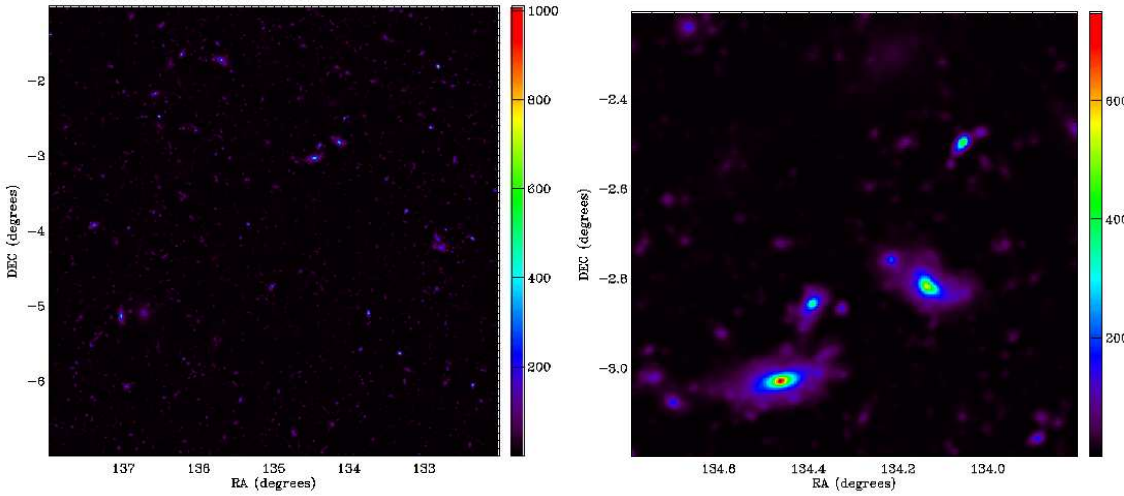

Figure 9: On the left, the SZ map (center on the WFS field) used to create the simulated timelines, and a closer look at some big clusters on the right (RA:133.8,134.8;DEC:-2.2,-3.2), the map is in μK.

- a 1/f noise, following the model $P_N(f) = \sigma^2 \left[1 + \left(\frac{f}{f_{knee}}\right)^\alpha\right]$, with the parameters f_{knee}=10 mHz, α =-2, and σ =280μK/$\sqrt{Hz}$

Each timeline has a sampling frequency of 10 Hz (to reduce data size), and 20 millions samples will be used for the map-making. The noise is simulated in one chunk, which is not precisely correct as between 8 hours of observations there is 16 hours where WFS can not be seen. We assume for now that the extra-correlation introduced is not important (the same analysis is underway for the more realistic noise).

The figure 10 shows how the power is distributed in the frequency space with the different scanning-strategy, and reinforces the conclusion of the previous section about the danger of using simple drift scan strategy, where a highpass filtering treatment (in case of non-gaussian low frequency noise) can suppress all the signal.

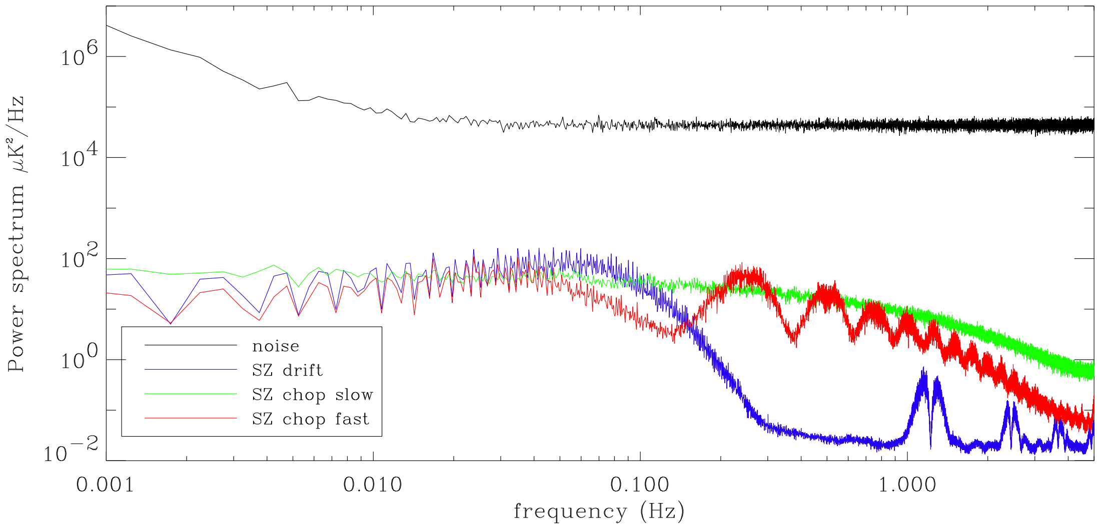

Figure 10: Power spectrum of the noise and of the SZ timelines built with the drift scanning (blue), telescope chopping (green), and mirror chopping (red). The drift scanning power spectrum decrease extremely fast at 0.2 Hz that correspond roughly to the beam size with these scanning strategy (0.8 arcminutes gives 0.3 Hz)

4 Map making

Using the simulations produced for each scanning strategies, we perform an optimal map-making using the MADmap software (http://www.nersc.gov/~cmc/MADmap/doc/index.html). We marginalize the frequencies under 2.8 mHz.

The resulting maps are shown on figure 11, 12, & 13. The simple drift scan strategy lead to a map very striped, which can be due to the small number of crossing in each pixels, the algorithm converge to a solution where the noise is on the sky. We verified that adding the dust and the CMB emissions do not help to converge to a better map, we also verify that adding a second detector we still converge to a striped solution. The 2 others scan strategy lead to better optimal map, however the fast chopped scan strategy require more iterations (about 4 to 5 time more) to converge.

We also look at the noise property of this map, first we look at the distribution of the noise map (subtracting the SZ map from the reconstructed map), and obtain the 3 distributions of figure 14. The simple drift map has of course much more noise than the 2 previous one, the fast chopping has a distribution a little bit wider (76.2 μK against 74.9 μK) even if the average observed time per pixel is bigger, this is certainly due to the wider distribution of the noise per pixel.

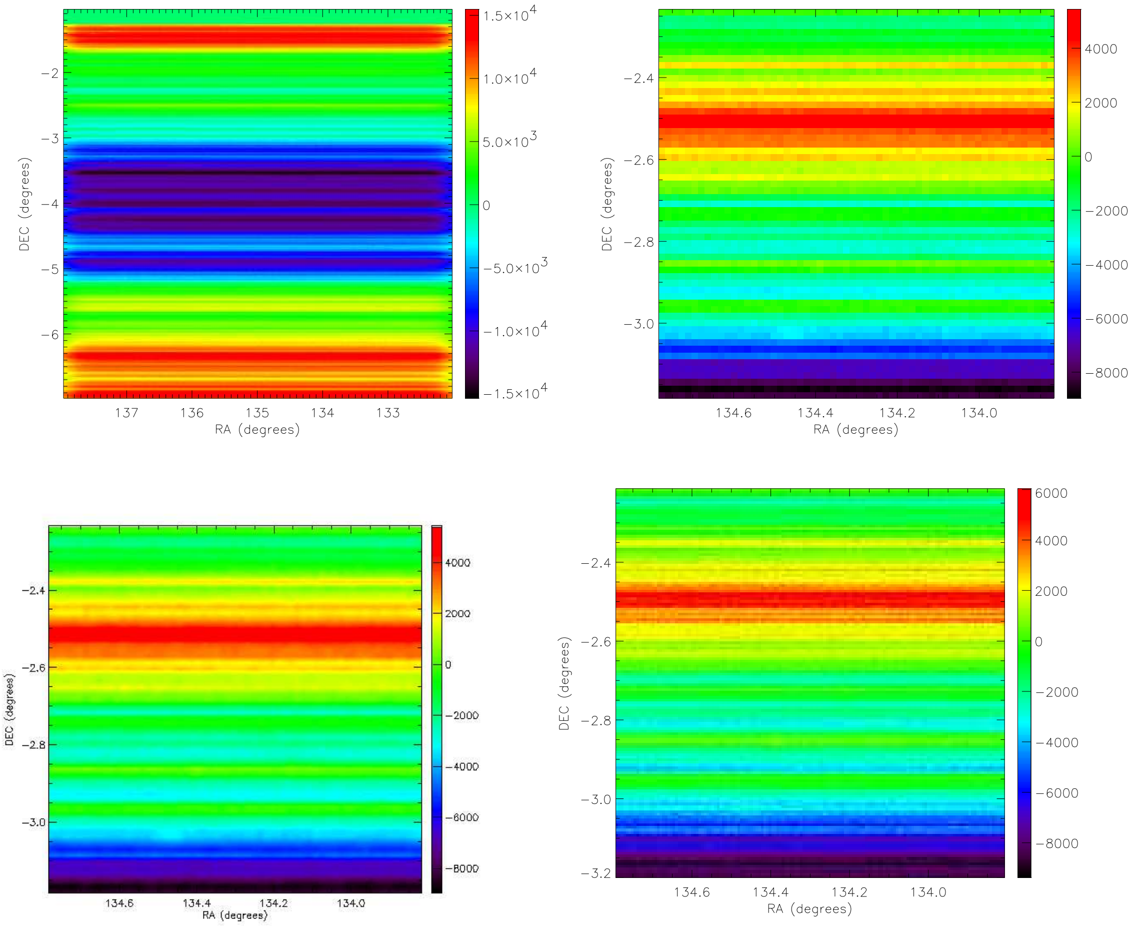

Figure 11: **Simple drift scan reconstructed map** : Optimal map of the 6x6 degrees field with a resolution pf 1 arcminute (left top), zoom of this map on the same region as for the figure 9 (right top), same map as the right top but with interpolation (left bottom), same area as the top right figure but with an optimale map with 0.4 arcminute resolution (right bottom). The map is dominated by noise signal, the algorithm has converged to a solution where the noise is on the sky.

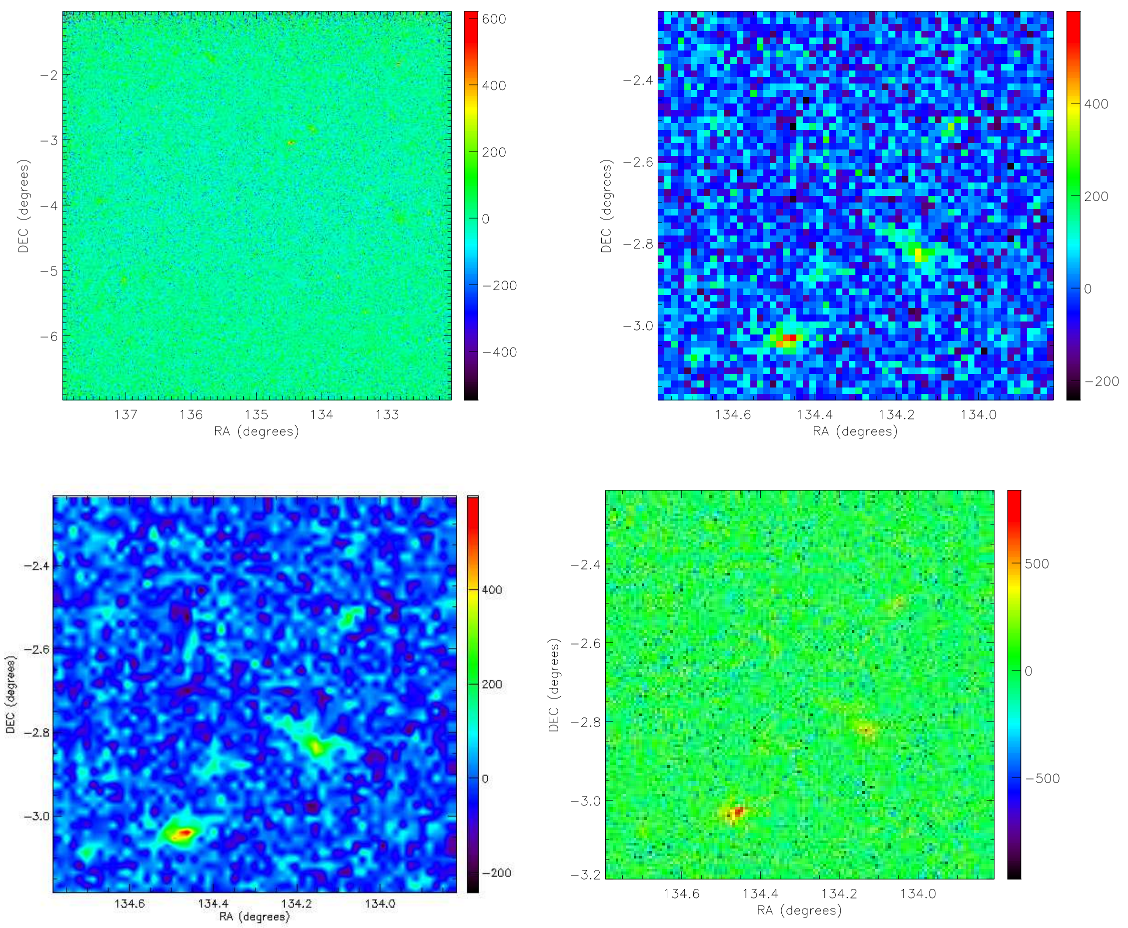

Figure 12: **Slow chopping scan reconstructed map** : Optimal map of the 6x6 degrees field with a resolution pf 1 arcminute (left top), zoom of this map on the same region as for the figure 9 (right top), same map as the right top but with interpolation (left bottom), same area as the top right figure but with an optimale map with 0.4 arcminute resolution (right bottom). The map are quite noisy (especially the 0.4 arcminute one), but we can recognize the 4 big clusters on the zoom area.

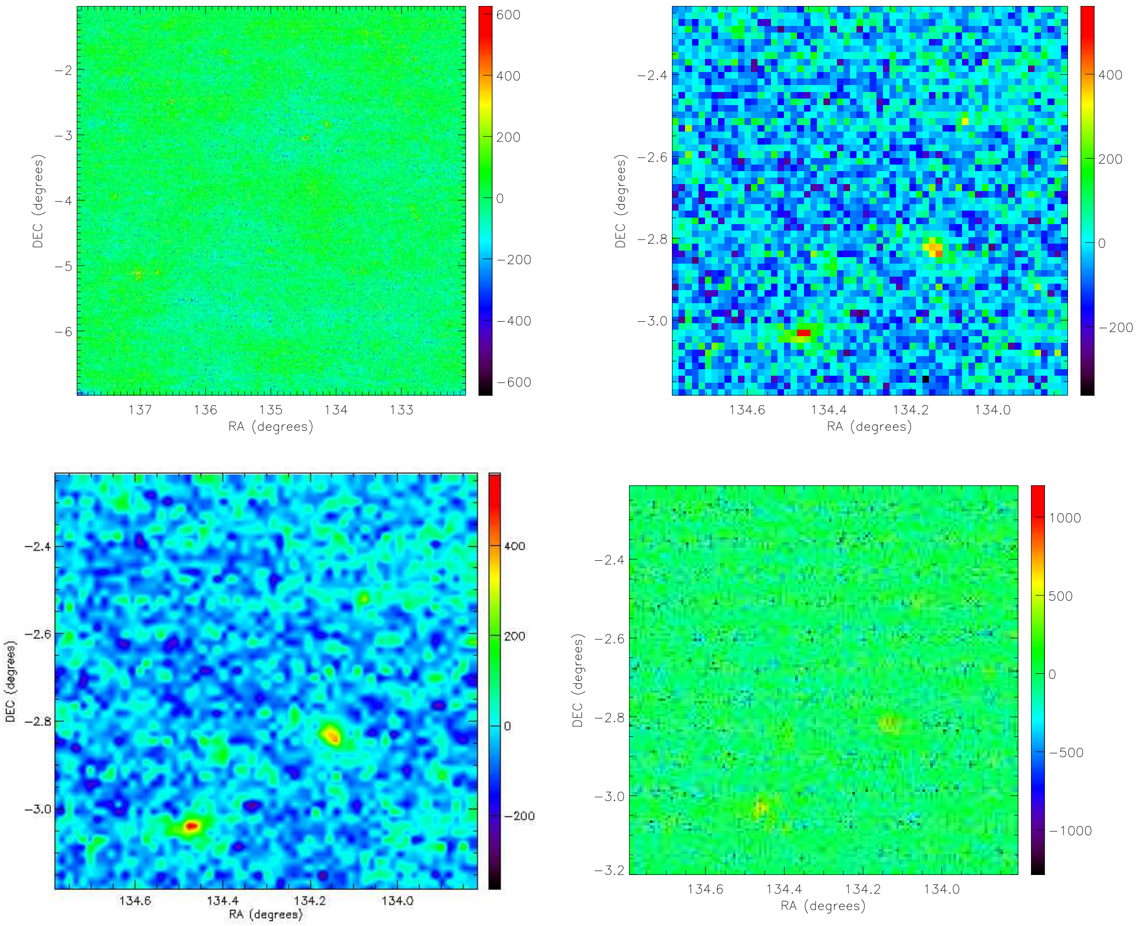

Figure 13: **Fast chopping scan reconstructed map** : Optimal map of the 6x6 degrees field with a resolution pf 1 arcminute (left top), zoom of this map on the same region as for the figure 9 (right top), same map as the right top but with interpolation (left bottom), same area as the top right figure but with an optimale map with 0.4 arcminute resolution (right bottom). The map are quite noisy (especially the 0.4 arcminute one), but we can recognize the 4 big clusters on the zoom area.

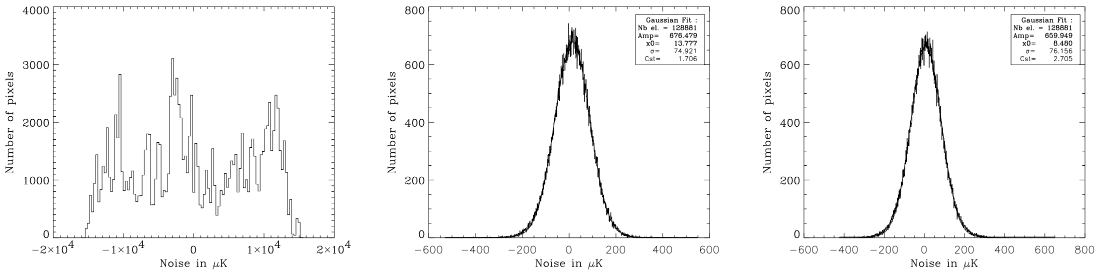

Figure 14: Histograms of the noise map for each scanning strategy (from left to right : simple drift, slow chopping, fast chopping), as the drift scanning map contains 1/f noise the noise level is very important, the average noise level in the 2 others map are respectively 74.9 and 76.2 μK.

As a next step we used MADCAP2.1 to look at the noise properties of the 2 best scan-strategies (ie the chopped ones). We look first at the distribution of the noise in the map and found as expected the compatible characteristic as the one of the duration of observations per pixels. The histograms 15 show that the slow chopping scan-strategy have a more homogenous noise level (8% against 20% of dispersion).

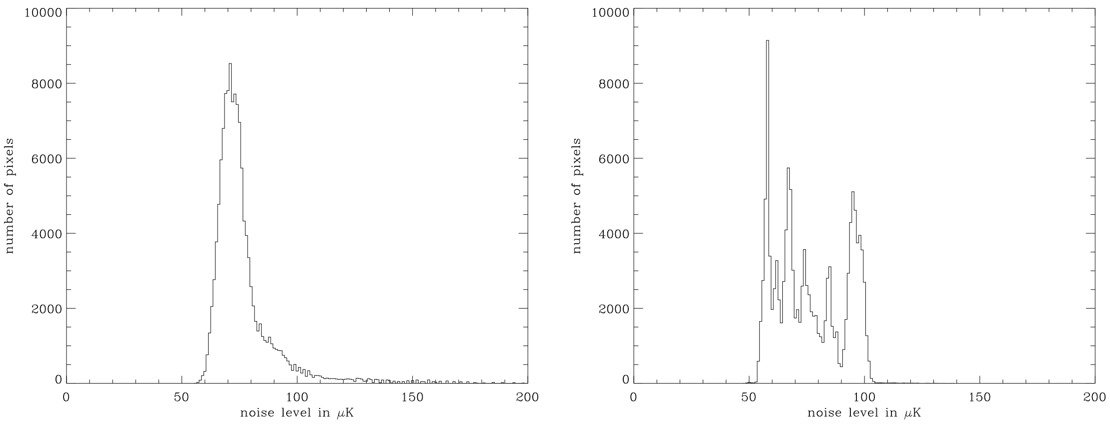

Figure 15: Histograms of the diagonal element of the pixel-pixel noise correlation matrix obtained with MADCAP, these histograms are compatible with the one of the observed time (figures 5 & 7)

The final point we look at is the correlation of noise between the pixels, in the ideal case we would like it to be null. The figures 16 & 17 show the topology of noise correlation between pixels for the first,middle and last pixels (these correspond to 3 row of the pixel-pixel noise correlation matrix). For each scanning strategy we recognize the shape of the movement on the sky on these maps, the auto-correlation is always 10 times bigger than the cross-terms (in μK) for the slow chopping scanning strategy and twice for the fast chopping one. The faster decrease of correlation in pixel domain may be explained by a better mixing of the measurements in the slow chopping case due to its slowness (in fast chopping case the measurements are more concentrated in pixel space).

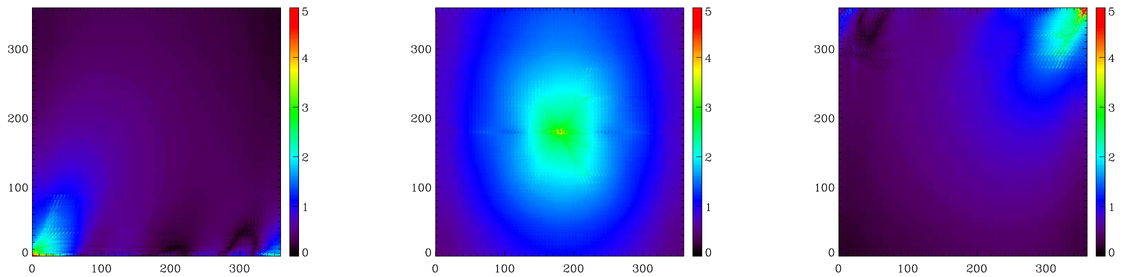

Figure 16: Pixel-pixel noise correlation (in μK) for the first, middle & last pixels (3 rows of the pixel-pixel noise correlation matrix) in the slow chopping scanning strategy. The autocorrelation value is respectively of 68, 67, and 296 μK, the correlation decrease quite fast. In these 3 maps, we can see the movement of chopping in addition to the drift movement.

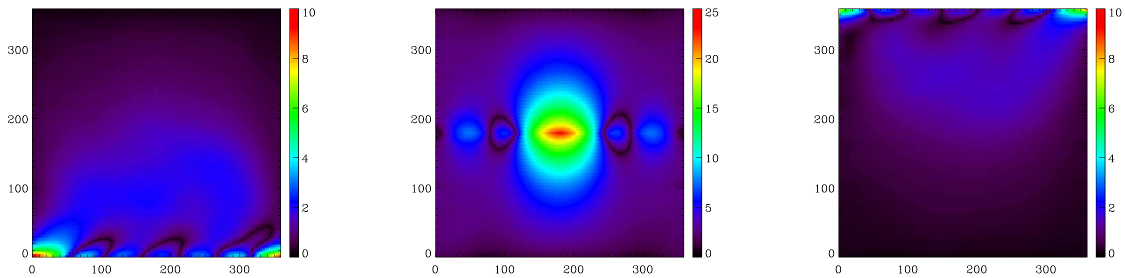

Figure 17: Pixel-pixel noise correlation (in μK) for the first, middle & last pixels (3 rows of the pixel-pixel noise correlation matrix) in the fast chopping scanning strategy. The autocorrelation value is respectively of 53, 57, and 76 μK, the correlation decrease less fast (especially for the center pixel, note the difference of scale from figure 16). In these 3 maps, we can see the movement of chopping in addition to the drift movement.

The figure 18 represents the decrease of the correlation versus the distance from the pixel, it shows the fast decrease for the closest neighbours, and then slower decrease for both scanning strategy. In agreement of the figures 16 & 17, we see that the correlation on average decrease faster for the slow chopping scanning strategy (decrease of 17.5 on first neighbours for slow chopping and 3.5 for fast chopping).

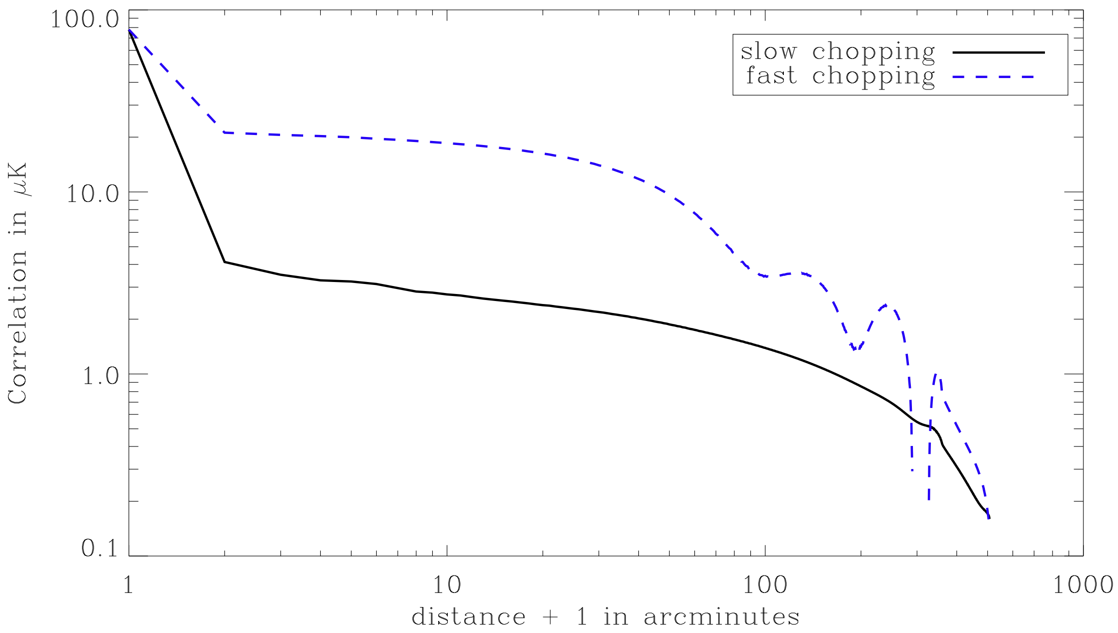

Figure 18: Correlation between pixels (in μK) versus their distance (1 arcminute is added to allow logarithmic scale, so first point is auto-correlation) for the two scanning strategies. We see that on average the correlation decrease faster for the slow chopping scanning strategy (factor 17.5 versus 3.5 for the first neighbours).

5 Conclusions

We have tried 3 kind of scanning-strategy to cover a small field with the Apex experiment and found that the best kind of scanning strategy consist in a slow motion of quite big amplitude (in our case 2 degrees of amplitude with a 20 s period). This scanning strategy keep a quite good noise homogeneity in the map, move the signal in a safer frequency domain, allow a good and fast map-making (due to the crossing produced), and may allow to neglect the pixel-pixel noise cross-correlation term (fast decrease of the correlation even with first neighbours). The simple drift scanning strategy is certainly to avoid, and the fast chopping strategy to the extend of this study is not as good (slower map-making, less noise homogeneity, more pixel-pixel correlation).