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STRIPED FABRY- PEROTS : Improved Efficiency for Velocimetry

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Striped Fabry-Perots: improved efficiency for velocimetry

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ABSTRACT

Removing a narrow stripe of the reflective coating from the input mirror of a Fabry-Perot interferometer can dramatically increase the amount of light transmitted through the system; we have observed gains in excess of 50 when we compare a conventional Fabry-Perot with the striped Fabry-Perot under similar lighting conditions. The stripe affects the distribution of light in the Fabry-Perot peaks causing them to be lower in the center of the pattern. We examine this distribution, and discuss its application in analyzing velocities.

1. INTRODUCTION

In velocimetry applications,[1] photons returned from strongly shocked surfaces are at a premium. This has lead to the suggestion that the removal of a stripe of the reflective coating from the input mirror of the Fabry-Perot system may give substantial gains in the light throughput of the system.[2] This system has been further analyzed by Goosman[3] who noticed that a further gain of two was available in the striped system when the input mirror had a reflectivity near 1 and the reflectivity of the output mirror was varied to maintain the finesse of the instrument. These types of gains have been noticed by others studying weak spectral lines,[4,5] using a Fabry-Perot and removing a circular region from the input mirror. The non-imaging geometry of a velocimetry system using a cylindrical lens at the input of the interferometer leads to substantial preservation of throughput as the system goes out of focus in the striped configuration.

Before using such a system on expensive and difficult experiments, we felt that any possible effects on the accuracy of the velocity measurements from a striped system should be thoroughly investigated. In particular, it is necessary to show that the square of the Fabry-Perot fringe diameters are indeed proportional to the fringe number, and that the finesse of the system is not unacceptably degraded by the presence of the stripe. Analysis of the fringe locations is complicated by diffraction at the input stripe. Thus, the most satisfactory answer to these questions is an experimental one.

An additional benefit of carrying out the experiments to verify accuracy is that we have been able to make detailed measurements of the increased throughput of the striped system when compared to an unstriped system as the target location changes. These are of practical importance when the velocity of a target must be measured over an extended distance.

2. EXPERIMENT

To make the most straightforward comparison between the striped Fabry-Perot and the nonstriped, the configuration of Fig. 1 is used. Mirror M_1 can be changed to compare fringe intensities. M_1 is 99% reflectivity mirror for both striped and nonstriped cases while M_2 has 93% reflectivity. The striped mirrors we used had a stripe width of $700\mu m$. Other reflectivity values can be used to compare the striped Fabry-Perot with the more conventional embodiment, *e.g.* using two 96% mirrors. Both kinds of comparisons are necessary to understand the tradeoffs among various configurations. The static target can be moved along the light axis to measure throughput at various target positions. Note that the target position affects the stripe "fill" (for air transport) so the benefit of using the stripe varies as the target position changes (more discussion follows). The field lens L_1 requires careful alignment to ensure that its axis is coaxial with the light paths. Cylindrical lens, L_2, must have its axis parallel to the stripe. Visual observation of the Fabry-Perot transmission while moving the Fabry-Perot from side to side is an acceptable indication for alignment of L_2. An angular rotation of about 3 mR is the alignment accuracy achievable. The transport distance L_1 to L_2 is less than 40 cm to avoid serious vignetting effects when the target is located on either side of focus.

A CCD camera coupled to a microscope objective is used to locate the focal plane of L_3. To record clean fringes, the focal plane must be established to ± 3 mm. Finesse and fringe intensity measurements are taken with a linear diode array, digitizer and computer system while fringe radial position measurements are taken from hard film.

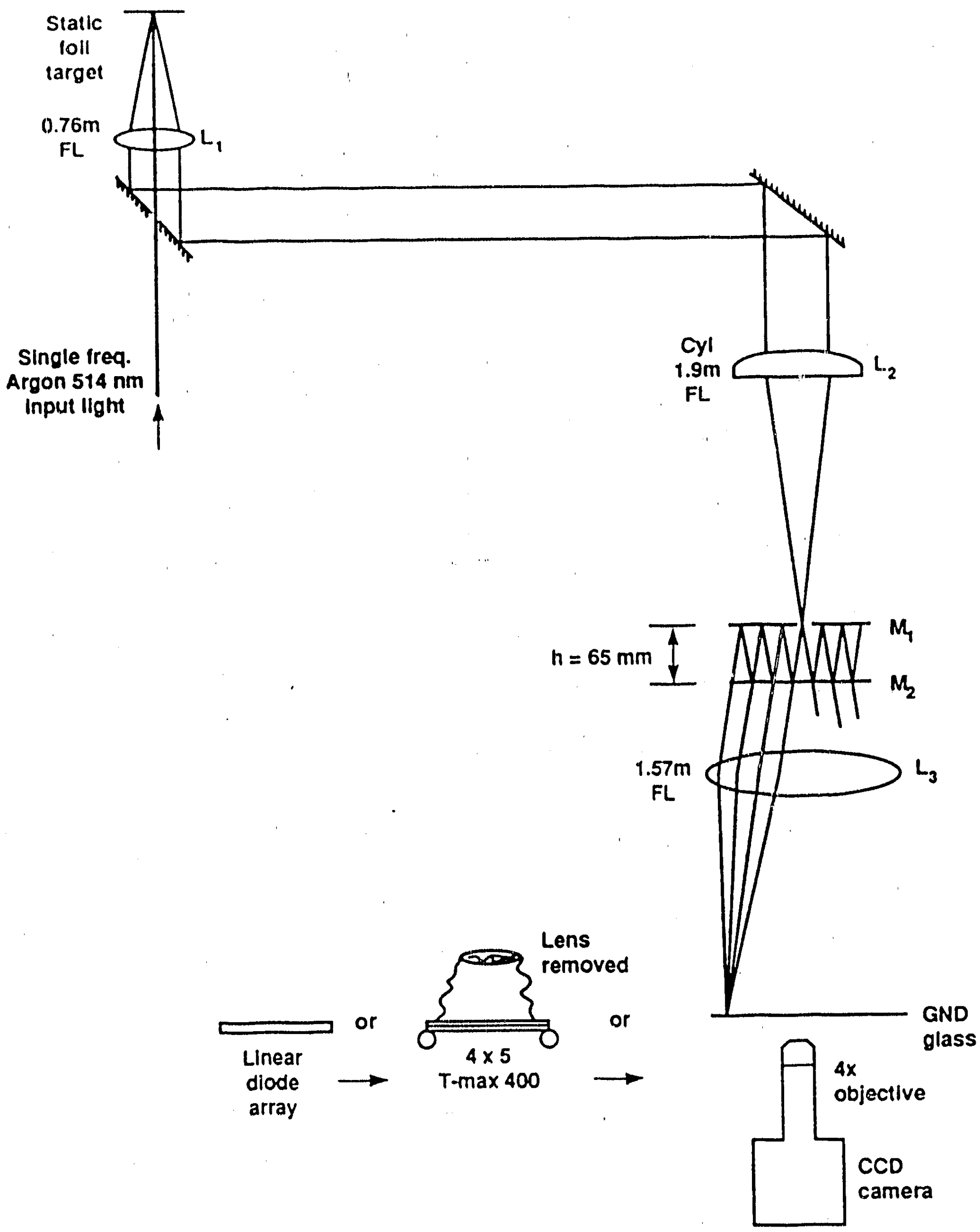

Figure 1. Experimental layout for measuring fringe locations and comparing throughput through striped and non-striped Fabry-Perot systems.

In the course of these experiments, we had access to four mirrors which had been striped. Two of these were made by scraping the coating material off a normally prepared Fabry-Perot mirror with cold coatings. The other two were prepared by putting a resist on the glass in the region of the stripe, then putting a hard coating on the mirror and removing the resist section. The first of the two mirrors prepared by removing the cold coating was produced by scraping the reflective coating off the mirror using a razor blade that had had the corner ground to the desired width of the stripe. The razor blade was then drawn by hand along a straight edge laid across the surface of the mirror. The second was made in a jig that held the mirror and a cutting tool that could make multiple passes across the mirror to ensure that the coating was being cleanly removed.

3. RESULTS

There are three areas in which we examine the effect of the stripe on the Fabry-Perot system as we use it for velocimetry: the fringe spacing, the finesse, and the efficiency.

3.1 Fringe Spacing

The spacing of the Fabry-Perot fringes is crucial to measuring velocities with this system since the wavelength of the light returned from the target, and the thus the velocity, is determined by the fringe spacing. Were there to be any deviation from the expected fringe spacing, this could prove fatal to the plan.

The fringes are expected to obey the relation

$$D_p^2 = \frac{4\lambda f^2}{h}(p - 1 + \varepsilon) \tag{1}$$

where p is the fringe number counting the central fringe as 1, D_p is the diameter of the p^{th} fringe, f is the focal length of the lens used to form the pattern, h is the separation of the mirrors and ε is the fractional order at the center of the pattern. Thus, if diameter squared is plotted versus fringe number, we expect a linear relation. Any substantial deviation from a linear relation would indicate a problem caused by the slit.

Using flat mirrors, we made photographs of the fringe patterns extending out to ten fringes from the center of the pattern, the positions of the fringe peaks were measured on a comparitor with a reproducibility of ± 2 μm. The difference between the data and the fit is what we would expect from measurement error. Thus, we conclude that the striped Fabry-Perot is acting exactly as we would expect it too. There does not appear to be any change in the peak locations.

In the course of studying these fringe patterns, we found that the outer fringes on the mirrors with the hard coatings showed side lobes, sometimes extending all the way between the major peaks at a much reduced amplitude as shown in Fig. 2. While the presence of these side lobes didn't appear to affect the location of the main peaks, we were concerned about them since we didn't understand them.

We noticed that the mirrors were not flat and appeared to have a curvature of approximately $\lambda/16$. A 2-D wave propagation code was used to model this system, and we found that the computed shape produced the same type of side lobes. Further experiments using the mirrors with cold coatings, which appear to be flat to about $\lambda/100$ did not show these side lobes.

Based on these experiments, we prefer the technique of mechanically removing the reflective coating from a mirror with cold coatings since it does not seem to introduce curvature into the mirror. The hard coatings are applied hot and appear to leave stress in the mirror that can degrade it's figure producing spurious fringes in the outer part of the pattern.

3.2 Finesse

The finesse of the system is important because it determines the velocity resolution that can be expected. When the finesse is low, it is harder to determine the location of the peak of the fringe. Hence, there is more uncertainty in determining the fringe locations and in the inferred velocity.

In comparing the finesse of the striped and unstriped interferometers, it is very easy to be fooled. Since the striped interferometer is illuminated along a line at the center, the light has only half the width of the mirrors to bounce across before it is lost from the system. Furthermore, the number of bounces that the light will make is a function of the mirror radius, the angle of the incoming light, and the mirror separation. The walk-off problem has a substantial effect on the finesse. When we use an unstriped Fabry-Perot, we normally put the cylindrical lens as close the interferometer as possible to minimize the effect of walkoff. However, in this case, we have used the same illumination in the unstriped as the striped case to see whether the stripe was affecting the finesse. We also adjusted the interferometer so that the fringe position was approximately the same in both cases.

Since the intensity of the central fringe of the pattern is radically altered by the stripe, it is not a good one to use in looking at the finesse. We have chosen to use the second fringe for the comparison. Comparing the striped with the non-striped case, we see that the striped finesse is 31 while the non-striped finesse is 33 for comparable illumination systems and reflectivities. These are the same to within our measurement errors.

3.3 Efficiency

In addition to providing more useful light, the striped Fabry-Perot distributes the light into the fringe pattern differently than a normal Fabry-Perot does. Figure 3 shows a comparison between a striped and an unstriped pattern when the target is at the focal point of the input lens and the intensity of the normal pattern has been

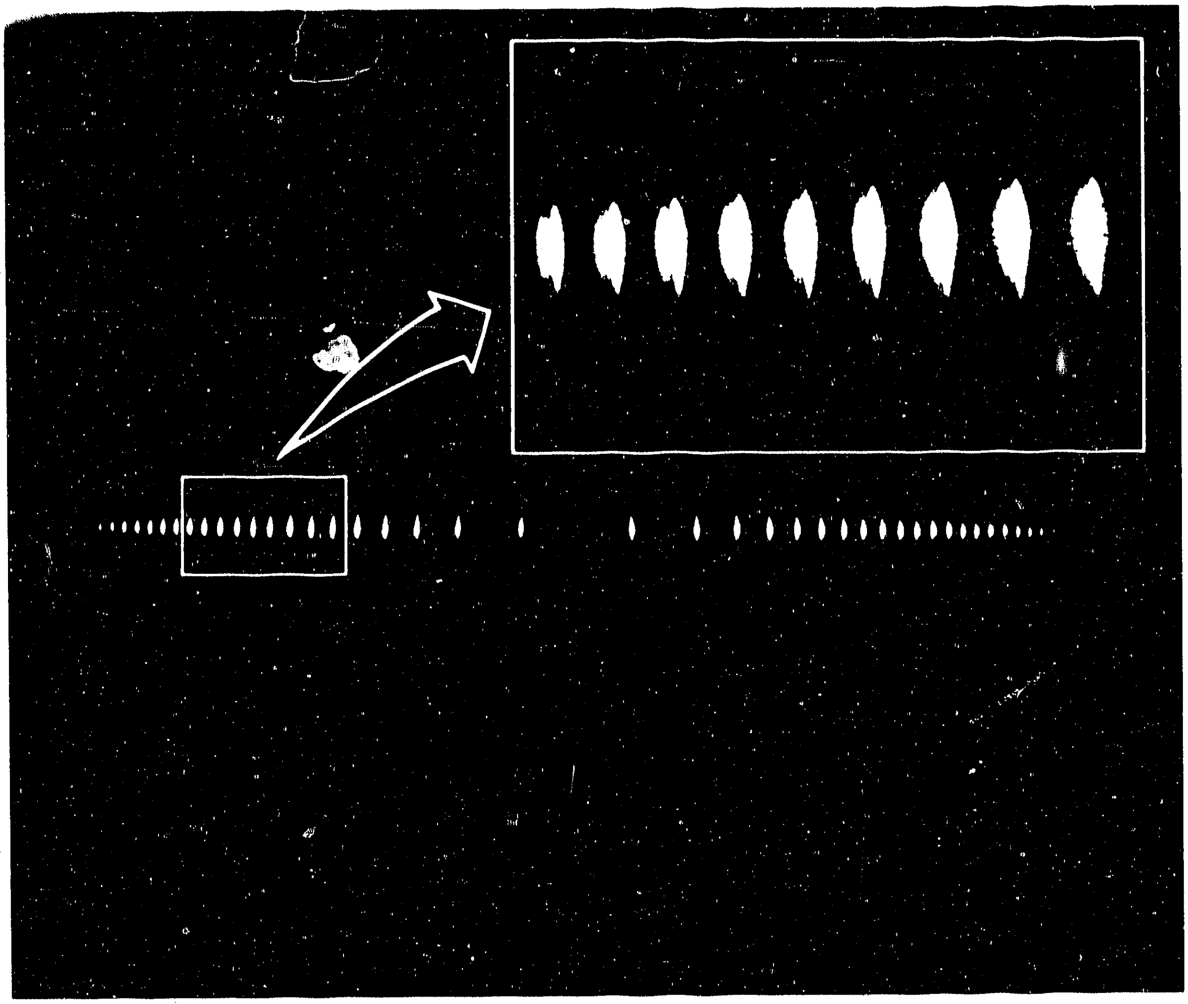

Figure 2. Side lobes around main Fabry-Perot fringes in the outer part of the pattern caused by mirror curvature.

increased by a factor of 50 so that it is visible on the same scale as the striped pattern. From the figure, it is apparent that the envelope describing these two patterns is different. Furthermore, the envelope changes with target position. In order to compare the efficiency of these two techniques for making velocity measurements, we have chosen the integral of the intensity between the second and the fifth fringes as a measure of how much light is available for velocimetry. This measure is not sensitive to how the light is distributed between the peaks so that if all the light were in one peak and none in the others, it would not be a useful measure. However, the distributions we are dealing with are uniform enough that it seems to provide a reasonable comparison.

Table 1 shows a comparison of the integrated intensity at three target positions. The second column shows that for the normal Fabry-Perot, the intensity falls off approximately symmetrically as the target is moved on either side of the focus of the collection lens. For the lens system we have used, the drop is a factor of five. For the same target motion, the striped interferometer exhibits a greater loss of light relative to that available when the target is in focus. In addition, the loss is not symmetrical as the target is moved on either side of focus, being four times brighter when the target is moved away from the collection lens than when it is moved toward the lens. The final column shows the ratio between the striped and the normal Fabry-Perot at each position of the target. Over the range of distances we tested, there is more useful light in the striped interferometer than in the normal one.

The asymmetrical behavior of the striped Fabry-Perot is highlighted in Fig. 4 where the intensities from the extremes of target travel are compared. It is clear that not only it the total energy different, but the envelope of the pattern is different as well. Intuition suggests that the symmetrical behavior of the normal Fabry-Perot would carry over to the stripe, so an explanation of the asymmetry is needed.

The primary reason for the difference in behavior on opposite sides of target focus is that we have a Gaussian

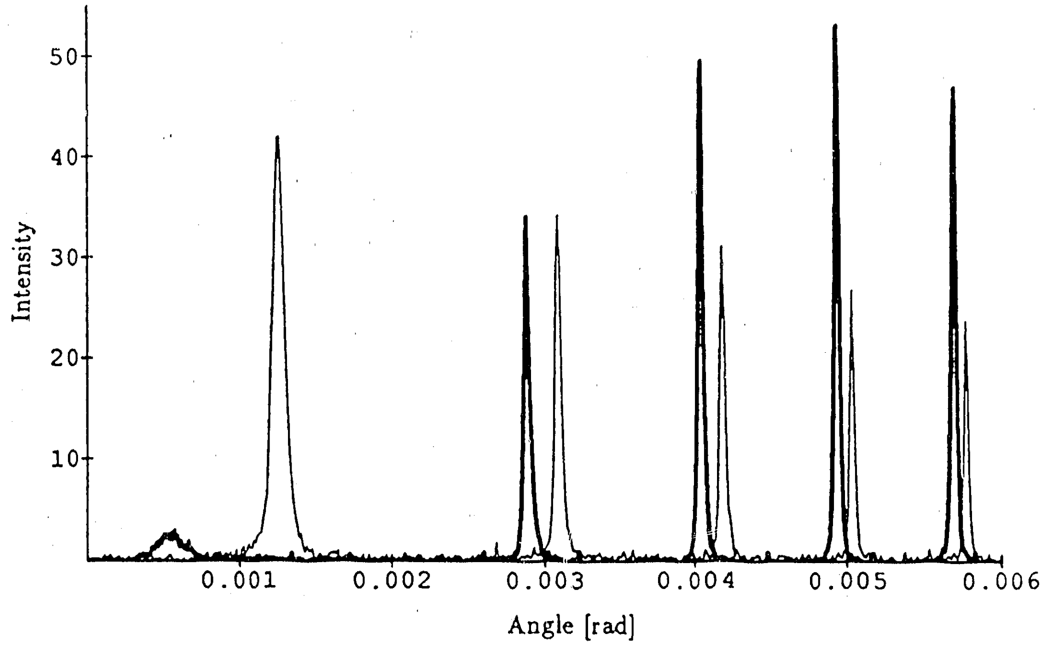

Figure 3. Comparison of a striped Fabry-Perot (heavy line) with the normal Fabry-Perot (light line) with the intensity increased by a factor of 50. The target was at the focus of the collecting lens.

Position relative to focus [cm]	Intensity relative to focus, normal	Intensity relative to focus, striped	Ratio of Intensities striped to normal
-2.5	0.19	0.01	3.5
0.0	1.00	1.00	54.0
2.5	0.18	0.04	12.0

Table 1. Comparison of the integral of intensity between the second and fifth fringes for the striped Fabry-Perot and the normal Fabry-Perot.

illumination beam leading to nonuniform illumination on the stripe. Nonuniform illumination plus the fact that the region of the stripe that allows light into the interferometer varies as a function of angle produces the effect.

Consider a ray entering the stripe at angle θ and position x. If the stripe has a width $2r$ and is centered on the axis and the Fabry-Perot mirrors are separated by distance h, the ray will return to the entrance mirror at a position

$$x' = x + 2h \tan\theta\,. \tag{2}$$

If $|x'| > r$ then the ray will remain in the interferometer and multiply reflect, contributing to the interference pattern. if $|x'| < r$, then the reflected ray will leave the interferometer through the stripe and be lost. Rearranging Eq. 2 we find that for a particular angle, the region of the stripe that contributes to the interference pattern is

$$x = \begin{cases} \max(r - 2h\tan\theta, -r) & \text{if } \theta >= 0 \\ \min(-r - 2h\tan\theta, r) & \text{if } \theta < 0 \end{cases} \tag{3}$$

where for positive θ the region that contributes is between x and r and for negative θ it is between $-r$ and x. For small angles, only rays entering the stripe near its edge contribute to the interference. As the ray angle increases, an ever increasing portion of the stripe area contributes to the interference pattern until at large angles, rays entering the stripe over its entire area contribute to the interference.

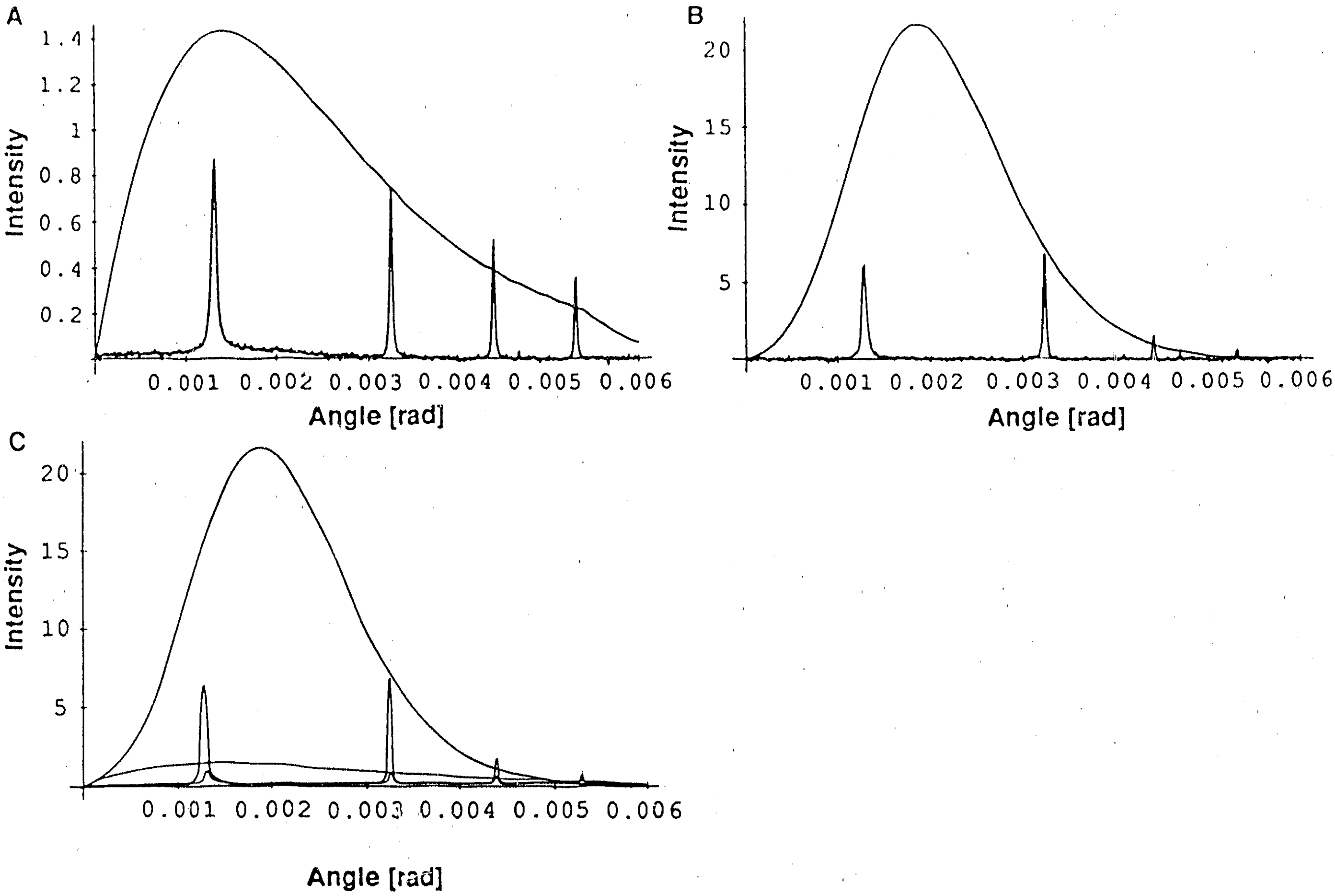

Figure 4. **A** Intensity pattern when the target is 2.5 cm closer to the lens than the focal point, experimental pattern and calculated envelope, **B** Intensity pattern when the the target is 2.5 cm farther from the lens than the focal point, experimental and calculated envelope, **C** Overlay of A and B on the same scale showing the difference between the two patterns.

If we now examine what happens as the target moves on either side of the focal point of the collecting lens, we find that an image of the Gaussian illumination pattern on the rough target is produced on either side of the input mirror. These images are not exactly the same distance from the mirror, nor are the Gaussian illumination patterns the same width, but the differences are small, and for the sake of illustration, we will assume that they are the same distance away and the same size. If the optical system is correctly aligned, the peaks of the illumination pattern will lie along the optical axis and be centered on the stripe. A set of parallel rays passing through the stripe at an angle chosen to be at one of the peaks of the Fabry-Perot pattern will intersect the illumination pattern as shown in Fig. 5. Since the illumination pattern is symmetrical about the optical axis, the total energy sampled by the rays will be the same, however, the distribution across the stripe will be different. One side will yield a maximum on the left side of the stripe while the other will yield a maximum on the right side. The asymmetry comes about because only part of the stripe contributes to the multiple reflection in the interferometer as shown by the equations above. The shaded region in the figure illustrates the part of the beam that contributes to the interference pattern. In one case, the part of the illumination pattern that contributes comes from the tail of the Gaussian, in the other, from the peak. Thus we get very different intensities in the Fabry-Perot pattern when the target is on different sides of the focal point of the collecting lens.

Figure 6 shows the intensity distribution at the stripe for the extreme cases of target motion at a single angle. These calculations have been done without the simplifying assumptions of the earlier illustration. They show the complete distribution of light on the stripe and that portion of the light that contributes to the multiple reflection.

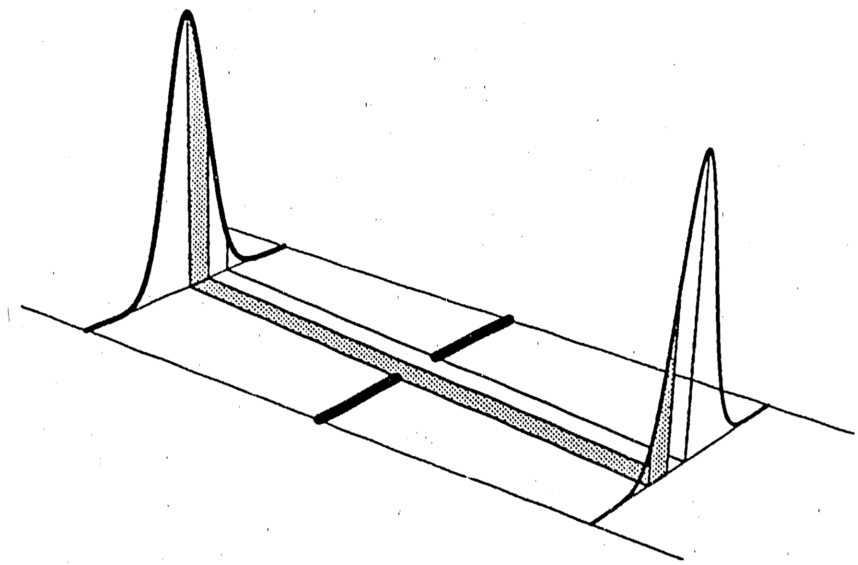

Figure 5. Rays passing through the stripe intersecting the image of the Gaussian illumination on the target when the target is on either side of focus

The envelopes shown in Fig. 4 where calculated taking into account the non-uniform distribution of light on the stripe and the walk-off on the mirrors. While not a perfect description of the shape of the Fabry-Perot pattern, this model appears to account for the major factors in a striped, air-transport, Fabry-Perot velocimeter.

4. CONCLUSION

While these ideas are interesting to examine in the laboratory, the more interesting question is, have they been useful on dynamic experiments? We have had an interferometer with a striped mirrors for over two years that has been used in a range of experiments using electric guns, powder driven guns, and high explosives as velocity sources. The improved efficiency of the interferometer in using the light returned from the experiment has made it possible to do experiments that were previously beyond our capability.[6]

Based on our experiments, we observe improvements in the throughput of the Fabry-Perot interferometer of up to a factor of 50 and useful improvements over a range of target motion. The location and width of the peaks of the Fabry-Perot fringes are not affected by the stripe. It's only effect is on the intensity of the fringes, dramatically decreasing the intensity of the central fringe relative to other fringes in the pattern and increasing the total light available.

The total light available in the fringes is greater than the unstriped case as the target moves out of focus, but the difference between the in focus and out of focus positions is greater with the striped than with the unstriped interferometer. Thus, if large target motions are required, the striped interferometer requires greater dynamic range and has more available light than the standard Fabry-Perot system.

Ideal applications for this system are experiments where the target motion is small or those in which the light is carried to the interferometer by a fiber so that the position of the light on the interferometer does not change during the course of the experiment.

5. ACKNOWLEDGEMENTS

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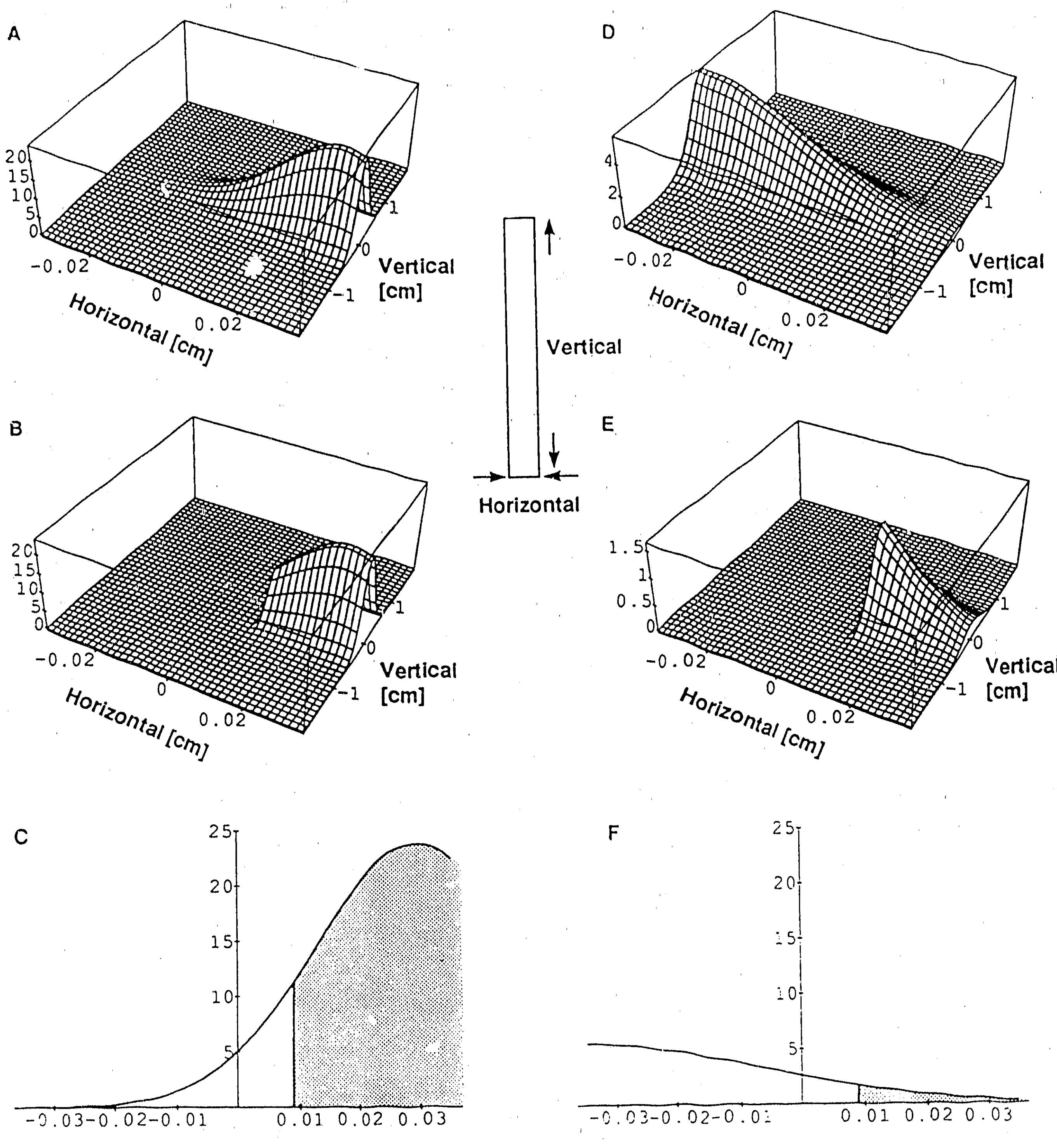

Figure 6. Intensity distribution across the stripe for the target farther from the collection lens (**A** - **C**) and closer to the collection lens (**D**-**F**). The patterns show the total intensity on the stripe at a particular angle, the portion of the incident intensity that contributes to multiple reflection, and a cut through the center of the pattern showing similar information.

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