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UTILIZATION OF MOIRÉ PATTERNS AS AN ORBITAL DOCKING AID TO SPACE SHUTTLE/SPACE STATION FREEDOM

Final Report

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ABSTRACT

Moiré patterns are investigated as possible docking aids for use between the National Space Transportations System (Space Shuttle Orbiter) and the Space Station Freedom. A sight reticle placed in optical conjunction with a docking target can generate moiré fringes from which position and alignment can be inferred. Design specifications and a mathematical development to meet those specifications are discussed. A motion based simulator and experimental hardware have been constructed.

INTRODUCTION

Space operations in the mid to late 1990's will require frequent rendezvous and docking missions between the Space Shuttle and numerous on orbit spacecraft, especially construction and servicing of the Space Station Freedom (SSF). At costs on the order of $3,000 a pound for carrying Shuttle payloads to low earth orbit, any hardware or protocol which can be developed to reduce the amount of contingency fuel required to be carried aloft, at the expense of payload, will quickly pay for itself. To ensure a successful docking between Shuttle and SSF, current scenarios and simulations dictate a large, heavy capture mechanism with a large capture cross section. Alternatively, a smaller mechanism with a correspondingly smaller capture cross section requires a greater quantity of reaction control system (RCS) propellant and exacerbates the problem of Shuttle plume impingement on SSF. Either solution reduces the Shuttle payload on every docking mission to SSF.

Improved pilot sighting and sensing systems are an alternative to the "brute force" solutions mentioned above. One of several techniques proposed to alleviate the docking scenario is the utilization of moiré patterns generated between a sight and a docking target. Moiré patterns are the fringes generated between two approximately equally spaced grids[1]. They can be designed to have the property of being quite sensitive to their relative translation and rotation, and their basic properties have been commented on since the 1800's.[2] Contemporary applications are numerous and include

[1]The French word "moiré" and its English translation "water" may both mean a wavy pattern imprinted on fabric, as in "watered silk". The term moiré has now come to represent many families of interference fringes.
[2]Lord Rayleigh (J.W. Strutt), Phil. Mag. 47, 81, 193 (1894).

the evaluation of replica gratings[1], metrology in general[2], measurement of refractive index gradients[3], recording contour lines of an object[4]. They even embrace the field of "Optical Art"[5].

While moiré theory and application is well represented in the literature, its use to infer position in three dimensions is very recent[6]. This work is done as an outgrowth of that effort in direct collaboration with the patent applicant and Principal Investigator, Dr. Richard D. Juday.

Patterns can be designed to be sensitive to those parameters which aid successful docking and to be relatively insensitive to those parameters which do not affect the miss distance. In short, the design will enhance the coupling between what the pilot observes in his docking sight and what occurs at the docking port interface.

MOIRÉ THEORY

The theory of moiré fringe formation under incoherent illumination is well established in the literature from different perspectives. The most common theory involves basic geometry[7], discribed by an indicial representation method[8]. Alternatively, the pattern can be thought of as the low spatial frequency components of the combination of the original patterns. The patterns must be resolved into the spatial frequency components to interpret the moiré pattern by the use of communication theory[9]. The latter is the approach used in the calculations to follow. The theory developed in the past for moiré fringe formation under incoherent illumination is almost exclusively restricted to two dimensions. For space docking application involving two independent gratings, offset by a comparatively large distance and each with nominally six degrees of freedom, a slight extension of theory is required. Appropriate

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[1] J. Guild, The Interference Systems of Crossed Diffraction Gratings (Oxford University Press, London, 1956).

[2] J. Guild, Diffraction Gratings as Measuring Scales (Oxford University Press, London, 1960).

[3] Y. Nishijima and G. Oster, J. Opt. Soc. Am. 54, 1 (1964).

[4] D.M. Meadows, W.O. Johnson, and J.B. Allen, Applied Optics, Vol. 9, 4 (1970).

[5] G. Oster, Applied Optics, Vol. 4, 11 (1965).

[6] R. Juday, Patent disclosure, Feb. 5, 1989.

[7] M. Stecher, Am. J. of Phys. Vol. 32, 4 (1964).

[8] G. Oster, M. Wasserman and C. Zwerling, J of Opt. Soc. Am, Vol. 54, 2 (1964).

[9] Yokozeki, Optical Communications, Vol. 11, 4 (1974).

simulations will also have to be made before final flight hardware can be designed.

The moiré pattern itself, a periodic spatial function, can be formed optically by addition, subtraction, and multiplication of two (or more) spatially varying structures (gratings or filters). The most common way to combine the two original structures is by their transmittance or reflectance functions. The illuminating light is affected by the product of their transmittances and/or reflectances. We say then that when the same light field has impinged on each of the original structures in turn, a multiplicative pattern has emerged. This can be illustrated by the following two periodic structures and their product

$$A(x) = \frac{1}{2}(1 + \cos 2\pi f_1 x) \tag{1}$$

$$B(x) = \frac{1}{2}(1 + \cos 2\pi f_2 x) \tag{2}$$

$$A(x)\,B(x) = \frac{1}{4}(\cos \pi (f_1 + f_2)\, x * \cos \pi (f_1 - f_2)\, x) \tag{3}$$

Being a low pass filter, the eye will pass the low frequency component, which will be manifested by readily resolvable fringes. A multiplicative moiré fringe is used in our design.

An additive type pattern, in contrast, occurs when two separate light fields impinge on the two separate structures, and are then superposed to form

$$A(x) + B(x) = 1 + \cos \pi (f_1 + f_2)\, x * \cos \pi (f_1 - f_2)\, x \tag{4}$$

which yields a modulated sinusoid that is far more difficult to resolve. This effect would be important if an attempt were made to modify the existing Crew Optical Alignment Sight (COAS) to accept a moiré reticle. The COAS works on a projected backlit reticle imaged at infinity. Thus, a moiré-generating reticle inserted in the COAS would yield an additive moiré pattern when placed in conjunction with a moiré-generating docking target placed on SSF. For a more thorough treatment of types of superposed patterns in optics, see Bryngdahl.[1]

DOCKING ENVIRONMENT AND GEOMETRY

The current Shuttle to SSF docking scenario involves a series of primary, secondary, and emergency sensors. These include ground tracking, rendezvous radar, the star tracker, and visual acquisition to bring the Shuttle to the vicinity of SSF. The docking scenario is specified for a totally passive SSF, although it is assumed that SSF Attitude Control System (ACS) is operational. At approximately 50 feet out, the pilot, flying from the aft bay, observing through the overhead window, will attempt to keep the Shuttle within an acceptance cone with a full width vertex angle of 6-10 degrees. From here until docking, the pilot will probably have range and range rate data fed to him via a laser sensor. At from 10-20 feet from docking, the pilot will attempt to hold his lateral misalignment to less than a six inch radius circle. He makes closing velocity (z-direction) and lateral alignment corrections (x-y) by pulsing Reaction Control System (RCS) thrusters. The other three degrees of freedom, roll, pitch and yaw, are held steady within one-degree accuracy by the Shuttle Attitude Control System (ACS). Roll, pitch and yaw are also held steady within one-degree accuracy by the ACS on the SSF. These attitude uncertainties are known as the deadbands of the Shuttle ACS and SSF ACS, respectively. The anticipated closing velocity is on the order of one-tenth of a foot per second.

This final closing range, from 10-20 feet to dock, is where accuracy must be improved to less than approximately six inches. Current contingency docking scenarios for the Shuttle to the docking mast of SSF utilizing the COAS do not provide adequate accuracies (close to twelve inches) for a single docking attempt. Shuttle Closed Circuit Television (CCTV), placed at the docking port, does meet the requisite accuracy (approximately three inches), but is objectionable from a reliability standpoint[2]. Though the COAS is a reasonably precise instrument for the applications it was originally designed for, its difficulty with Space Shuttle/Space Station Freedom docking is the offset distance from the sight to the docking port adapter. Figure 1 shows how this offset acts as a lever arm, converting acceptable roll,

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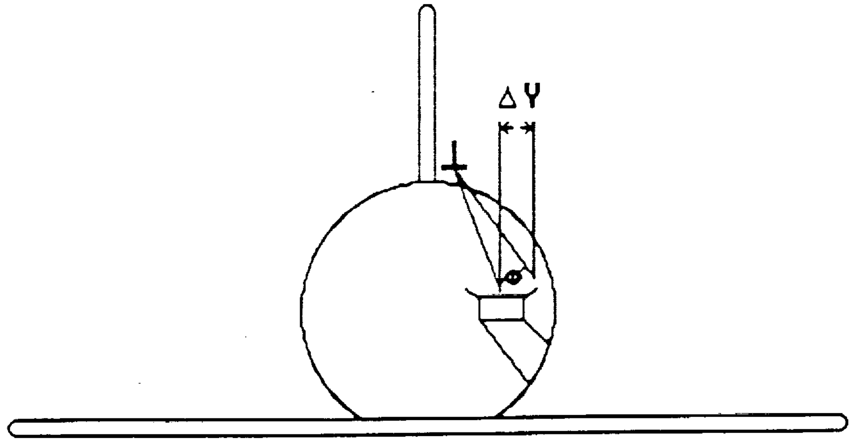
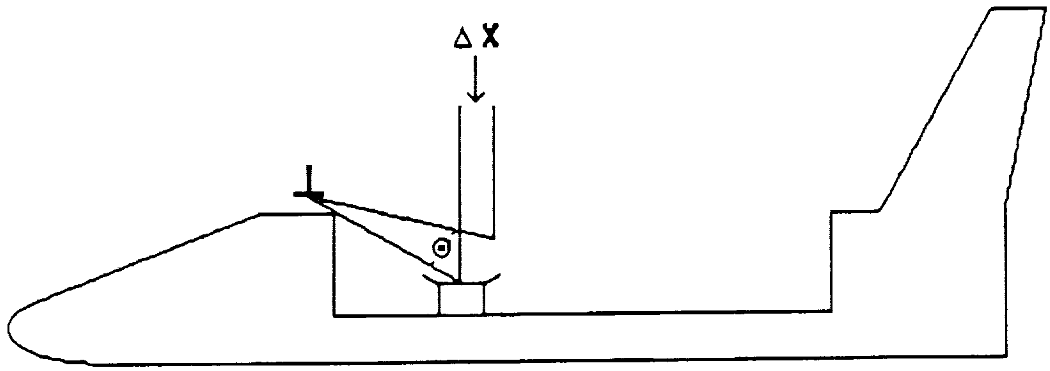
[1]O. Bryngdahl, Opt. Soc. of Am., Vol. 66, 2, (1976).

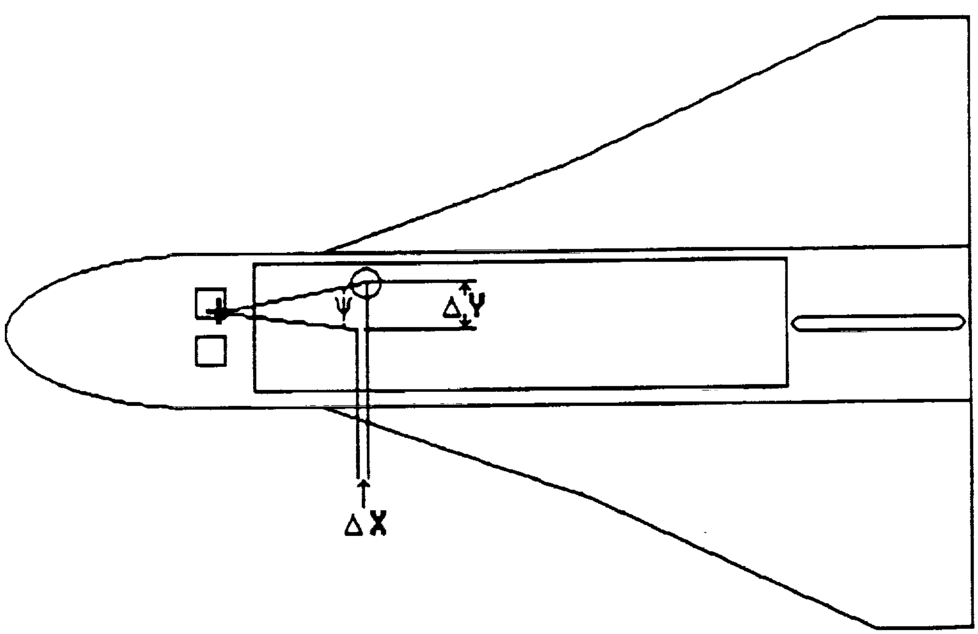
[2]Miss distances were provided based on simulations run by Brian Rochon, as presented in Analytical Docking Contact Conditions, April 13, 1989.



Roll Induced System Error



Pitch Induced System Error



Yaw Induced System Error

figure 1.

pitch and yaw deadband error of the shuttle at the sight-docking target point of reference, into an unacceptable miss distance at the docking port. The same lever arm also affects instrument error and pilot error. Our design, essentially replacing the COAS with a robust, simple, small telescope must negate this effect to achieve miss distances less than six inches.

Referring to figure 2, note where and how our COAS-replacement system will be mounted. It will be mounted in approximately the same location as the COAS in the aft bay overhead window. This figure shows the baseline SSF docking scenario, using a docking mast which will retract to mate airlocks after hard dock is achieved. Figure 3 shows the docking mast retracted. The standoff distance from the COAS or COAS-replacement to the SSF docking target is approximately 18 feet, if a non-retractable target is used.

DESIGN CRITERIA AND THE FIRST GENERATION DESIGN

Our design criteria, which should serve to minimize miss distances, are:

1. Maximal sensitivity to x-y translation as measured at the docking port location.
2. No yaw sensitivity about the docking port.
3. Acceptable sensitivity to roll and pitch.
4. Simple to interpret patterns.

The first criterion underscores that it is how far off you miss the docking port--not how close your sight is to its target's bullseye--that is critical (and is presently a problem with the COAS). Second, some yaw is acceptable about the docking port (<u>not</u> the center of mass). Sensitivity to yaw about the docking port should be removed, so a pilot will not inadvertently correct for a perceived (but not actual) misalignment. Third, some roll and pitch will be present due to the deadbands of the ACS. Our design must be able to accept this. Finally (and on occasion, neglected), the design must give completely unambiguous cues to the pilot during those critical last seconds of docking, both in terms of how far and in which direction from the optimum docking position he is, and in his ability to sense his direction of motion.

Even a casual examination of commercially produced moiré patterns indicates that a variable frequency, ("chirped") pattern can give excellent sensitivity. Yaw insensitivity can be readily included

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DOCKING MAST SYSTEM	STRUCTURES & MECHANICS DIVISION
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INITIAL CONTACT CONFIGURATION

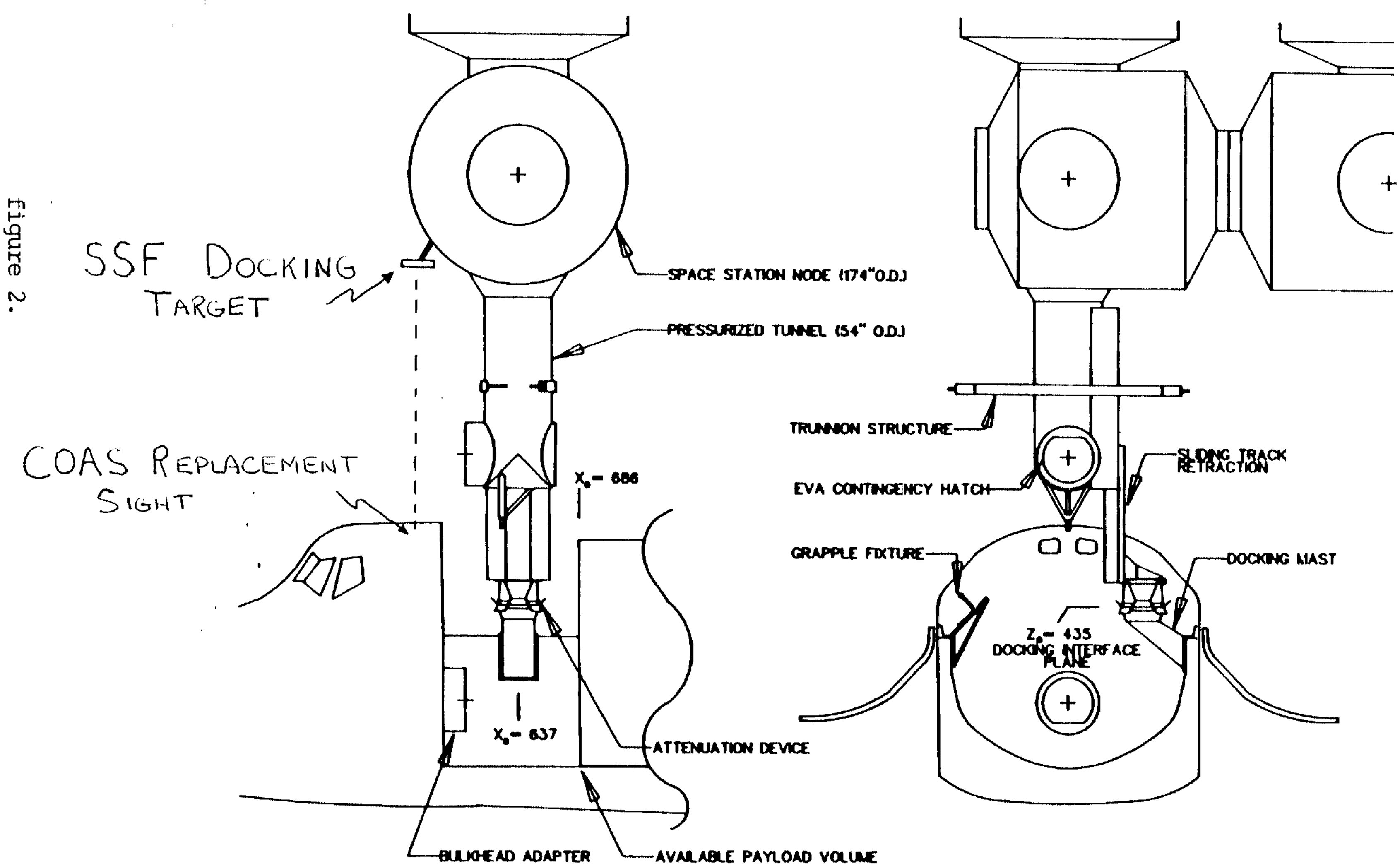

figure 2.

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DOCKING MAST SYSTEM

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FULLY DOCKED CONFIGURATION

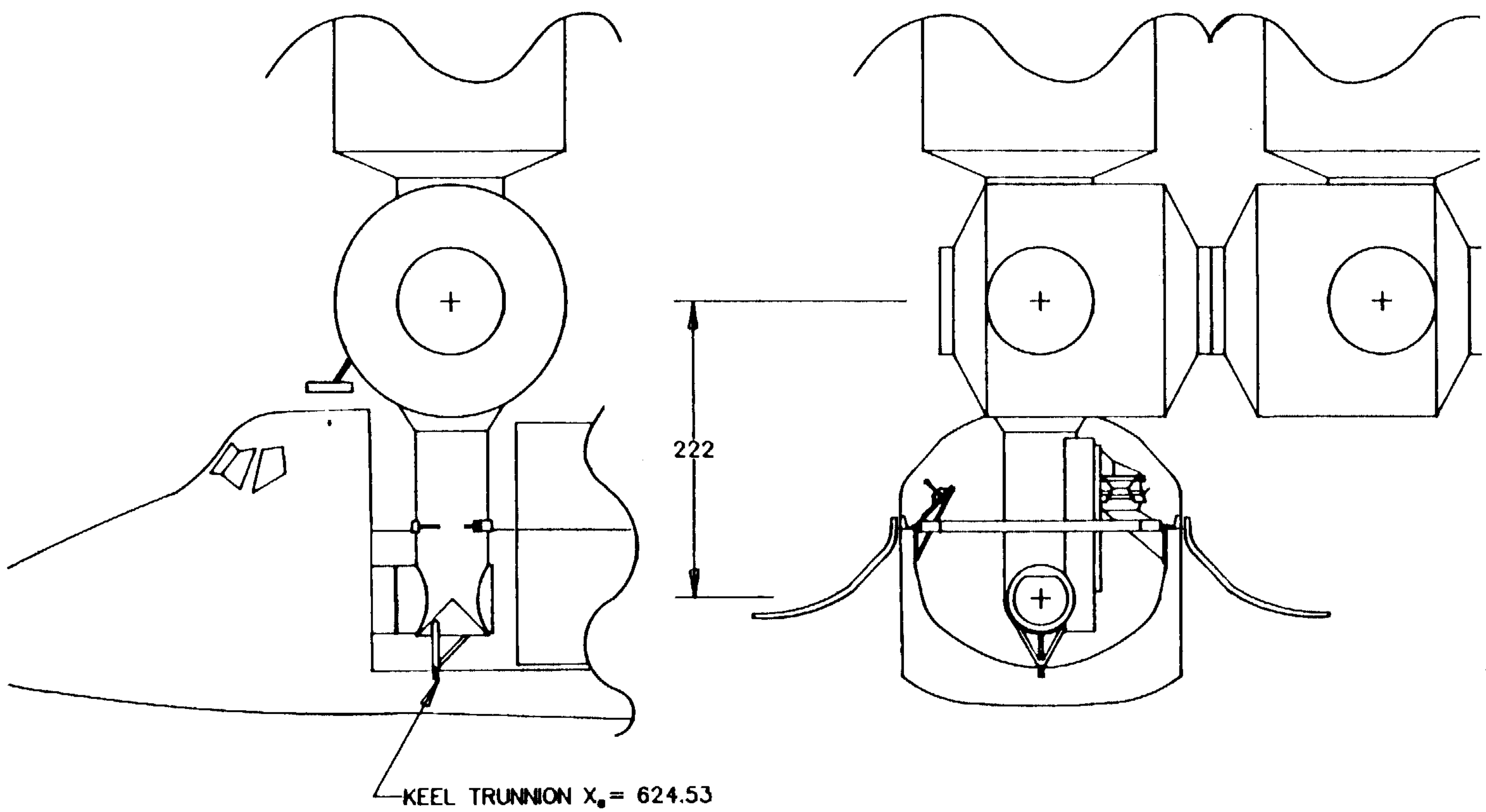

figure 3.

by making our patterns radially symmetric about the docking adapter axis. Combining these two properties yields an off-axis Fresnel zone plate as an excellent candidate pattern. A zone plate (figure 4) is a series of bright and dark rings about a central circle, and is notable in that each ring and the circle ("zone") has the same area. The equation of the radii that would draw such a figure is

$$r_m = B\sqrt{m} \tag{5}$$

where r_m is the mth radii, B is some constant to be determined, and m is an integer.

When two identical zone plates are overlapped with an offset less than the radius of the inner circle, a series of bars results perpendicular to the direction of the offset. Figure 5 demonstrates this fringe pattern, while the mathematics of this using the indicial equation method is shown by Oster et al[1].

SIGHT RETICLE AND DOCKING TARGET DESIGN

While an off axis zone plate will generate a series of equally spaced, equal thickness bars, for alignment purposes it is better to vary the frequency function of at least one zone plate to permit centering of the sight. Our first "centering chirp" is of quadratic form.

First, we must select a phase function $\phi(r)$ whose zeros of $\sin\phi(r)$ will correspond to an arc with radius r_m to construct the zone plate. This condition is met by the function

$$\phi(r) = \pi \left({}^{r}/_{B} \right)^2 \tag{6}$$

where B has yet to be specified. We next need to determine the spatial frequency f(r). It relates to phase $\phi(r)$ by

$$f(r) = {}^{1}/_{2\pi}\ {}^{d\phi(r)}/_{dr} = {}^{1}/_{2\pi}\ {}^{d}/_{dr} \left[\pi \ (r / B)^2 \right] = {}^{r}/_{B^2} \tag{7}$$

$$f(r) = {}^{r}/_{B^2} \tag{8}$$

[1]G. Oster, M. Wasserman and C. Zwerling, J. Opt. Soc. Am, Vol. 54, 2 (1964).

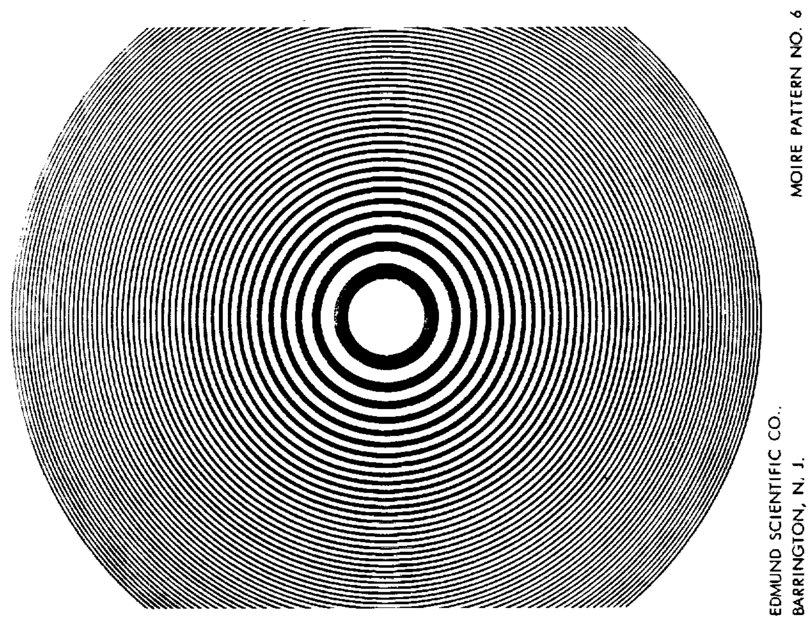

figure 4.

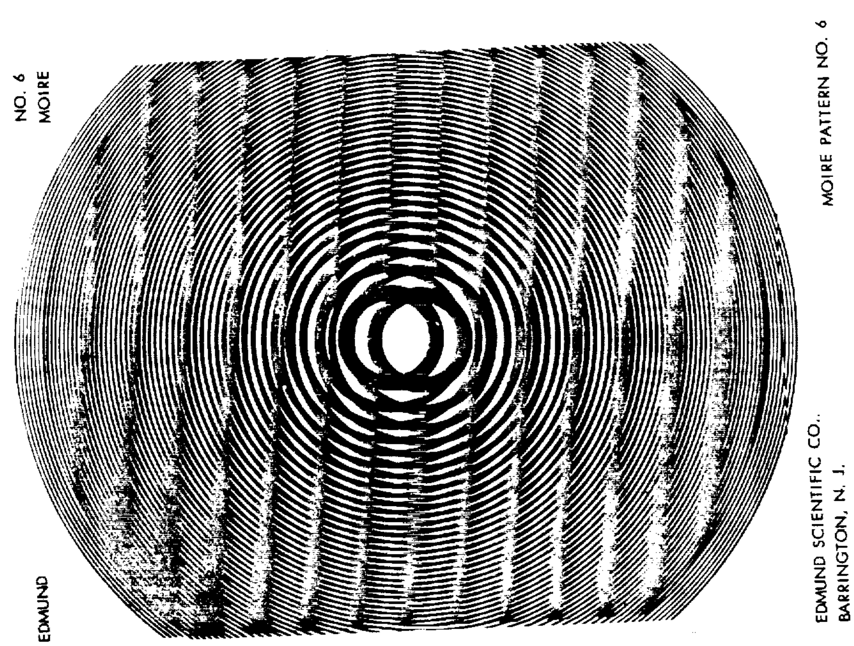

figure 5.

We now subscript T for target and R for reticle, and introduce a quadratic chirp into f_T. This quadratic chirp in f_T is symmetric about the center of the target, which in turn is 114 inches from the docking port (the origin of our pattern). Our target frequency is thus

$$f_T = f_R + D\,(r - 114)^2 + E \qquad (9)$$

which can be interpreted by the following figure

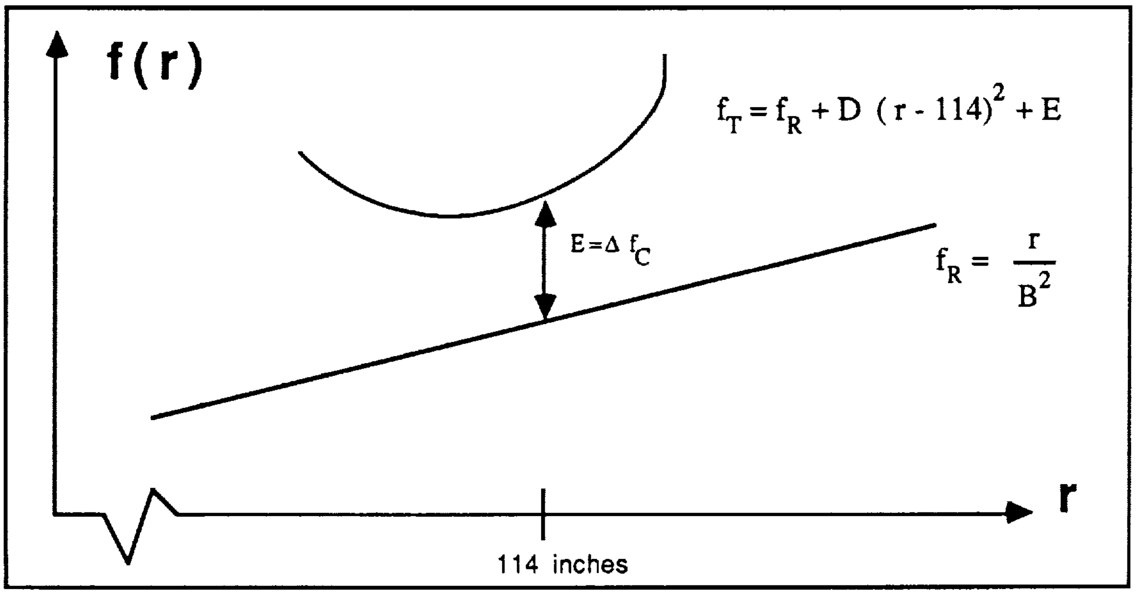

figure 6.

Noting that our target frequency f_T will correspond to the inverse of our chosen arc width, d, constraints may now be imposed to solve for the constants D, E and B. The constraints are:

1. Choose a differential frequency ratio of say, two times, edge to center.
2. Design to give 5 fringes (thus easy to observe) in moiré pattern between $r = 102$ and $r = 126$ inches for a 2 foot by two foot target.

From the first constraint, we see that

$$E = 144\,D\,. \qquad (10)$$

Next, the number of fringes must equal the number of arcs in the target less the number of bars in the reticle, edge to edge; thus

$$\text{N fringes} = (\phi_T - \phi_R)/_{2\pi}\,. \tag{11}$$

The phase difference from center to edge has half the fringes, and recalling
N = 5,

$$5\,\pi = \Delta\,\phi_{C\text{-}E}\,. \tag{12}$$

This is also equal to the integrated phase from the center to edge

$$2\pi \int_{\xi=0}^{12} (E + D\,\xi^2)\,d\xi \tag{13}$$

yielding

$$^5/_2 = 12\text{ E} + 576\text{ D} \tag{14}$$

Rewriting equation (9) at its maximum value at r = 126,

$$[f_T]_{MAX} = \frac{1}{d_{r=126}} = \frac{126}{B^2} + 144\,D + E \tag{15}$$

and selection of an appropriate cut width d yields suitable solutions for the constants.

To cut the sight reticle recall that a zero occurs (and hence a cut in our pattern) for the sine of the phase function every π radians, so

$$\phi_R\,(r_m) = m\,\pi = \pi\,\frac{r_m^2}{B^2} \tag{16}$$

which leads immediately to equation (5) to control our cuts.

To find where to make the cuts in the target, its phase function is found as a function of r. This equals the integrated frequency,

$$\phi_T\,(r) = 2\pi \int_0^r f_T\,(\xi)\,d\,\xi \tag{17}$$

resulting in the following cubic equation for the target phase function,

$$\frac{\phi_T(r)}{2\pi} = \frac{r^2}{2B^2} + r\,E + \frac{D}{3}\left[\,(r-114)^3 + 114^3\,\right]. \tag{18}$$

As with the phase function of the reticle,

$$\phi_T(r_m) = m\,\pi \tag{19}$$

will lead directly to a cubic equation in terms of m and r_m. An algorithm using Newton's method then solves the cubic and control the cutting of our target pattern.

Finally, our reticle pattern is photo reduced to place it in the focal plane of our telescope.

PHYSICAL IMPLEMENTATION

The objective of the experiment was not only to generate the functions of a suitable moiré-generating telescope reticle and docking target reticle, but also to translate them into laboratory hardware. The patterns were created by cutting a membrane of red plastic layered on a transparent substrate, then peeled to create alternating red and clear arcs. This process is known as "ruby-lithography" or "ruby-lith", and is traditionally used in miniaturized electronic circuit fabrication. Arcs can be cut as close as every 15 mils without undue tearing, but to ease the burden of iterative fabrication, an arc width of about 50-60 mils was selected.

The ruby-lith software had no trouble with either of the equations used to generate the two templates, not even the routine to solve the above mentioned cubic equation using Newton's method, though it was painfully slow and required frequent human-intervention due to memory limitations.

The target pattern eventually used for flight hardware will need to be made of high contrast alternating reflective and absorptive bands, as the shuttle floodlights will be the only lighting we can confidently depend on under our "passive SSF" criteria. For our first generation tests using off-the-shelf ruby lith, a light box or simple lamp will provide high contrast rear illumination.

A target just under two feet square was initially used to ensure the field of view of our test telescope would be filled by the target at the initial test ranges of between 18 and 28 feet.

An inexpensive four power rifle telescopic sight was disassembled to gain access to the focal plane. The eyepiece, photo reduced reticle and telescope were placed in optical mounts, and the photo reduced reticle was placed at the focal plane.

The telescope assembly was mounted on a three degree of freedom motion based, full scale simulator. The "Shuttle" could then translate (z-direction) toward "SSF" at a realistic one-tenth of a foot per second, while simultaneously translating laterally (x & y directions), as illustrated in figure 7. Near term simulator improvements will allow all six degrees of freedom, incorporating roll, pitch and yaw.

Of particular note in the figure is the offset "docking port" marker on the boom of the simulator. This demonstrates in full scale the relation between how close the pilot has in fact docked compared to what he observed in his docking sight.

LABORATORY RESULTS

Laboratory runs are now begining to evaluate the first generation docking targets and reticles. The data will published in a future publication by Juday and Dottery, et. al.

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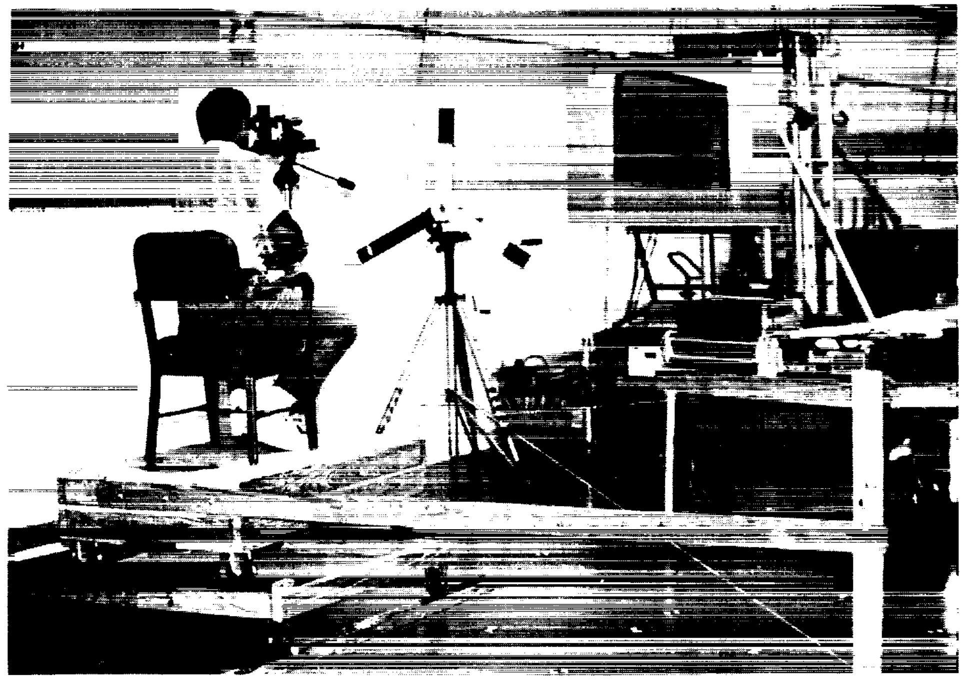
BLACK AND WHITE PHOTOGRAPH



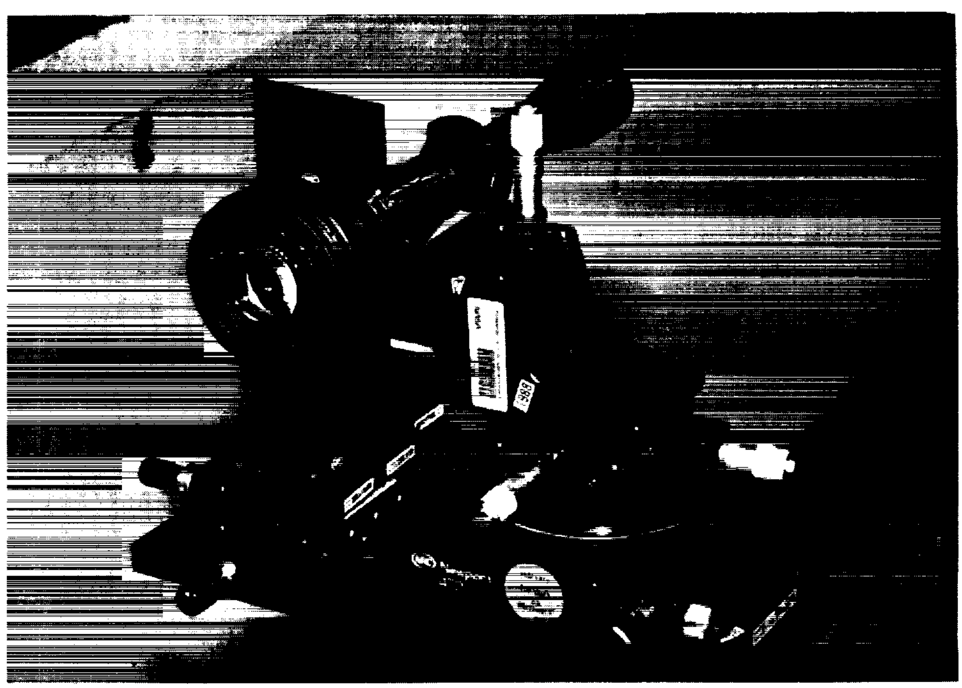


figure 7.