Repetitive music and gap filling in full disc helioseismology and asteroseismology of solar-like stars

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ASTRONOMY AND ASTROPHYSICS

Full disk helioseismology: repetitive music and the question of gap filling

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Abstract. Helioseismology requires continuous measurements of very long duration, months to years. This paper addresses the specific and limited case of full disk measurements of p-mode oscillations, although it can be generalized, to some extent, to the case of imaged helioseismology. First, a method of mode by mode (or rather pair of modes by pair of modes) interpolation of the signal in gaps is tested, and shown to be efficient for gaps as long as two days, but limited to the frequency range where the signal to noise ratio is good. It is then noted that the autocorrelation function of the full disk signal, after dropping quickly to zero in 20 or 30 minutes, shows secondary quasi periodic bumps, due to the quasi-periodicity of the peak distribution in the Fourier spectrum. The first of these bumps, at 4 hours or so, is higher than 70 percent and climbs to nearly 90 percent in limited frequency ranges. This suggests that an easy gap filling method can be developed, with a confidence of nearly 90 percent across all the frequency range, as long as the gap does not exceed 8 hours, with at least 4 hours of data at both ends. Even a short gap of one or two periods is better filled by the data taken 4 hours earlier or later than by local interpolation. This relaxes quite considerably the requirement of continuity of the observations for the case the full disk p-mode helioseismology. Applied to 7 years of IRIS data, this method permits the detection of all

age, 24 hours per day and 365 days per year. This is mainly for the sake of avoiding the presence of "sidelobes" in the Fourier spectra. These sidelobes are produced by the convolution of the Fourier transform of the true signal by the Fourier transform of the temporal window function, which generally contains at least the one-day periodicity when the observations are made from the ground. In the Fourier domain, each peak, signature of a solar oscillation, is then spread over the Fourier transform of the window function, with secondary peaks, or sidelobes, which will unavoidably interfere with other real peaks, thus making accurate p-mode parameters measurements difficult.

However, the ultimate goal of 100 percent duty cycle has never been achieved by any kind of observation, so that the analyst is always facing the presence of gaps in the time series subject to Fourier (or any other) analysis. Most generally, these data gaps are very simply filled by zeroes. It must be realized that "zero" is not "nothing". It is a number, which is taken into account by the Fourier transform and weights as much as the value of any measurement. Then, these zeroes are the result of an intrinsic physical assumption: the sun does not oscillate when it is not observed. Clearly, this is among the most stupid assumptions that can be made, and the purpose of this paper is to try and do somewhat better. Please note that the following

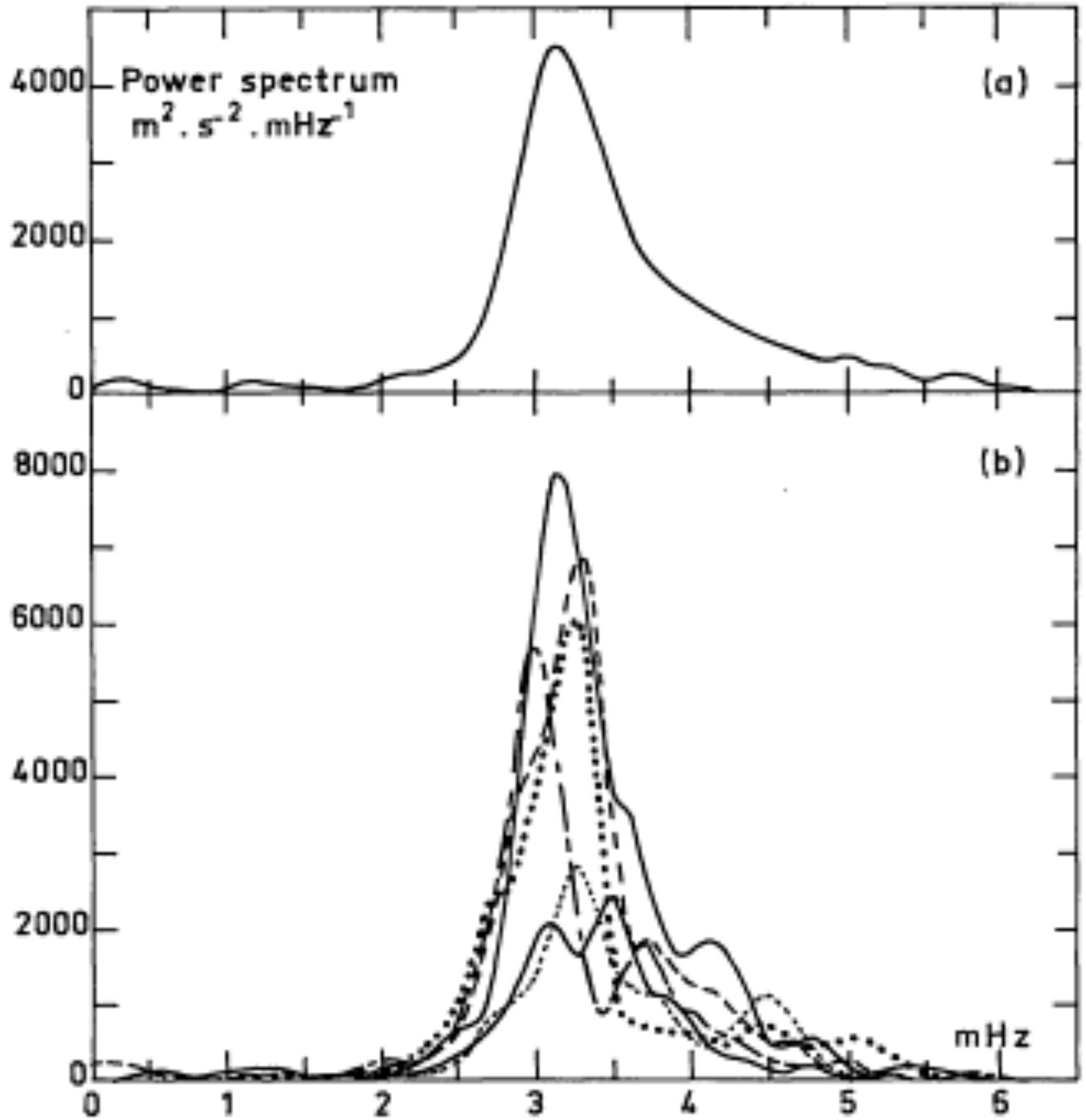

Fig. 7a and b. Power spectra of individual time series (a) 2 to 4 hrs long are very different because of the large statistical uncertainty. The average power spectrum (b) shows a single peak of F.W.H.M. 0.9 mHz. (Results from one minute diameter observations)

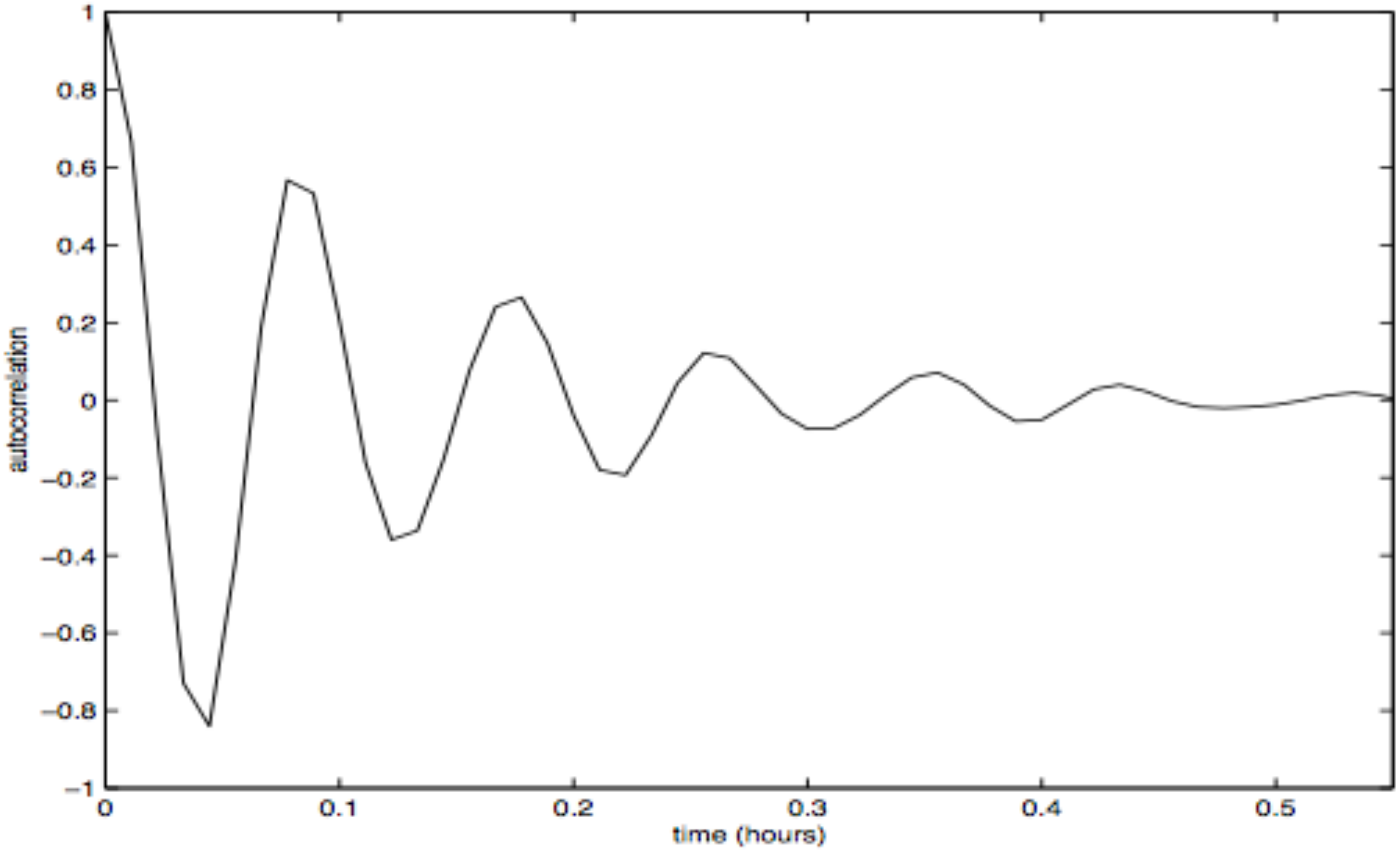

Fig. 1. First half hour of the IRIS autocorrelation function of the full disk velocity signal. The coherence drops quickly to zero due to the incoherent addition of about two hundred independent oscillations of different frequencies. The typical coherence time of about 15 minutes is the inverse of the 1 mHz bandwidth of the p-mode frequency range.

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ASTRONOMY AND ASTROPHYSICS

Research Note

Photospheric Oscillations

IV. An Accurate ω-spectrum at Low Values of *k*

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Summary. Two power spectra of the five-minute oscillation averaged respectively on 8.′5 and 36″ aperture are presented. From their comparison it is concluded that the dependence of unresolved ω-spectrum on wavenumber is probably fairly low and that the average of these two power spectra is a good estimation of this ω-spectrum.

Key words: Sun — photosphere — oscillations — optical resonance

The only information that one can achieve from observation in this low-wavenumber range is the best ω-spectrum possible integrated in a given *k*-bandwidth. Theoretical calculations will have to be made by taking account of this fact to be usefully compared with these observational results.

86 h (from 12 individual observations) of velocity integrated on a 8.′5 aperture have been recorded with the

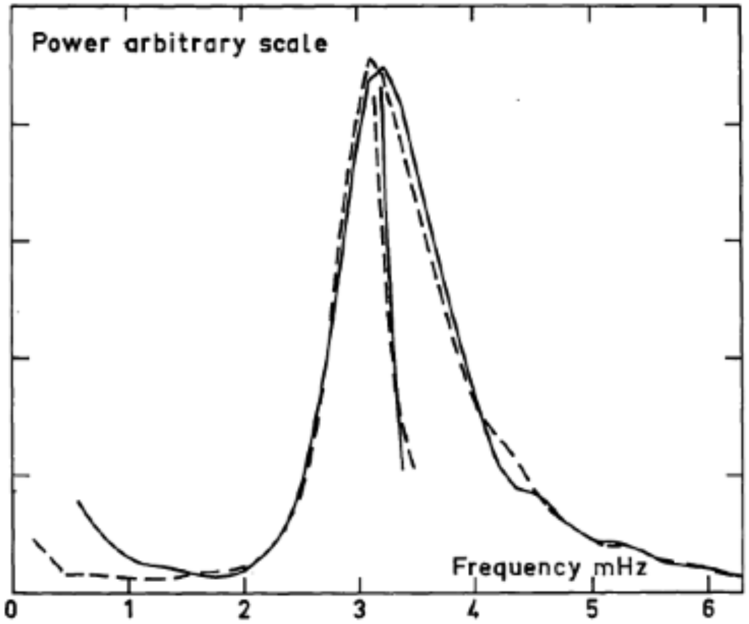


Fig. 1. Full line: power spectrum of velocity integrated on a 8.′5 aperture. Dashed line: the same for several smaller apertures, with an average diameter of 36″. The two power spectra have been calculated with a resolution of 0.3 mHz. The power scale has been calibrated so that the integral of the two curves is the same between 1.6 and 6.2 mHz. Also are shown, respectively in full and dashed line, the median of the power distributions. The two curves appear almost identical except for the low frequency range where the difference is caused by large amounts of atmospheric noise

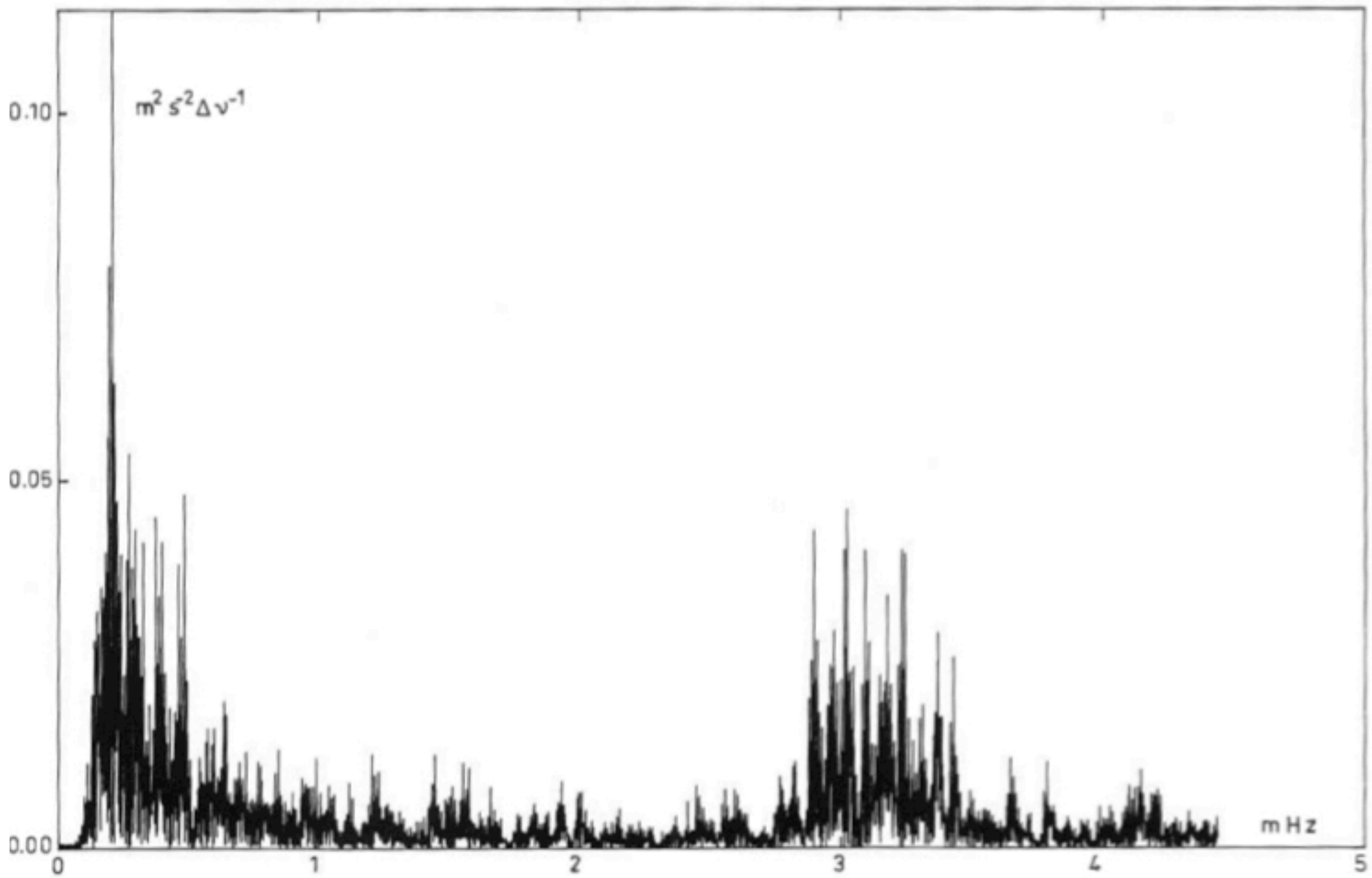


Fig. 13. High resolution power spectrum of the four days of data treated as a single time series. Power scale is $m^2 s^{-2}$ per step frequency, of the order of (5 days)$^{-1}$. The higher peak corresponds to a r.m.s. velocity of 34 cm s^{-1}

Figure 2- First published power spectrum interpreted as evidence for global low degree solar p-modes.

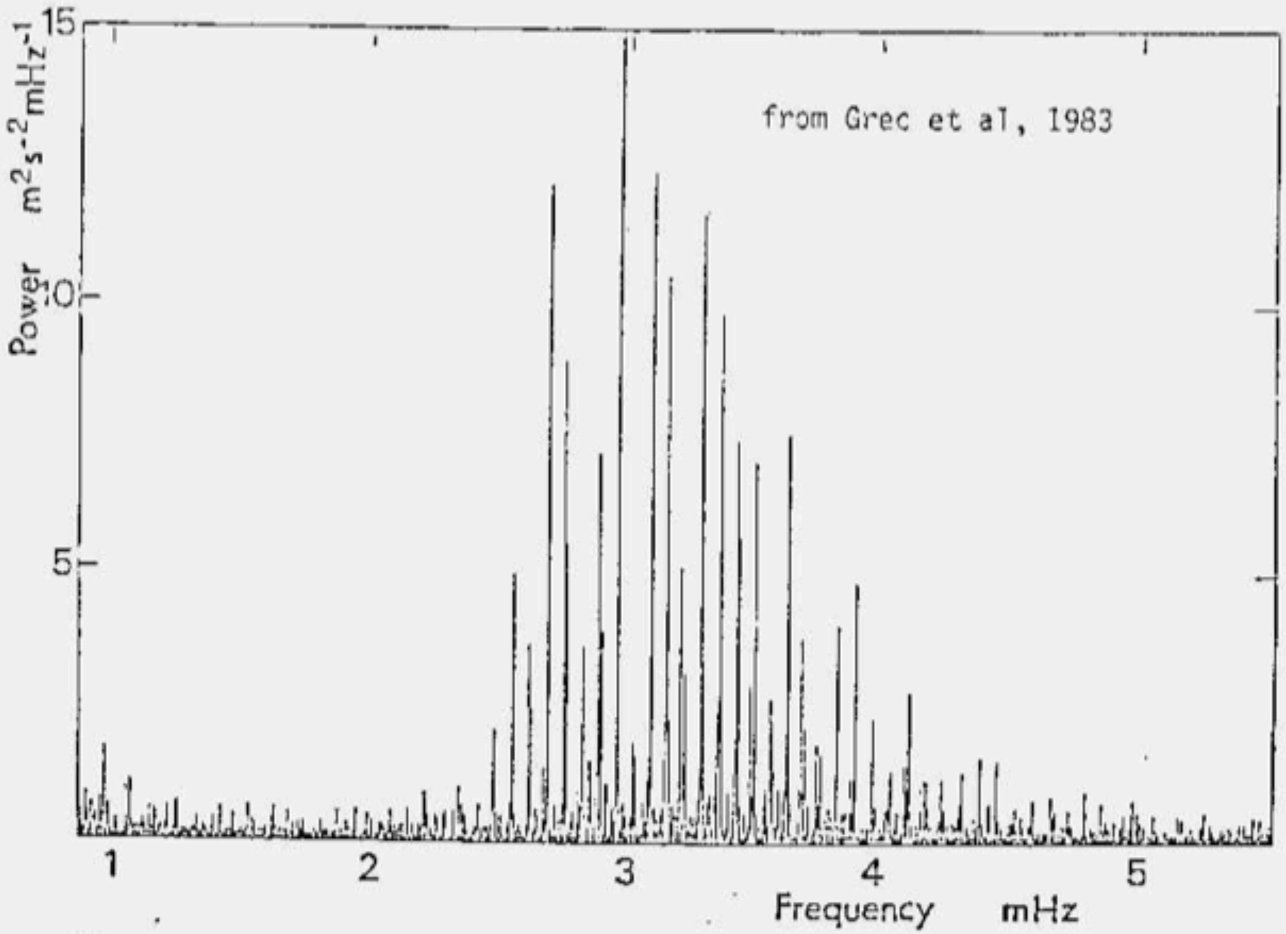


Figure 3- Same as figures 1 and 2, from 6 days of data obtained at the Geographic South Pole in January 1980

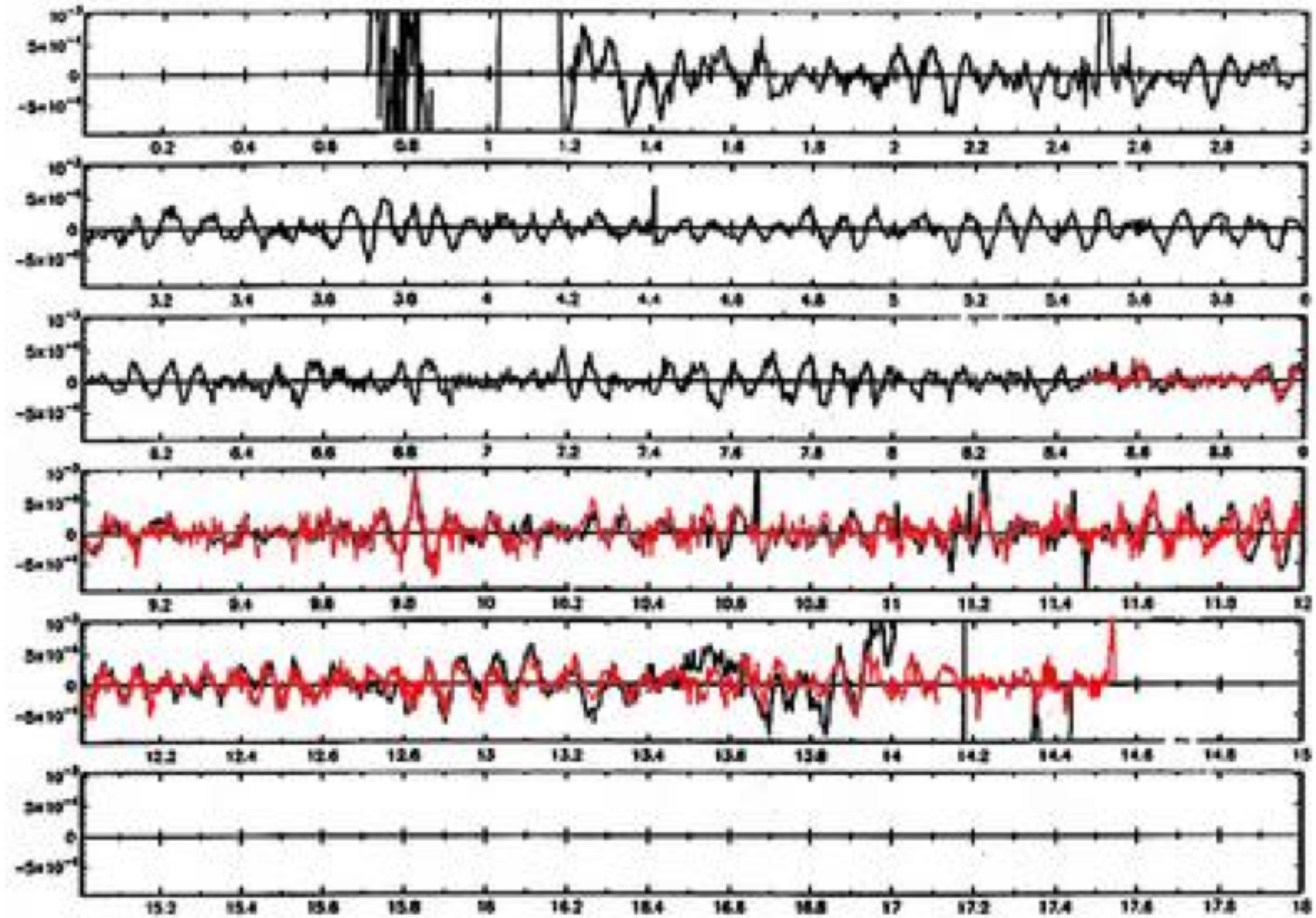


Figure 5: Two merged records showing 7.5 hours of solar oscillations obtained on 27 July 1989 at the Kumbel (black line) and Oukaïmeden (red line) stations.

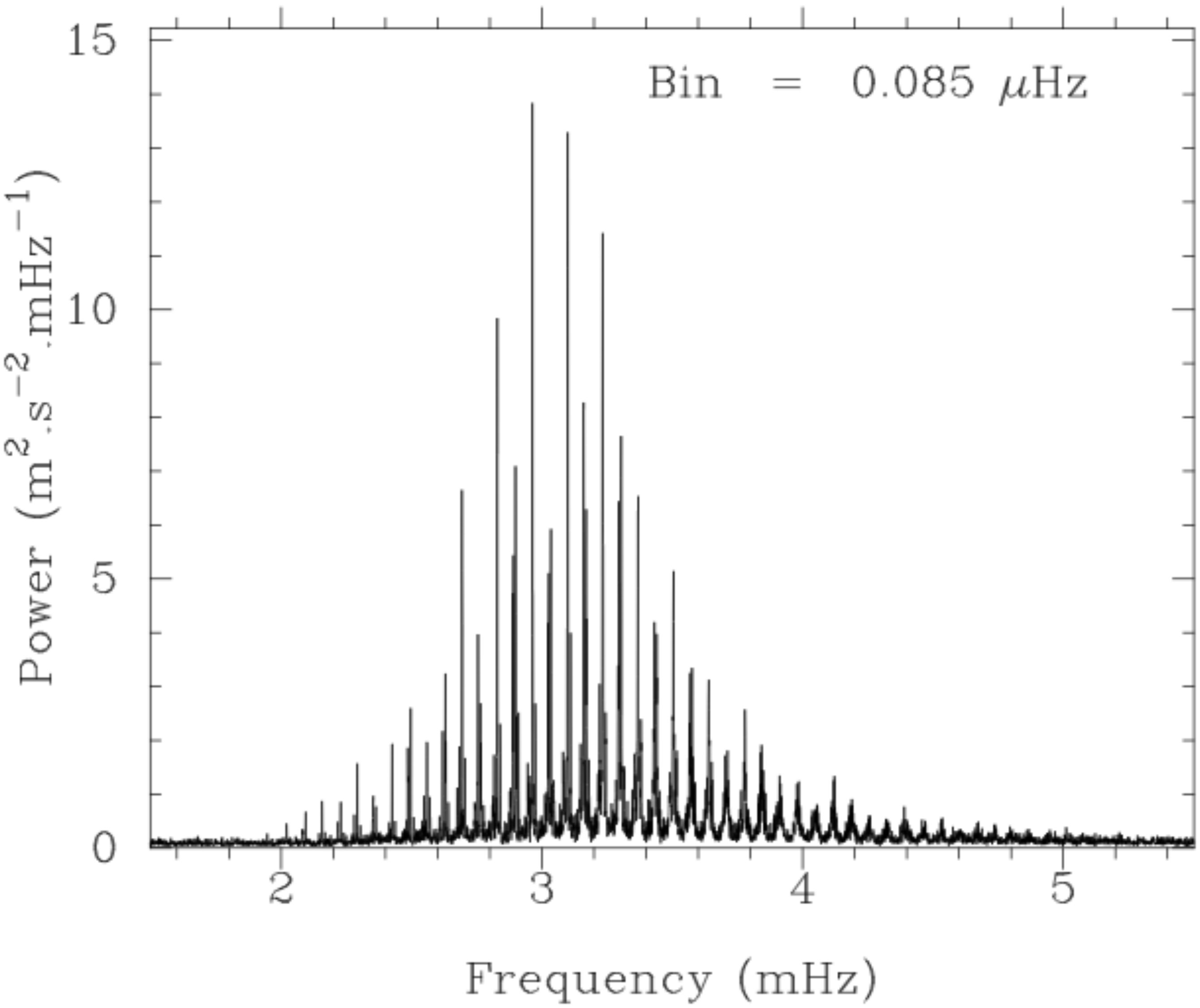
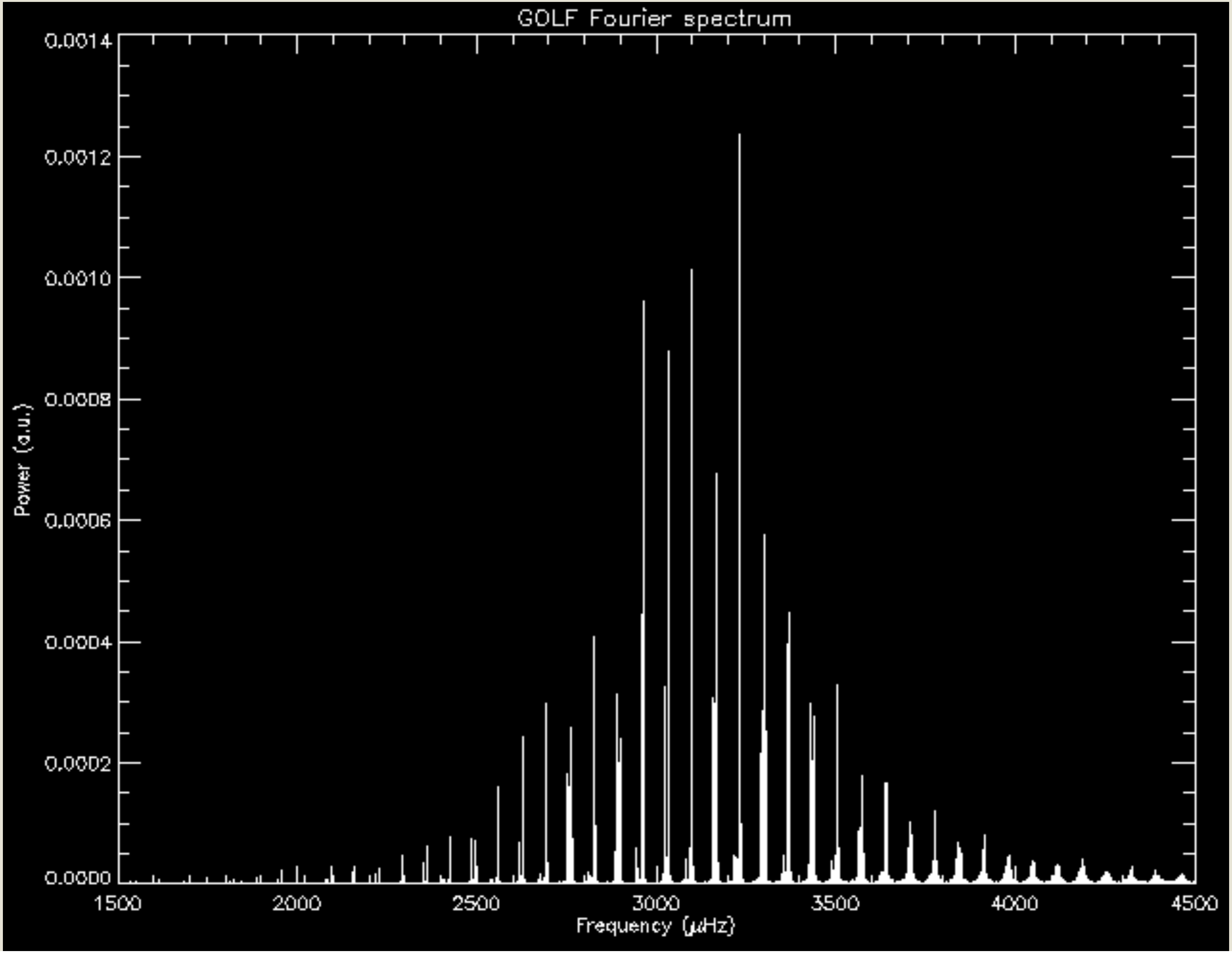


Fig. 1. The 1991 power spectrum. At the scale shown here the daily sidelobes coming from having “only” a 57% duty cycle are not visible. The first sidelobes still contain 25% of the power of the central peak.



GOLF Fourier spectrum
0.0014
0.0012
0.0010
0.0008
0.0006
0.0004
0.0002
0.0000
Power (a.u.)
1500
2000
2500
3000
3500
4000
4500
Frequency (μHz)

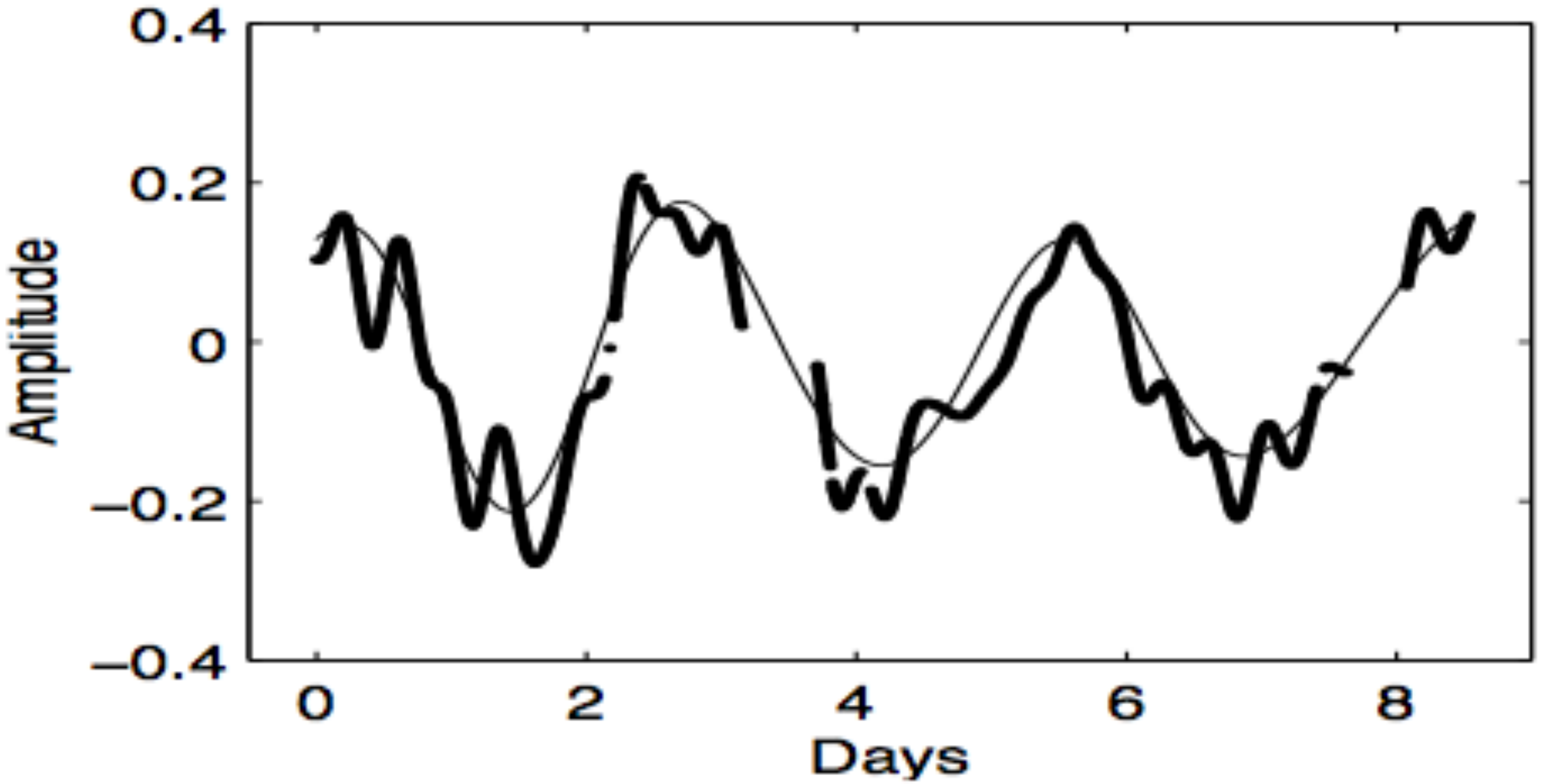


Fig. 2. This is the variation of amplitude of a pair of modes (l=0–2) during about 8 days, the measurement being interrupted by the data gaps. The main feature is the beating between the two frequencies, everything else being changing more slowly. A sine wave fitting of a few parameters around the beating frequency is used on such a 8-day temporal window for estimating the missing amplitude inside the gaps.

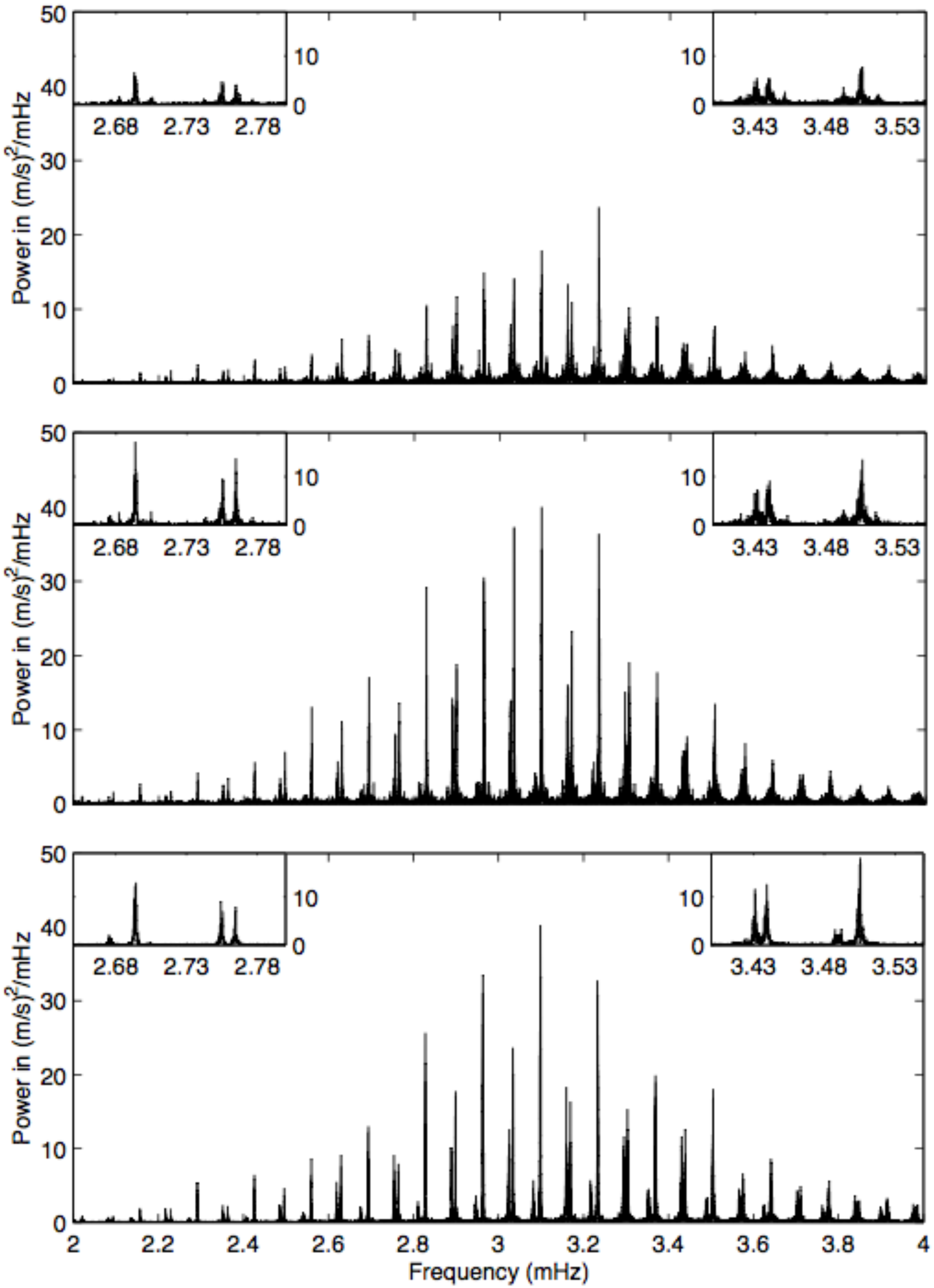


Fig. 3. The upper part is the direct (averaged) power spectrum of the 4 summer seasons of the IRIS network data, from 1989 to 1992. Each file has a duration of 136.5 days, so that the frequency resolution is equal to 0.085 μHz. The perturbation of this power spectrum by the window function is clearly visible in the magnified small samples. The middle part is the same power spectrum obtained by means of a Richardson-Lucy deconvolution. Each peak is roughly multiplied by the inverse of the duty cycle, which means that a large part of the surrounding noise was only due to the window function and has been pulled back inside the peak. However, it is not optimized, and the sidelobe structure, although reduced, is still visible. The lower part shows the same power spectrum now obtained after the pair-of-modes by pair-of-modes gap filling. The background noise is dramatically reduced, and the sidelobes structure is fully eliminated. See the text for more information on the limits of the method.

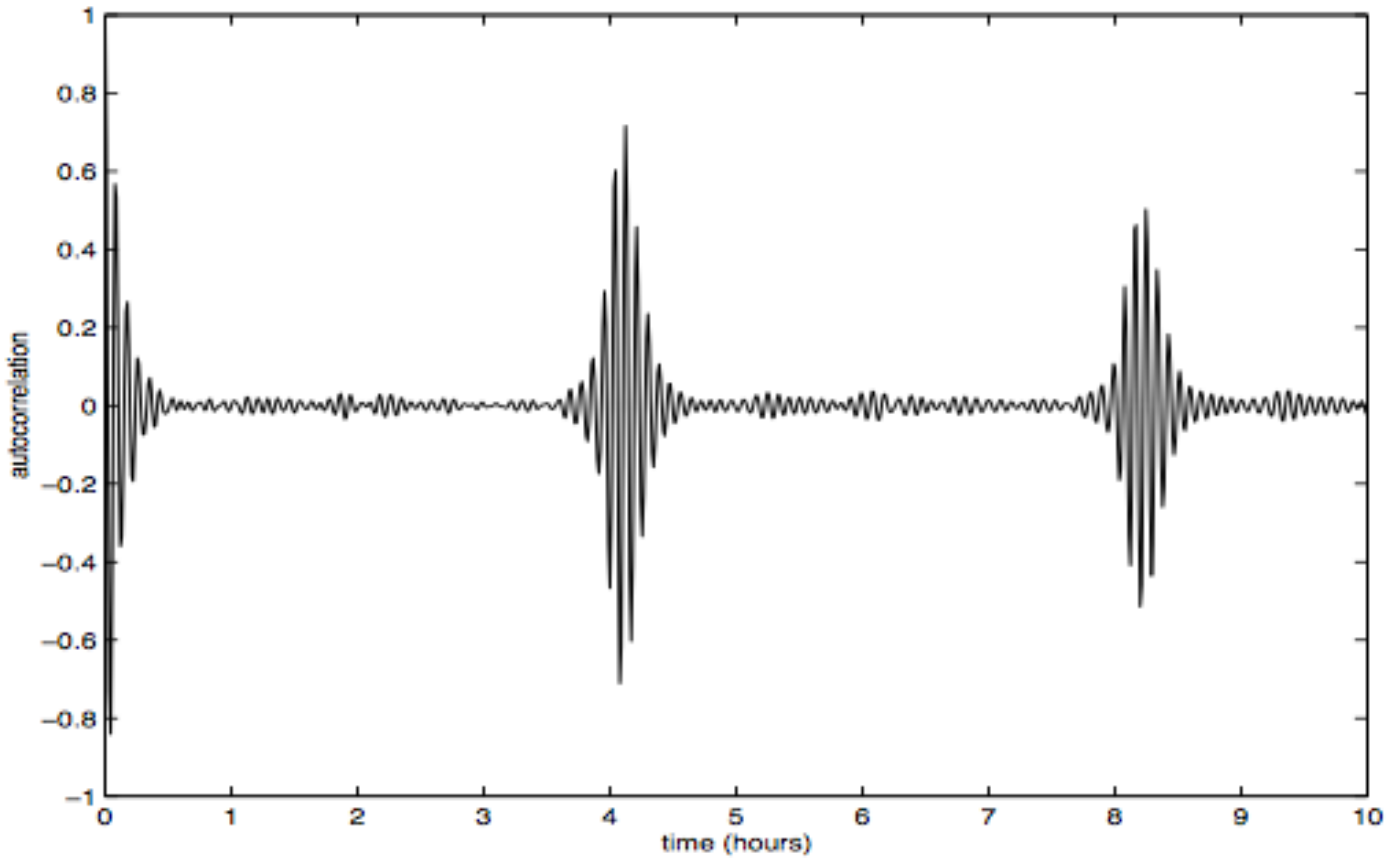


Fig. 4. The first ten hours of the IRIS data autocorrelation (filtered in the p-mode range, from 1.5 to 5 mHz) shows that beyond the quick drop at the beginning, there are secondary bumps around 4 and 8 hours. They are due to the quasi-periodicity of the peaks in the Fourier spectrum. The important point is that the second maximum is higher than 70 percent, and shows that the signal obtained after 4 hours is more correlated than the signal obtained after one period of 5 minutes. An easy and very efficient method of gap filling can be deduced from this simple fact.

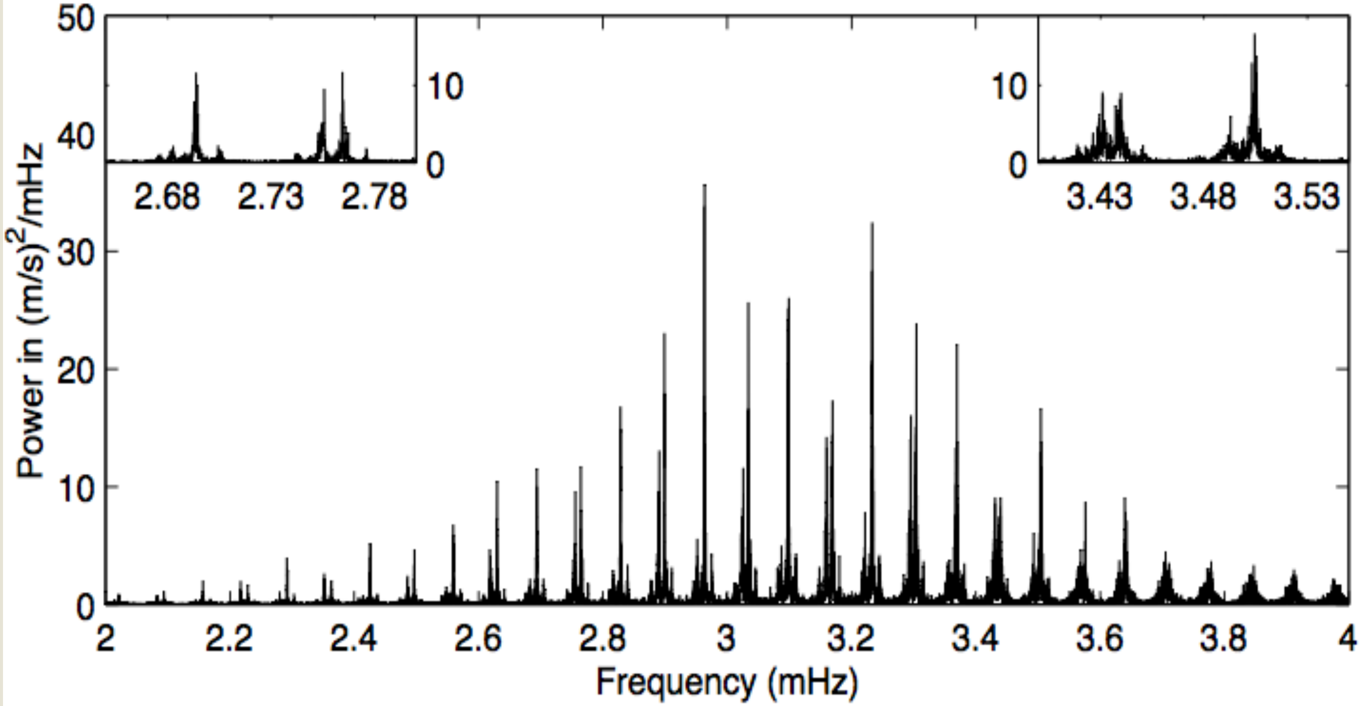


Fig. 5. Power spectrum of the same data (as Fig. 3) after the "repetitive music" partial gap filling. The visible benefit is not as spectacular, but it is more "honest" in the sense that now, there is not any surrounding noise which is artificially pulled inside the peaks. It can be noted that the background noise is modulated with the 67.5 μHz periodicity. The fine adjustment of the method consists of placing the maxima of this modulation on the p-mode frequencies, so that the loss of information is only located in the noise.

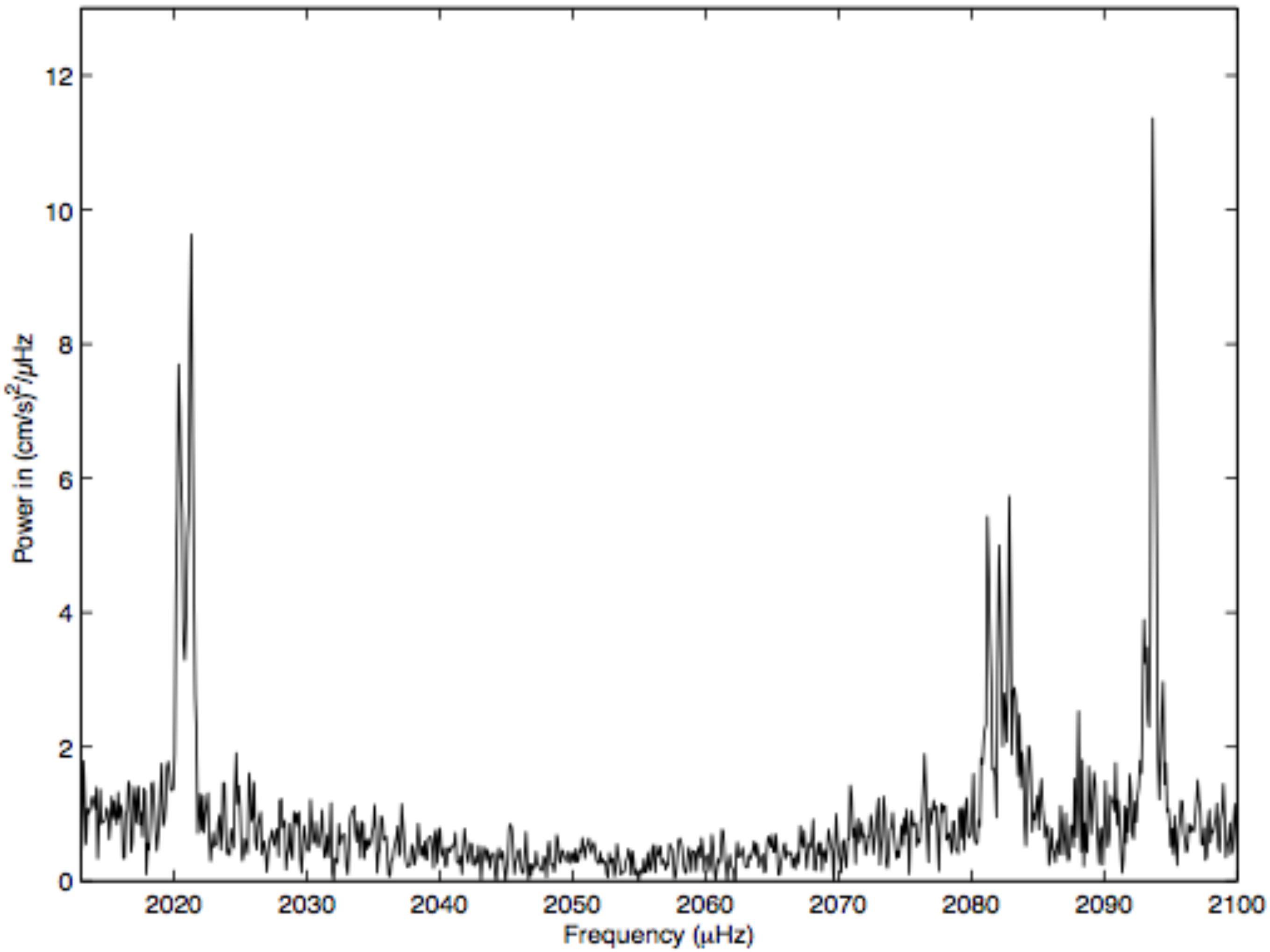


Fig. 6. A small spectral bandwidth shows the performance of this partial gap filling method. This is obtained with 7 years of IRIS data. All individual amplitudes in this spectral range are between 1 and 2 cm/s. Note the signal to noise ratio, and the sharp visibility of the rotational splitting of dipole and quadrupole frequencies. One can also see the modulation of the background, which reduces the sensitivity at frequencies where there is no mode to detect.

The acoustic spectrum of α Cen A*

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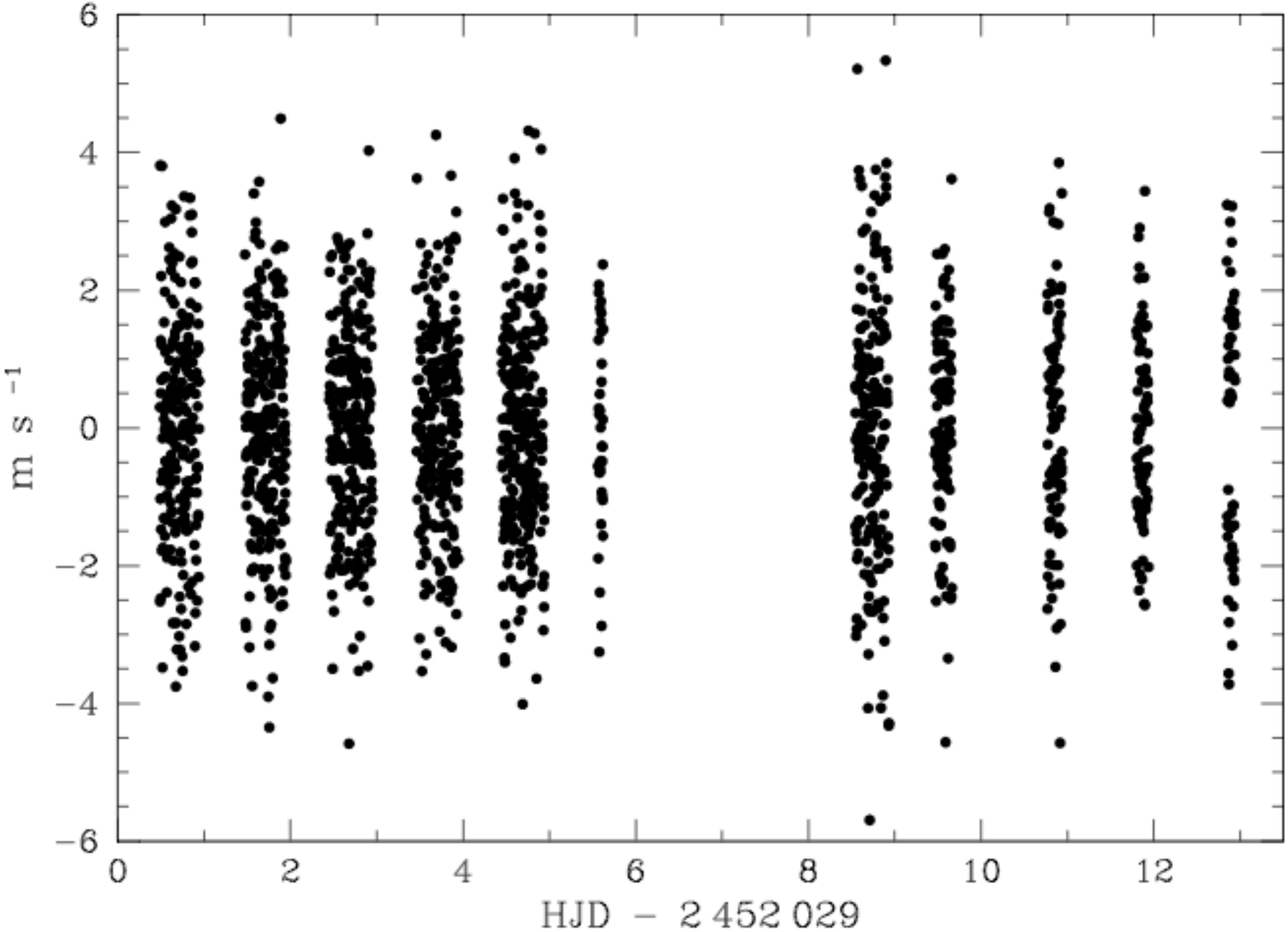
Abstract. This paper presents the analysis of Doppler p-mode observations of the G2V star α Cen A obtained with the spectrograph CORALIE in May 2001. Thirteen nights of observations have made it possible to collect 1850 radial velocity measurements with a standard deviation of about 1.5 m s^{-1}. Twenty-eight oscillation modes have been identified in the power spectrum between 1.8 and 2.9 mHz with amplitudes in the range 12 to 44 cm s^{-1}. The average large and small spacing are respectively equal to 105.5 and 5.6 μHz. A comparison with stellar models of α Cen A is presented.



6
4
2
0
−2
−4
−6
m s −1
0
2
4
6
8
10
12
HJD − 2 452 029

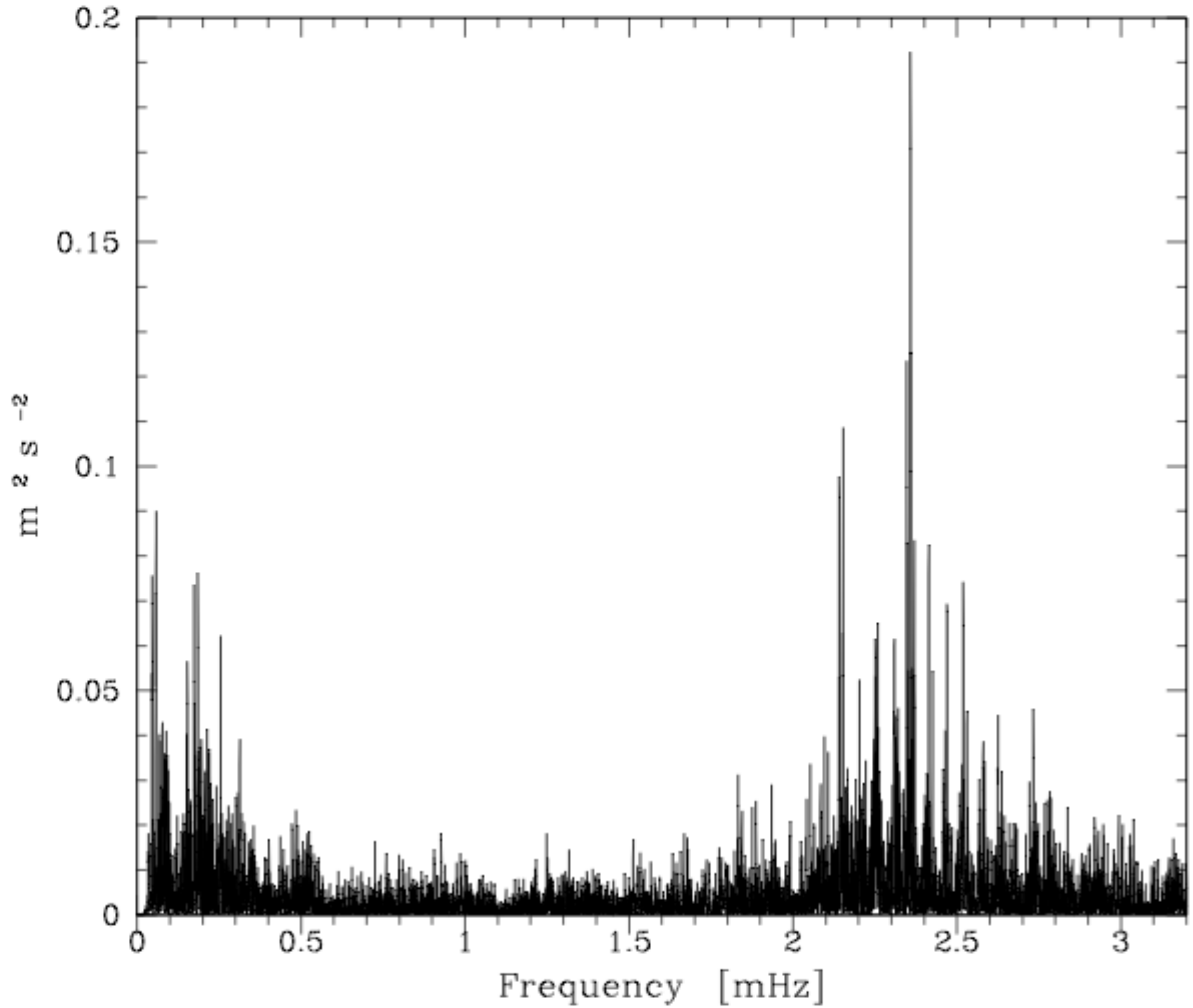


Fig. 2. Power spectrum of the radial velocity measurements of α Cen A.

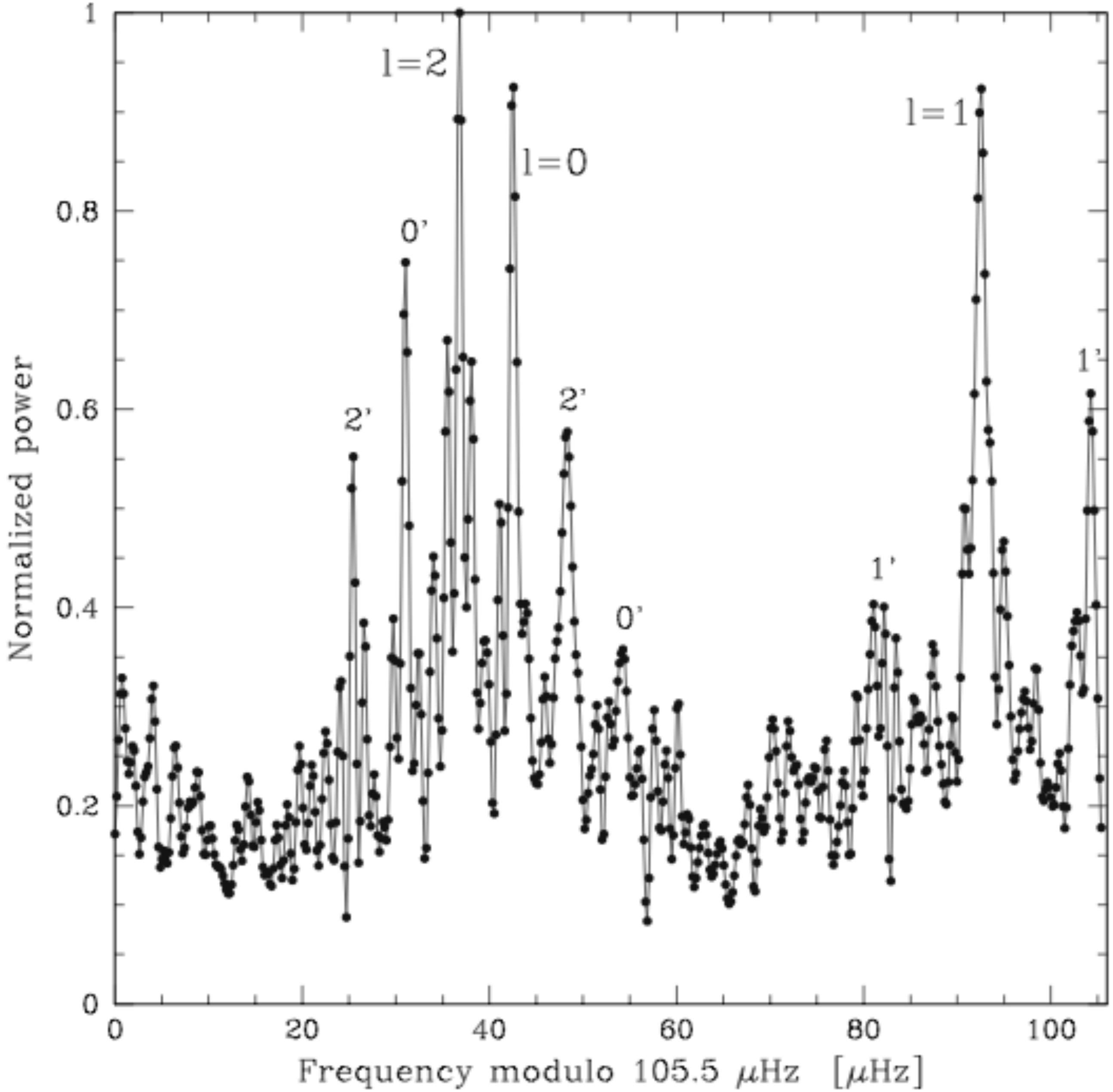


Fig. 5. Sum of the echelle diagram of α Cen A oscillations. Modes $l = 0$, 1 and 2 and their aliases are identified.

3.4. Gap filling process

In order to reduce the effect of single-site observation, the repetitive music process proposed by Fossat et al. (1999) was used. This method is based on the fact that the autocorrelation function of the full disk helioseismological signal, after dropping quickly to zero in 20 or 30 minutes, shows secondary quasi periodic bumps, due to the quasi-periodicity of the peak distribution in the Fourier spectrum. In the helioseismological signal, the first of these bumps appears at about 4.1 hours and corresponds to a

In the case of α Cen A, the periodicity of the modes is equal to $\Delta\nu_0/2 = 52.8$ μHz which correspond to a periodicity in time of the signal of about 5.26 hours. Considering that α Cen A was observed during the longest nights for a little less than 12 hours, this gap-filling process makes it possible to fill the duty cycle up to 90 %. The power

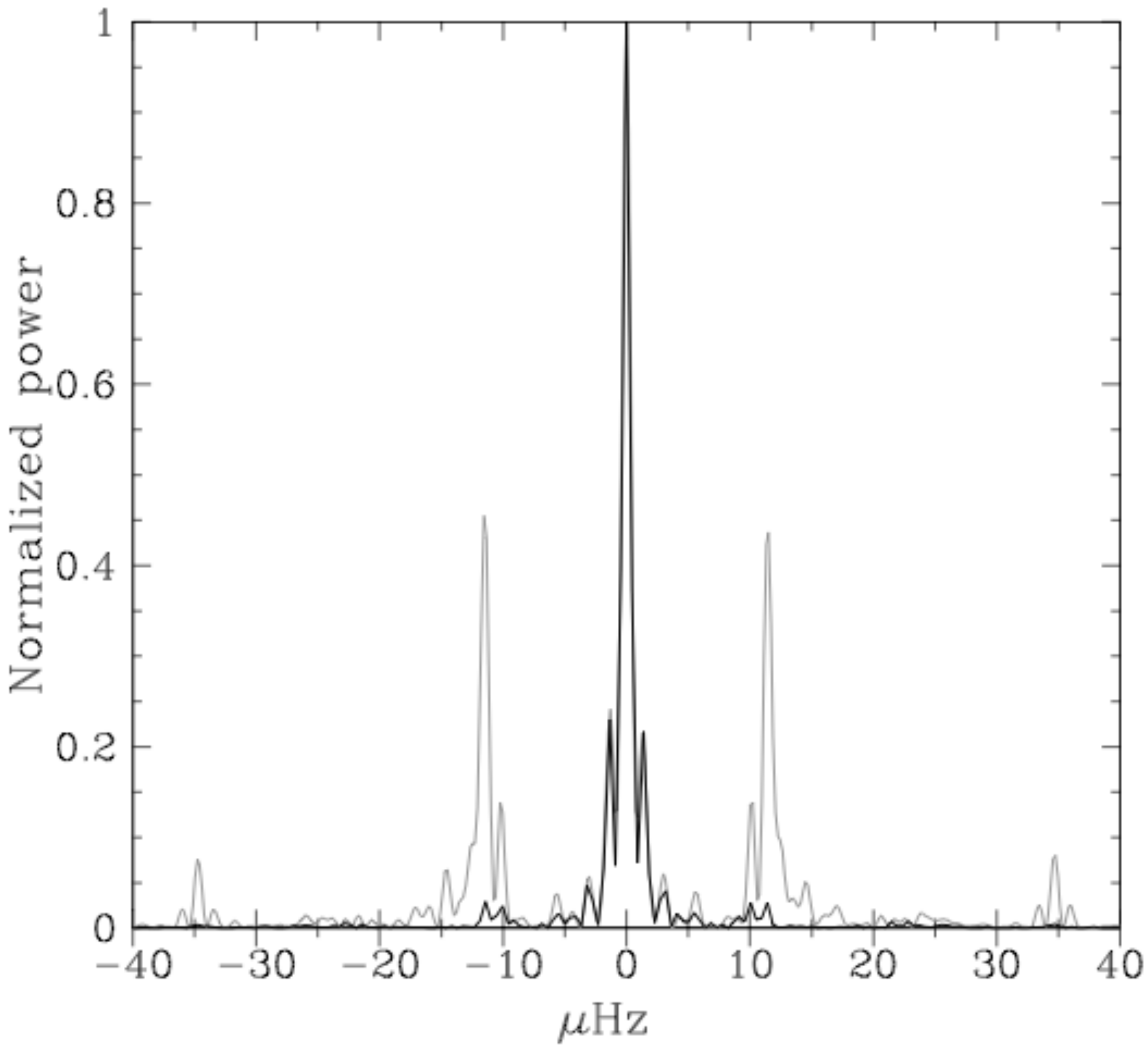
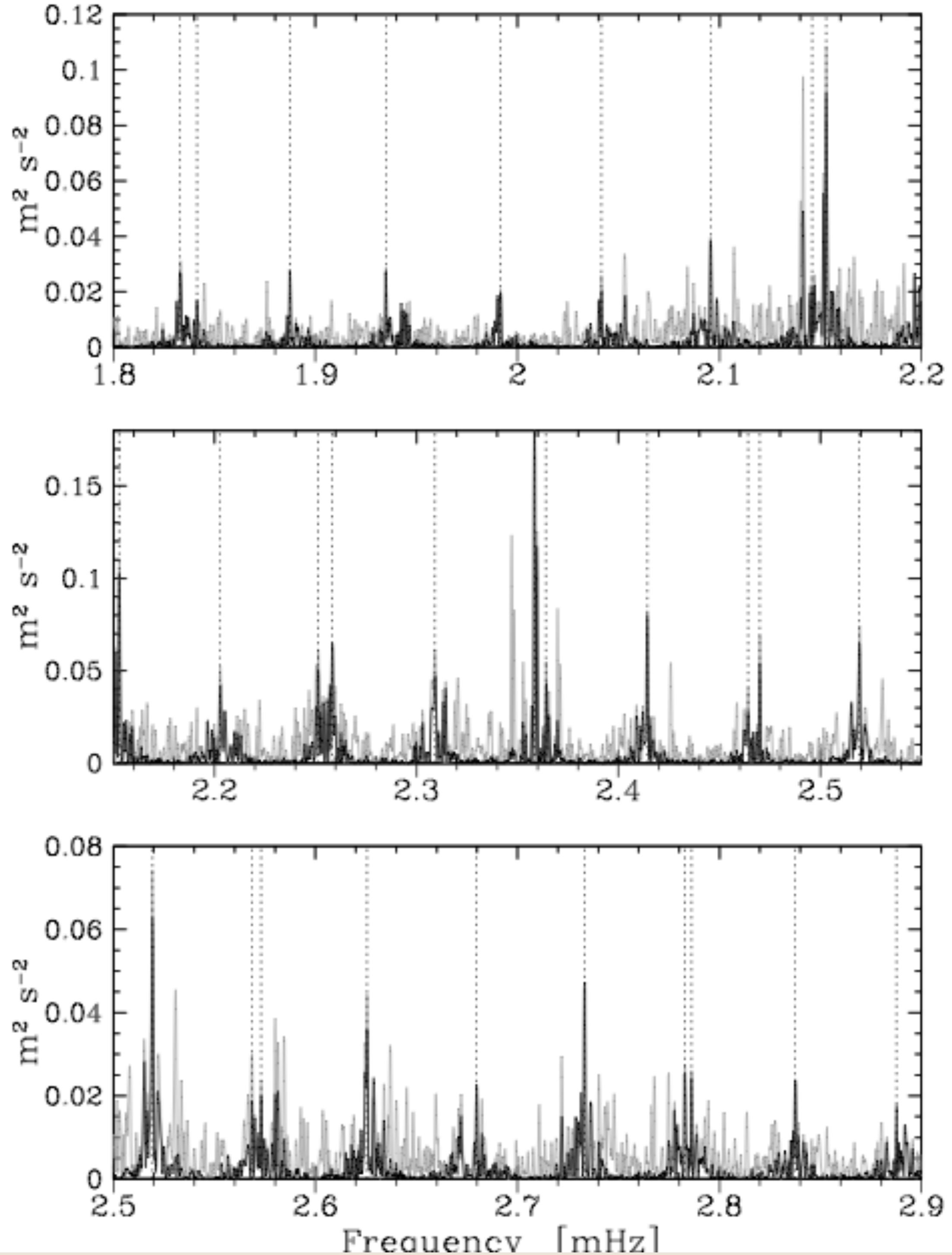


Fig. 6. Observational window response with (black line) and without (grey line) the gap-filling process.



0.12
0.1
0.08
0.06
0.04
0.02
0
m² s⁻²
1.8
1.9
2
2.1
2.2
0.15
0.1
0.05
0
m² s⁻²
2.2
2.3
2.4
2.5
0.08
0.06
0.04
0.02
0
m² s⁻²
2.5
2.6
2.7
2.8
2.9
Frequency [mHz]

Thanks !