Dispersion due to water vapor affecting MIDI

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1 Introduction

Longitudinal dispersion due to water vapor is expected to have a measurable and significant effect on detection of interference by the MIDI instrument of the VLTI. In some modes of operation and some methods of data reduction, this may entail errors in the measurement of visibility magnitudes and phases. This will especially affect wideband measurements since the effect of dispersion increases as the square of bandwidth. The following is an initial attempt to quantify some aspects of this problem based on the predicted and measured curves for the index of refraction of water vapor in the 10 micron band, as recently compiled [Hase F., Mathar R. J., 2001, "Water vapor dispersion in the atmospheric window around 10 microns," submitted to Appl. Opt.].

There are two aspects to the problem of differential dispersion affecting a stellar interferometer such as MIDI. First, there is a small *random* effect due to water vapor inhomogeneities in the atmosphere above the telescopes. Secondly there is a *large* effect due to water vapor in the air of the VLTI delay lines and relay optical paths. The latter in principle can be controlled and/or monitored, but may have a random component nonetheless. We will discuss the possible effects of these two contributions separately.

There are a number of potential consequences of material dispersion in the VLTI-MIDI system. Their implications are different for a large deterministic dispersion as may be caused by travel through the delay lines even if calibrated, and for a dispersion which is fluctuating and unknown. One effect of a *large* dispersion is to substantially reduce the fringe contrast at zero OPD (of course, with a large dispersion, there *is no* single OPD position that can properly be called zero!). If that loss is not exactly calibrated, or fluctuates randomly, an error in the estimation of fringe visibility may result when using methods which do not tolerate dispersion (including the "ABCD" estimator).

An effect which is observable at somewhat lower levels of dispersion, is an offset between the mean group delay and the mean phase delay. This can have implications for fringe-tracking, if not calibrated.

A more serious effect regarding fringe tracking may result when an external fringe tracker is employed using starlight in a widely separated wavelength band, as is planned for FINITO and PRIMA. The present analysis has not been extended to the near infrared band, so this problem is not addressed presently.

A fringe tracker which does not take dispersion into account, will also suffer a greater risk of "fringe-hopping," that is, mis-identification of the central fringe with respect to sidelobes. A discussion of this issue is included in a conference paper awaiting publication which may be viewed at: http://www.strw.leidenuniv.nl/˜ meisner/meisner2.ps .

Finally it must be pointed out that even small fluctuations due to dispersion may potentially be a dominant noise source in the case of observations where the primary observable is the phase of fringe visibility with respect to optical frequency. In the so-called "differential phase" method of planet detection, a phase shift signature across the optical spectrum is needed for the detection of a relatively dim planet or companion object. Since the magnitude of the phase shift in radians is no more than 2/c where c is the contrast ratio (usually greater than 1000 for extrasolar planets), errors due to dispersion in this case will be most troublesome.

2 Random atmospheric effects

Since the effects due to water vapor inhomogeneities in the atmosphere cannot be independently monitored in detail, the effect of this component of dispersion will be statistical. One important feature of this component of differential dispersion is that it is expected to be zero-mean. That is because the telescopes look through the same thickness of atmosphere, and the only difference between their views is the instantaneous position of water vapor inhomogeneities in their paths. Thus, in principle, effects which are first-order with respect to dispersion (such as visibility phase measurements) will average toward zero with increasing integration times. Exactly how fast the average will approach the mean, however, is dependent on details of the power spectra of the atmospheric water vapor inhomogeneities (in particular, the outer scale size) and their dynamics. The overall effect will also, of course, be proportional to the magnitude of such fluctuations at the Paranal location. This has not yet been researched.

Second order effects will *not* average to zero. However the maximum amplitude of the random component will probably be much smaller than what would be required to lead to significant second-order effects, so this is not worrisome.

Probably the only case in which random effects due to the atmosphere will become important, is in the case of precise phase measurements with respect to optical frequency, as in the case of proposed extrasolar planet detection.

3 Instrumental effects

We will call dispersive effects which occur following the collection of light by the VLTI telescopes "instrumental" since in principle we have control over what occurs inside of the laboratory. Unfortunately that is not perfectly true in the present case, because the VLTI permits the free flow of outside air through the light paths (including the delay lines). This makes even "instrumental" effects partly dependent on weather, in particular, the absolute humidity of the air entering the VLTI. This will have two undesired effects. First, the humidity of the unbalanced air path in the delay line will vary. Secondly, changes in the humidity may take place on a different time scale regarding their effect on the otherwise *balanced* light paths affecting the two beams.

The magnitude of the variations in question is a function of weather and has not been researched. However it clearly will be larger than the random atmospheric variations discussed above, especially on long time scales.

Two possible remedies for this problem should be considered. In the case of measurements requiring tight control of dispersion, it might be wise to reconfigure the VLTI infrastructure with appropriate entrance windows, and cut off the circulation of outside air inside the VLTI. If the humidity inside the structure is then stable, then perhaps a sufficient calibration of the dispersion can be effected.

The other approach would be to add a second wavelength laser to the metrology system in order to be able to detect in real-time changes in the net humidity affecting the two optical paths.

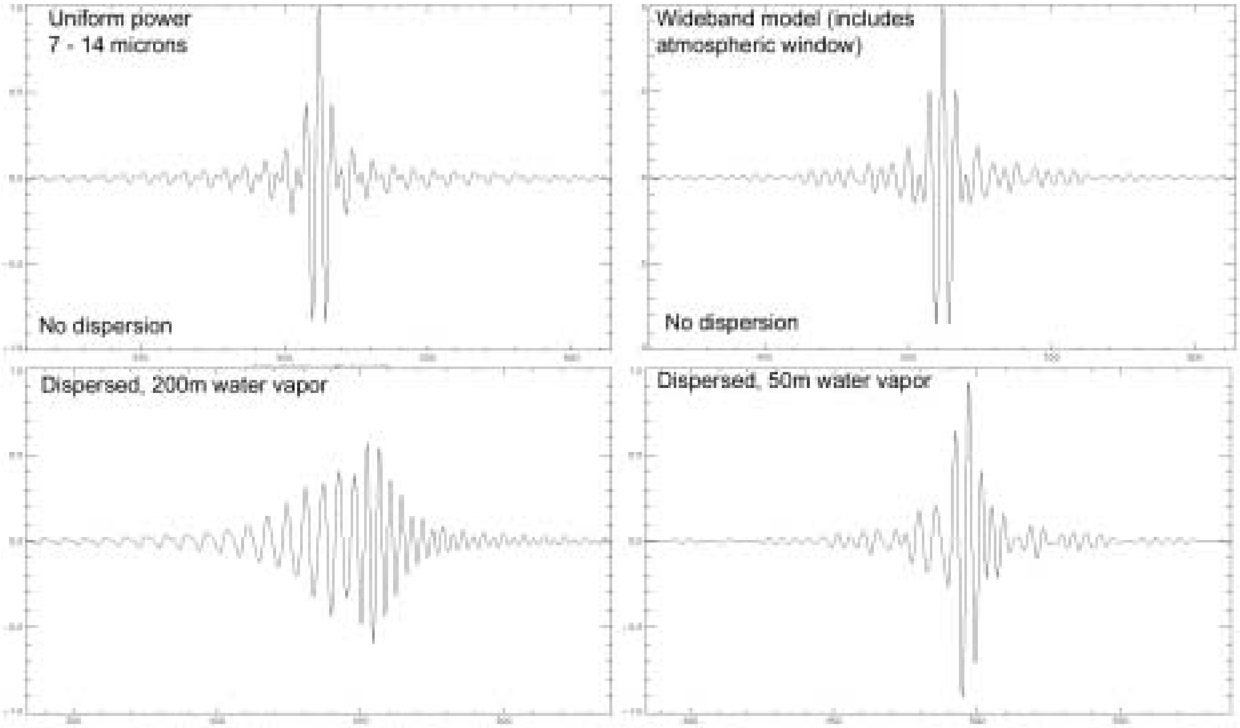

Figure 1:

4 Gross effects from water vapor in the air of the delay line

The only intentional asymmetry in the optical paths feeding MIDI is due to the fact that the extra geometrical delay *in space* due to the position of the celestial object in the sky, is compensated for using a delay-line in the VLTI lab consisting of an identical travel *in air*. At 10 microns, the dominant source of dispersion is due to water vapor in the air. We have modeled the effect of water vapor assuming a concentration of $10^{23} molecules/m^3$ which corresponds to a relative humidity of 28% at 12 degrees. The length of the unequal air travel in the delay line is equal to the baseline vector projected onto the celestial position; values on the order of 50 meters may be typical when using the longer baselines.

The effect of this dispersion may be viewed directly in the frequency domain, or in delay-space for a scanned "fringe" with a particular spectrum. These are fourier transform pairs, but supply different sorts of information. The left side of Figure 1 is based on an absolutely worst case for MIDI. The top left shows the fringe in delay space that would be produced by radiation having an equal detection level uniform (in optical frequency) between 20 and 40 Terahertz (7.5 to 15 microns). Note that this is a bit unrealistic, but nevertheless a "worst case" since the effective bandwidth will almost certainly be smaller in practice. The fringe is seen to have 100% visibility at zero OPD, as it was simulated.

In the lower left pane of Figure 1, we see the effect, in delay space, of unbalanced travel through 200 meters of moist air (as described above), which again is unrealistically long in order to emphasize the effect. We can see that the maximum fringe amplitude has been reduced to about .6, and that the energy of the fringe has been substantially widened. It is possible to see the effect of an increasing group delay with frequency, as a "chirp" has been generated with the leading edge of the fringe being rich in lower frequency components compared to the trailing edge. The sharp distinction between the central fringe and the sidelobes in the top

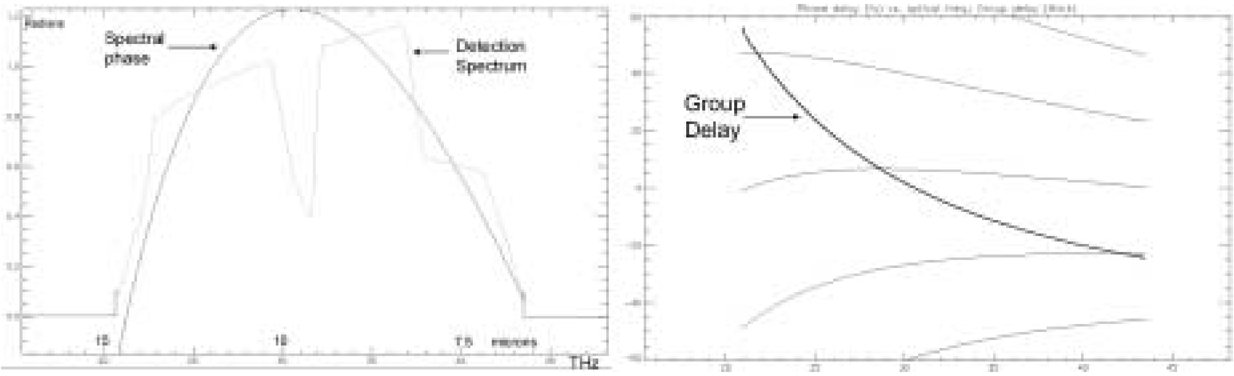

Figure 2:

figure, is sharply deteriorated so that a naive fringe tracker would find it difficult to distinguish between those peaks. However if data were taken over the entire delay range depicted, then the dispersion could be “removed” in the processing to recover the original fringe shown in the upper figure. From the standpoint of delay tracking, this is equivalent to correlating a detected dispersed fringe with a matched filter to determine its delay offset.

The right panes of Figure 1 show a more realistic example. In this case a detection spectrum has been generated based on the atmospheric transmission model and instrumental characteristics of MIDI assumed in the present version of Midisnr.exe with wideband detection (no spectral filter) and uniform detector quantum efficiency assumed. A more realistic value of 50 meters of dispersive delay is modeled, producing the dispersed fringe in delay space shown in the lower right. Although much less pronounced than the comparable figure on the left, one can still see the “chirp” due to the variation in group delay across the bandwidth, and the consequent broadening of the energy envelope in delay space. The left pane of Figure 2 is a plot of phase and amplitude of this fringe versus optical frequency. The phase is seen to vary over a range of about 1.3 radians across the bandwidth; note that this phase curve is not unique but depends on the arbitrary choice of the zero OPD position.

The right pane of Figure 2 amplifies the nature of this dispersion in the frequency domain by plotting the phase and group delays. Again these have an arbitrary offset depending on the assumption of the zero OPD position, and the phase delays have an additional free parameter corresponding to the addition of $2\pi N$ to the phase, generating multiple curves. The group delay is unique (except for the position of the zero point) and illustrates the cause of the “chirp” observable in Figure 1. A change in the group delay of 70 femtoseconds (2.1 wavelengths at 10 microns) is observed across the band, accounting for the slight broadening of the fringe in delay space seen in the lower right pane of Figure 1.