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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 low frequency p-modes already seen by 2 years of the GOLF instrument data, and makes possible the measurement of their frequencies with an accuracy consistent with the partially filled 7 years of statistics.

Key words: methods: data analysis – Sun: oscillations

1. Introduction

All helioseismological instrumental programs during the last twenty years have aimed at obtaining the best temporal coverage, 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 study is strictly limited to the helioseismological full disk signal, such as obtained by IRIS, BiSON, GOLF, VIRGO or DIPHOS instruments. It is also strictly limited to the p-mode frequency range.

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2. Gap filling

The window effect is a convolution in the Fourier space, for which the deconvolution is obviously impossible: by Fourier transform, a convolution becomes a multiplication, and we already know that in the time domain, we have the multiplication of the true signal by the window function made of 1 or 0. The deconvolution in the Fourier space is the division in the time domain, which cannot be done with the zeroes. One approximation consists of assuming that the power spectrum is also modified by a convolution operation. This becomes asymptotically true with infinite time of integration and complete independence between signal and window (Lazrek & Hill, 1993). Several methods of approximate deconvolution have then been attempted, to provide corrected power spectra, without access to the approximation of the true signal in the time domain. See for instance the theses of Loudagh (1995) and Pantel (1996). These methods work to some extent, reducing the sidelobe amplitudes and pulling back inside the peaks some of the power which was spread around. However, they are less and less efficient with reduced duty cycle, and they work already badly around 50 percent. An important point is that they completely ignore the specific properties of the solar oscillation signal, so that they are clearly not optimized for our problem. The other approach is to take into account what we know of the solar signal and to see how reliably we can try and imagine the signal which has not been observed.

Of course, the question of filling gapped data is not a new one. Already in 1982, Fahlman & Ulrych (1982) described a method for estimating the power and phase spectra of gapped time series, using maximum entropy reconstruction of the data in the gaps. An adaptation of these ideas to the solar oscillation data was then attempted by Brown & Christensen-Dalsgaard (1990), then by Anderson (1993), while the case of stellar oscillation data was also addressed by Serre et al. (1992), using a prediction method for the evolution of a dynamical system. The conclusions are very similar. Namely, gaps of a few periods duration can be efficiently filled, provided the signal to noise ratio is high enough and the duty cycle of the observations is not less than 50 percent. Unfortunately, the typical periods of solar oscillations are short (a few minutes), so that many gaps, longer than, say, 15 to 20 minutes, remain unfilled or badly filled, and the signal to noise ratio becomes evidently poor at both ends of the spectral range, where the best possible duty cycle becomes quite crucial.

3. Interpolation

3.1. Principle of the method

It is extremely difficult to interpolate, from the beginning to the end of a gap, the solar oscillation signal that contains many (more than 200) different oscillations of various degree, radial and tesseral order. As a result of this large number, the temporal coherence of the signal is limited to a few periods, so that an easy interpolation is only limited, as already mentioned, to a gap not longer than a few periods. This is clearly shown by the beginning of the autocorrelation function of the velocity signal, which drops to zero in less than half an hour (Fig. 1).

However, we know that each individual oscillation has a coherence of several days, even much longer in the lower part of the frequency range. So, if we could isolate the spectrum of one single mode, it would be made of a single peak surrounded by the window function. An inverse Fourier transform would then provide this single mode oscillation, multiplied by the window function, i.e. by gaps. Amplitude and phase are changing slowly,

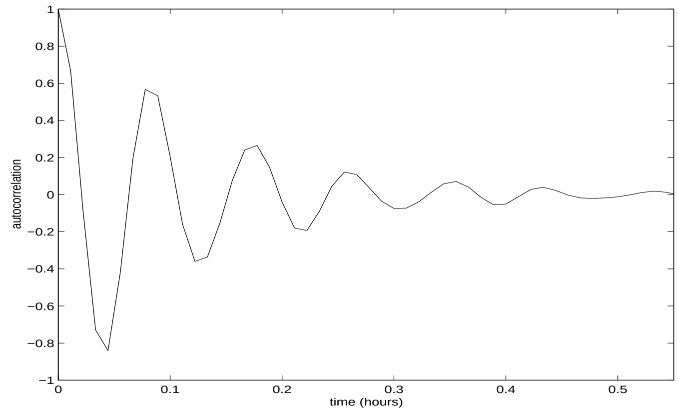

Fig. 1. First half hour of the IRIS autocorrelation function of the full disk velocity signal. The coherence drops quickly to zero due to the incoherent addition of about two hundred independent oscillations of different frequencies. The typical coherence time of about 15 minutes is the inverse of the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

losing memory only after several days. In this ideal case, the signal in gaps could be reliably interpolated up to duration of the order of half the coherence time, a good fraction of several days.

Unfortunately, it is not possible to isolate one single peak and the frequency range of the window function in the Fourier domain. They are just too many, too close to each other. But some kind of compromise can be found. After filling the short gaps (less than about 15 minutes, or typically 3 periods) in the original signal, by any kind of interpolation method, we can select a frequency bandwidth of about 67.5 μHz, which contains one pair of modes (either a pair 0–2 or a pair 1–3), together with a significant fraction of the window function of these two peaks. Assuming that most of the window function is contained in this bandwidth (at least the first and second $(1day)^{-1}$ sidelobes on each side) and also assuming that almost none of the window function of other peaks is present, an inverse Fourier transform provides a filtered signal which contains the two modes, a smoothed approximation of the window function, and the true modulation of their amplitude and phase due to their intrinsic lifetime as well as to their multiplet structure caused by the solar rotation. Both these modulations are slow and permit some interpolation inside the gaps.

An easy way of doing it is to translate the frequency bandwidth to zero in order to eliminate the periodicity at the mode frequencies. We are left, then, with a 1.5 or 2-day modulation due to the doublet 0–2 or 1–3, with a slow evolution provided by the splitting and the amplitude and phase coherence time. The next step is again a multiplication by the window function, which has only been approximately reproduced by the inverse Fourier transform. The signal of each individual mode has a memory of a few days. Moreover, the direction of time cannot be identified, so that a missing part of the signal can be extrapolated back from the signal coming later, as well as forward by the signal recorded just before the gap. The procedure that we used consists then in selecting a running window of the order

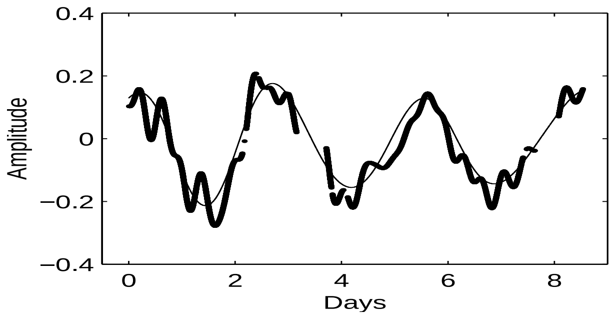

Fig. 2. This is the variation of amplitude of a pair of modes (l=0–2) during about 8 days, the measurement being interrupted by the data gaps. The main feature is the beating between the two frequencies, everything else being changing more slowly. A sine wave fitting of a few parameters around the beating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

of two times a few days. We took 8 days. Inside this running window, we have signal and gaps. Here, the so-called signal is only the slow modulation of the amplitude and/or the phase of the selected pair of p-modes. In fact we don't treat the amplitude and phase, but rather the real and imaginary part, which is equivalent and easier in practice. The gaps are interpolated by means of a fit on all the signal present during these 8 days. We tried polynomial fitting or sine waves fitting. The second choice appeared to be much more reliable, because the polynomials have the mathematical possibility to go to infinity, which both the true signal and the sine waves cannot. Each gap can be approximated many times by this method, when moving the running window by substantially less than 8 days. For each individual point of each gap, we simply take the average of these many approximations.

Fig. 2 shows an example of a 8-day amplitude modulation, with its gaps and the interpolation. Having then filled all gaps with amplitude and phase, everything is brought back to the original frequency range. The complete process is done again for the next pair of even or odd modes, until the full range of p-modes has been covered. The complete p-mode signal has thus been approximated, and the p-mode time series subject to Fourier analysis is now free of any gaps shorter than about half the mode lifetime.

3.2. Performance and limits

Many results already published by the IRIS community have used the network data of the four summers of 1989 to 1992. Fig. 3a shows the direct power spectrum of this data set. It is an average of the 4 individual spectra, with a resolution of 0.085 μHz. Fig. 3b shows the power spectrum of the same data obtained after a deconvolution of the window function by means of the Richardson (1972) and Lucy (1974) algorithm. Fig. 3c shows the power spectrum of the same data now obtained after the gap filling method briefly described here above. At first sight, the improvement is really spectacular. However, first sight is certainly not enough to estimate the real performance and it is necessary to look in more detail.

A first and obvious limitation is the lifetime of the individual modes. It is not possible to fill reliably a gap longer than the mode lifetime, a few days. This is intrinsic to the mode physics and can certainly not be improved by any mean. The only solution is to avoid any gap longer than a few days in the time series! Now, the mode lifetime is of the order of a few days only in the 2 to 3.5 mHz range. In this frequency range, the method is then expected to be very efficient. Let us just mention that a quick look shows frequencies and splittings in very good agreement with our published values, just easier to estimate (and consequently presumably more accurate) for the two reasons of a better signal/background ratio and of the absence of sidelobes.

At higher frequencies, the lifetime becomes progressively shorter (the peaks are broader and broader in the Fourier space), so that the duration of the longest gaps efficiently filled gets shorter and shorter. Roughly speaking above 4 mHz, the spread of power due to the window function is replaced by an uncertainty due to the decreasing level of confidence in the gap filling, so that the improvement drops down to nearly nothing. At the other end of the p-mode spectral range, the problem is a little more subtle. The lifetime is increasing from a few days to at least a week near 2 mHz, and then to several weeks, or even months around 1.5 mHz and less (Libbrecht, 1988). The gap filling method could then in principle be much more efficient. However, the poorer signal to noise ratio kills this hope. In the 3 mHz range, the inverse Fourier transform is able to separate reasonably well the true mode modulation from the window function because most of the background power around the peaks is due, indeed, to the window function. When the signal to noise ratio decreases as it does below 2 mHz, most of the background around the peaks is now made of noise, and the effects of this noise and of the window function are mixed. A consequence is that our method is able, indeed, to bring back a lot of power at the mode frequency, but a significant fraction of this power is due to the interference between the noise and the peak window function, and has little to do with the real p-mode peak when the ratio between window function and noise becomes less than 1. This gap-filling method was initiated by a 5-month student research (Sadikhbeily, 1998). However, we shall see below that it can be improved to a large extent.

4. Repetitive music

We have then seen that the short gaps (a few periods) can be filled efficiently because the velocity signal has a memory that lasts a few periods, as shown by the autocorrelation function. Now, as shown by Gabriel et al. (1998), it is extremely interesting to have a look at this autocorrelation function somewhat further than the first half hour. Fig. 4 shows the first 10 hours of the IRIS autocorrelation function (Gabriel et al. show the same for the GOLF signal).

We have filtered the signal in the p-mode frequency range (from 1.5 to 5 mHz). It appears that the signal has a very high level of coherence after a little bit more than 4 hours. It is above 70 percent, and this is significantly greater than its coherence after just one period of 5 minutes. It has been interpreted by

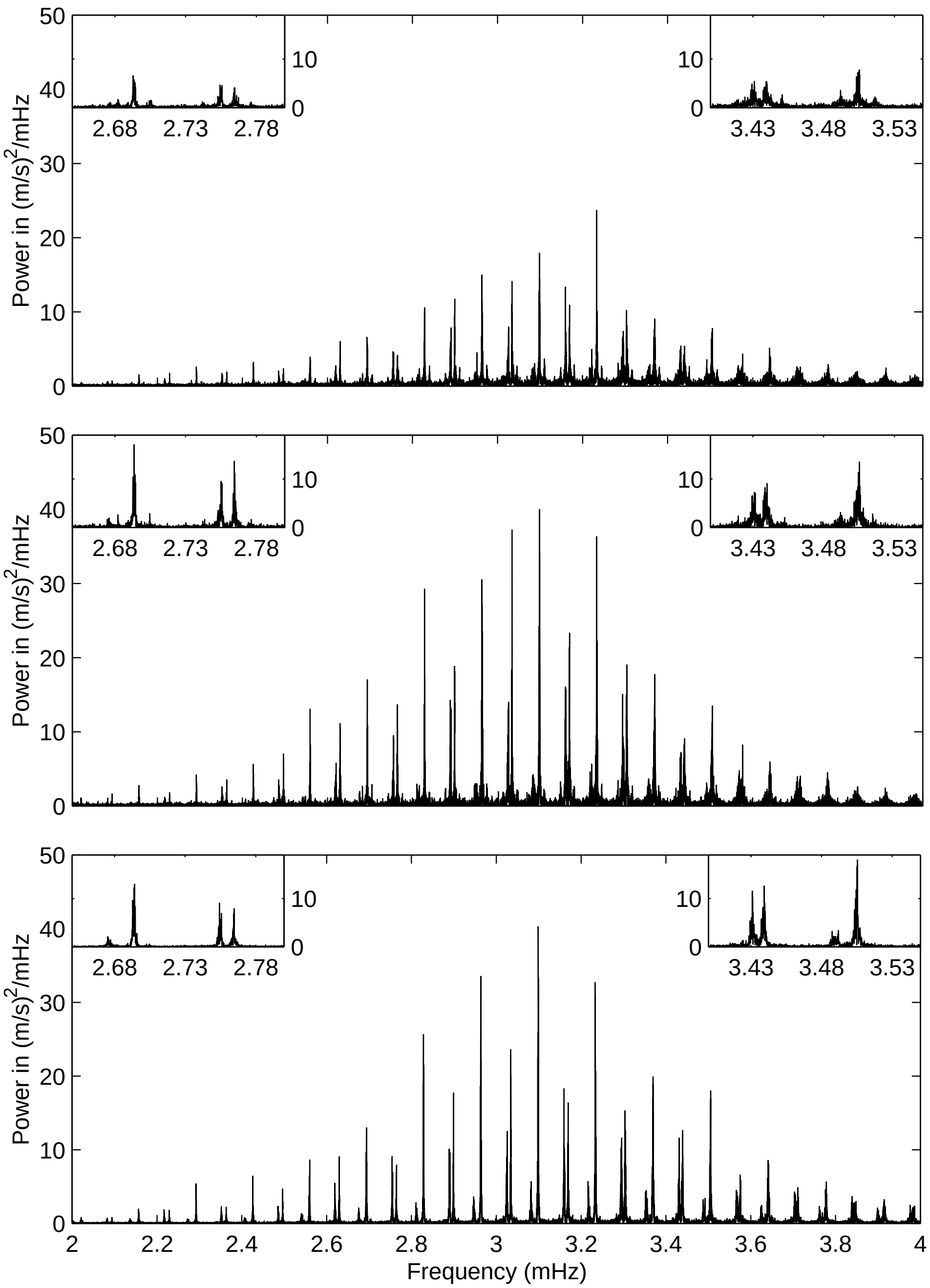

Fig. 3. The upper part is the direct (averaged) power spectrum of the 4 summer seasons of the IRIS network data, from 1989 to 1992. Each file has a duration of 136.5 days, so that the frequency resolution is equal to 0.085 μHz. The perturbation of this power spectrum by the window function is clearly 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.

Gabriel et al. as the consequence of the almost equally spaced frequency peaks in the Fourier domain. But it has an additional extremely important consequence to be noted here: it means that very much like in many musical songs, or preludes, or sonates, etc, the original signal is almost periodic in time, with a quasi periodicity of a little more than 4 hours.

An obvious consequence is that simply replacing a gap by the signal collected 4 hours earlier or 4 hours later provides a gap filling method with more than 70 percent confidence. Surprisingly, even filling a gap as short as 5 minutes is better done by means of the data obtained (if so) 4 hours earlier than by interpolating the nearby data before and after the gap.

If the p-mode frequency range is somewhat more restricted, like from 1.8 to 3.5 mHz, this secondary peak of the autocorrelation function climbs to nearly 90 percent because in this limited range, the p-mode equidistance is an approximation much closer to reality. The ultimate limitation (less than 100 percent) comes from two simple facts: on one hand, the p-modes come in pairs, and there is a beating of each pair which is long, but not indefinitely long, as compared to 4 hours; on the other hand, the lifetime is long, but also not indefinitely long, as compared to 4 hours, so that each mode amplitude and phase has slightly changed during this time. However, by cutting the frequency range in just 3 parts (roughly below 1.8 mHz, from 1.8 to 3.6

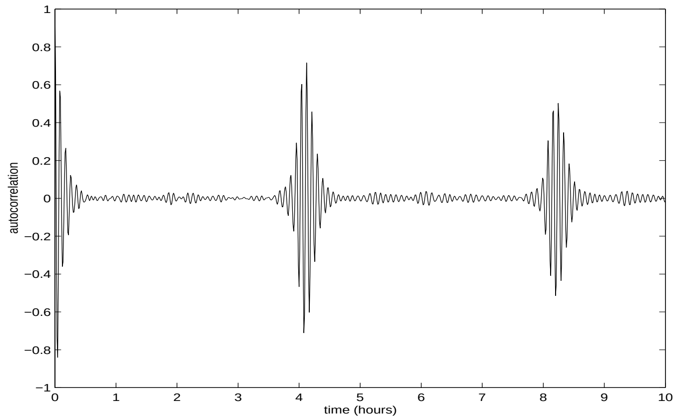

Fig. 4. The first ten hours of the IRIS data autocorrelation (filtered in the p-mode range, from 1.5 to 5 mHz) shows that beyond the quick drop at the beginning, there are secondary bumps around 4 and 8 hours. They are due to the quasi-periodicity of the peaks in the Fourier spectrum. The important point 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.

Table 1. Frequencies of low degree low order p-modes measured from 7 years of IRIS data. The mean duty cycle has been increased from about 50 percent to about 80 percent by means of the "repetitive music" gap filling method. The data cover the years 1990–1996, and this includes the complete range of solar activity levels. Even if these low frequencies are less sensitive to the magnetic activity, Fig. 7 shows that a small drift is clearly visible.

n/*l*	0	1	2
8		1329.64 ± 0.04	
9	1407.50 ± 0.04	1472.89 ± 0.04	1535.92 ± 0.04
10	1548.30 ± 0.04	1612.78 ± 0.04	1674.58 ± 0.04
11	1686.64 ± 0.04	1749.37 ± 0.04	1810.40 ± 0.04
12	1822.27 ± 0.04	1885.18 ± 0.04	1945.94 ± 0.04
13	1957.50 ± 0.04	2020.86 ± 0.04	2082.11 ± 0.04
14	2093.70 ± 0.04		

and more than 3.6 mHz) and with a fine tuning of the temporal periodicity in each one of these 3 frequency ranges, *it is possible to fill gaps as long as 8 hours with a 90 percent confidence!*

The idea is extremely simple. Doing it in practice is also very simple, and it demonstrates that p-mode helioseismology is not so demanding of the duty cycle, and that it can be all done with ground based programs of observation.

In the most extreme favorable situation, we can imagine a data set with 33 percent duty cycle, 4 hours of data followed by 8 hours of gap, and so on. After this "repetitive music" gap filling, it is not possible to distinguish a Fourier peak from the original one. Data obtained in space with a low orbit and a 90 minute periodicity (such as ACRIM or DIPHOS) can be recovered at very nearly 100 percent, with all obvious benefit of such a dramatic duty cycle improvement. The background becomes modulated with the 67 to 68 μHz periodicity in frequency, but the fine tuning mentioned above consists of carefully placing the maxima of this modulation on the pairs of p-mode frequencies, so that the only information that is lost is a part of the noise (Fig. 5).

The limitation of the method is clear: gaps shorter than 8 hours. But this is already doing a significant fraction of the job in the case of the presently existing data sets of ground based networks. For instance, an IRIS window function of 50 percent duty cycle becomes filled at 83 percent, of the order of the performance of the networks operated with a really significant financial support. As an illustration, Fig. 6 shows a selection of a 7-year IRIS power spectrum. The very high level of signal to noise ratio permits to detect and accurately measure all p-mode frequencies of radial, dipole and quadrupole modes down to the present limit of 1329 μHz (l=1, n=8), with an amplitude of the order of 3 mm/s. After the partial gap filling, the duty cycle on subsets of 4 months reaches values that lie between 50 and 90 percent, depending on the season. There is an agreement between the IRIS and the LOWL (Tomczyk et al., 1995) projects that in the near future, the integrated LOWL images will be included in the data bank. The filled duty cycle, starting at the date of the beginning of the LOWL operation (February 1994) will then rise to values between more than 60 percent in the worst cases and close to 100 percent during the northern summers.

Table 1 gives the frequencies of the low order modes (below 2.1 mHz). Only in this low frequency range, the p-modes are stable enough in time to be worth being integrated over so many years. More complete frequency tables, with the solar cycle dependency, will be published soon. The comparison with the GOLF frequencies deserves some attention. For this comparison, we have used a more recent, and thus more precise because of the longer integration, GOLF frequency table than the published one (Lazrek et al., 1998). Fig. 7 shows the difference (IRIS-GOLF), where the GOLF frequencies are provided by M. Lazrek (priv. comm.). A small trend is visible, and is interpreted (Libbrecht & Woodard, 1991) as the fact that the IRIS measurements are integrated over a complete half solar cycle, this slowly drifting upwards the frequencies while GOLF measurements have only been made during the solar minimum. Around this trend, the r.m.s. scatter is of 0.05 μHz. This scatter is due to the incoherent (quadratic) sum of the GOLF and the IRIS uncertainties. As the GOLF uncertainties are, on the average, slightly larger than 0.05 μHz, this small scatter qualifies the partial gap filling method, and the fact that the IRIS frequencies are more precise than the GOLF frequencies, thanks to the longer time of integration. The 0.04 μHz 1-σ uncertainty of the Table 1 is a conservative value, slightly pessimistic.

The performance of the method is clearly understood. Its limitations are very small, besides the 8 hours maximum gap duration. The increasing lifetime of lower frequencies makes the method even more precise in this range. There is no longer a possibility of confusion between noise and window function. Even at the other end, in the high frequency range, the lifetime of the modes remains longer than 4 hours until at least 5 mHz, so that the 90 percent confidence is only slightly reduced above 4 mHz.

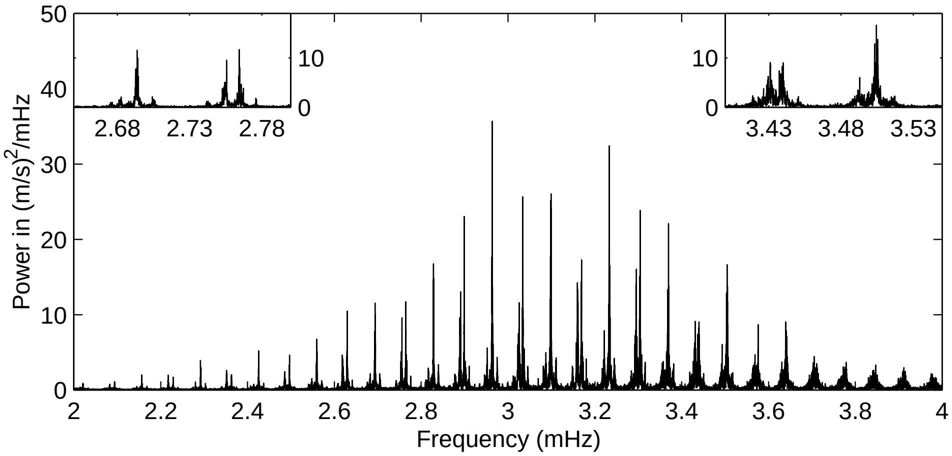

Fig. 5. Power spectrum of the same data (as Fig. 3) after the "repetitive music" partial gap filling. The visible benefit is not as spectacular, but it is more "honest" in the sense that now, there is not any surrounding noise which is artificially pulled inside the peaks. It can be noted that the background 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.

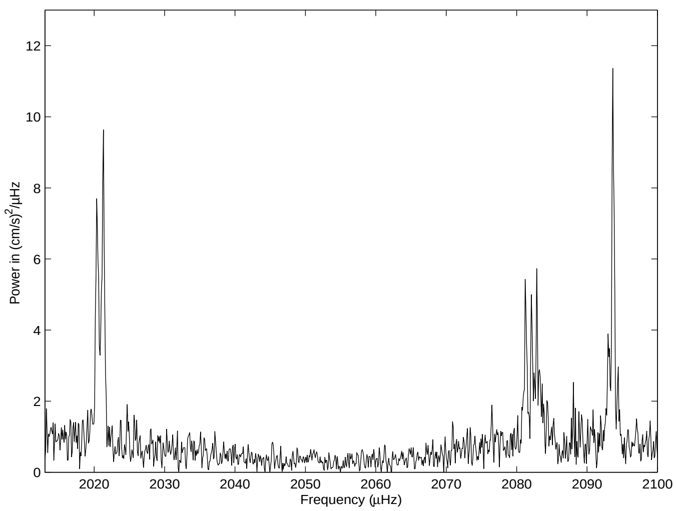

Fig. 6. A small spectral bandwidth shows the performance of this partial gap filling method. This is obtained with 7 years of IRIS data. All individual amplitudes in this spectral range are between 1 and 2 cm/s. Note the signal to noise ratio, and the sharp visibility of the rotational splitting of dipole 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.

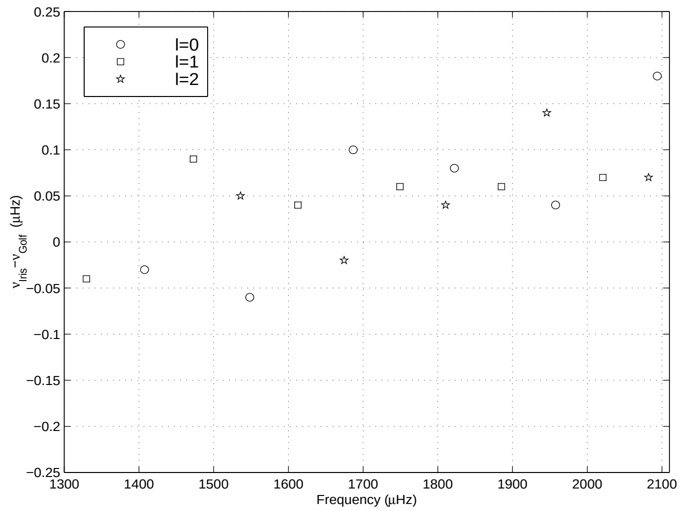

Fig. 7. Difference between the frequencies of Table 1 (each one identified by the mode degree) and recent GOLF frequencies obtained with two years of data from the SOHO spacecraft in orbit around the L1 Lagrange point. The small drift upwards is due to the integration of the IRIS data through all the phases of the magnetic activity cycle, and shows the mode inertia sensitivity to this activity. The scatter of individual points around this mean trend is not larger than 0.05 μHz, which demonstrates that both frequency lists are more accurate than this number. The error bar of 0.04 μHz included in the Table 1 is a conservative value.

5. Combining the two gap filling methods?

We have a first method of gap filling, operated mode by mode, and doing a good job for modes with long enough lifetime and high enough signal to noise ratio. In the five-minute range, it is working well for filling gaps as long as about half the lifetime, around two days. But it is not so efficient at high and low frequencies, where the problem is even more crucial than in the central one.

The "repetitive music" method is doing a quasi perfect job at any frequency, but is limited to gaps shorter than about 8 hours. It is then tempting to think of a combination of the two methods: filling all gaps shorter than 8 hours by the repetitive music method, and then filling the remaining gaps longer than 8 hours but shorter than 2 days by the mode by mode interpolation method. That will further improve some more the efficiency in the five minute band, while it will artificially increase the low amplitude peaks, at the expense of their reality, by pulling some of the surrounding noise inside the peak. Conceptually, it seems possible, again, to also improve the final performance even in the low frequency range: by separating the network data into two sub-network independent time series, the gaps to be filled by the mode to mode interpolation method are longer, but remain in most cases shorter than 2 days. We obtain two independent time series, free of side lobes but with noise added in the low amplitude peaks. A cross-spectrum analysis of these two time series can then be done, with a resolution of a few months, enough to provide the optimum frequency resolution of nearly all peaks, but short enough to make possible an averaging of many different realizations. It will kill most of the uncorrelated noise, leaving also the small amplitude peaks freed of noise, provided the number of averaged realizations is large enough. This idea remains to be tested in detail, we may mention already that without the second part (mode by mode) of gap filling, the cross-spectrum analysis of two independent subsets of the network is sometimes already the most efficient method to give access to the smallest amplitudes.

6. Conclusion and prospects

Two different methods of full disk p-mode helioseismological data gap filling have been investigated. The first one, which consists of interpolating the signal after filtering bandwidths of 67 μHz, is very efficient for gaps as long as half the modes lifetimes, as long as the signal to noise ratio is high enough. It then excludes both ends of the p-mode spectrum. The second method, that we call repetitive music, takes advantage of the quasi-periodicity of the full disk p-mode signal due to the quasi-periodicity of the peaks distributed in the Fourier spectrum. This makes it possible to fill gaps as long as 8 hours (slightly more, in fact) with a confidence of nearly 90 percent across the complete p-mode frequency range. Such a gap filling possibility relaxes considerably the requirement of continuous observation in full disk helioseismology.

In this paper it has been explored only in the case of the full disk low degree data. It seems possible, to some extent, to generalize to other degrees since any two-dimensional degree/frequency diagram displays some kind of peak equidistance along the frequency axis at any value of the degree. This remains to be investigated but must be regarded, as suggested by our referee, as potentially useful. Another promising generalization will be, of course, the case of asteroseismology of solar type stars. The method presented here must be fully efficient in this case, after the frequency spacing has been identified, and of course, it can greatly help this identification.

Applying it to 7 years of data provided by the IRIS network, with an average duty cycle not over 50 percent, makes it possible to access all p-modes detected by GOLF, and to the measurement of their frequencies at a level of accuracy consistent with the data set statistics (0.02 to 0.04 μHz.

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