

OPTICAL CONSIDERATIONS IN INFRARED HETERODYNE SPECTROMETER DESIGN

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ABSTRACT

The optical design considerations for optimization of sensitivity, tuneability and versatility of an infrared heterodyne spectrometer will be discussed using the GSFC CO₂ laser heterodyne spectrometer optical front end as an example. Problems related to the coherent nature of the laser local oscillator beam (e.g. interference effects at edges of optical elements and at the beam combining beamsplitter) will be described and proper beamsplitter design discussed. Optimum matching to the telescope will be discussed. The severe effects of large central obscuration on the coherent telescope efficiency will be described and steps to partially recover the lost system sensitivity will be proposed. Measurements made with the GSFC 48-inch telescope (linear obscuration ratio = 0.5) and the KPNO McMath telescope (no obscuration) will be given as examples.

DISCUSSION

Sensitivity of infrared heterodyne spectrometers can be expressed by the instrumental noise equivalent flux

$$(\text{NEF}) = \frac{\Delta}{\sqrt{B\tau}} \text{ photons/sec Hz}$$

The degradation of performance from ideal, Δ , is a total degradation factor - due to effects of chopping, polarization, detector-preamplifier efficiency, phase front misalignment, beam filling factor, line shape distribution, and optical losses (refs. 1,2).

In an operating system the optical degradation factor consists mainly of two components - losses due to the telescope and the system-telescope matching, and losses in the optical front end. Careful optical design can limit both losses to essentially those due to optical transmission of the components ($\Delta \sim 1.2$). However, highly obscured telescopes and improper front end design can introduce significant degradation in heterodyne

efficiency. In this paper we will describe a representative heterodyne system design and discuss several of the many optical problems arising on the optical table as well as in coupling the system with a field telescope.

Let us consider the optical design of the Goddard Space Flight Center CO₂ laser-infrared heterodyne spectrometer (Figure 1). The design goals were to optimize system sensitivity while maintaining maximum spectral tuning range, permit easy tuning and absolute calibration, and in general maintain system versatility for field or laboratory use.

In Figure 1 the signal beam S (source) from the telescope is chopped against a reference beam R (sky). A dichroic mirror D₁ permits a portion of the visible beam to enter a guiding eyepiece. It also can be moved to, in effect, interchange the S and R beams. The telescope beam, ν_{IR} , is collimated by an off-axis parabola. The output beam, ν_{LO} , of an in-house built grating tuned, line center stabilized CO₂ laser is attenuated, expanded, collimated and combined at a ZnSe beamsplitter with the telescope beam. The two matched collimated beams are then focussed onto a HgCdTe photomixer (supplied by Dr. David Spears, MIT Lincoln Laboratories). A portion of the visible signal is again transmitted to a guiding eyepiece by dichroic D₂. The difference frequency $|\nu_{LO} - \nu_{IR}|$ generated in the photomixer over a bandwidth of ~ 2 GHz is then fed into our R.F. spectral line receiver (ref. 3). System calibration can be done by inserting a kinematic mirror M₁ and measuring a calibrated black body reference. This arrangement can also be used for laboratory spectroscopy of target field molecules (refs. 4,5).

Minimum optical transmission losses and elimination of chromatic effects were achieved by the use of all reflecting optics (except beamsplitter and dewar window). Thus, all focal points and all major component positions (e.g. off axis parabolas, pinholes, photomixer) are independent of the operating wavelength and no adjustments are necessary as one tunes the local oscillator. This concept is even more important for more broadly tuneable systems such as diode laser heterodyne spectrometers.

Even with the basic design goals met, many problems can arise to further degrade heterodyne performance, such as optical feedback into the laser cavity, optical standing waves, internal reflections and interference. These problems can be minimized by tilting and wedging various system components.

Let us look at two specific problems, both of which are consequences of the coherent nature of the CO₂ laser local oscillator. The first problem is illustrated in Figure 2. Displayed are scans of the expanded laser beam cross section. The upper plot shows a nearly Gaussian cross section of the laser beam which is ultimately combined with the signal beam. If the optical elements in the beam path (e.g. mirrors, apertures, beamsplitter) are smaller than the beam diameter (\sim distance between $1/e^2$ power points) Fresnel fringes related to edge diffraction patterns are formed (lower plot). Focussing such a local oscillator intensity distribution on the photomixer can introduce phase cancellation and noise,

and can degrade the heterodyne signal to noise.

A second problem is related to the design of the combining beamsplitter. If sufficient laser power exists, proper dielectric coating (or substrate) will enable maximum coupling of the signal beam $\geq 95\%$ of signal) with sufficient local oscillator signal (≤ 1 mW) for shot noise limited operation. The beamsplitter is designed to reflect the LO beam, the front surface being the beam combining plane. The back surface will also reflect a portion of the LO beam. Interference fringes will thus be generated with their separation dependent on the wavelength and the path difference between the reflected beams (i.e. wedge angle between the two surfaces). Figure 3 illustrates this problem for a 30 arc-second wedged ZnSe beamsplitter. Fringes due to the reflected CO₂ laser beam were measured by scanning a detector across the beam. The fringe spacing was consistent with the measured wedge angle. The intensity distributions and positions of the principal and second surface reflected beams yielding such fringes are plotted below. If the usable, matched beam diameter is about 2.54 centimeters (1 inch) centered on the optic axis (center of principal beam), the laser beam profile incident on the mixer is reduced in power and is far from Gaussian. It is obvious this can introduce significant degradation in the resultant heterodyne signal. The worst case would be if the intensity minimum occurs on the optic axis. This problem can be solved by designing sufficiently wedged beamsplitters so that the back surface reflection is deflected out of the optical acceptance angle of the system.

Let us now look at the degradation associated with telescope - system interface and matching. Ideally, the optics are matched to the diffraction limit of the telescope aperture and the only loss is the optical transmission of the telescope. Telescopes with a central obscuration can, however, introduce greater losses in heterodyne signal. Such effects are illustrated in Figure 4. Assuming a plane wave incident on the telescope at first glance the losses expected would be due to area blockage by the obscuration and a relative measured signal, heterodyne or direct, can be represented by the equation

$$I_{\text{Het}} = \left[1 - \left(\frac{D_{\text{obs}}}{D_A} \right)^2 \right]$$

where D_{obs} and D_A are the obscuration and aperture diameters. This parabolic curve is plotted in Figure 4 (upper solid curve).

For a point source, the intensity and phase distributions at the telescope aperture are both uniform (neglecting seeing). The local oscillator beam has a Gaussian cross section and is matched to the Airy pattern of a fixed size aperture. As the central obscuration increases, the Airy pattern becomes narrower and less power is concentrated in the central maximum and more in the secondary maxima (ref. 6). For a matched fixed area detector this leads to lower incident power and signal cancellation due to the out of phase components of the electric field in the secondary maxima, which are now within the detector area. These effects on the

heterodyne signal were calculated by Degnan and Klein (ref. 7) and are plotted in Fig. 4 (crosses). These losses are seen to be greater than areal.

For an extended source (planets, Moon, Sun) the intensity pattern at the telescope aperture is a planar distribution. Assuming a detector size matched to the first Airy maximum (i.e. $2.4 \lambda / D$), then the measure of source coherence, the mutual coherence function (MCF), takes the form of an Airy pattern with first minima occurring at the edges of the telescope aperture (ref. 8). Since heterodyne detection is a coherent technique, one would expect any obscuration of the mutual coherence function to introduce additional losses. To demonstrate this on the optical table, a variable obscuration telescope and source were simulated with an extended black-body reference source and several annular apertures inserted in the source beam. The resulting heterodyne signals (circles in Fig. 4) show even greater losses than the point source case, at large obscuration ratios. Similar measurements on the Sun increasing the 0.45 linear obscuration of the 48 inch GSFC telescope (triangles) show a similar trend.

The extent of this "coherence" loss can be estimated for a given obscuration by integrating the unobscured annulus of the mutual coherence function. Assuming a direct relationship between this integral and the heterodyne signal one can compare the results to our measurements. The Airy-like curve in Fig. 4 represents these calculations and indeed is in good agreement with measured points.

Varying the central obscuration in a 10 inch off-axis aperture in the 48-inch primary shows a heterodyne signal dependence more like the simple area blockage case. This is consistent with the present arguments since the system optics are matched to the f/no. and aperture of the 48-inch telescope. The IR mixer thus "sees" the whole aperture and the full mutual coherence function. A 10 inch slice of the 48-inch wide MCF will not vary significantly and blocking this more uniform function is similar to the simple plane wave case. The intensity distribution on the fixed area detector will also not change appreciably, since the detector intercepts only $\sim 1/5$ of the Airy intensity pattern of the 10 inch aperture. Thus, as the obscuration is modestly increased, the active intensity on the detector is not severely altered.

We attempted to improve the heterodyne efficiency on extended sources at a highly obscured telescope by varying and matching the intensity pattern from the local oscillator to that of the telescope. We were able to recover $\sim 50\%$ of the signal (star in Fig. 4) by introducing a matched central obscuration in the L.O. beam. However, this results in a great reduction of laser power on the photomixer and it may not always be possible to recover the necessary power from weak lasers to obtain optimum heterodyne efficiency at the mixer (shot noise limited operation). This may be impossible with present diode laser local oscillators, implying that central obscurations should be avoided in diode laser heterodyne

spectrometers. Theoretical treatment of the obscuration effect for extended sources by Degnan (ref. 9) suggests that it may be possible to recover all but the areal losses; however this was not found to be true on our measurements, possibly because not all the Airy lobes fall onto our photomixer.

Measurements on the Sun, identical to those taken at the 48 inch Goddard telescope, were made with our heterodyne spectrometer matched to the 55 inch McMath telescope at Kitt Peak National Observatory. Under matched conditions, and after accounting for the differences in the transmission between the two telescopes, the Sun signal measured at the unobscured McMath telescope was a factor of 2 to 3 greater than at GSFC. A degradation factor $\Delta_A \sim 1.3$ is due to area blockage alone. An additional "coherence" component Δ_{coh} of up to 2.2 was thus observed at the 48-inch telescope ($D_{obs}/D_A \sim 0.5$).

It is thus clear that coherence effects in infrared heterodyne system optical design and use have to be carefully considered in order to obtain optimum heterodyne performance. In particular, highly obscuring telescopes are inappropriate for sensitive heterodyne measurements, particularly when using diode laser local oscillators.

References

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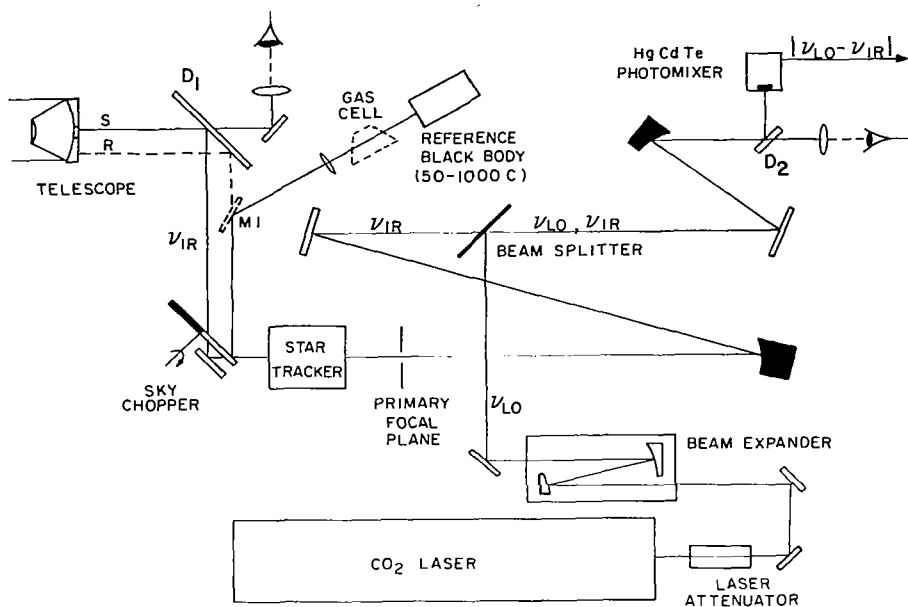


Figure 1.- GSFC CO₂ laser-infrared heterodyne spectrometer.

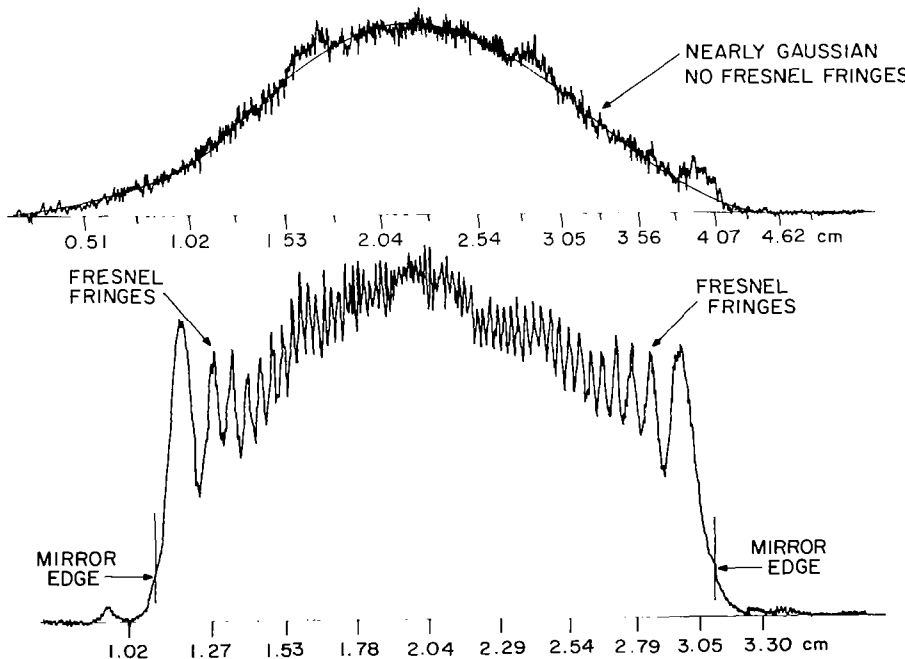


Figure 2.- CO₂ laser beam cross section. Upper plot shows nearly Gaussian output beam. Lower plot shows edge diffraction of beam by undersize mirror resulting in Fresnel interference fringes on laser beam profile.

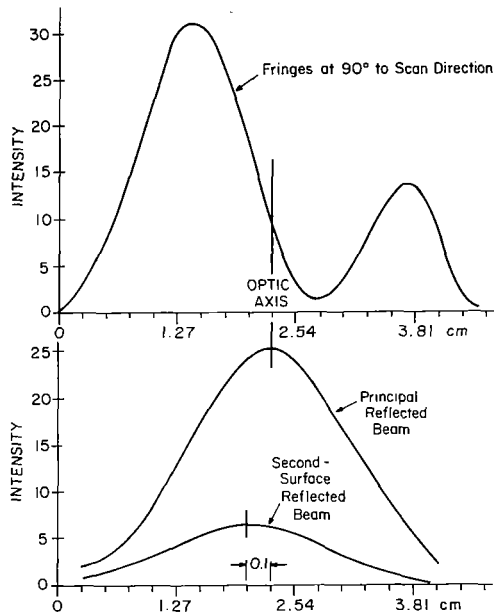


Figure 3.- Beam splitter interference fringe. The upper trace is the intensity distribution of the local oscillator measured after the beam splitter. The front and back surface reflected beams which interfere to give this pattern are indicated in the lower half of this figure. A sufficiently large wedge angle will cause the converted beam to miss the focussing parabolic mirror, eliminating heterodyne efficiency losses. Wedge angle = 30 arc-seconds.

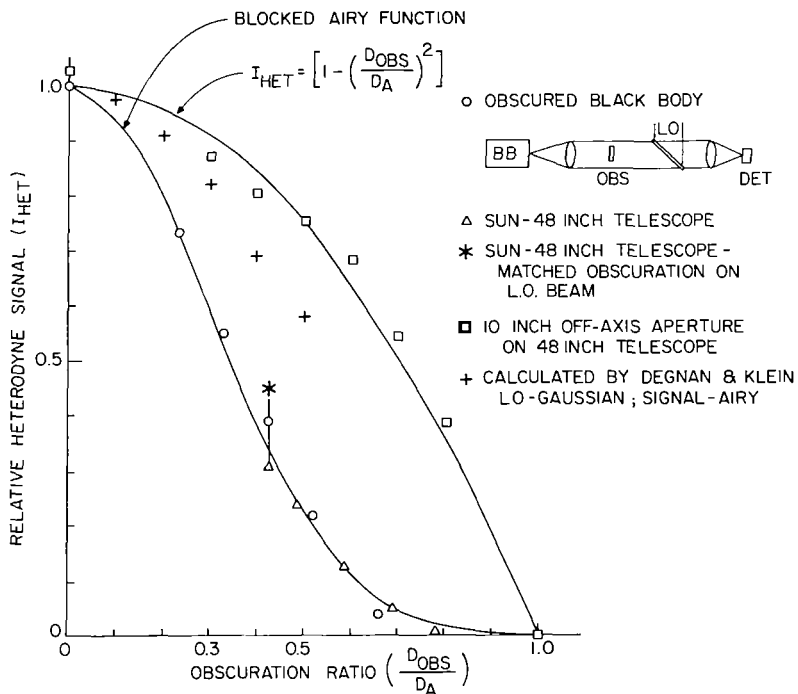


Figure 4.- Heterodyne signal losses due to central obscuration of the signal beam.