Background

All wind calculations from aircraft are based on measuring the velocity of the air relative to the aircraft and the velocity of the aircraft relative to the ground, then finding the wind from the sum of these two vectors. Modern measurements of the velocity of the aircraft relative to the ground are made using IRS (INS) or GPS systems. The Litton LTN-51 was the INS used some time ago, and much of the code was developed for that system including the WP3 algorithm, about which I wrote a separate note. This note explores the consequences of changing the vertical-wind calculation to use the variable VSPD instead of WP3.

The current preferred variable for vertical wind is WIC. WI was a previously used name, but this was (usually) based on WP3 and has mostly been superceded by WIC.[1] The name of this variable in the netCDF headers is "GPS-Corrected Wind Vector, Vertical Gust Component" but that is misleading because the algorithm in use has no dependence on measurements from the GPS. The dependence arises from using the horizontal velocity components VEWC and VNSC in "gust.c", where the horizontal wind indeed depends on the GPS measurements, but the code in gust.c shows that WIC does not depend on those variables (even through coordinate transformations). The name implies that this is updated to match the GPS vertical wind, but that is incorrect; as calculated from VSPD, it only depends on IRS measurements and radome gust measurements. For reference, the equations used to calculate vertical wind in gust.c are reproduced here:

α = angle of attack
β = sideslip angle
ϕ = pitch angle
γ = roll angle
TAS = true airspeed
WP = vertical motion component of the aircraft in an inertial frame
B_c = boom correction (not reproduced here, dependent on rotation rate of the aircraft)
w = vertical wind

$$w = -\frac{TAS(\sin\phi - \tan\beta\cos\phi\sin\gamma - \tan\alpha\cos\phi\cos\gamma)}{\sqrt{1+\tan^2\alpha+\tan^2\beta}} + WP + B_C$$

An issue that has arisen from the change from the Litton LTN-51 to the Honeywell Laseref systems is that the acceleration and vertical aircraft velocity are already filtered as received from the Honeywell system, and furthermore both are already modified by updating via a baro-inertial loop similar to that used in conjunction with WP3 in code for the older Litton systems. [2] This has two

[1]There has been some inconsistency in names. For example, in TREX, WI was based on VSPD_G even though WP3 was calculated and included in the output data files. WIC was called GPS-corrected, but it was based on VSPD instead and so did not have any correction based on GPS measurements.

[2]Older documentation (e.g., Bulletin 23) states that the baro-inertial loop has a 60-s time constant, and the coefficients in subroutine ins.c (no longer used) indeed are {0.314159..., 0.03289866, 0.00114838} as would be appropriate for this time constant. In irs.c, however, the coefficients are {0.15, 0.0085, 0.000125} and a comment in the code says that this represents a 126-s time constant. These values are also those listed in a document on algorithms for the

consequences. First, we should not apply such a loop again, especially if it involves correction for local gravitational effects of latitude, altitude, and centripetal effects, because those corrections have already been applied before the acceleration is transmitted from the Honeywell IRS. Indeed, examination of PREDICT flights shows that the mean acceleration over entire flights is close to zero, closer than would be expected if there had been no updating during the flight. Second, because filtering is applied to the outputs (including VSPD) before they are transmitted from the IRS, we may lose important information that we need to measure the full spectrum of the vertical wind. This note is an exploration of that second issue.

There are three processing steps internal to the Laseref IRS that may affect the resulting outputs for acceleration and velocity:

1. A baro-inertial loop is implemented, with updating to pressure altitude, that affects both vertical wind and vertical acceleration as outlined in Bulletin 23, but with different coefficients. The intent of this loop is to adjust for offsets in the acceleration and hence in the vertical velocity of the aircraft, rather than to filter the outputs, so this step should have little effect on the variance spectrum of those variables except perhaps to introduce a small amount of additional variance around the frequency of the loop.

2. At the output stage, the vertical wind (and measurements of pitch and roll) are filtered with an exponential filter[3] having a time constant of about 1.4 s. The accelerations are not similarly filtered.

3. A Butterworth filter is applied to the acceleration, and the filtered result is integrated to get a filtered vertical velocity. I have not been able to understand the section that describes this (on p. 57) or to find where the resulting velocity might enter the output, so it isn't clear to me what effect this filter has. The coefficients used are {-0.02, 0.028, 1.4, and 0.972} for factors that multiply, respectively, the velocity feedback to the acceleration, ??, ?? (affecting only the walking-window average as far as I can tell), and the attenuation of the acceleration upon filtering. The latter seems to point to a time constant of about 36 cycles or 0.72s at 50 Hz.

I am therefore unable to determine the filtered characteristics of VSPD from the document that describes the Laseref IRS algorithms, except to expect that the results are filtered with a time response that is at least more than about 1.4 s. The acceleration may be subject to less filtering; at least, it does not appear to be subject to the final-stage 1.4-s filter that may limit the response of VSPD.

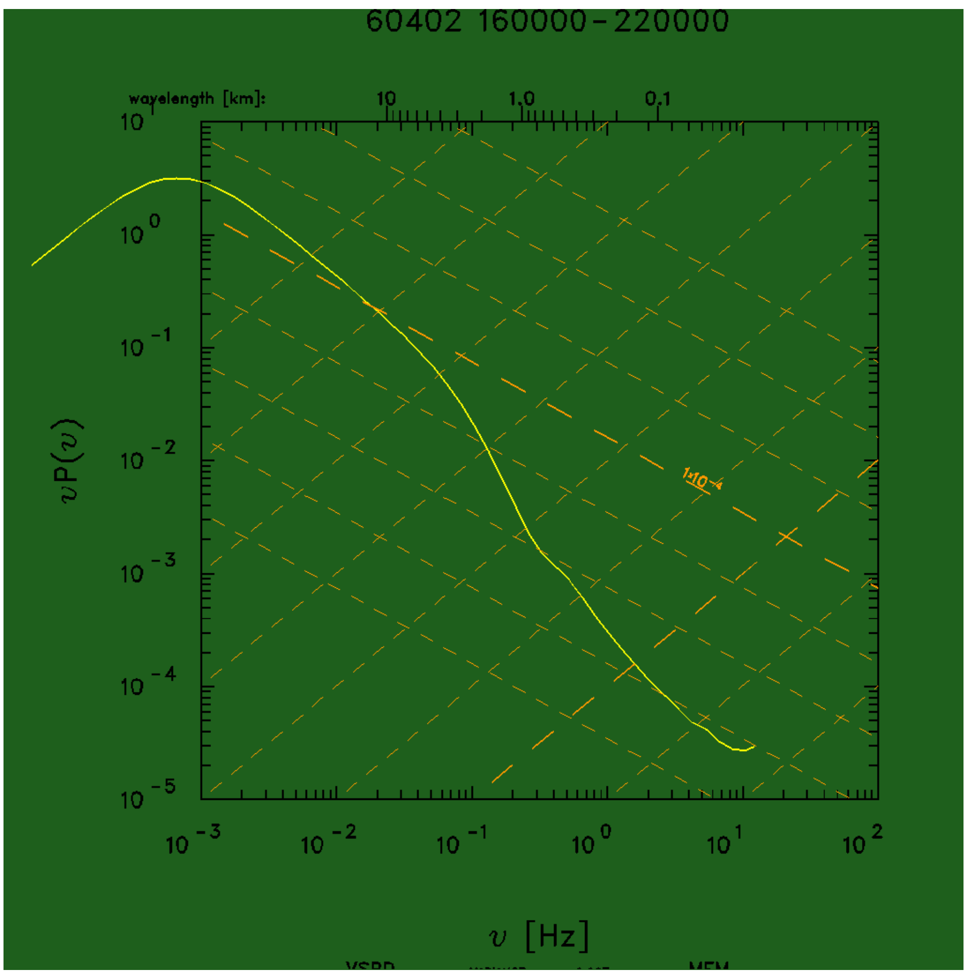
Laserref IRS that was provided by Honeywell.

[3]

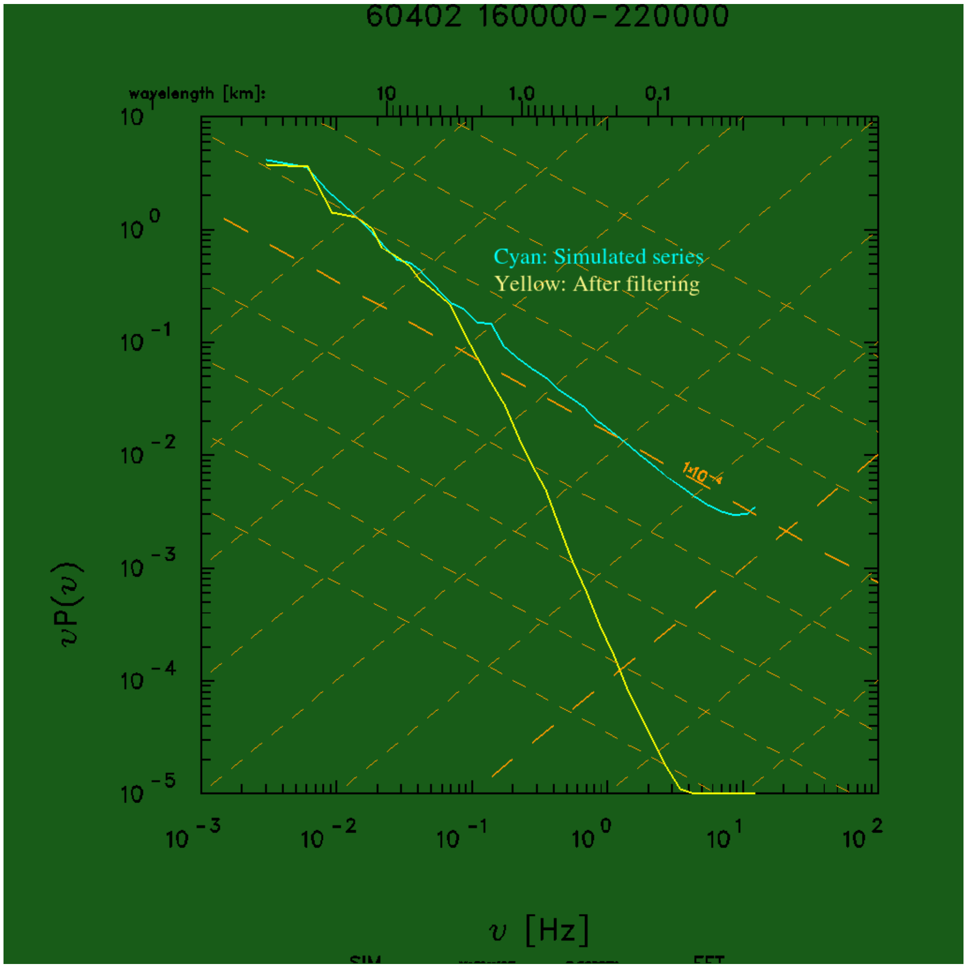
```
by "exponential filter" I mean application of this algorithm, where the measurements are wMeasured
wFiltered += (wMeasured-wFiltered)/(SampleRate*tau)
```

Changes in vertical wind with short wavelength will be seen as changes in measurements from the gust probe, changes with intermediate wavelength will be seen as changes in the vertical motion of the aircraft, and changes with long wavelength will again be seen as changes in the gust measurements because the pilots or autopilot will correct for them. These transitions must occur seamlessly if the measurement of vertical wind is to cover the full spectrum of motions. Introduction of a filter into one of the key measurements, the measurement of vertical motion of the aircraft, has the potential to affect the part of the spectrum removed by that filter.

The documentation we have from Honeywell indicates that the vertical wind is filtered by a simple first-order running-average exponential filter, via a constant called "KT50" (because it is applied to signals at a 50-Hz rate). The value is KT50=0.35474, and the equation where this is used is on p. 62 of the Honeywell document. The following shows a plot of the variance spectrum of VSPD from a GV flight:

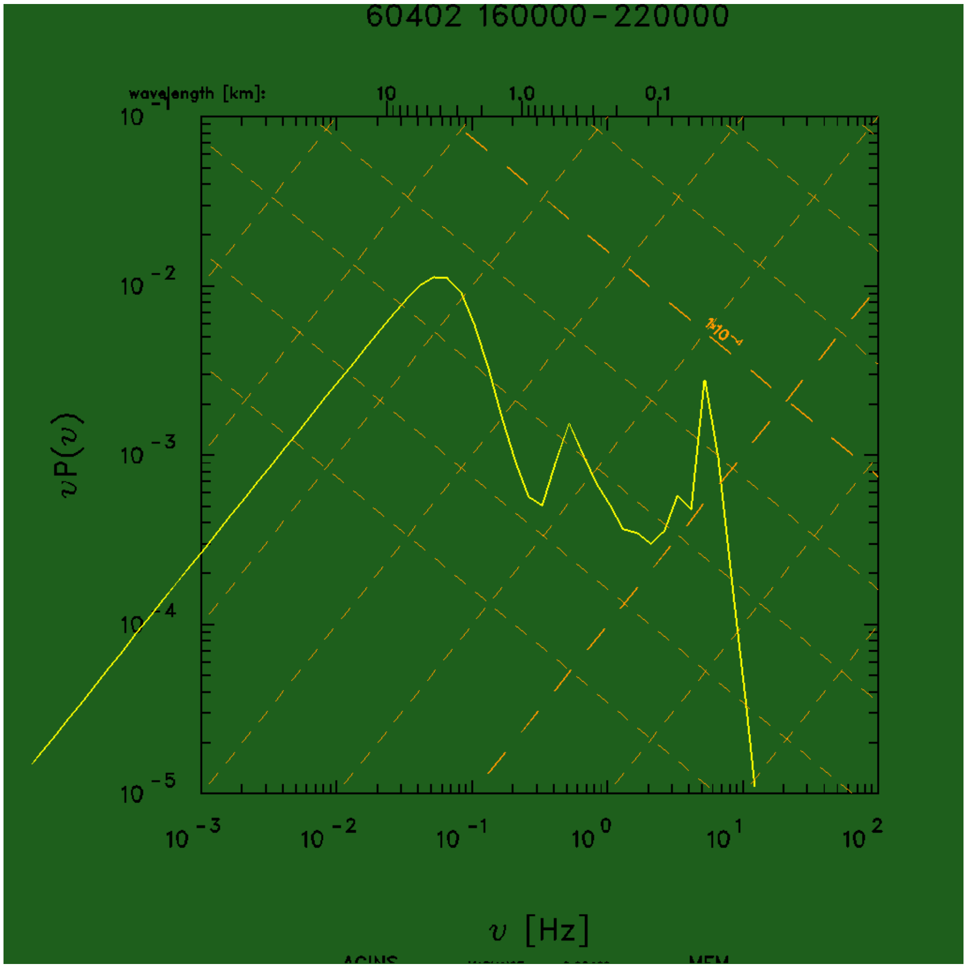


Beginning at about 0.1 Hz, there is a pronounced decrease in variance compared to the slope expected for a -5/3 spectrum (the dashed lines that decrease with frequency). To see if this is consistent with an exponential filter, I simulated a time series with an approximately realistic spectrum (via a long-time-constant exponental filter applied to a random series, then filtered it with exponential filters having various time constants. The next figure shows the result for a 1.5-s time constant:

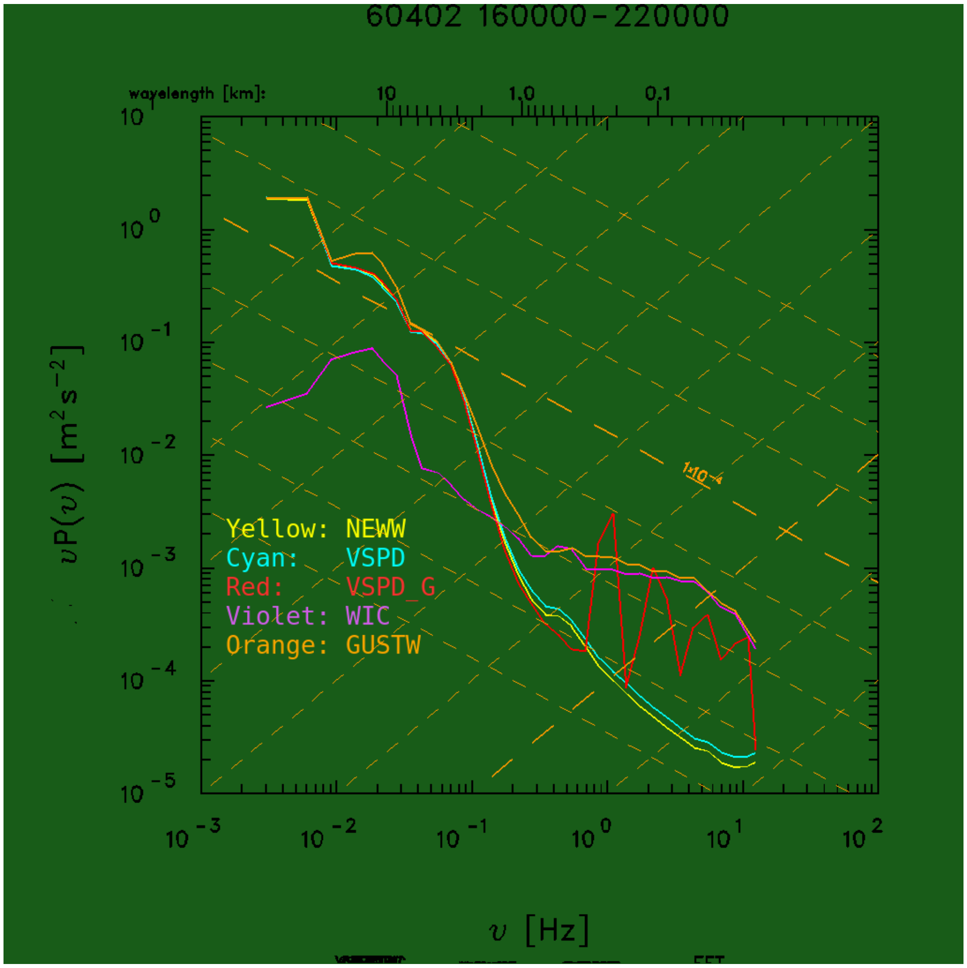


The effect of such a filter produces a roll-off with frequency that is similar to but even more extreme than that in the measurements of VSPD. There is expected effective filtering of VSPD by the response of the aircraft that will cause some reduction like that shown in Fig. 1, but Fig. 2 suggests that the roll-off can be explained by the effect of the internal filter in the IRS.

One check on this is to consider if the integration of ACINS can provide a vertical-wind measurement with more high-frequency variance. The baro-inertial loop is designed to remove the long-term drift, not the high-frequency response, so there may still be higher frequency in this measurement. Indeed, the variance spectra from ACINS do appear to have more high-frequency, although in a complex spectrum that may have components from noise (above 1 Hz), electronic filtering (above 10 Hz), and maybe the auto-throttle loop (at around 0.5 Hz):



To explore if integration of this signal can retrieve information lost to the VSPD filter, the variable ACINS was integrated over the course of one TREX flight to obtain an alternate measurement of vertical wind (called NEWW in these plots). The result was in most regards the same as VSPD, except for pronounced drift that the filter has removed from VSPD. The variance spectra calculated over 6 hours of flight in TREX (rf06) are shown in the following figure:



The reason for the offset at higher frequency may be that the acceleration as used to produce VSPD is adjusted to maintain a velocity consistent with the measured pressure, while the acceleration output as ACINS does not have this same adjustment. (Over the course of six hours, NEWW accumulated an offset of about 80 m/s and the trend leading to this had to be removed when the above variance spectrum for NEWW was calculated.)

Several conclusions are suggested by Fig. 4 (which shows variance spectra from some additional variables discussed below):

1. There is no additional information in NEWW (from integrated ACINS) that is not in VSPD. The small difference that exists is in the high-frequency region that has negligible influence on WIC.scale-factor

2. The information from the GPS variable VSPD_G is essentially identical (in regard to variance spectrum) to that from VSPD, except for an apparent influence of noise (perhaps produced by brief drop-outs in signal reception) at frequency higher than about 0.7 Hz. In regard to the overall shape of the variance contribution to WIC, there seems to be little difference between VSPD aand VSPD_G.

3. The vertical-wind variance spectrum (WIC, violet line), perhaps may have a deficiency in variance at frequency around 0.1 Hz. Other spectra from regions of more intense turbulence appear better, so this is not conclusive evidence of a problem. The low-frequency peak may be real because this was a TREX flight over the mountains in stable conditions.

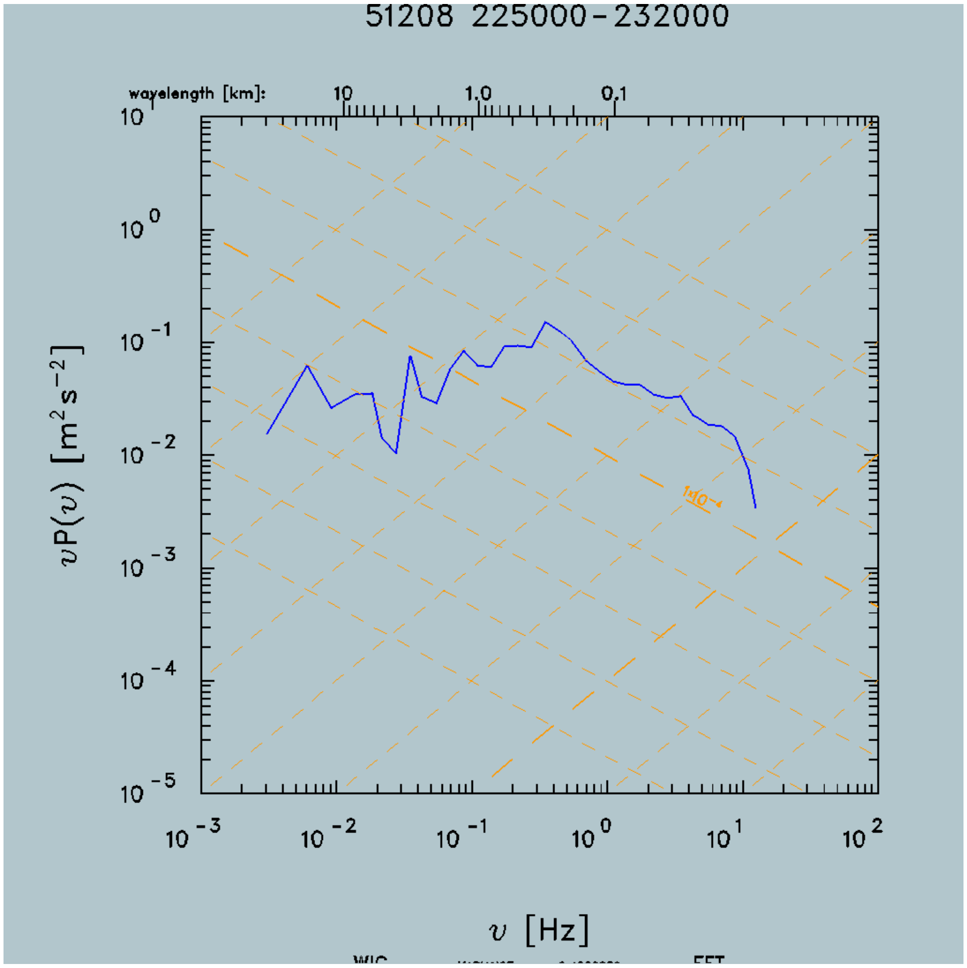
4. The variable GUSTW (orange line in Fig. 4) was calculated from the gust component of the vertical wind, using the part of the formula at the top of this note that depends on gust measurements. This dominates the contribution to WIC at frequency above about 0.3 Hz. Below that frequency, both spectra from both GUSTW and VSPD show more variance than WIC, showing that proper measurement of the vertical wind at these frequencies depends on correct cancellation of opposing contributions from these two signals.

I think the conclusion from this comparison is that the final exponential filter applied to VSPD (which is not applied to ACINS) has a negligible effect. This still leaves unresolved the effect of the Butterworth filter, which I think is applied to both, but in different ways.

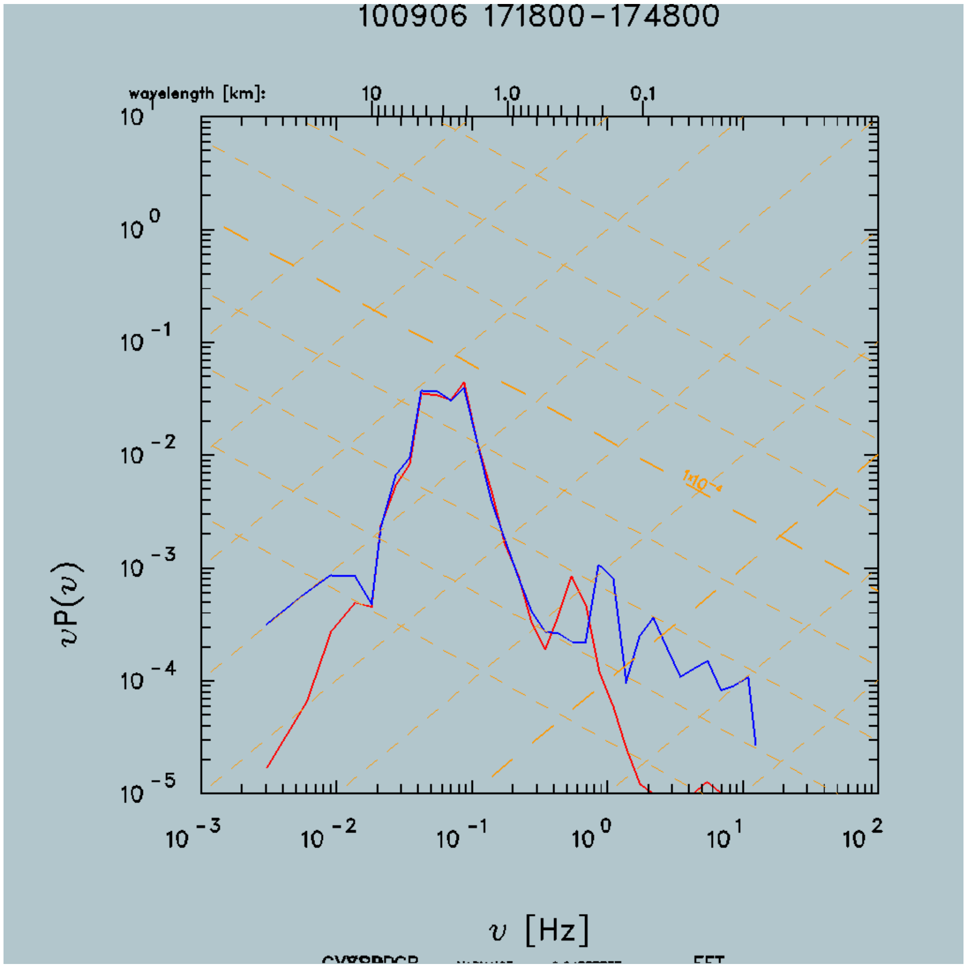
Another relevant measurement that might help resolve this question is the measurement of vertical aircraft velocity from the CMIGITS system in the gust pod.[4] This was available during PREDICT flights. (should try to get HR data for this.)

Perhaps the strongest evidence that VSPD is not affected by inappropriate filtering is from the Progressive Science flight of 12 May 2008 (flight 4), where the flight extended into the boundary layer over the Pacific Ocean for two 30-min segments (approximately 2100-2130 and 2250-2320) in low-level circles. The variance in the vertical wind is much higher than in the plot above, and in this case looks much more consistent with a -5/3 slope without the apparent gap present in some of the low-intensity plots from PREDICT (including that from the only low-level flight segment of PREDICT, in RF12, not shown here). An example is shown in the following figure:

[4] The recorded values do not include accelerations from the CMIGITS

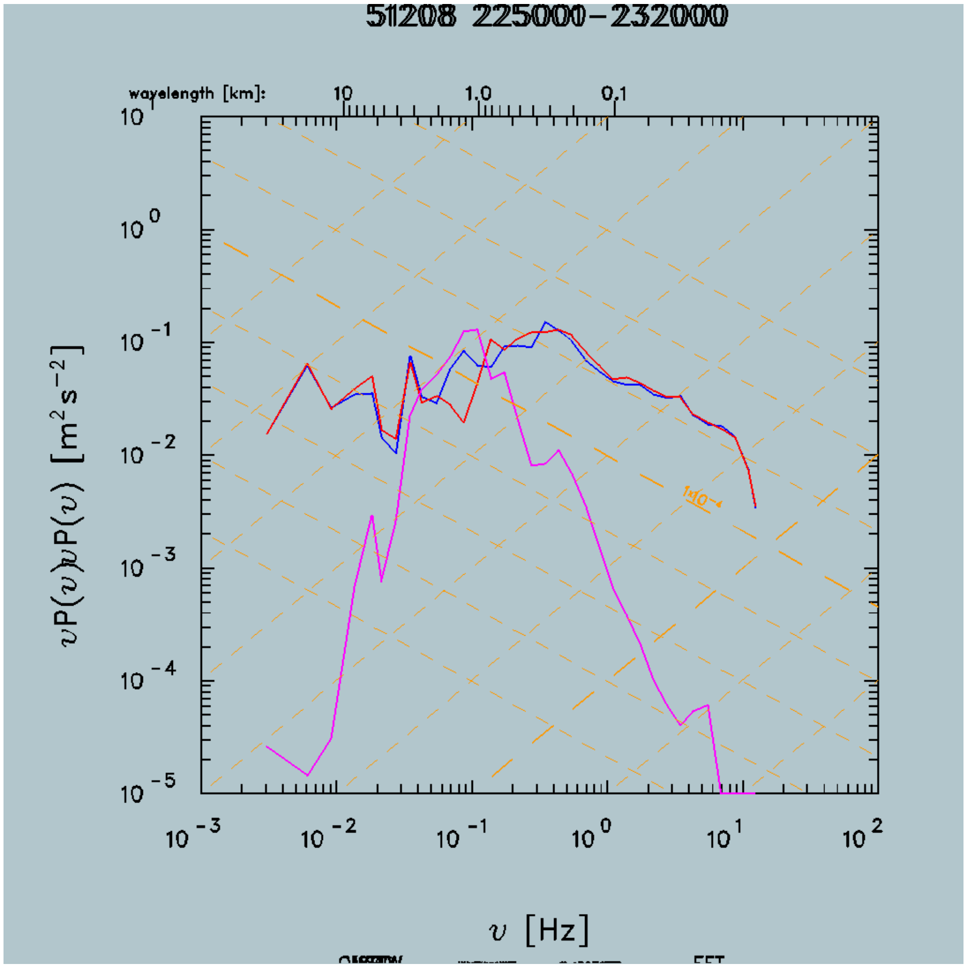


The following plot shows the variance spectra for the variables VSPD and CVSPD_GP, the latter from a CMIGIT sensor in the under-wing gust pod:



In this figure, the red line represents VSPD and the blue line CVSPD_GP. They are almost identical for periods from 5-50 s, but at high and low frequency CVSPD_GP shows more variance. This may be real variation in the wing location, at high frequency (from vibration) and perhaps also at low frequency (from turns). (?) The entire high-frequency region, however, is well below the variance in WIC so there is little influence on the wind measurement from either at frequencies above about 1 Hz.

Despite the good appearance of the spectrum for vertical wind in the Progressive Science flights, this dataset does not provide support for the validity of the IRS measurements. The reason can be seen in the following figure, which shows the separate contributions of VSPD and the gust-probe measurement of air motion relative to the aircraft for the same flight segment shown before. The blue trace is the spectrum for vertical wind (WIC), while the red and magenta lines show the respective contributions from the gust component and the IRS component (VSPD). The good appearance of the spectrum for the vertical wind arises almost compleetely from the gust measurements, and the IRS contributions only become significant near 0.1 Hz. The vertical-wind spectrum departs from expected -5/3 behavior near about 0.2 Hz, but it is unclear if this is real or if it arises from absence of correct variance in the VSPD measurement at this frequency.



The status of this study, for now, is that it is not clear if there is a problem with measurement of VSPD and consequently if the vertical wind measurements are valid at frequencies around 0.2-0.5 Hz, where there is often an apparent deficiency in variance in spectra measured when the total variance is low.