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Planetary Waves and Tides Found using Lomb-Scargle Periodogram Analysis of Rayleigh-Scatter Data above Utah State University

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Abstract   Because of the significant gaps in nighttime-only data, traditional Fourier techniques are difficult to use to identify tides and short-period planetary waves (PWs). The Lomb-Scargle periodogram is a method that was developed by astronomers to identify oscillations in nighttime-only and otherwise incomplete data. For the same reasons, it is also a powerful tool for aeronomers. The Lomb-Scargle technique is described with particular emphasis on its application to nighttime-only lidar data. Because of the gaps in the data, attention is also placed on techniques used to identify aliasing in the Lomb-Scargle periodograms. The method is applied to mesospheric temperatures from the Rayleigh-scatter lidar at the Atmospheric Lidar Observatory (ALO; 41.7°N, 111.8°W) at Utah State University (USU).

DATA AND ANALYSIS METHOD

The Lomb-Scargle or least-squares periodogram (LSP) method is an alternative to traditional Fourier analysis. It's significant advantage is that it applies a sinusoidal least-squares fit to unevenly sampled data. The mathematical treatment is given by *Press et al.* [1992] and the references therein.

Two 7-day periods of hourly temperature profiles from the Rayleigh-scatter lidar at ALO at USU [*Herron*, 2004] are treated here

• February 20-26, 1995 — Winter
• August 15-21, 1995 — Late Summer.

In this analysis [*Nelson*, 2004], the data points are 2.4 km apart and span the interval 40–80 km. are analyzed for the most significant long period spectral components. Because of periodic (daytime) gaps in the data, careful attention has to be paid to the possibility of false spectral peaks from spectral leakage.

SPECTRAL LEAKAGE

False spectral peaks from aliasing and other forms of spectral leakage can be detected by using one or more of the following techniques:

• Curve-fit subtraction [*Horne and Baliunas*, 1986]. The largest spectral peak at frequency ν_k is usually trustworthy. Fit a sine wave at ν_k to the data and then subtract the fit from the data. Perform a LSP analysis on this residual. In addition to the peak at ν_k, peaks aliased from ν_k will also disappear. We could repeat this process a second time or we could fit and subtract two spectral peaks.

• Visual evaluation of curve fit(s). Do curves at ν_j and ν_k fit the data equally well?

• Multiple altitudes. Does the spectral peak at ν_k occur at more than one altitude?

• Vertical phase progression. This refers to the motion of a peak or valley in a series of temperature profiles [e.g., as done by *Meriwether et al.*, 1998, for this same February 1995 data.]

• Aliasing mask. This is made from a Fourier transform of a vector of 0's and 1's representing the observation times [*Palo et al.*, 1997]. A spectral peak at ν_0 signifies that power in the LSP at ν_k could lead to a false peak at $\nu_0 + \nu_k$.

ANALYSIS

Figure 1 shows the LSP for the February data at 53.8 km altitude, along with 3 dashed lines representing approximate significance levels of 0.95, 0.90, and 0.50. (Because of data clumping, the actual significance levels are greater.) The most significant spectral peak has a period near 160 hours.   It is a quasi-5-day planetary wave (PW). The second most significant wave has a period near 20 hours. **Figure 2** shows the LSP for the same data as in Fig. 1 after a 160-hour, curve-fit wave has been subtracted. The 20-hour wave disappears, indicating that it is aliased from the 160-hour PW.
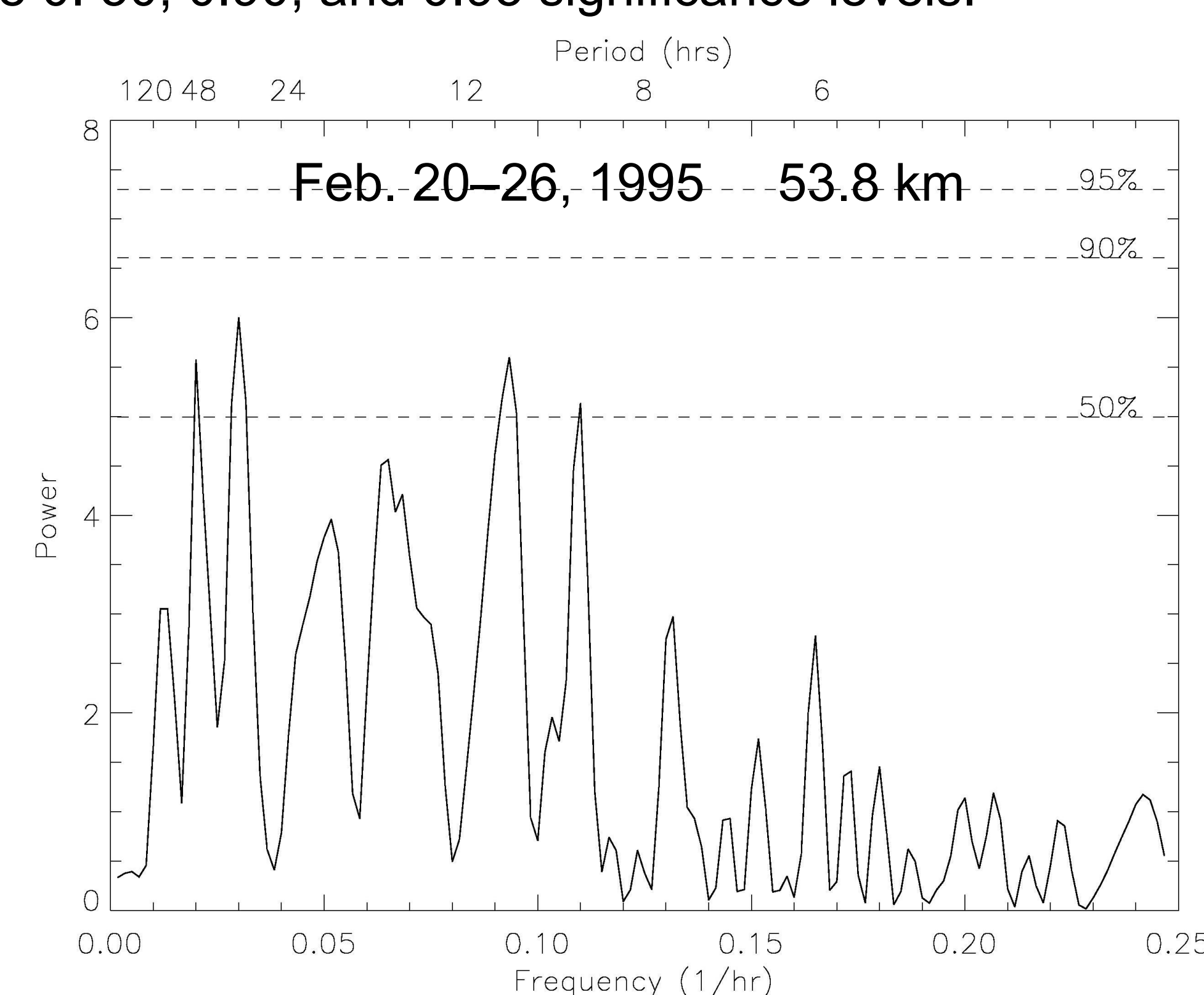
Feb. 20–26, 1995   53.8 km

Figure 1. LSP for February 1995 at 53.8 km along with the 0. 50, 0.90, and 0.95 significance levels.

Figure 2. LSP for the same data as in Figure 1, but after subtraction of a 160-hour, curve-fit wave. A 3-parameter fit was used. No significant waves remain.

A LSP, as in Fig. 1, can be calculated at every altitude for the February 1995 temperatures. **Figure 3** shows a contour plot of the 0.50, 0.90, and 0.95 significance levels from such a series of LSPs. The line at 53.8 km marks the altitude of the LSP in Fig. 1. The line at 44.8 km marks the altitude of a LSP referred to below. The dominant feature at all altitudes is a quasi-5-day PW with a period of approximately 160 hours.

The second major feature in Fig. 3 is an approximate 20-hour wave at 42–55 and 60–70 km. When the quasi-5-day PW is curve-fit and subtracted from the data at 53.8 km (Fig. 2) and these other altitudes, this aliased feature disappears. With it removed, significant power levels appear at slightly shifted frequencies. For instance, at 44.8 km, a LSP shows peaks near 48, 24, and 12 hours that exceed the 0.95 confidence level. At most altitudes below 55 km, LSPs indicate that the power in the 24-hour wave is much greater than in the 12-hour wave.   It is most likely the diurnal tide, while the 12-hour wave is probably an aliased artifact. The signal at 48 hours is possibly from a quasi-2-day planetary wave.
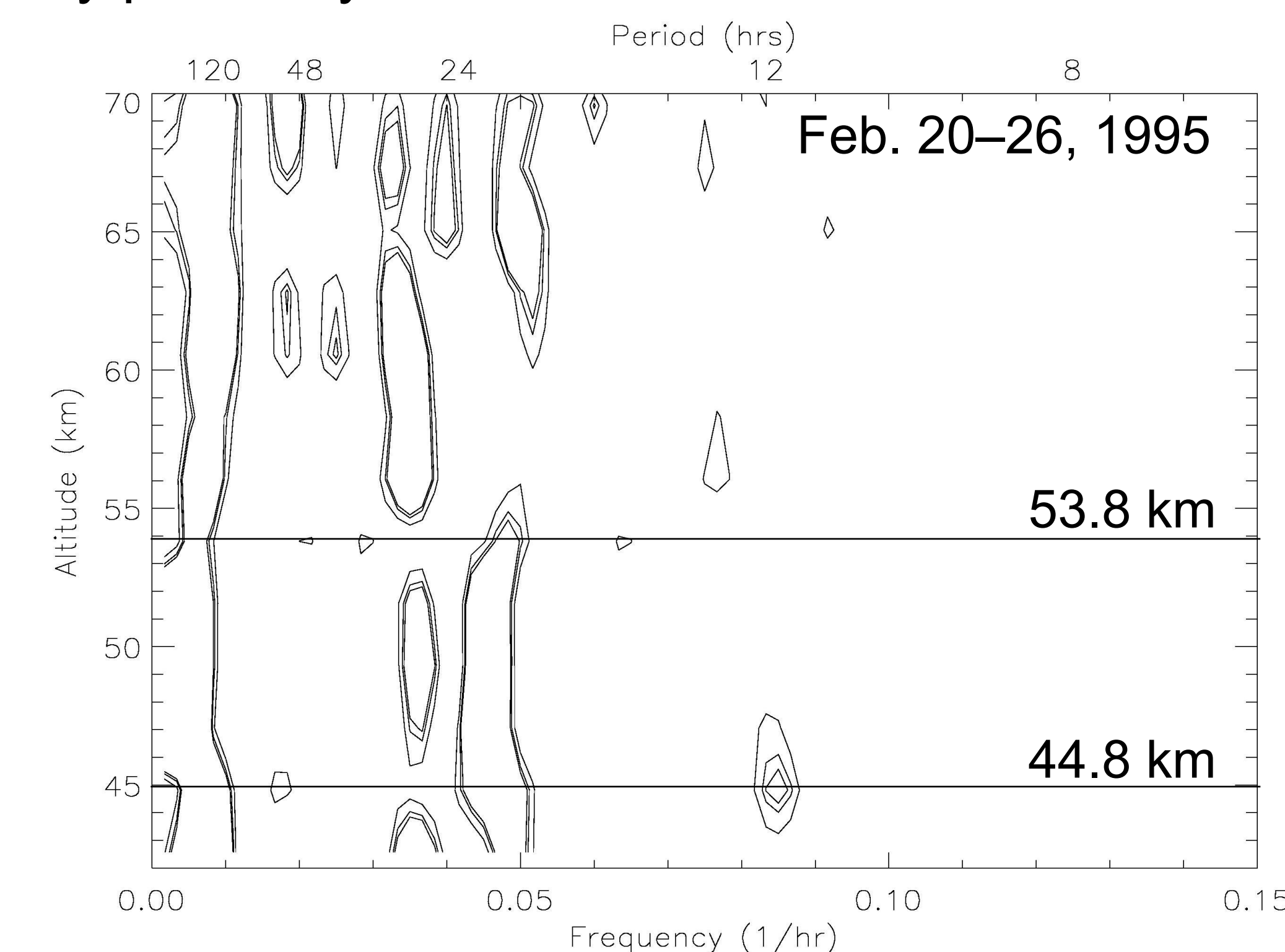

Figure 3. Contour plot of the 0.50, 0.90, and 0.95 significance levels from the original LSPs for February 1995.

Figure 4 is analogous to Fig. 1, but for 44.8 km from the August data set. There are 5 significant spectral peaks: a quasi-5-day PW with a 150-hour period, and peaks at 27, 24, 12, and 8 hours. **Figure 5** shows the LSP for the data in Fig. 4 after the curve fit and subtraction of the 150-hour wave. The 27-hour wave from Fig. 4 disappears, leaving what appear to be 24-, 12-, and 8-hour waves. The semidiurnal tide dominates, indic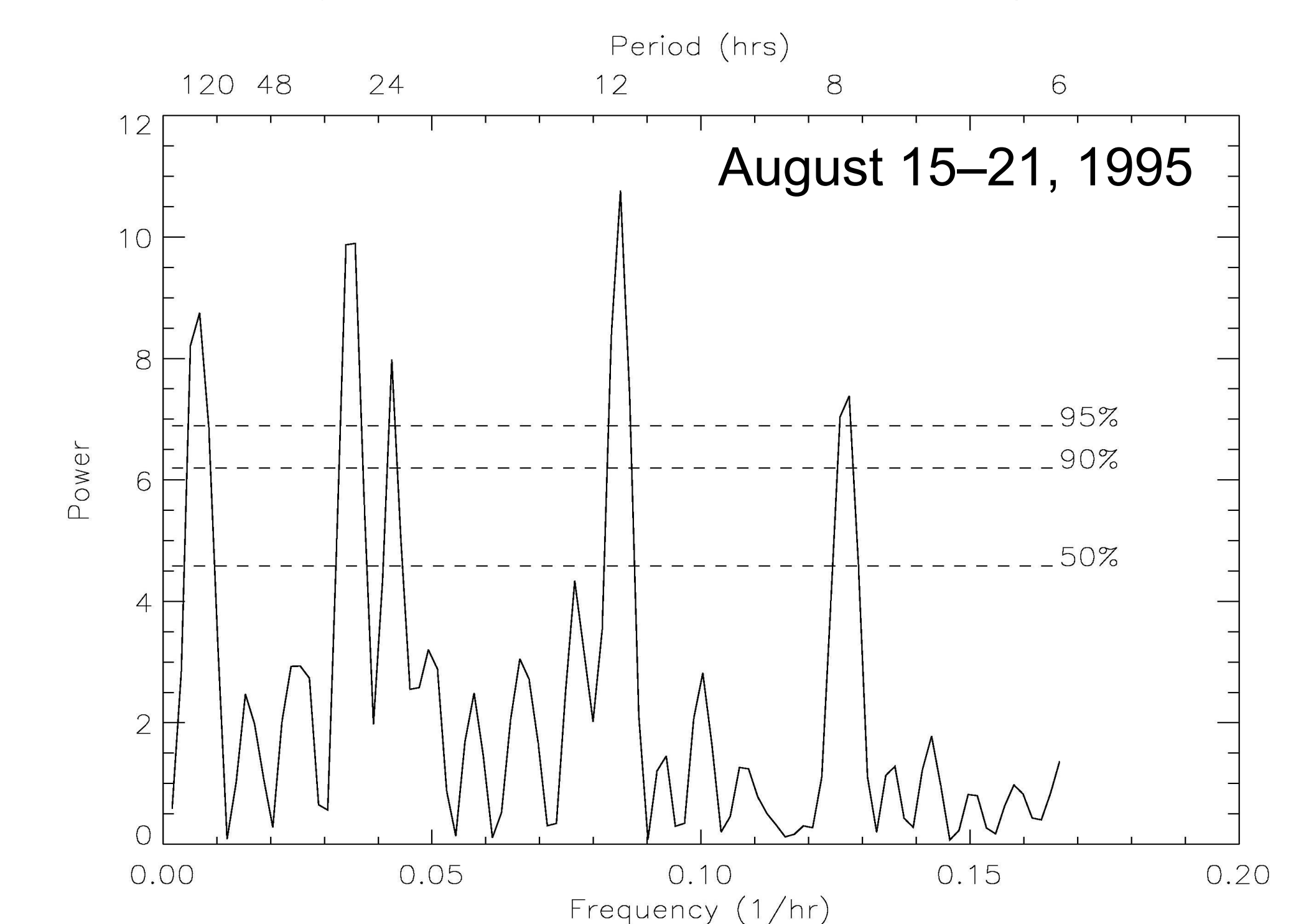ating it is probably real. The diurnal tide might be an aliasing artifact, but it comes to dominate at higher altitudes, indicating that both tides may be real. The terdiurnal may be real at these low altitudes.

Figure 4. The LSP for August 1995 at 44.8 km along with the 0.50, 0.90, and 0.95 significance levels.
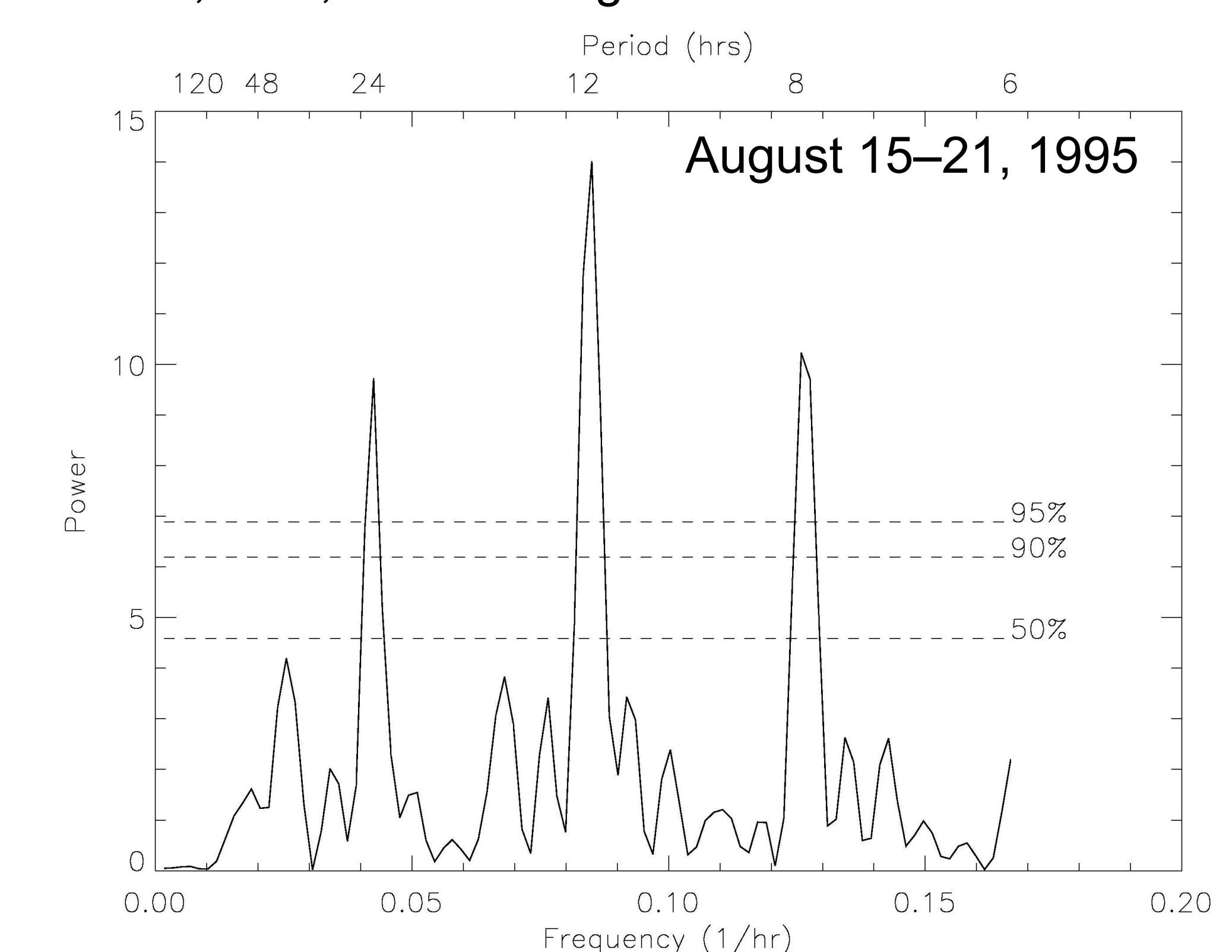

Figure 5. LSP for the same data as in Figure 4, but after subtraction of a 150-hour, curve-fit wave. A 3-parameter fit was used. Three significant spectral peaks remain.

Figure 6 shows the contour plot of the confidence levels for the August 1995 data. The results from 44.8 km extend up to 57 km with altitude gaps in the quasi-5-day PW and possible terdiurnal tide.

For 57–67 km, the strongest feature has a 53-hour period, probably a quasi-2-day PW. The next strongest has a 17-hour period. The curve-fit subtraction method shows the latter to be an aliased artifact from the 53-hour wave. The quasi-5-day PW and the tides do not appear in this region.

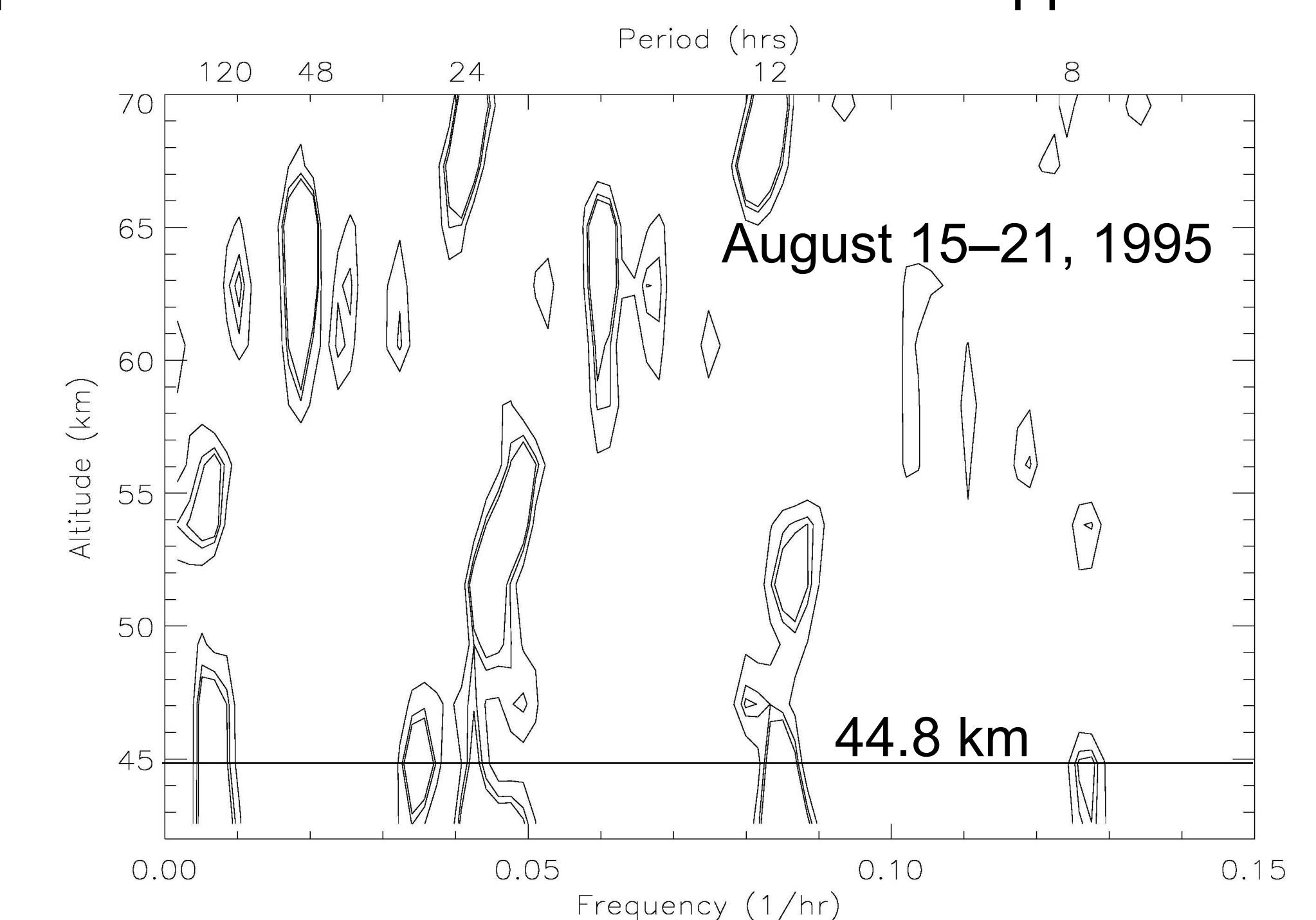However, for 67–72 km, all PW activity disappears and the 12- and 24-hr tides reappear.

Figure 6. Contour plot of the 0.50, 0.90, and 0.95 significance levels from the LSPs for August 1995.

CONCLUSIONS

• The Lomb-Scargle periodogram technique has been successfully applied to ALO lidar data to find tides and PWs in the 42–80 km region.
• The February period is dominated by a quasi-5-day PW at all altitudes and shows a 24-hr tide at lower altitudes. The occurrence of the PW at all altitudes in winter is consistent with its upward propagation for eastward directed, mesospheric, zonal winds. Strong mesospheric inversion layers at this time have been associated with the interaction of gravity waves and the 24-hour tide. Because of the strong PW, this explanation may have to be reexamined.
• The August period also has a quasi-5-day PW, but only in the lower mesosphere, and a quasi-2-day PW in the upper mesosphere. The occurrence of the latter only at higher altitudes suggests it might have been created there.
• Another unusual feature in August is that 24-, 12-, and maybe 8-hour tides exist up to 57 km, disappear from 57–65 km, and then the 24- and 12-hour tides reappear from 65–72 km.

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