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IMAGE MEDIA INVESTIGATION FOR HOLOGRAPHIC STAR FIELD MAPPER

By J. D. Welch

January 1970

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Electronics Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Cambridge, Massachusetts

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1.0 INTRODUCTION

This report summarizes the results of a brief investigation performed by the Space Division of the General Electric Company and funded by NASA under Contract No. NAS-12-2148.

This investigation was concerned exclusively with one specific aspect of the application of coherent optical data processing techniques to "real time" star field recognition and tracking: the specification and selection of an "input" imaging medium on which to record the "candidate" star field which is to be recognized and tracked by a "holographic" star field mapper.

Recognition and tracking of star fields have utility in a spacecraft for the following functions:

1. Vehicle attitude determination and reference (e.g., determination from any arbitrary attitude)

2. Navigation reference (when used, for example, in conjunction with spatial filtering techniques for landmark recognition and tracking)

3. Verification of star acquisition (e.g., verification of acquisition of Canopus)

4. Precise reference for pointing various scientific payloads

5. Updating gyro references.

Coherent optics spatial filter techniques are uniquely qualified to perform the function of recognizing and obtaining a precise tracking fix on star fields. Unlike most noncoherent optical techniques (e.g., "correlographs"), this type of recognition does not require precise mechanical or optical registration between the input image and the stored reference image. On the contrary, precise reference direction in terms of location of the "correlation spot" on the "output plane" is one of the directly measureable system outputs.

One of the important considerations of this application is devising a practical technique for storing a large number of star field patterns in some type of "multiple filter," or other means, so that a spatial frequency representation of any part of the celestial sphere can be readily accessible. This is a technical area to which J. Hallock of NASA-ERC has made some unique contributions (see Ref. 44).

Another important aspect of the usual approach to coherent recognition (and one which is more directly applicable to the effort reported on in this document) is the specification and selection of an optimum medium for recording the candidate star field image so that it can be operated on in the coherent system. Most work by various researchers to date in solving similar problems has used conventional silver halide photographic techniques in the form of a transparency. However, several alternatives which exist are evaluated here, for example: various types of photodeformables (which may be operated in either a transmissive or reflective mode), photochromics, as well as several rapid process silver halide techniques.

In order to arrive at an optimum system design, it is first necessary to define the specifications for such a medium and then evaluate potentially applicable media in relation to those specifications. Some of the key material characteristics which we have considered in this investigation are photometric sensitivity in the spectral regime of interest, resolution, possible reusability, and inherent noise characteristics.

Also evaluated for this space application is a capability of exposing the medium to the star field image, developing the exposed medium, and using the recorded image in such a way as to preserve the relative position and orientation data of the star field. One ideal way to accomplish this would be to use an image medium which can be developed "in place" and in an arrangement such that the input image, exposure, development, and subsequent recognition can be performed without any movement of the imaging medium.

An alternative approach for media where "in place" development may not be feasible for certain media would be to use a precise indexing technique to ensure that the imaging material is precisely positioned and oriented in the recognition system.

An image medium should also be capable of processing and use with a minimum of mechanical distortions such as warpage, shrinkage, or bowing, as these characteristics can degrade image performance. Media not requiring a liquid gate are to be favored.

The presently reported work addressed itself to these material investigations. The effort was pursued by appropriate analysis, by soliciting data from many producers and developers of advanced media and, in some cases by performing key experiments.

The work was pursued in two general steps:

1. Determination of image media specifications

2. Evaluation of potentially available media in relation to those specifications.

The evaluation of various media was made on a best effort basis based on available data. In some cases, complete data was known not to be freely available. In some of these cases, restrictions are known to exist for proprietary or other reasons. It is also recognized that research and development in the field of advanced image media is proceeding at a rapid pace. Consequently, it is recommended that an effort be pursued so as to continuously update the results of the present effort.

2.0 SUMMARY OF RESULTS

The details of the results of this investigation are found in the text and in the various plots of this report. Here we will only summarize some of the highlights of these results.

The initial part of the investigation was concerned with determining the specification of the imaging media. One of the most critical specifications is the photometric response to star images. NASA guidelines indicated that stars as faint as 4th magnitude and fields of view up to 45° should be considered.

It is evident that the media specification will be highly dependent on vehicle attitude stability, allowable sizing of the optics, etc. However, an engineering judgement of these factors indicates that, with "realistic" optics, the imaging media should, as a minimum specification, be responsive to collected optical power levels in the typical range of 10^{-12} to $5 (10^{-11})$ watts focused over a point spread function diameter typically ranging from 10^{-3} to 10^{-2} cm. This typically corresponds to power densities ranging from 10^{-7} to 10^{-5} watts/cm^2. For realistic exposure times, this corresponds to energy densities typically ranging from 10^{-7} to 10^{-4} joules/cm^2. (Although sensitivity of media in terms of required energy density does not completely define photometric response to star images, it is of interest since it is frequently the only response data supplied by many sources of advanced imaging media.)

In addition to photometric response, media which can be processed rapidly "in place" and which are reusable have obvious advantages.

As one might expect, when one investigates media and processes which are potential candidates for the intended applications, they are found to generally fall into two categories:

1. Those having very high sensitivity and resolution, but tending to be irreversible and complex in processing (as typified by silver halide media and its associated processing techniques).

2. Those having capability for rapid, in-place development (and in many cases reusability) but often with rather severe restrictions on sensitivity (as typified by many of the advanced nonsilver media). Many of these media are also still in the research and development stage and some questions may arise as to the near-time practicality of some of these media.

In summary, the plot of Figure 2-1 provides an indication of how some of the typical media meet these specifications. This figure shows a field of media sensitivity
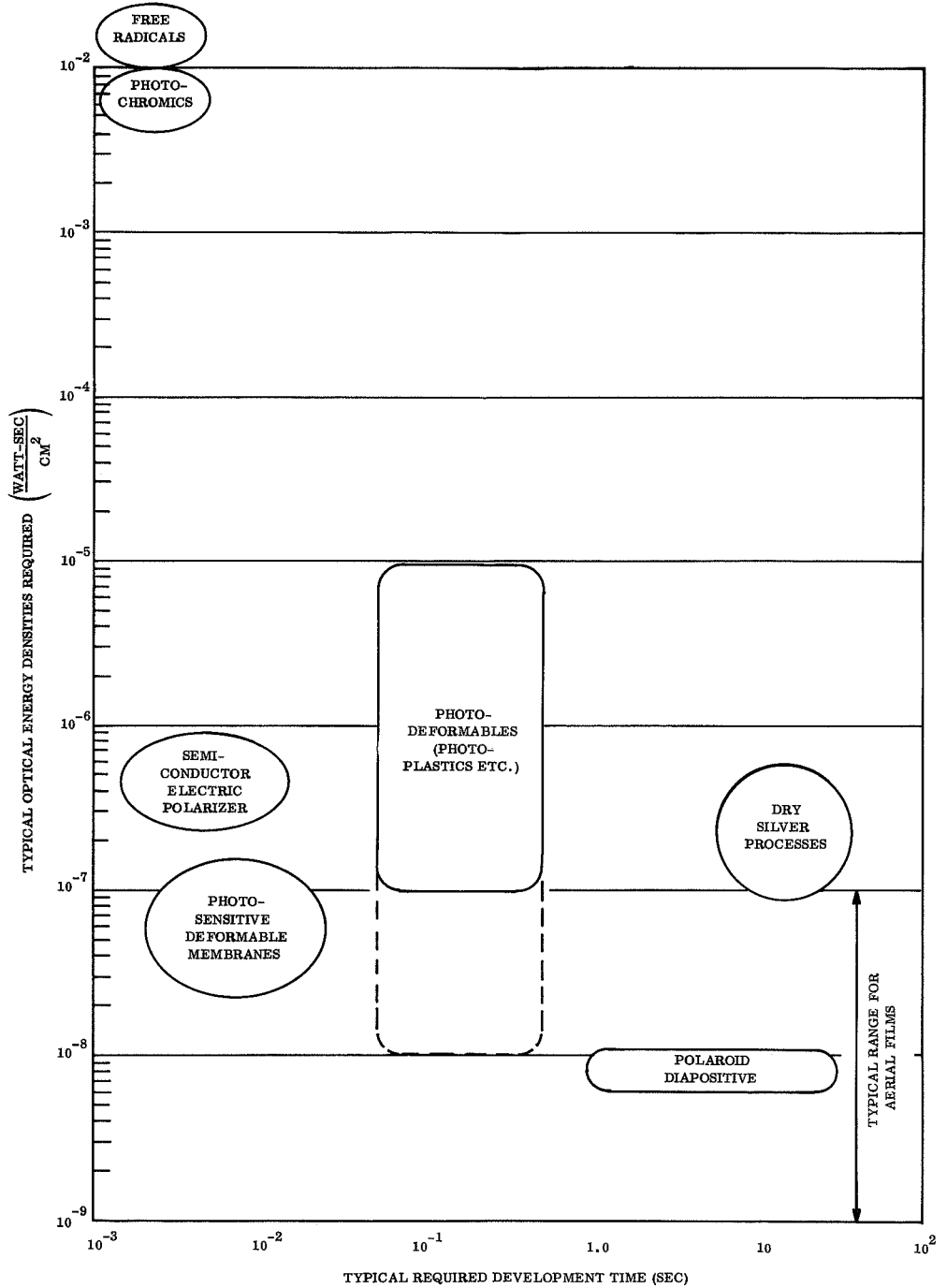
Figure 2-1. An Image Media Domain for Typical Energy Density and Exposure
Time Required Versus Typical Media Development Time

(in terms of required optical energy density) versus required media development time. It also shows an indication of sensitivity in terms of minimum exposure time for two cases: a "typical case" and a case judged to represent an extreme requirement. It may, at first, seem that required development time is a peculiar parameter to plot versus sensitivity. However, development time, like sensitivity, is also a key parameter. This is so not only because we wish to have a real time system, but even more important because development time is typically indicative of system complexity. Those media requiring long development times also typically require more moving parts and more weight and, since they are usually non-reusable, require a larger supply of media, and in some cases, may require liquid baths, etc.

It is cautioned that Figure 2-1 obviously does not provide the entire detailed story as far as all the characteristics of all the media investigated are concerned. It is merely a brief summary intended to show, in a general way, some overall typical results. As mentioned previously, details of the results are found in the body of the report.

With respect to specific media, we can cite these key results:

1. Most silver media have a photometric response which is adequate for the present application. However, most of the available rapid processing techniques for silver halide are expected to be too complex and bulky for the present application. The most promising exception of available silver media which has been found appears in the type of rapid processing material typified by Polaroid type 46L diapositive. We have experimentally demonstrated simulated star field recognition after developing this material for only 1 second. In-place development of this material also appears feasible.

2. With respect to nonsilver media, the optically sensitive thermoplastics (or photoplastics) appear most promising. Although they presently have sensitivities typically about 1 to 2 orders of magnitude less than that of typical high speed silver media, they merit further investigation due to their rapid, in-place development and their reusability. Furthermore, the photoplastics appear ideally suited for landmark tracking where the sensitivity requirement is less severe.

    Some limited experiments of photometric response of one photoplastic material to simulated star fields, while not totally conclusive, encourage a more complete experimental investigation.

3. Other still newer media appear to have considerable potential merit from a photometric response point of view, but at present are judged to be probably insufficiently advanced from the standpoint of research and development or evaluated applicability as inputs to a coherent

system. Typical of these are the optically sensitive deformable membrane transducers (e.g., by Perkin-Elmer and also GE) and the semiconductor field polarizing media (e.g., by Itek). These media merit further investigation for application in the more distant future.

4. Many advanced media appear to have only limited potential applicability primarily from the standpoint of sensitivity and, in some cases, state-of-the-art development. Among these are photochromics, free-radical dye media, vesicular films, and certain dry silver media.

5. A brief evaluation of the applicability of image intensifiers has been made. These devices have recently become available in compact, lightweight form. A listing of some of these is provided. Optical gains of several orders of magnitude are possible. They merit continued evaluation from the point of view of application with advanced media which otherwise may not be applicable for reasons of sensitivity.

6. The image motion problem has been investigated. In one typical example, it is shown that typical attitude rates up to 1 rpm can be tolerated for rapid process silver halide and typical rates up to 10^{-2} rpm for advanced media such as photoplastics. Tolerances to angular rates under other conditions are presented graphically.

3.0 CONCLUSIONS

Based on this investigation, there appear to be media which are potentially applicable for the presently planned purpose. Specific media which appear most applicable are rapid process silver halide, particularly of the type typified by Polaroid diapositive (e.g., type 146L) and also photodeformable thermoplastics (i.e., "photoplastics" and thermoplastic xerography). Further experimental evaluation is desirable, however, particularly in the case of the photodeformables.

Several other media may look promising as they continue to be developed and evaluated. Among these are the deformable membrane modulators and the semiconductor electric field polarizer media.

Applicability of image intensifier for use with media otherwise not having sufficient sensitivity deserves further investigation.

4.0 RECOMMENDATIONS

As a result of the investigation, the following recommendations are made:

1. Perform further experimental evaluation of those media which have been cited in this report as having the most merit. These experiments should not only evaluate the point spread function photometric response, but should also include correlation response with the media in evaluation being used to record the input image. These experiments should emphasize rapid process silver halides and photodeformables.

2. Make selective experiments with image intensifiers and selected media which otherwise appear to have insufficient sensitivity.

3. Extend the image media investigation effort to include the problem of recording images of landmarks under a wide range of photometric conditions as required for an autonomous landmark tracker.

4. Continue to investigate other areas of coherent optical trackers such as optimum design of the frequency "band-limited" spatial filters, laser evaluation and selection, selection of the electro-optical readout system, and overall configurational design of the system.

5.0 DETERMINATION OF MEDIA SPECIFICATIONS (CONTRACT ITEM No. 1)

5.1 General Considerations for the Static Case

Here we will first consider the primary input image storage medium considerations involved in coherent star field correlation in the static case (i.e., with a vehicle perfectly stabilized relative to stellar space).

In general, the recognition and tracking of the entire system will be determined largely by the various point spread functions, modulation transfer functions, and coherent transfer functions of the various parts of the system.

The principal factors expected to be significant are:

1. The point spread function of the input optics (i.e., the star field telescope optics).

2. The point spread function of the input imaging media (i.e., the sensor spread function).

3. The transfer function response of the spatial filter. (This is influenced by the transfer response of the filter making system, the input image from which it was made, and especially the modulation transfer function of the filter media). Typically the spatial filter will be frequency band limited.

4. The coherent transfer function response of the recognition system.

5. The response function of the correlation function (correlation spot) electro-optical readout system.

Since these various system component parts include both coherent and non-coherent response functions as well as square law detector response, considerable caution must be observed in analytically combining their overall responses.

The subject of the present effort relates to the input media of the recognition system. However, the specifications of this media cannot be determined without consideration of the other system elements. For example, if the resolution of the input optics is less than that of the input media, then the resolution of the media may not represent a critical design specification. Likewise, the granularity of the electro-optical readout system may limit the overall tracking accuracy rather than the resolution of the input media.

We will consider first the likely response of input optics which are believed to be typical of star field telescope optics.

5.2 Why Photography of Stars Significantly Differs from Photography of Extended Objects - A Qualitative Discussion

Astronomers have, for a long time, realized that photography of stars differs significantly from photography of extended objects. One cannot simply use normal considerations of sensitivity (e.g., ASA rating) and optical energy to predict modulation of the media. Factors such as optical "blooming" in the media and the spread function (e.g., diffraction and aberration) of the optics becomes very significant in predicting the photographic response to a star image. Here, we will briefly discuss some of the fundamental considerations as applied to star photography with both conventional and nonconventional media.

Since the stars have no size no matter how much they are magnified, they are a special photographic problem. The photographic image intensity of an <u>extended</u> <u>object</u> is proportional to the square of the relative optical aperture:

$$\left(\frac{A}{F}\right)^2$$

where

      A is the clear aperture of lens
      F is the focal length

and the image size (or scale factor) is proportional to F. However, for a point object such as a given star, the photographic image intensity varies as A^2. That is to say, it depends on the clear aperture only, and the size is dependent chiefly on the diffraction characteristics and quality of the lens.

Thus, the magnitude of the faintest star shown on a given photographic plate, with a given exposure, depends on the clear aperture of the lens; to put it another way, with a lens of given aperture and a plate of given speed, the magnitude threshold depends on the length of exposure. Hence, for star field photography, focal length can be used to determine the scale of the star field on the plate and the lens aperture (not relative aperture) to determine the magnitude of the detectable star for a given exposure.

Consider now the problem from the film speed aspect. If the exposure time is limited by motion or other difficulties, and the aperture in a spacecraft is limited by physical size and weight, then the film speed must be high enough to record the required magnitudes.

The "blooming" of overexposed images is a property of the photographic image spread function. Most conventional photographic materials are turbid, and light tends to spread out sideways so that an overexposed image may grow to nearly any size with sufficient light. This property is closely linked with turbidity which, in turn, depends

on particle size such that fine-grained and slow emulsions tend to have less image spread. Extremely fine-grained emulsions with particle sizes less than 0.1 micron have image spreads measurable in microns.

In order to achieve the desired correlation function response, it is probably desirable to have the same general degree of image spread in the sensitive material used in a star field correlation as was used to image the reference star field which was used to make the filters supplied to the star field tracker. The image given to the recognition system contains only two kinds of information about the stars:

1. The geometric configuration of the star field

2. The relative "size" of each star in the field

This latter item is somewhat artificial since this size is chiefly due to the spread function of the material on which the photograph was made. Nevertheless, relative size of the star image on the developed media is a function of star brightness (and of the media "blooming" and other factors listed above).

At this point, one should ask the question: In star field recognition, should one make use of both of these kinds of information, or should one attempt to normalize the size effect and operate only with the geometric configuration data? This question may seem unnecessary. However, it arises because, for certain imaging media, there may be uncertainties in the relationship between star image size and stellar magnitude. This might be especially significant if different media were used for recording the candidate star field image on the vehicle. A tentative opinion would suggest that both types of data should be retained. This may require using the same media for the two functions discussed above.

We note in passing that it is common practice to make the photographs for a star atlas or map on plates particularly chosen to show different magnitudes of stars as different size images.

Before leaving the subject of star photography, some consideration should be given to spectral response of stars. Spectral sensitivity is difficult to evaluate. The majority of stars produce considerable blue and near ultraviolet light so that a photograph taken on a plate sensitive to blue and ultraviolet gives only an approximation as to what the eye sees or what can be photographed on a panchromatic emulsion. There are a few red stars, but their number is small. On the other hand, since most stars are essentially black body radiators with a few superimposed emission lines, photography in the visible or infrared spectrum will make little difference except to differentiate the relatively few near infrared stars present.

At this point we should make some passing comment on reciprocity of the media. Reciprocity is probably of somewhat limited concern since, in general, we are always considering relatively short exposures. None-the-less we would expect that the media should exhibit a considerable degree of reciprocity for exposures up to 5 or 10 seconds.

5.3 Response of the Star Field Telescope Optics

Here we will make some quantitative evaluation of the response of the star field telescope optics.

Specifically we will determine as functions of the parameters of the optical telescope:

1. The optical point function response (i. e., image blur circle)

2. The total optical power collected as a function of stellar magnitude

3. The average optical power density of the focused star image

The optical power density is simply obtained from the other two response quantities: optical point function response and total collected optical power. Hence, it does not provide any new data and it would not be especially useful were it not for the fact that sensitivity of media are so frequently specified in terms of energy density (e. g., as specified in watt-sec/cm^2 often without indicating the corresponding resolution).

In order that a star field can be identified, a sufficient number of stars in the optics field of view must be sensed to form a recognizable pattern. The number of detectable stars in the optics field of view depends on the optics clear aperture (A), optics focal length (F), and recording medium size. For instance, if the star sensing system has only medium sensitivity, then one needs a relatively large optics clear aperture and a relatively large field of view. This field of view is obtained by choosing as short a focal length as possible consistent with the recording medium width (image size) and realizable optics f/number.

We will not, in this effort, enter into the matter of stellar populations as a function of star magnitude in the various portions of the celestial sphere. This topic is of obvious concern in determining the requirements for an all-attitude system. The present effort, however, which is concerned with imaging media, will take guidance from NASA and other studies in this matter. Based on these inputs, we will be concerned with stellar magnitude as faint as 4th magnitude and optical fields of view as great as 45°.

For convenience, we summarize the interrelationship of the optical parameters here:

$$\text{Field of view} = \left(\frac{D}{F}\right); \qquad \text{f/No.} = \frac{F}{A}$$

where

D = image format diameter

F = focal length

These relationships are shown diagramatically on the left side of Figure 5-1.

The relationships are shown for two values of image format diameter which are expected to be realistic: 2.5 and 5.0 cm. The former value is typical of 35 mm film width, while the latter is associated with 70 mm film. If the image diameter is selected, its combination with a field of view gives the optics focal length (F). If the optics clear aperture is also selected, then the optical speed (f/number) follows.

Depending on the value of the focal length, the f/number, and image diameter, present state-of-the-art optics can realize optics spread function diameters shown on the right side of Figure 5-1.

The point spread function (image blur circle diameter) is a function of the f/no. and the focal length, where this relationship may be either a simple diffraction response (Airy Function) or a more complex function of the aberration of the optics.
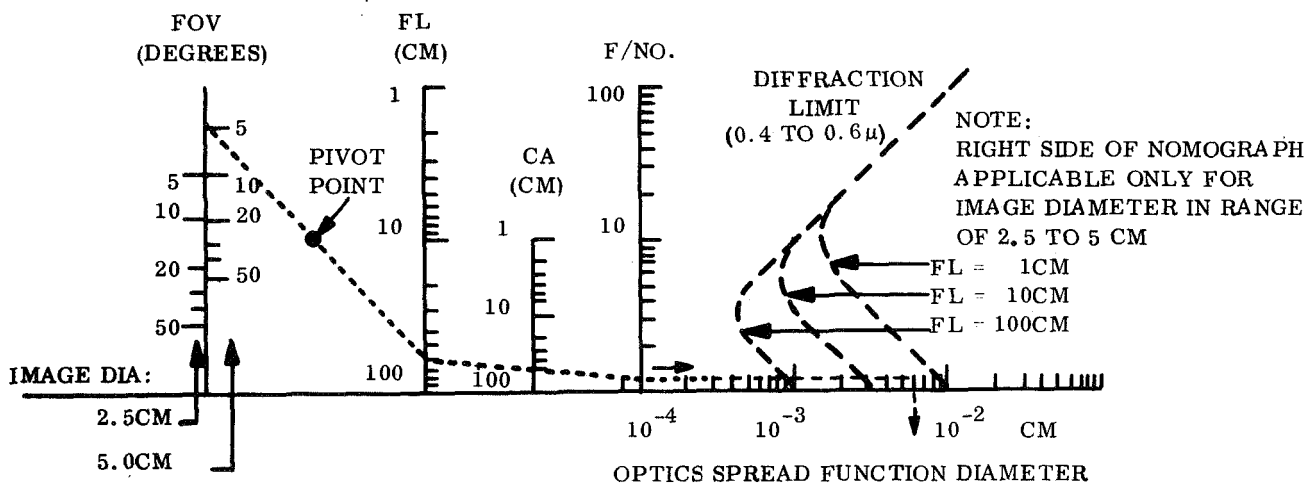

Figure 5-1. Interrelationships of Parameters of Star Field Telescope and its Point Spread Function (i.e., Blur Circle) for Realizable Optics

Whether or not the optics are truly aberration-limited depends on the focal length and the image size for a given f/No., and also on the care and expense with which the optics are designed. Typical blur circle response is shown the right side of Figure 5-1 corresponding to realistically available optics. Note the effect of aberrations for the lens shown as 3 possible curves depending on the focal length. (By blur circle diameter, we mean diameter to the first minimum in the case of diffraction limited optics and to the diameter containing about 90 percent of the energy in the case of aberration limited optics.) For most realistic optics, it is expected that the optics spread function diameter will have a value in the general range between 10^{-3} to 10^{-2} cm.

The overall purpose of Figure 5-1 has been to provide a means of determining the image size over which the stellar optical power will be spread on the input imaging media as a function of the optical parameters. It remains now to determine the amount of optical power to be collected by a given optics as a function of the stellar magnitude and the optical parameters. As discussed above, the primary optical parameter which is of concern in determining the brightness of star images will be the clear aperture. Combining this collected power data with the point spread function or blur diameter data (as shown on Figure 5-1) will allow us then to determine optical power density obtained on the media. Then, by making some judgment with respect to exposure times, this can be related to the energy density required for the various media being considered.

Figure 5-2 shows the optical power density relationship. On the left side we see power collected by the optics from a single star of a given magnitude and as a function of the clear aperture. The collected power is shown as that radiated over the entire spectrum.

It next becomes necessary to relate sensed power to collected power where we here define sensed power as that fraction of total collected power which lies within the sensitive spectral range of the sensor material.

The power collected from the source is larger than the sensed power value, due to the spectral mismatch between source and sensor. If the source is a star (with typical color temperature ranging from 6,000 to 12,000°K), a wide variety of sensor materials will register a fraction typically equal to about 0.4 of the total power collected (wavelengths zero to infinity). When evaluating a specific new medium, consideration must be given to its spectral response so as to determine the ratio of sensed power to collected power for that medium.

On the right side of Figure 5-2 we show lines of constant average energy density as a function of total sensed power (in watts) and diameter of the sensed spread function. Here we define the sensor spread function as a measure of the size of the resolution element of the sensing media.
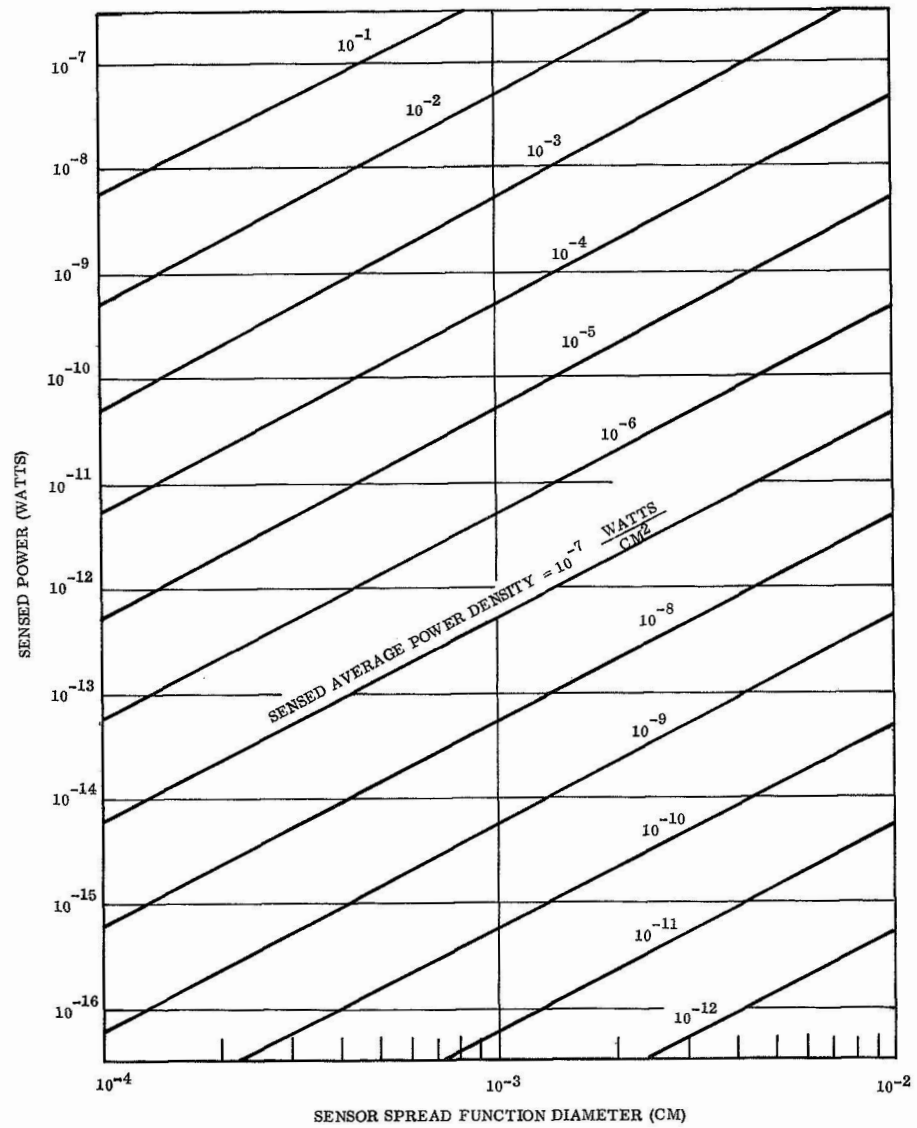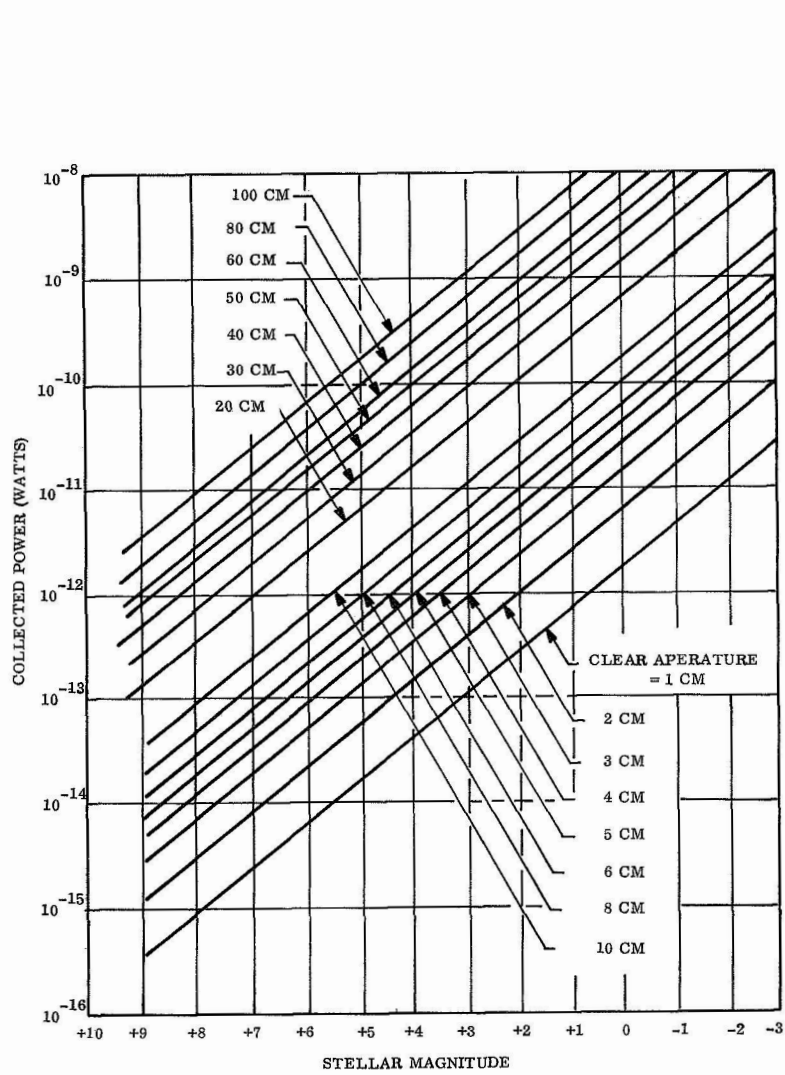
Figure 5-2. Optical Power Density as a Function of Stellar Magnitude and Sensor Point Spread Function

Consider now the relationship between the sensor spread function and the previously defined optics spread function. A matched design where these two spread functions are nearly equal is expected to be optimum for many applications. In any event, it is expected that the optics point spread function should not be greater than the sensor spread function. Typically it should be somewhat smaller.

If, for example, the optical point spread function were larger than the sensor point spread function, then we would have, in effect, parallel sensing paths and a consequent reduction in the effective use of the available optical energy.

If, on the other hand, the optical point spread function were significantly smaller than the sensor point spread function, then we may be imposing excessively severe requirements as far as the design and fabrication of the optics is concerned. Nonetheless, this situation where the optics point spread function is smaller than the sensor point spread function would have some unique advantages with respect to tolerance of image motion, rotational mismatch and/or distortion (e.g., stretching) of the imaging media.

We conclude that in a well-designed system, the optical point spread function should, at most, not be greater than the sensor spread function. It may, however, be somewhat less (say by a typical factor of 2) than the sensor spread function.

These factors of the relative size of these two spread functions must be taken into consideration when interpreting the data of Figures 5-1 and 5-2 with the objective of determining available optical energy density for a given stellar magnitude and a given set of optical parameters. When these factors are appropriately considered, one can use the data of these figures to determine the optical power density response of a given star magnitude and telescope optics.

For example, consider a specific typical case where:

Field of view $= 20^{\text{o}}$

Image diameter $= 5$ cm

Clear aperture $= 10$ cm

The resulting optical spread function diameter $= 2(10^{-3})$ cm. When detecting a 4th magnitude star, we see that total collected power $= 2(10^{-12})$ watts.

Assuming a 0.4 ratio of sensed power to collected power, the results indicate total sensed power $\approx 10^{-12}$ watts.

Assuming that the optics spread function and the sensor spread function are nearly equal, we have:

$$\text{Sensed power density} = 3(10^{-7}) \ \frac{\text{watts}}{\text{cm}^2}$$

With the data and assumptions of Figures 5-1 and 5-2, we can then plot contours of constant sensed power as a function of the two most interesting parameters: clear aperture and field of view. This is done for two values of image format diameter 2.5 cm and 5 cm as shown in Figure 5-3. The data shown in this figure is that for a 4th magnitude star (which was specified in the contract work statement as of special interest, being the faintest star which we would find necessary to sense).

The data plotted in Figure 5-3 is directly useable in determining the required range of exposure times in order to obtain the energy density (watt-sec/cm^2) required for any particular sensing medium. This we will do subsequently for specific media.

Engineering judgment would indicate that realistic clear apertures are expected to lie in the range of about 4 to 40 cm. Likewise, the most likely range of the field of view is 4° to 40°. (This area is indicated in Figure 5-3 where we have made a compromise assuming an image size of 4.5 cm. We see from this presentation that about the lowest power density which we need consider is 10^{-7} watts/cm^2 (for a 4th magnitude star and a clear aperture of 4 cm). The highest power density which can be anticipated (for 4th magnitude stars) is about 10^{-5} watts/cm^2.

We conclude that, as far as the static case is concerned, we should concern ourselves with media which are sensitive for realistic exposure times in the general range of 10^{-5} to 10^{-7} watts/cm^2.

Of course, relaxing the stellar magnitude requirement would relax this sensitivity requirement. Likewise, use of an image intensifier could relax this requirement by perhaps 2 orders of magnitude or more.

In order to define the media energy sensitivity required, we need to make some judgment as to exposure times. This, of course, involves image motion which is the subject of the next section. At this time, however, we would expect that exposure times should preferably be limited to no more than about 10 seconds. This would indicate a requirement for a media which is adequately responsive to energy levels of about 1 microjoule/cm^2.

Furthermore, considerations of realistic optics indicate that this energy will be imaged over an image spread function diameter ranging from 10^{-3} to 10^{-2} cm.
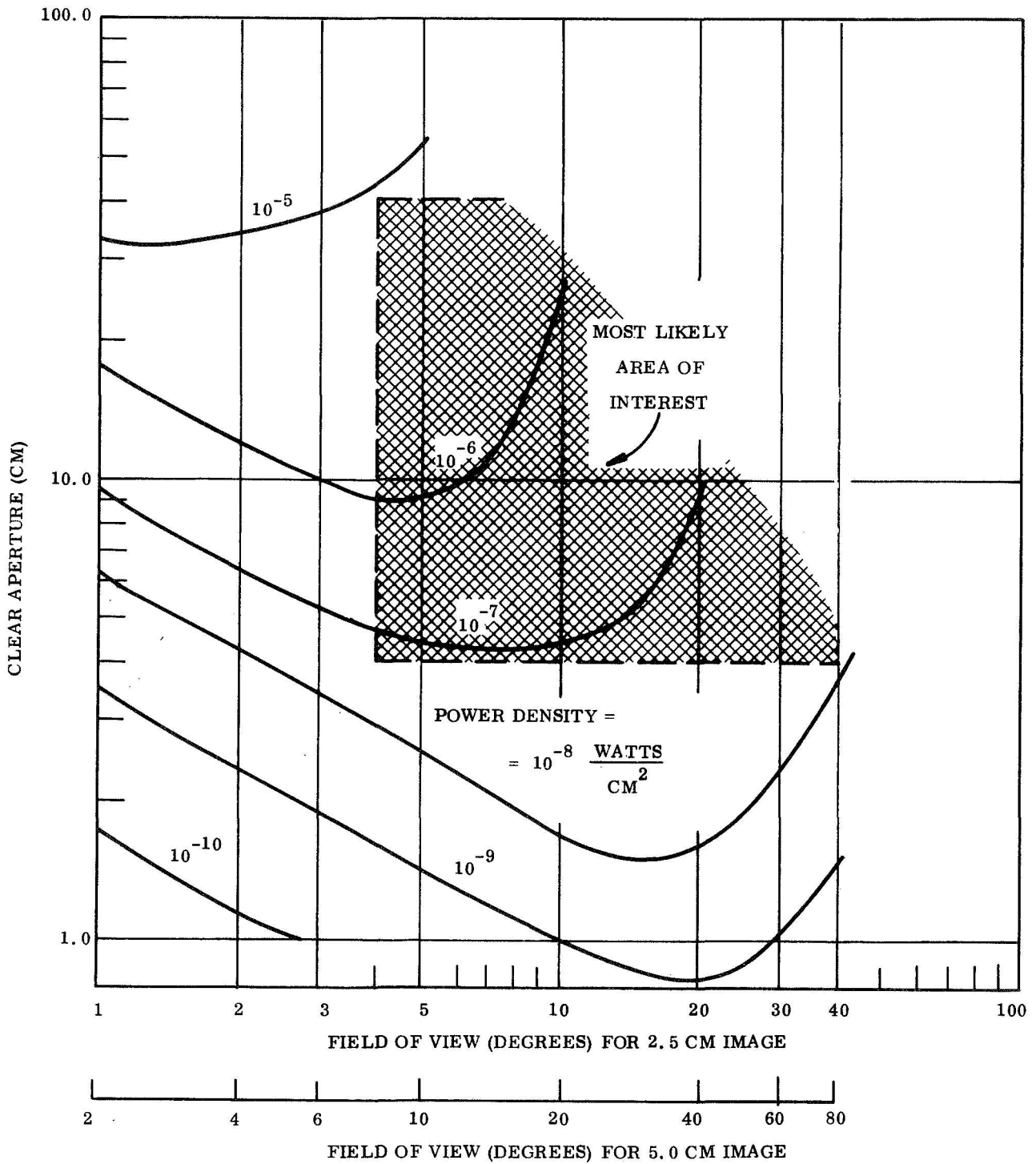
Figure 5-3. Clear Aperture Versus Field of View Showing Contours of Power
Density Resulting from a 4th Magnitude Star and Realistic Optics

6.0 CONSIDERATIONS OF IMAGE MOTION DUE TO VEHICLE ATTITUDE RATE ON THE COHERENT CORRELATION

6.1 General Effect of Angular Rate on Correlation

Vehicle attitude rates during exposure of the input image are going to generally result in star images on the image plane which are lines (i.e., arcs) of finite width and length rather than point spread functions. The length of the arc will, of course, be a function of the exposure time, the attitude rate, and the position of the star on the image plane relative to the axis of rotation.

In general, presuming for the moment adequate exposure, one would expect two effects of image motion: a broadening of the cross correlation function on the output plane and a reduction in the peak value of the correlation function. This is illustrated in a simplified concept in Figure 6-1 in the case of a single star image.

INPUT STAR IMAGE   INPUT STAR IMAGE

REFERENCE STAR IMAGE   REFERENCE STAR IMAGE

CORRELATION RESPONSE   CORRELATION RESPONSE

A. CORRELATION WITH 1 STAR   B. CORRELATION WITH 1 STAR
   (NO IMAGE MOTION)   (LINEAR IMAGE MOTION)

Figure 6-1. A Simplified Illustration of the Effect of Image Motion on Star Image Correlation (Where all Images are Shown in the Spatial Domain as Binary Images with no Frequency Band Limiting)

In general, as the image is smeared due to attitude motion about some vehicle axis during image exposure, one would expect an elongation of the correlation response (i.e., correlation spot in the output plane). This has been observed experimentally. When one considers the appropriate scale factors relating the output plane to the magnitude of the vehicle rotation, then one would expect that the elongation of the correlation function would correspond in magnitude and in axis of rotation to that of the vehicle during the exposure.

Whether or not that elongation of the correlation function would or would not correspond to an uncertainty in the tracking of the star field depends on other design factors of the instrument. For example, by some added complexity one could design an electro-optical readout logic to determine the center (or beginning or end) of such an elongated correlation function. In this way one could design a readout that could not only determine angular orientation at any unique time during the exposure but could even determine angular rate during the exposure (by measuring the length of the correlation function). Going further, o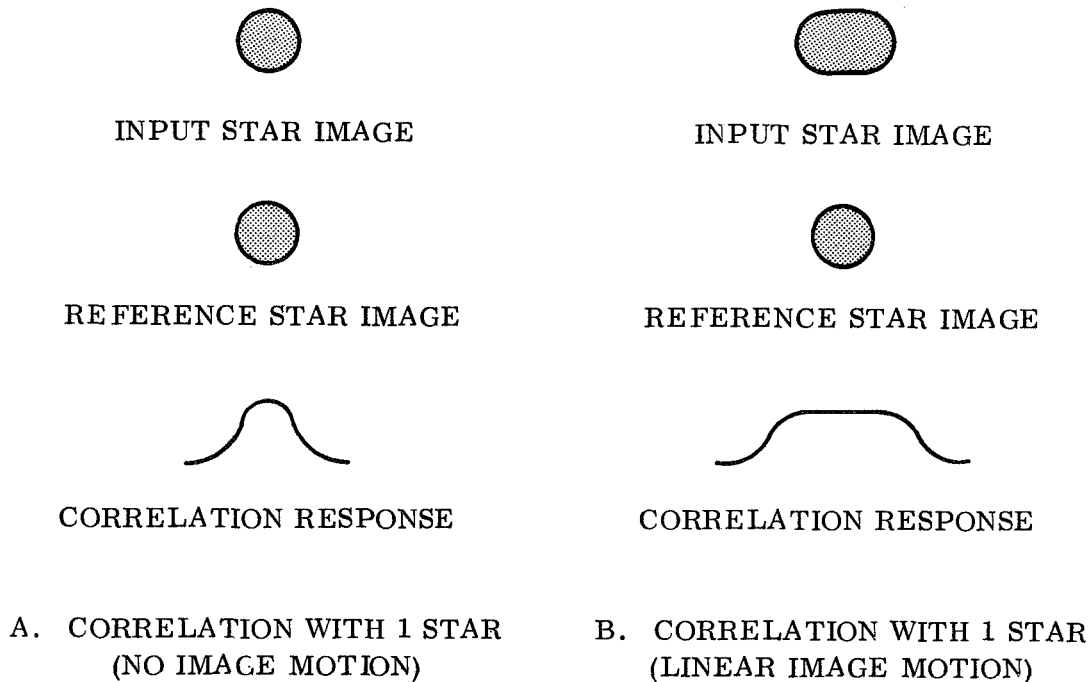ne could conceive of a readout logic which could even compute the center of the arc of a curved correlation function in order to determine the axis of rotation during the exposure. The implementation of such schemes, however, presumes no significant attitude acceleration during exposure. This is probably a realistic assumption. (Considerable question exists, however, with respect to the practicability of this approach as the best technique for measuring vehicle angular rates.)

Nevertheless, it is pointed out that an elongation of the correlation readout does not necessarily imply an increase in uncertainty in obtaining the vector direction to the star field.

Consideration will next be given to how great a vehicle attitude rate can be tolerated in view of the exposure time required to form an adequate modulated image on the various media.

6.2 Maximum Permissible Vehicle Angular Rates as Determined by Exposure Requirements

It has been seen in the discussion on the static case that one can relate required minimum exposure time to the parameters of the optics, the sensitivity of the image media, and the intensity of the star.

In the dynamic case, image motion imposes one further limitation. This can be described as the maximum permissible value of the minimum exposure time. (In an alternative viewpoint, one can ask the question: what is the maximum permissible attitude rate as a function of the minimum exposure time as defined for the static case ?) Here, by minimum exposure time, it is meant that minimum value of exposure, as defined by the static conditions discussed previously. By maximum allowable value

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of that minimum exposure time, one refers to that maximum value as imposed by image motion considerations (i.e., motion which will cause an excessive displacement of the optical blur circle on the imaging media during exposure).

In summary, one defines:

$(\Delta t)_{min}$ = minimum required exposure time as defined by static case.

$\left((\Delta t)_{min}\right)_{max}$ = maximum allowable value of minimum exposure as constrained by image motion considerations.

It is evident that one has an acceptable photometric condition whenever:

$$(\Delta t)_{min} \leq \left((\Delta t)_{min}\right)_{max}$$

and an unacceptable photometric condition whenever:

$$(\Delta t)_{min} > \left((\Delta t)_{min}\right)_{max}$$

More specifically $\left((\Delta t)_{min}\right)_{max}$ will be that time during which the star image optical blur circle has not moved, due to image motion, by more than some acceptable fraction, K_a, of the point spread function (i.e., size of the resolution element) of the imaging medium.

Stated another way, one would expect that the star images should not move more than some fraction of the sensing medium resolution element size during the exposure time which provides the minimum necessary energy for the available optics and media.

Let it be assumed that the vehicle has an angular rate, ω, about some axis fixed relative to the vehicle. If Δt is the exposure time, then the vehicle will have rotated about the axis of rotation through an angle of $\omega \Delta t$ during the exposure.

Then a given star (the ath star) will have rotated, during exposure, through an angle $(\omega \Delta t) \sin \theta_a$, where θ_a is the angle between the vehicle axis of rotation and direction to the ath star.

For a telescopic optical system which is imaging the stars on the input plane, one can relate the angular displacement of the star image $(\omega \Delta t \sin \theta_a)$ to a displacement, (Z_a), on the input plane:

$$Z_a = (\omega \Delta t \sin \theta_a) F$$

where F is the focal length of the telescope optics.

If one limits the displacement of the star image to some fraction (K_a) of the sensing medium resolution element (which will be denoted by D_m), one then has:

$$K_a D_m = \omega \left((\Delta t)_{min} \right)_{max} F (\sin \theta_a)$$

or

$$\left((\Delta t)_{min} \right)_{max} = \frac{K_a D_m}{\omega F \sin \theta_a}$$

This equation says that for a given vehicle attitude rate, ω, about a given vehicle axis oriented along some axis relative to a selected a^{th} star (which determines θ_a), and for a given optical system and imaging medium (which respectively determines F and D_m) that there exists some maximum allowable value of minimum exposure time which can be tolerated without permitting excessive motion of the ath star blur circle during exposure.

Note that image motion does not necessarily impose a limitation on maximum exposure time $(\Delta t)_{max}$. As has been discussed in Section 6.1, a long exposure time may be permissible if the electro-optical readout can properly interpret the elongated correlation function response and if the dwell time on each blur circle area is also long enough to adequately expose the media.

As one will see, D_m may typically range from 10^{-3} to 10^{-2} cm, depending on the medium.

In order to achieve integration of adequate optical power density over a given resolution element, it would be expected that K_a should be limited to some fraction typically ranging from 0.1 to 0.5. For present purposes in the illustration and plots, a value of $K_a = 0.5$ will be chosen.

Shown on the following plots (Figures 6-2 to 6-4), are the maximum allowable value of the minimum exposure time $\left((\Delta t)_{min} \right)_{max}$ as a function of vehicle angular rate, and the parameters of the optics and the imaging medium: the focal length, F, and size of the medium resolution element.

For convenience, this data is plotted as a function of the ratio of $\frac{D_m}{F}$, which is the diameter of the resolution element as normalized to the focal length of the optics. Since D_m will typically lie in the range of 10^{-3} to 10^{-2} cm and since the focal length will typically lie in the range of 5 to 50 cm, one will be most interested in that region of the ratio $\frac{D_m}{F}$ ranging between 2 (10^{-5}) and 2 (10^{-3}).
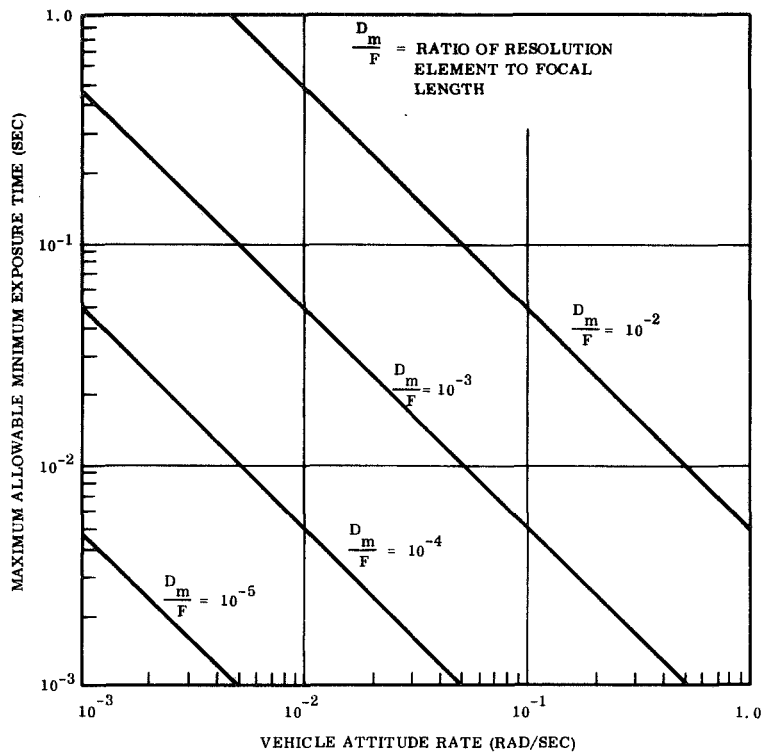
Figure 6-2. Maximum Allowable Minimum Exposure Time as Limited by Vehicle Attitude Rate - Case 1: $\theta = 90^{\circ}$
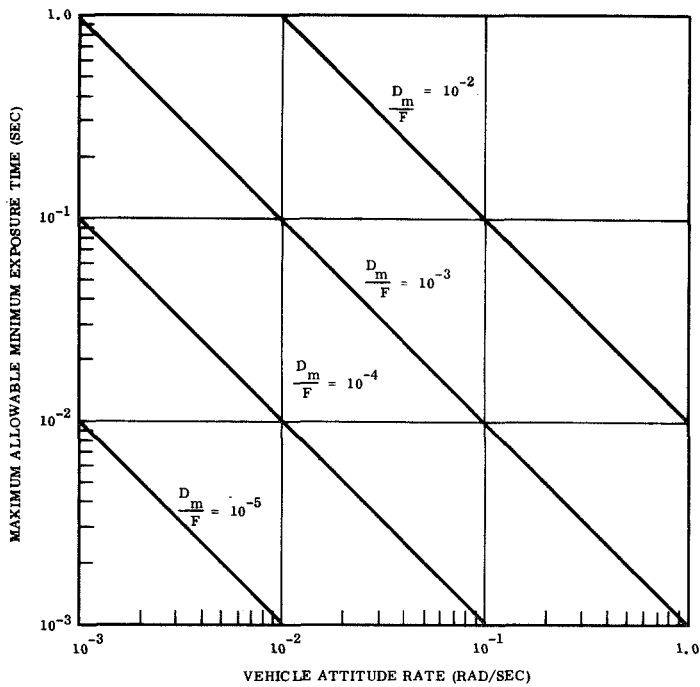
Figure 6-3. Maximum Allowable Minimum Exposure Time as Limited by Vehicle Attitude Rate - Case 2: $\theta = 30^{\circ}$
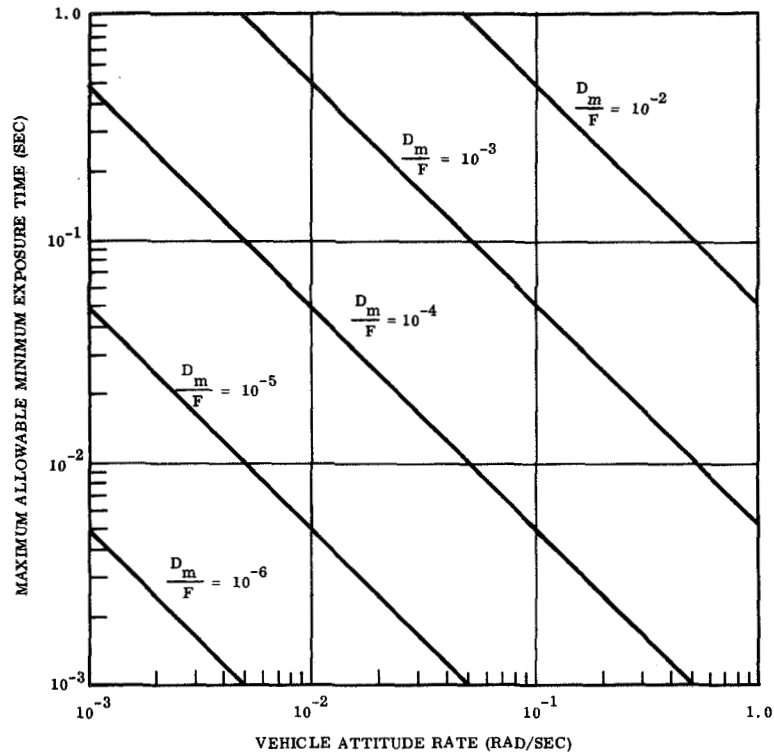
Figure 6-4. Maximum Allowable Minimum Exposure Time as Limited by
Vehicle Attitude Rate - Case 3: $\theta = 6^O$

Three plots are shown for three values of θ_a: 90°, 30°, and 6°, the angular displacement of the axis of rotation relative to the direction to the star.

It is evident that these plots could also be interpreted as showing the maximum allowable vehicle attitude rate for a given minimum exposure time.

As one would expect, it can be seen from these plots that as vehicle altitude rate (ω) or displacement angle (θ) or focal length (F) are increased, the maximum allowable value of minimum exposure time is reduced. Likewise, as the size of the resolution element is increased, the maximum allowable value of exposure time is increased.

What has been said so far refers to images of single stars. But the relationship also applies to star fields provided the value of θ_a is approximately the same for all stars in the star field. This is nearly true for large values of sin θ (e.g., when $\theta = 90^O$). It is also a reasonable approximation whenever half the optical field of view is significantly less than the angle between the attitude rate axis and the optical axis of symmetry.

In other cases, for example, where the spin axis lies within the optical field of view, the requirements on the maximum allowable minimum exposure time will be some-what conservative. A precise evaluation of the maximum allowable minimum exposure

time as a function of roll rate (or conversely the determination of maximum allowable angular rate as a function of minimum exposure time) for the case where the vehicle is spinning about an axis located in the field of view of the optics would require a knowledge (or, at least a statistical measure) of the location of each star in the star field. This is judged to be beyond the scope of the present effort.

6.3 A Specific Example of Image Motion

Now consider a specific example of how one might use the above described plotted data. Consider, for our typical example, the same parameters as considered in Section 2.0 and Figure 2-1. For purposes of simplicity, it will also be assumed that the optics point spread function is here equal to the medium resolution element.

Let us assume we have the following optics:

Field of view $= 10^{o}$

F $= 20$ cm

Clear aperture $= 15$ cm

Format size $= 2.5$ cm

f/No. $= 1.3$

Resulting blur circle diameter $= (2) 10^{-3}$ cm (See Figure 5-1.)

$\dfrac{D_m}{F} = 10^{-4}$

For the case of a 3rd magnitude star, this will result (see Figure 5-2) in an optical power density of $2(10^{-6})$ watts/cm^2 (average).

As one will see, this compares, for example, with typical estimated energy density requirements of:

Typical rapid process silver halide: $5(10^{-9})$ to $5(10^{-8}) \dfrac{\text{watts-sec}}{\text{cm}^2}$

Typical photodeformable: $(5) 10^{-7}$ to $5(10^{-6}) \dfrac{\text{watts-sec}}{\text{cm}^2}$

For this specific case, this leads to the following required minimum exposure times as determined by sensitivity in the static case:

Rapid process silver halide: $2.5(10^{-3})$ to $2.5(10^{-2})$ sec

Photodeformable: $2.5(10^{-1})$ to 2.5 sec

Entering this data on the preceding 3 plots, one can determine maximum allowable vehicle attitude rate as a function of required media exposure energy. This is shown in Figure 6-5 for the typical case considered. Vehicle stability requirements for other assumed parameters can be determined in a similar manner.

For the typical case shown, it is evident that for many of the advanced media considerable vehicle stability would be required (typically rates not greater than 10^{-2} rpm). Using faster media such as rapid process silver halide can greatly relax those vehicle stability requirements (typically rates up to one rpm could be tolerated).

In general, more sensitive media, larger apertures, shorter focal lengths, or the use of image intensifiers will permit greater acceptable vehicle attitude rates. The concepts presented here can be applied to any specific media and optics parameters being considered.
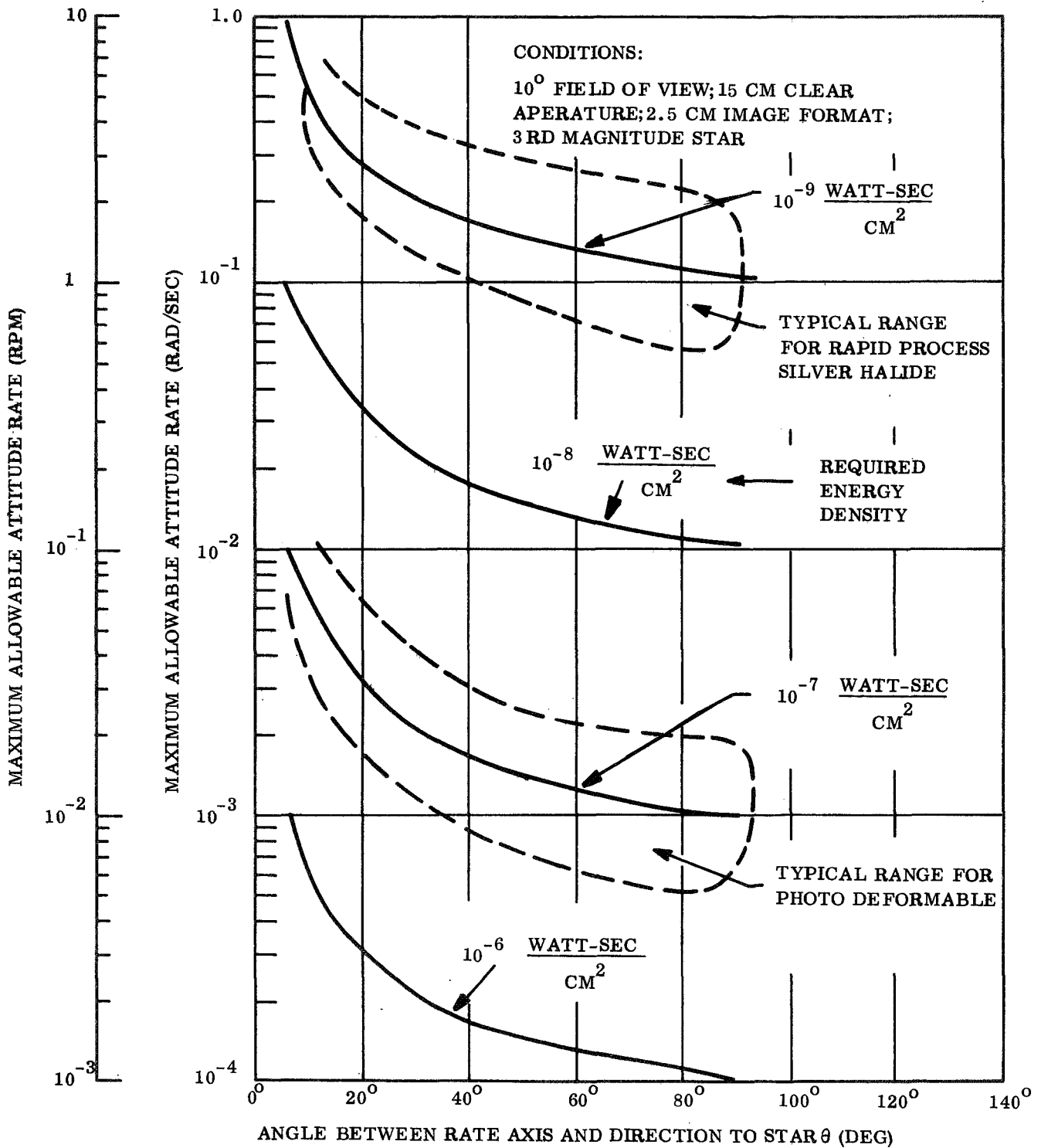
Figure 6-5. A Typical Case: Maximum Allowable Attitude Rate as a
Function of Required Media Exposure Energy

7.0 DISCUSSIONS OF IMAGE MEDIA AND PROCESSES

A large number of suppliers and developers of imaging media were contacted with the objective of obtaining as much information as available on media and media processing techniques which might be applicable for the present purpose. Although much data was obtained as a consequence, it is also evident that several companies were unwilling to provide data for reasons of proprietary security. One can conclude that several organizations are conducting extensive efforts in the field of advanced imaging media. Consequently, a review of media becoming publicly available should be made periodically.

Table 7-1 summarizes the data obtained on the various candidate image media and media developing processes. A brief discussion of some of the more promising of these media and processes follows.

Some caution should be observed with respect to interpreting Table 7 particularly in the subject of resolution and sensitivity: Values given for maximum sensitivity are not necessarily applicable to conditions of maximum resolution as listed. Frequently maximum sensitivity will be achieved at spatial frequencies which are considerably lower than the maximum which is achievable.

In most cases data listed in Table 7 is based on that which was supplied by various image media suppliers or was available from open literature. This accounts for some divergence in units of sensitivity and resolution. For example sensitivity is sometimes indicated in terms of required optical energy density. In other cases it is indicated as an "equivalent" ASA.

7.1 Rapid Process Silver Halide Processors

A number of these automated processes for developing silver halide are available (see Items 7, 8, and 14 through 18 of Table 7-1, for example). With a few exceptions, most of these have been developed for commercial purposes and are not readily adaptable to application in a spacecraft. Processes which require one or more liquid baths are not considered practical for the present purposes.

At least two processes, Bimat (by Kodak and Mark Systems, Inc.) and Poromat (formerly known as Fairweb, and now produced by Townley Chemical Company, but formerly by Fairchild Camera and Instrument), have been developed for space application. Bimat was successfully used on the Lunar Orbiter, for example. Poromat is believed to provide only a positive print whereas Bimat gives both a negative and positive. In general, these processes tend to use equipment which is heavier and bulkier than one would like for a compact holographic star field mapper.

No processor of this type is known, for example, to be able to develop an image "in place" as would be desirable. One of the most compact silver media developers of

this type which has been seen is the model 1200 developed by Mark Systems Inc. It is not known whether or not this type of processor can be modified for a space application.

From a photometric response point of view, most of these various automated processes can operate with a wide range of photographic film with little or no degradation of film response. At the present time they are judged, however, to be disadvantageous for reasons of complexity of mechanization, significant time delays in processing, lack of in-place development, and in some cases, noncompatibility with operation in a space environment.

7.2 Polaroid Lantern Slide (Diapositive) Media

One of the more promising of the silver halide media is of the type made by Polaroid: Polaroid diapositive Lantern Slide film (Types 46L and 146L).

These two types have these general rated approximate characteristics:

Type	ASA	Contrast	Resolution	Recommended Development Time
46L	800	Medium Contrast	35 l/mm	190 sec
146L	800	High Contrast	35 l/mm	15 sec

Unlike most Polaroid film, these films produce a positive transparency which is the ideal form for an operating medium for star field recognition.

These films require a further operation ("Dippit") to produce a dry and hardened copy. This "Dippit" operation, however, is not considered necessary for an application such as the presently considered one where only one coherent processing operation and no permanent storage of the image is required.

Some experiments have been performed with these Polaroid films. In one series of experiments, an effort was made to determine how much shorter the development time could be made. At ambient temperatures, it was found that for Type 146L film the development time could be reduced to about 3 seconds (from the recommended 15 seconds) without experiencing significant image degradation. By applying heat, in the range of 115°F, it was possible to develop good usable photos in about 1 second.

Some experiments were made to determine the response in the coherent correlator when Type 146L film was used to store an input image. These experiments, which did not use a liquid gate, are described in Appendix C. They show that it is possible, when using films developed in about 2 seconds, to achieve correlation performance, for one typical case, which is only slightly degraded from that obtained with Type 649 Micro flat plates (S/N ratio of 33:1 as compared to 42:1).

This media, of course, is not reusable and it is normally not developed in-place. Nonetheless, it is expected that it would not be difficult to design a technique for in-place development so as to avoid tracking errors which might result from moving a recorded image from an exposure station to a separate coherent processing station.

Yet to be more fully explored are problems associated with long-time operation in a space environment.

Based on the above results and discussion, silver halide media of the Polaroid diapositive Types 46L and 146L appear to be among the more promising candidate media. It is recommended that a compact in-place device, capable of being heated, be implemented so as to experiment with using this type of media with even shorter processing times and to perform further coherent optical experimentation. It is also recommended that the required amount of film for various realistic missions be estimated.

7.3 Photosensitive Photodeformables

Under this heading is found a type of materials which are generally referred to by a variety of names such as: photoplastic recording (PPR); photosensitive thermoplastics and thermoplastic xerography. The command elements of these media are photosensitivity (by a photoconductor) and subsequent surface deformation by temporary thermal modification of the rheological properties of the plastic media.

General Electric has worked in this area for more than a dozen years. Besides General Electric, Xerox Corporation is known to be active in the development of this type of media. Other organizations are known also to have been active in the area of this type of photodeformables. However, for proprietary or other reasons, it has not been possible to obtain related data on sources other than GE and Xerox Corporation (see Items 1 and 2 of Table 7-1 for a summary of GE and Xerox supplied data.)

Since these media are among the more promising, it is worthwhile to discuss them in somewhat further depth. This discussion will be found in Appendix B.

With respect to the range of sensitivity of photodeformables, Xerox quotes a usable range of required energy densities from 10^{-7} to 10^{-4} $\frac{\text{watt-sec}}{\text{cm}^2}$ depending on the selection of the photoconductor. It is not known just what usable means here in terms of signal-to-noise ratio in a coherent system. A more recent paper (Reference 43) cites, without further interpretation, a sensitivity for thermoplastic xerography in the range of 10^{-8} to 10^{-5} $\frac{\text{watt-sec}}{\text{cm}^2}$ required energy density.

General Electric has measured required energy densities in the range of 0.5 (10^{-5}) to 10^{-4} $\frac{\text{watt-sec}}{\text{cm}^2}$ depending on the particular sample and the method for conducting the experiment. (See Appendix A for a discussion of one experiment conducted for this present program.) It is expected that, with very thin PPR film, energy densities in the range of 10^{-8} to 10^{-6} $\frac{\text{watt-sec}}{\text{cm}^2}$ may produce deformations in the range of 0.05μ.

It is cautioned that sensitively can be defined only in terms of observed performance of the total system as defined by a signal-to-noise criteria.

As far as resolution is concerned, resolution up to several hundred lines/mm (i.e., greater than that of typical optics) can be achieved by using very thin films.

In general, these materials look very promising and require energy densities typically in the range of 10^{-7} to 10^{-4} $\frac{watt-sec}{cm^2}$. This is very acceptable for landmark tracking and depending on tolerance for optics size and/or vehicle stability, may be promising for star field recognition even without an image intensifier.

Although these photoplastics do not have sensitivity as great as that of silver halide media, they are of great potential interest because they can be developed in-place in times as short as 50 milliseconds and because they are reusable.

7.4 Deformable Membrane Transducers

These are deformable transducers of rather recent origin. In general, these devices are also photosensitive deformable materials. The photocharge imaging takes place typically by means of a photoconductive or photosensitive mechanism. In this respect there is some similarity with the photoplastics previously discussed. (See Items 27 and 28 of Table 7-1.)

The selective charge distribution results in a deflection of a membrane suspended with very low tensile forces over a field of aperatures having typical sizes of 10 to 100 microns. This, in principle, can permit resolution up to 100 lines/mm.

This device can be configured to be responsive to either optical power (as in the case of the Perkin-Elmer device) or optical energy (as in the case of the General Electric device). Required power or energy densities, as the case may be, are generally expected to be in the range of 10^{-4} $\frac{watts}{cm^2}$ and 10^{-7} $\frac{watts-sec}{cm^2}$, respectively.

These media are read out reflectively. Simultaneous read in and read out is thus possible. It is expected that realistic concern should be given to the matter of flatness of the device.

Since these devices are reversible and no development is required, and since the sensitivity looks attractive, they look promising in principle for the present application.

No evaluation of these media for an application such as the present one is known to exist. Because they appear to have some potential applicability, it is recommended that they be further evaluated experimentally.

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7.5 Photochromics and Other Imaging Media

Considerable work has been accomplished in the area of photochromics. Most of the published data, however, indicates that photochromics are photographically rather slow. Otherwise, they would be suited for the proposed application. Typically they require optical energy levels ranging from 5 (10^{-2}) to 10 watts-sec/cm^2, which would seem to put them out of reasonable consideration for this application even if they were used with an image intensifier (see Item 10 of Table 7-1).

Other media of various types, not always easy to categorize, have also been reported. Tubbs, Beesley and Foster, associated with Warwick University and S.E.C. in the U.K., for example, have announced some applicability of lead iodide film to instant holography. However, film speed is several orders of magnitude slower than any typical silver halide film.

For a number of years, Horizon's Inc. has been working on the development of a free radical type photosensitive dye process. All published data on this material indicates that it too is very slow (typically requiring energy densities of $10^{-2} \frac{\text{watt-sec}}{\text{cm}^2}$ or more).

Another recent paper describes a new Kodak photodevelopable dry process which uses a thermal technique for fixing. Since this is not reusable and requires energy densities one to two orders of magnitude greater than Polaroid silver halide diapositive media, for example, it does not appear very applicable for this task.

Hughes Research Lab has indicated effort in the area of photopolymers. Because of indicated sensitivities ranging from an ASA of 10^{-5} to 10^{-1}, these are judged as being too slow, at least without an image intensifier.

7.6 Photosensitive Semiconductor Phase Modulator Device

Some information on this device is listed in Item 22 of Table 7-1. This device, when exposed to light, causes a selective bi-refringence which results in a phase modulation of read-out light.

Because it has been indicated by Itek to have a relatively high sensitivity, requiring energy densities in the range of $10^{-6} \frac{\text{watt-sec}}{\text{cm}^2}$, it is recommended that the applicability of this media be explored further.

TABLE 7-1. CHARACTERISTICS OF CANDIDATE IMAGING MEDIA

Media (or Process)	Type of Media	Source	Status or Availability	Measure of Sensitivity	Resolution	Development	Reusability	Comments	References
1. Photoplastic (GE-PPR) a. Transmissive Version b. Reflective Version	Optically sensitive photodeformable	GE (Research and Dev. Center)	Available on limited basis	$0.5 (10^{-5})$ to 10^{-4} watt sec/cm^2 for "deep deformations". 10^{-7} to 10^{-6} watt sec/cm^2 for "shallow deformations".	Response up to several hundred cycles/mm has been achieved	Thermal; in-place; can be less than 50 msec	Potentially many times reusable	A photodeformable which can be read out either reflectively or transmissively. Sensitivity and resolution highly dependent on film thickness.	21, 45
2. Thermoplastic Xerography	Optically sensitive photodeformable	XEROX Corp.	Not available commercially	10^{-7} to 10^{-4} watt-sec/cm^2	Indicated as being as high as 600 cyles/mm for thin film	Thermal; in-place; less than 1 sec	Potentially many times reusable	Sensitivity described as highly dependent on choice of photoconductors. Sensitivity and resolution highly dependent on film thickness.	1, 2, 3, 43
3. Other Photosensitive Photodeformables (photoplastics)	Optically sensitive photodeformable	Other organizations have been active in this area.	Unknown	Unknown	Unknown	Unknown	-------------	------------------------	---------
4. Free Radical Photographic Media	Formation of dye molecules (opacity change) due to free radical transfer mechanism initiated by photon energy.	Horizons, Inc. (Cleveland, Ohio)	Not believed to be commercially available	Estimated equivalent to 10^{-1} watt-sec/cm^2	1000 lines/mm	----------------	Not reusable	Sensitivity appears to be main problem (probably 1 to 2 orders of magnitude); too insensitive for this application	4, 5, 6
5. Photopolymer Media	A free radical dye material.	Hughes Aircraft Corp.; DuPont DeNemour Co.	Unknown	ASA equivalent to 10^{-5} to 10^{-1}	Up to 1000 cycles/mm	Thermal or optical fixing; in-place; can be processed in 0.5 sec	Not reusable	Judged to be too slow for present application	7, 8
6. Polaroid Lantern Slide Diapositive Type 46L (normal contrast) Type 146L (high contrast)	Rapid process silver halide positive black and white transparency.	Polaroid Corp.	Readily available in photographic market	Type 46L - ASA800 10^{-8} watt-sec/cm^2 Type 146L - ASA 200	35 lines/mm (for both types)	Recommended development times; 120 sec for type 46L; 15 sec for 146L. By applying heat, 146L has been developed in about 1 sec.	Not reusable	Sensitivity very good. Further tests needed to determine effect of graininess, and to determine if development time can be reduced below 1 sec.	9, 42
7. Poromat Process (previously also known as Fairweb)	A rapid process silver halide developing technique used with conventional silver halide film.	Townley Chemical Corp. (previous source Fairchild C&I Corp)	Process now available. Can be used with a wide range of standard films	Sensitivity depends on silver halide selected	Resolution depends on silver halide selected	Rapid process silver halide. Cannot be developed in-place. Can be developed in less than 10 sec.	Media is not reusable	Processor has been developed for NASA (Langley and JPL) for space applications. Photometric response of silver halide material is judged adequate. Although this process is judged a possible candidate for the present application, other rapid techniques using a simpler processor appears more attractive. Unit built for Langley weighed 55 lb for camera, processor, and solid-state readout. Needs no refrigeration.	16
8. Bimat Process	A rapid development process which uses standard silver halide film.	Kodak; Mark Systems Inc.	Now commercially available	Depends on film being used	Depends on film being used	Developed by diffusion process with heat. Access time 1 to 20 min. With certain special films and using heat, access time may be reduced to 3 sec.	Media is not reusable	Bimat used successfully on Lunar Orbiter. Original Bimat process needed refrigeration. Produces a negative and a positive. Mark Systems, Inc. now makes a small Bimat unit weighing 20 lb.	29, 30, 31

TABLE 7-1.   CHARACTERISTICS OF CANDIDATE IMAGING MEDIA (Cont'd)

Media (or Process)	Type of Media	Source	Status or Availability	Measure of Sensitivity	Resolution	Development	Reusability	Comments	References
9. Kalvar Film	Vesicular film (dry non-silver photography)	Kalvar Corp.	Available	Sensitive to ultraviolet light. Needs high energy levels (ASA 10^{-6} to 10^{-5}).	200 to 300 lines/mm	Thermal development	Not reusable	Because of low sensitivity, limited to UV region; this is not a likely candidate	17, 19
10. Photochromics	Materials that display reversible color or optical density changes due light energy. Color centers may be imbedded in plastic or glass (e.g., Corning)	Corning Glass, NCR, Varilight, plus several other companies	Generally available on the market	0.05 to 10 watt-sec/cm^2 (ASA: 10^{-5} to 10^{-4})	Can be over 1000 lp/mm	Self developing on exposure	Reversible photochromics are reusable	Judged as being far too insensitive. May be some possibility of use with an image intensifier. (Photochromics are being used by Schulman NASA-Langley in real time holography)	10, 11, 12, 13, 14
11. Diazo Process	Technique for image printing. High energy required.	Technifax Corp.	Available	Estimated 3 watt-sec/cm^2 (ASA: 10^{-6} to 10^{-5})	Approximately 1000 lines/mm	-----------	------------	Judged as much too insensitive for this application	15, 19
12. 3M Dry Silver Process	Dry silver halide process	3M Corp.	Available	Known to be rather slow. (ASA reported to be 10^{-3} to 10^{-1})	Up to 1500 lp/mm	Thermal in 3 sec in-place	Not reusable	Expected to be too slow for present application	18
13. Kodak Dry Process Film	Dry silver process	Eastman Kodak	Unknown	ASA 1	500 lp/mm	Thermal in 6 to 10 sec (Access time: 3 to 4 sec)	Not reusable	Produces a negative. Rather slow for this application.	
14. Automatic Silver Halide Processor - HRB-SINGER	Airborne technique for rapid processing of silver halide films. (Rapid Access Ditrecon Diffusion Transfer)	HRB-SINGER	Available	Depends on film being used	Depends on film being used	Diffusion transfer process. Development time less than 10 sec	Media not reusable	Present designs appear to be large units for developing large quantities of film. Does not appear appropriate for present application unless it can be packaged much more compactly.	27
15. Automatic Silver Halide Processor - GAF	Automatic silver halide processor	GAF Corp.	Available	Depends on film being used	Depends on film being used		Media not reusable	Available literature only describes commercial film processor. Not known if this Company makes a processor potentially suitable for space application.	28

TABLE 7-1. CHARACTERISTICS OF CANDIDATE IMAGING MEDIA (Cont'd)

Media (or Process)	Type of Media	Source	Status or Availability	Sensitivity	Resolution	Development	Reusability	Comments	References
16. Rapid Access Film Processor-MARK SYSTEMS	Multi-bath and mono-bath automatic development systems (silver halide) built for in-flight purposes	Mark Systems Inc. (Note this company also makes Bimat processors - see Item 8)	Available	Depends on film being used	Depends on film being used	Wet processing. In some cases, access time can be 10 to 30 seconds	Media not reusable	Processor available includes a small 3 x 2 x 1 inch processor	32
17. Rapid Process for Silver Halide - BELL & HOWELL	A dry silver halide gel web processing technique	Bell & Howell	Unknown	Unknown	Unknown	Gel web system	Not reusable	Present status of this project is unknown	33
18. AGFA - Gevaert Easy Access Photo Stabilization Film	Rapid process silver halide (diffusion transfer process and viscous techniques)	AGFA- Gevaert	Development status is proprietary	Unknown	Depends on silver halide film being used	Diffusion process can be as low as 1 sec. Viscous process may take over 1 men. to obtain diapositive	Not reusable	Diffusion process might be promising for this application if mechanization can be simplified. Viscous technique would be attractive if a positive could be used. Looks too complex if need negative.	34
19. Electrophotographic Processes	Electrophotographic techniques used primarily for duplicating	Xerox and several others	Available	--------------	--------------	--------------	Not reusable	Generally require high light levels. Not considered usable for present application.	22
20. Varian Electrophotographic Process	Electrically operated electrophotographic media not requiring a conventional shutter.	Varian Associates	In product development	--------------	--------------	--------------	--------------		23
21. Matsushita Organic Photoconductor	Electrophotograhic technique using new high sensitivity organic photoconductor.	Matsushita Electric Corp.	Available	Equivalent to ASA2	About 150 lines/mm	Electrical	Not reusable	This process recently developed by Matsushita for office copy, microfilm work, etc., is claimed to have sensitivity 50 X that of previously available electrophotographic media	24, 25
22. Itek Reusable Image Storage Material	Photosensitive semiconductor in crystal or epitaxial film form	Itek Corp.	In research and development	Detectable output has been obtained when exposed at 10^{-6} watt-sec/cm^2 (of 0.4μ radiation)	Currently 50 lp/mm; goal 100 lp/mm	No development required (in-place operation)	Reusable	Exposing light energizes photoconductors which result in internal electrical field. Electrical field causes birefingence which results in phase modulation of readout light. Read in and read out light wavelengths must be appropriately chosen so as to avoid destructive readout. Because of its high sensitivity, this media merits more evaluation. Further design concepts appear to be needed to adapt this type of media to a coherent correlation.	26

TABLE 7-1. CHARACTERISTICS OF CANDIDATE IMAGING MEDIA (Cont'd)

Media (or Process)	Type of Media	Source	Status or Availability	Measure of Sensitivity	Resolution	Development	Reusability	Comments	References
23. Liquid Crystals	Cholesteric and nematic liquid crystals	Liquid Crystal Ind. Inc., (Pittsburgh) and others	Expected be very slow	Unknown	Unknown	Electrical	Reusable	Expected to be too slow for present use.	20
24. Nonsilver Electrophotographic Process	Nonsilver electro-photographic	Varian	Development status is proprietary	Unknown	Unknown	Unknown	Unknown	Varian indicates it has development work in this area. However, all data is evident proprietary.	35
25. IBM Material	"A material which would be applicable to our purpose"	IBM	In development	Unknown	Unknown	Unknown	Unknown	IBM indicates that it is developing a material which would be applicable to our present requirements. However, all information is proprietary.	36
26. DuPont UVI (Dylux)	Rapid access material	DuPont	Unknown	-------	--------	Fixed with blue-green light	---------	Produces a negative. Sensitive to ultraviolet light.	
27. Advanced Image (Membrane) Transducer GE	Deformable membrane light modulator	GE (Electronics Lab)	In research and development	Estimated in range of 10^{-7} watt-sec/cm^2	100 lp/mm	No development needed	Reusable	This is a photodeformable consisting of a deformable membrane covering of field of micro-apertures. The membrane elements are deflected electro-statically by a field set up by surface charge resulting from irradiation with photon image. Since the media is read out reflectively, concern must be given to the high degree of media flatness which is required.	
28. Membrane Light Modulator (MLM): Perkin-Elmer	Deformable membrane light modulator	Perkin-Elmer	----------	Typically 10^{-4} watts/cm^2 (Note: P.E. device is sensitive to power, not energy)	Typically membrane segment size 10 to 100 micron	No development required	Reusable	This is the only media investigated which was indicated as responsive to power density rather than energy density. Like all reflective media, one should be greatly concerned with the high degree of flatness which is required.	37, 38

8.0 SUMMARY OF DATA ON IMAGE INTENSIFIERS

Image intensifiers are of interest since they may make it practical to use certain imaging media which may otherwise not have sufficient sensitivity. Table 8-1 provides a summary of key data of some of these devices.

As the table shows, there is a wide range of gains available. This is largely a function of the number of stages providing amplification.

These intensifiers are relatively small, lightweight, and consume modest power. Typical diameters range from less than 1 inch to 4 inches. Typical lengths range from 2 to 8 inches. Weights range typically from 0.5 to 1.5 pounds. Required power may be typically as small as one watt.

Other performance parameters would require further evaluation for the present application. For example, image distortions in some cases may cause uncertainties in a star image displacement as great as 1 to 5 percent of the field of view. This would not necessarily rule out the use of these devices, but it may somewhat restrict the angular accuracy potential. At least one of the listed intensifiers (BX 749) is thought to have relatively low image distortions.

This data on image intensifiers as of interest to the present application is, of necessity, very preliminary. Clearly, further evaluation is needed here, especially as regards to how maximum resolution relates to the level of background illumination.

TABLE 8-1. IMAGE INTENSIFIER TUBE DATA

Manufacturer	Type	Input/Output Diameter (mm)	Input Resolution at 20% Modulation (lp/mm)	Resolution Ratio Edge to Center	Lumen Gain	Equivalent Background Illumination (lumen/cm^2)
Westinghouse	WX30677A	40/25	20	0.75	200	5×10^{-11}
Westinghouse	WX30677B	40/25	20	0.75	150	5×10^{-10}
Aerojet-Delft	FFF	77/25	15	0.25	300	5×10^{-11}
Aerojet-Delft	G	25/25	40	0.8	50	-
ITT	F 4051	40/40	40	-	100	-
ITT	F 4711	37/37	40	-	35,000	-
EMI	9694	48/48	20	-	$10^5 - 10^6$	5×10^{-10}
EMI	9723	48/48	25	-	$10^5 - 10^6$	2×10^{-9}
Bendix	BX 749	25/25	20	0.95	25	10^{-10}

9.0 CONTRIBUTORS TO PRESENT EFFORT

The presently reported effort was conducted under the technical direction of Mr. Joseph D. Welch of the General Electric Space Division who was also a major technical contributor and who also prepared the final report. Mr. A. Hartman, also of the General Electric Space Division was a major contributor in the area of photometric analysis for the formation of star images for the static case and also for the experimental evaluation of the photoplastic recording.

Mr. John Holeman performed the experimental evaluation of the Polaroid material in a coherent system and also contributed to some of the thoughts on photometric response of star images. For cómparison purposes, earlier work by Mr. J. E. Bigelow on the matter of photoplastic recording photometric response was cited. Both Mr. Holeman and Mr. Bigelow are with the General Electric Research and Development Center.

APPENDIX A

EXPERIMENTAL EVALUATION OF THE SENSITIVITY OF PHOTO-PLASTIC MATERIAL (PPR)

A.1 General

As indicated in Section 7, photo-deformables, including GE's PPR, are among the more attractive media candidates which merit further evaluation. These media can be processed rapidly "in place" and are reusable. Furthermore the sensitivity of these materials, while significantly less than that of most conventional silver halides, is orders of magnitude greater than that of most of the other non-conventional media such as photo-chromics.

Because, however, only limited sensitivity data of this material to star images was available, it seemed appropriate to initiate a brief experimental program to obtain more data. Unfortunately no samples of photo-deformables for evaluation in these experiments were available from sources other than General Electric. Consequently, the experiments described herein were concerned exclusively to GE's PPR (Photo-Plastic Recording).

Most previous related sensitivity experiments with this material were concerned with recording of extended images. Here however we will be concerned primarily with the recording of point spread function images.

A.2 Results

An interpretation of the results of the brief experiments of this program indicates that present GE PPR has a point energy sensitivity in the neighborhood of $2 (10^{-10})$ watt sec when the illuminating energy is in the spectral response band of the medium. The medium spread function has a diameter of less than 14 microns. This suggests that a representative required energy density lies in the general neighborhood of 10 to 100 (micro-joules/cm^2).

Earlier work by J. E. Bigelow of the GE Research and Development Center indicate a required optical energy density in the general range of 5 to 50 micro-joules/cm^2 for extended images having spatial frequencies in the region of the resonant spatial frequency of the media.

Considerable caution must be exercised in the interpretation of these preliminary results. These experiments have, for the most part, only evaluated some measure of photometric response of the medium. A more complete evaluation would necessarily also include the coherent optical pattern recognition aspect of the total problem. Whether or not the photometric response of the media is adequate can only be completely evaluated by an interpretation of the resulting output signal to noise response of the complete coherent system.

Furthermore, the experiments discussed here relate only to one particular sample of PPR. As noted in Appendix B, thickness of the photo-deformable layer, for example, is a key parameter which influences the photometric response as well as the resonant spatial frequency of the media.

The choice of photoconductor and the material properties also influences the response. A recent GE development in materials has, for example, demonstrated a 2:1 improvement in sensitivity.

A.3 Conclusion of this Brief Experimental Program

The experimental results of this program have been sufficiently encouraging as to recommend a more thorough experimental evaluation of photo-deformables. This evaluation should include coherent correlation evaluation and use of higher quality optics in the PPR camera.

A.4 Detailed Description of the Experiments

Experimental Setup

The radiation sensitivity of one sample of PPR was determined experimentally, using the setup of Figure A-1 to simulate the star images. This arrangement uses an inverted telescopic optical system in front of a regular PPR camera system, for the following reasons:

1. It realizes large working distances in a limited working space

2. It increases the demagnification by the camera, to such an extent that three of the five illuminated pinholes forming the object will be unresolved by the PPR camera optics. Consequently, these pinholes of different sizes can be used to simulate stars of different magnitudes.

The PPR camera optics is stopped down to F/16, in order to reduce its optical aberrations to below the diffraction limit.

A.4.1 <u>Calculation of the power density in the simulated star images.</u> - The spectral distribution of the calibrated source used to simulate the stars is given in Figure A-2. Also entered are the spectral response of the photoplastic media sample which was tested, that of the eye (for comparison), and the product of the source/PPR spectral characteristics. This shows an effective PPR sensitivity band width $\Delta\lambda = 0.53$-0.78 micron. The standard lamp selected produces, in this band, a power density at the plane of the diffuser equal to 2.0 mW/cm^2.
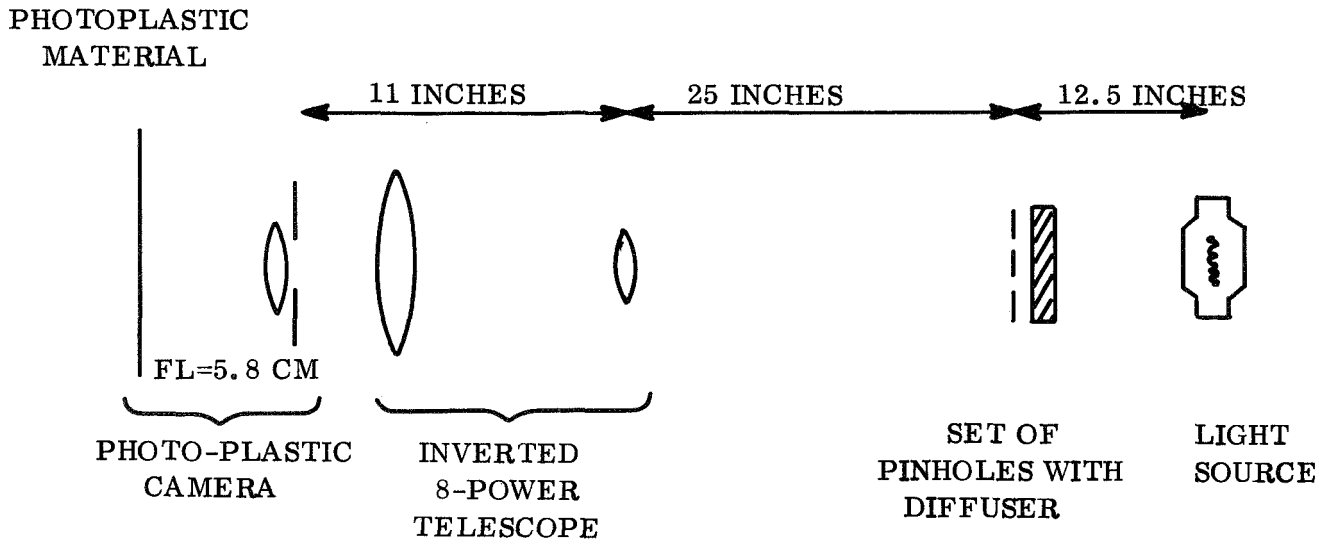
PHOTOPLASTIC
MATERIAL

Figure A-1. Setup for Determination of Energy Sensitivity and Spread Function
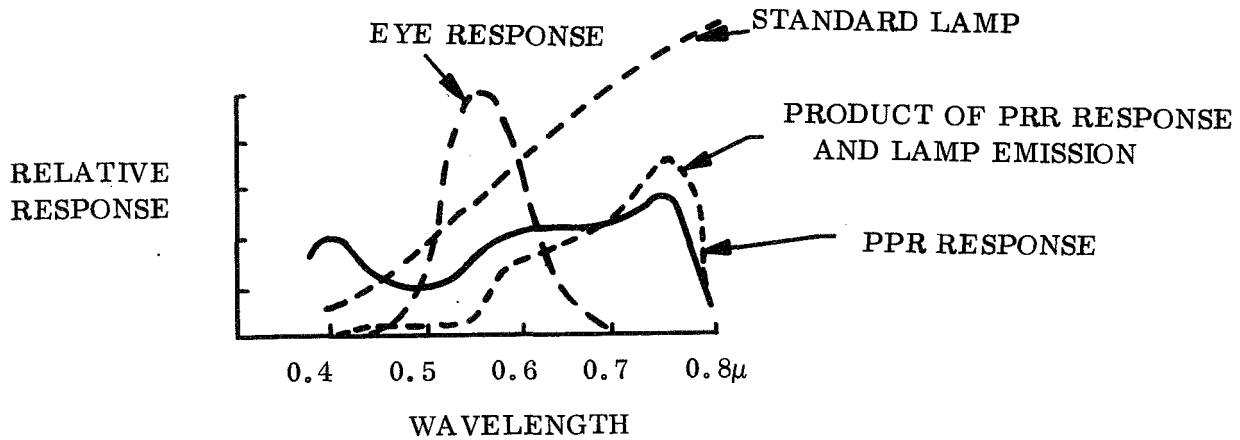Diameter of Photoplastic Recording Material

Figure A-2. Relative Spectral Response of PPR Sample, Simulation
Light Source and Eye

An ideal lossless Lambertian diffuser would provide in this band a total output of 2.0 mW/cm^2 into 2π steradian, or a brightness perpendicular to the surface of (0.65 mW)/(cm^2 ster).

Inserting now instead an available real diffuser, an opal glass of near-Lambertial character and 40 percent transmission (as determined in an earlier program), one finds a surface brightness: (2.6 x 10^{-4} W)/(cm^2) in the bandwidth $\Delta\lambda$.

Because the opal glass provided insufficient brightness we replaced the opal glass with an available ground glass diffuser which showed very pronounced forward scattering and found that a neutral density filter with a density between 3 and 3.5 had to be inserted to reduce the ground glass brightness to that of the equally illuminated opal glass. Based on this the ground glass surface is found to be about 2000 times brighter when viewed normal to its surface than the opal glass or (0.52 W)/cm^2 ster) in the $\Delta\lambda$ band.

The specially designed PPR camera lens has a focal length of 58 mm. It is stopped down to F/16 and an inverted 8-power telescope is placed in front. The collecting aperture for radiation has therefore an effective diameter 58/16x8 = 0.45 mm. It is 25 inches away from the illuminated pinholes, and the associated solid angle is 4.0 x 10^{-7} steradian.

Five illuminated pinholes are arranged behind the diffuser on a circle of about 0.5-inch diameter. When the normal to the pinhole plane, intersecting the center of the pinhole circle,is made to point directly into the 0.45 mm entrance pupil of the 8-power telescope, all pinholes are off-axis by an equal small amount. Due to the extreme forward scattering characteristics of the ground glass diffuser, the apparent brightness of these off-axis pinholes as seen by the telescope is reduced by a certain factor, visually determined to be about 2.

One can calculate that a 1 cm^2 source area, located off-axis to the same extent as the pinholes, would send into the optics an amount of radiation, the power of which is given by:

$$4.0 \times 10^{-7} \times 1/2 \times 0.52 = 1.0 \times 10^{-7} \text{ W/cm}^2 \text{ in the } \Delta\lambda \text{ band of interest}$$

The camera lens and the telescope have each an estimated transmission of 80 percent, hence 6.4 x 10^{-8} W/cm^2 $\Delta\lambda$ would be sent to the film by 1 cm^2 off-axis source.

The pinholes have diameters and areas given below.

Pinhole No.	Diameter	Area
1	2.05 mm	3.41×10^{-2} cm^2
2	1.43	1.6×10^{-2}
3	0.92	0.665×10^{-2}
4	0.55	0.238×10^{-2}
5	0.38	0.115×10^{-2}

Consequently, in the pinhole images the sensed power in the spectral band of interest is given by:

Pinhole No.	Image Power
1	2.2×10^{-9} watts
2	1.0×10^{-9}
3	0.43×10^{-9}
4	0.15×10^{-9}
5	0.074×10^{-9}

We have then obtained five simulated star images radiating a known calibrated power level. These star images are then used to determine sensitivity of the PPR.

A.4.2 Determination of the radiation sensitivity of PPR. - Recordings were made of the set of pinholes previously described and the images recorded on PPR were evaluated, noting:

1. Exposure Time

   The exposure times were 10, 5, 2.5 and 1-1/4 seconds.

2. Diameter of the Optical Images

   The total optical demagnification is 80, leading to pinhole image diameters 26, 18, 11, 7, and 5 microns at the image plane. The optical aberrations of the available PPR camera lens at full aperture were very much larger than this, necessitating stopping down the lens to F/16. By then, the

images were of diffraction-limited quality. The Airy disk had a visual diameter 12 to 14 microns, and the third pinhole was barely beginning to be resolved.

3. Diameter and Surface Depressing Depth of the Produced Recordings

The smallest images have 14 microns diameter (or 1.5×10^{-6} cm^2 area) according to interferometer measurements by J. M. Holeman. At 1-1/4-second exposure time, the smallest pinhole gave a barely detectable recording about 0.3 micron deep, while spurious tape deformations in this particular sample were observed to have a depth 0.2-0.3 micron. The next larger pinhole gives 0.4 to 0.5 micron depression depth, and is a better example of minimum detectable signal.

If we tentatively decide that, in view of the measured noise deformations in this sample of 0.2 to 0.3 micron depth, that an acceptable signal deformation should be at least 0.4 to 0.5 micron deep, then we would conclude that a "minimum detectable star energy density" would be: 0.15 (10^{-9}) watts (1-1/4 sec) = 2 (10^{-10}) watt-seconds. This deformation was detected over a diameter of 14 microns resulting in a corresponding energy density of about 100 micro-joules/cm^2. Again this assumes that the optical energy is within the spectral sensitivity band.

In this particular experiment the observed noise deformations of 0.2 to 0.3 microns were about 10 times greater than that which has been more usually observed. This suggests that this particular experiment may not have employed optimum development of the PPR, consequently the suggested sensitivity of 100 microjoules/cm^2 may be pessimistic by a factor of about 10. This would also be more consistent with the earlier experiments by J. E. Bigelow discussed below.

It should be recognized that this type of judgment is adequate only to roughly determine the range of sensitivity. As said before a complete sensitivity evaluation should also include a correlation read-out evaluation.

A.5 Comparison with Earlier Data

At the GE Research and Development Center, Schenectady, New York, similar measurements have been carried out on other earlier programs involving the use of photoplastic. J. E. Bigelow reported results of experiments in which the photo-plastic material was exposed to an image of equidistant parallel lines. After heat-development, a system of parallel grooves is obtained at the surface of the photo-plastic. The groove depth depends on the irradiation, the film thickness and the line frequency, as shown in Figure A-3 reproduced from Bigelow's report.

This figure suggests that the sensitivity of photoplastic is in the region of 10 to 100 micro-joules/cm^2 for spatial frequencies above 10 lines/mm, and may approach one micro joule/cm^2 for a line frequency of 40 lines/mm. This presumes that a signal deformation in a coherent system of about 0.02 micron is adequate.
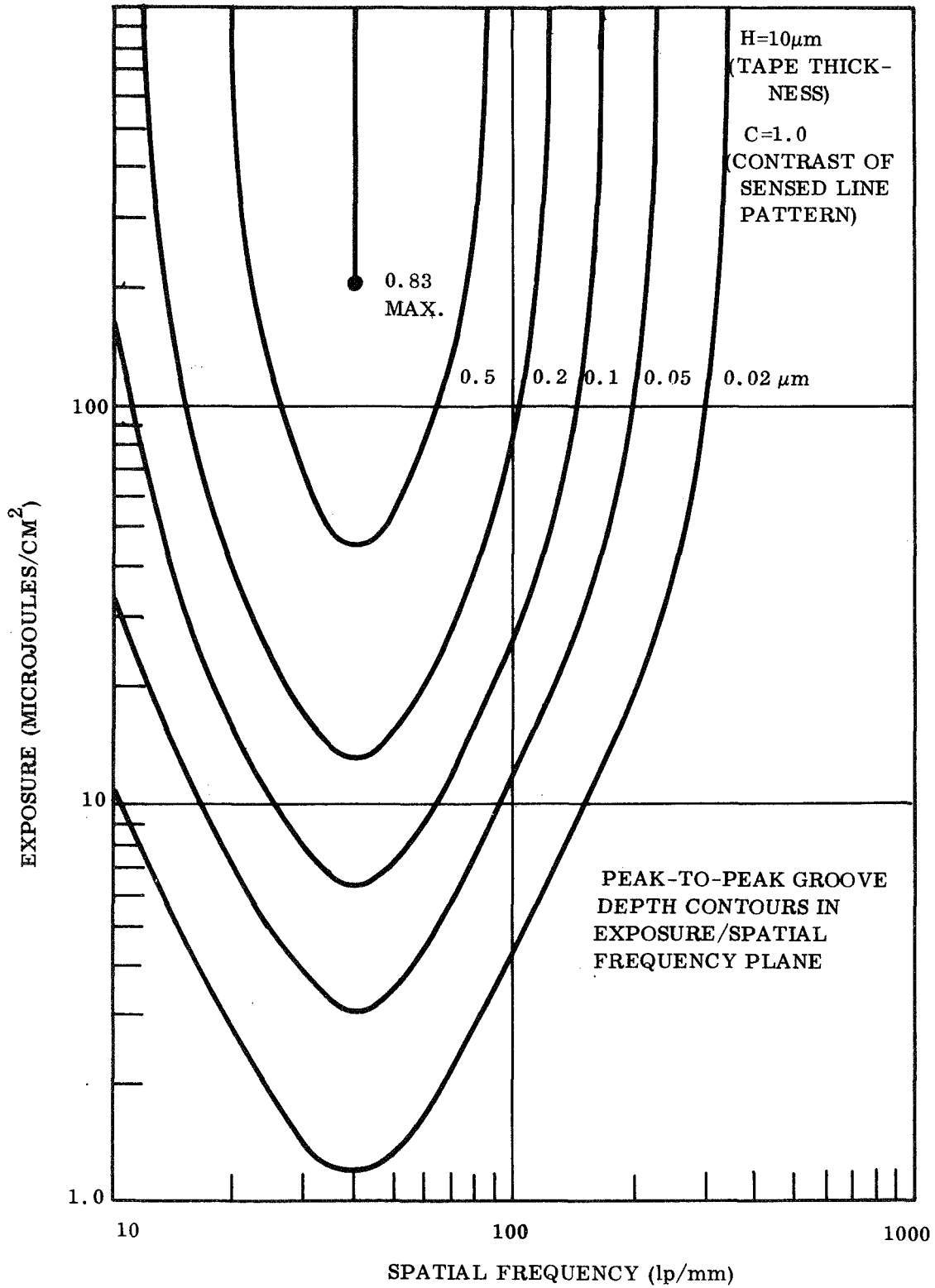
Figure A-3. Deformation Depths of Photoplastic Tape Exposed to Spatial Frequencies and Irradiation Levels

A direct comparison between this data from R&DC and the presently reported experiments is difficult, because the former uses line frequencies (and hence widths of tape surface deformations) impressed upon the system while the latter uses the unrestricted deformations of photoplastic tape due to illumination by isolated point-like images.

A. 5. 1 Determination of the radiometric transfer function of photoplastic.- In order to get an impression of the radiometric properties of photoplastic tape, the width and maximum depth of the obtained pinhole recordings were determined at the GE Research and Development Center using an interference microscope. The results are summarized in Figure A-4.
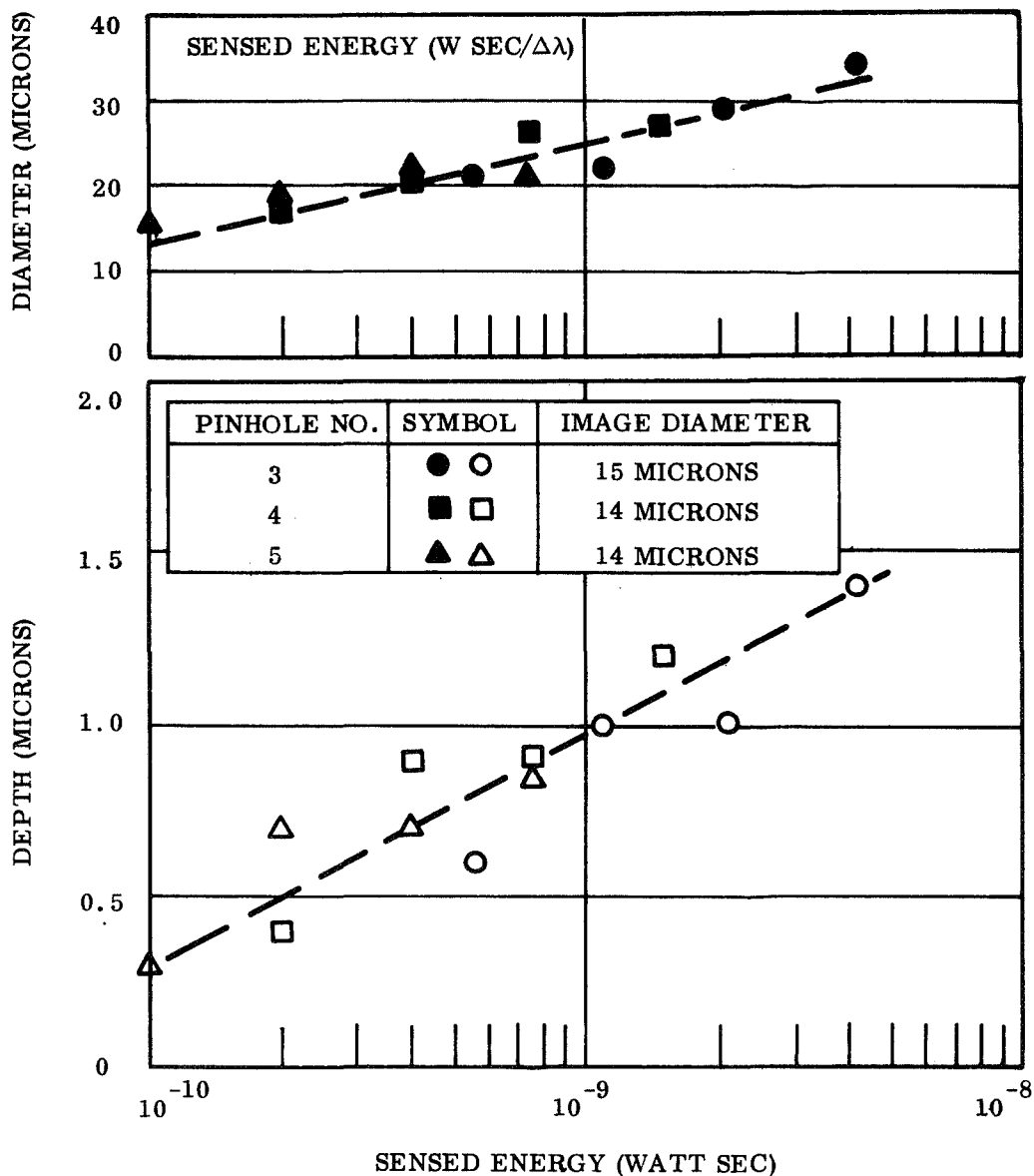

PINHOLE NO.	SYMBOL	IMAGE DIAMETER
3	● ○	15 MICRONS
4	■ □	14 MICRONS
5	▲ △	14 MICRONS

Figure A-4.   Diameters and Depths of Deformation in Photoplastic as a Function of Imaged Star Energy

APPENDIX B

DESCRIPTION OF OPERATION OF PHOTODEFORMABLES

Most theoretical development, as well as reported experimental results, presume the application of variable opacity transparencies as image media in spatial filter and other coherent optical data processing systems. However, other alternative media are not only possible, but may have some unique advantages. GE, for example, has pursued the theoretical aspects of the use of deformable media at some considerable length. GE has demonstrated the potentiality of phase media (deformables) for recording both input image and spatial filter. (Based on certain criteria, phase materials can be shown to be theoretically more efficient since they do not block out any of the incident light.) It has also been demonstrated that, in a given system, deformables or opacity media can be used in any combination for either or both input image media or spatial filter media.

There are several variants of deformable media which have been proposed and/or developed by various companies. Some of these are light-sensitive; others require writing by an electron beam. Here, however, we will discuss light sensitive "photodeformables" as, perhaps, being most typical of the available deformable media.

Since photodeformables (e. g., photoplastics) have potential application to the present problem, it is worthwhile to discuss briefly some of the mechanisms going on in the photodeformables, as well as some of their performance characteristics. First, we will mention some of the potential advantages for photodeformables. Photodeformables can be developed rapidly and in-place which has obvious advantages for the present problem.

Since they may be reusable, they can save on cost and weight. They also tend to be insensitive to the ambient radiation environment found in space. Furthermore, they are not sensitive to light until sensitized by placing an electric charge on them. Hence, they need not be stored in the dark until ready for use.

In order to evaluate the potential of photodeformables, one must understand some of the mechanisms going on in the photodeformable. Like most imaging media, the response and performance of photodeformables has, up to this time, been concerned with extended objects. Consequently, photodeformables will be discussed first as applied to extended objects; then, some expected differences when responding to star images will be pointed out.

Light-sensitive photodeformables are typically laminates having a cross section and operation as shown, for example, in Figure B-1. (As discussed below, a variation in which the thermodeformable and the photoconductor are in separate layers is also possible.
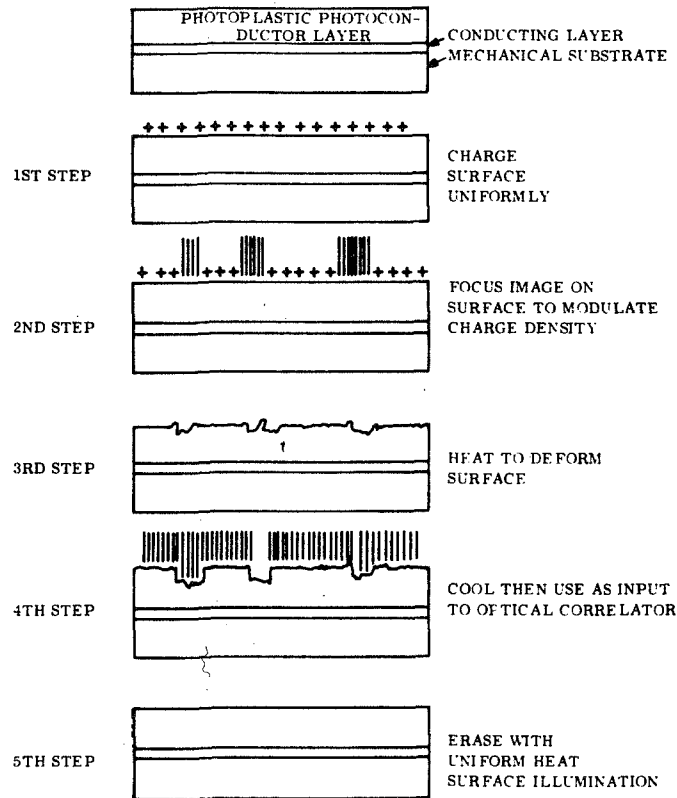
Figure B-1. Simplified Concept of How Photodeformable (PPR) Works
(Cross-Section View)

Because the material stores an image as a deformation, one would not expect in the case of an extended object to have a good reproduction of low spatial frequencies or low contrast extended scenes without the addition of a differentiating screen in the optical system. (In the case of star field images, however, there appears to be no advantage in screening the image.) An interpretation of Figure B-2, clarifies this and helps explain the response of a typical photodeformable. Figure B-2 is based on a predicted theoretical model which has been verified by experimental measurements with a photodeformable GE PPR Type 334. Since Figure B-2 describes only the degree of deformation as related to light energy on the photodeformable film, it will, of course, also be necessary to factor in the optical transfer characteristics which describe how the reflected energy of the object scene is transmitted to the image scene. Also, a factor will be how the coherent recognition system interprets a given groove depth or deformation in terms of recognition performance. These imaging and performance factors will be described subsequently.

1000

EXPOSURE (MICRO JOULES/CM^2)

GROOVE DEPTH
PEAK-TO-PEAK
(MICRONS)

0.43   0.2   0.1   0.05   0.02

100

21% T
84% R } ME

6% T
24% R } ME

10

15% T
6% R } ME

0.5% T
2% R } ME

PHOTOPLASTIC FILM
THICKNESS = 5 (10^{-6}) METERS
LIGHT MODULATION RATIO
ON PPR = 0.8

1.0

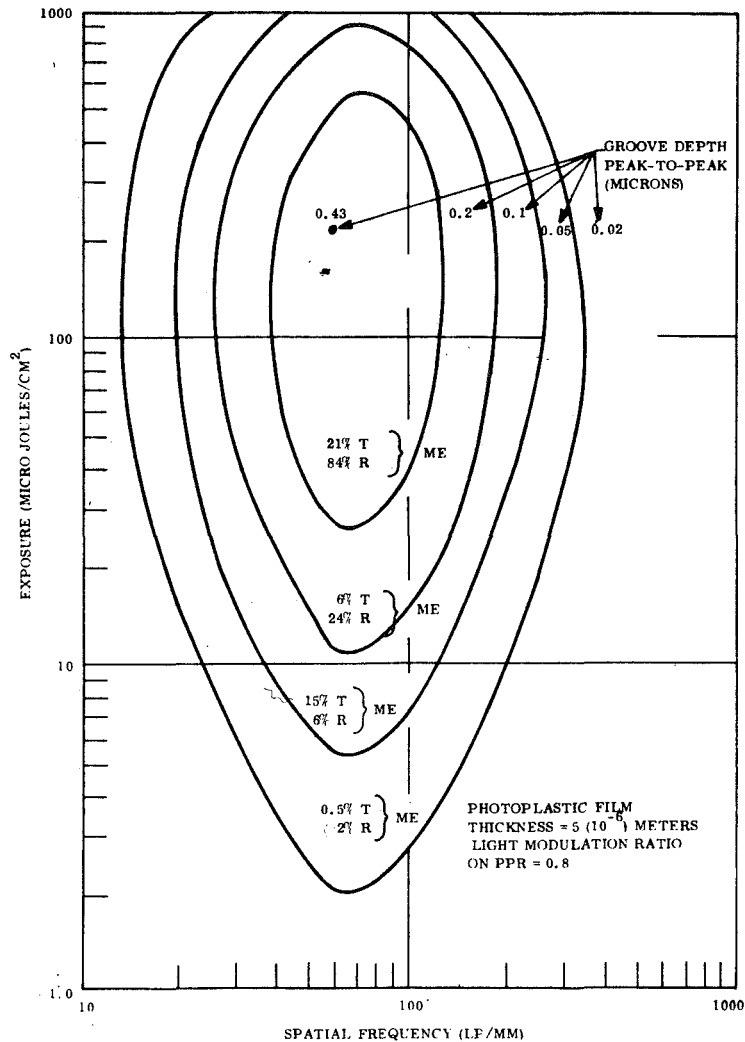10   100   1000

SPATIAL FREQUENCY (LP/MM)

Figure B-2. Typical Loci of Equal Groove Depth for PPR, Type 334
As a Function of Spatial Frequency and Exposure Energy on Film
(Loci are also labeled to show modulation efficiency (ME)
both transmissive (T) and reflective (R) PPR)

Notice that Figure B-2, which shows loci of equal groove depth on a focused energy-spatial frequency plane, is double-valued in the direction of both coordinates. Also notice that a maximum response is shown (for the particularly special case of 5 micron thick film and for a modulation ratio* of 0. 8) at a spatial frequency of about 70 lines/mm.

---

*Here we refer to the usual definition of optical modulation energy ratio: $\frac{\text{light-dark}}{\text{light+dark}}$.
Of course, with star images, this may approach unity.

Consider next a "horizontal slice" at an energy level of 150 microjoules/cm^2. At very low spatial frequencies (say near zero frequency), there is very little deformation. Physical consideration would predict this since such very low frequency deformations would require a physical rheological mechanism for large sidewise movement of the plasticized material. Evidently, no such mechanism exists (except conceivably for very thick films). At increasingly high frequencies (in this case increasing to about 70 line pairs per millimeter), the balance between the surface tension forces and the electrostatic forces are such as to preclude the formation of high surface curvature required to form deep grooves at high spatial frequency. (For fixed groove depth, required surface curvature is proportional to the square of the spatial frequency.)

It is evident that if we wish to record a wide range of frequencies in the case of an extended object, including very low frequencies, some form of screening (or image differentiation) must be used. A second important reason for using the screening is that screening always presents a high contrast ratio (modulation ratio of 0.8 or more) to the screen, even though the object screen may have a relatively low contrast ratio.

Let us now consider how response of photodeformables varies as a function of photoplastic film thickness and modulation ratio. Figures B-3 and B-4 show typically how these effects occur. We see that some increase in spatial frequency response may occur with thinner photoplastic layers, but usually at the cost of loss in peak response. In order to determine the advantages, if any, of going to very thin photoplastic layers, one must determine how the noise response varies with film thickness. Likewise, we see in Figure B-4 a sharp drop-off of response with lower modulation ratios. This last fact reinforces the argument for screening when using extended objects which can provide a modulation ratio of 0.8 or more.

Consider two variants of the photodeformable:

1. Transmission type (as has been shown in Figure B-1).

2. Reflective type (has a reflective surface coating on the deformed surface).

A spatial frequency data processor (coherent correlator) can be designed to use either type.

A groove in the reflective photodeformable retards light by an amount which is proportional to twice the groove thickness; whereas, a groove in the transmissive photodeformable retards light by an amount which is proportional to the groove depth times the difference in the refractive index between air and the photoplastic. For the materials usually used this is equivalent to a relative sensitivity advantage for the reflective photodeformable of about 3:1.
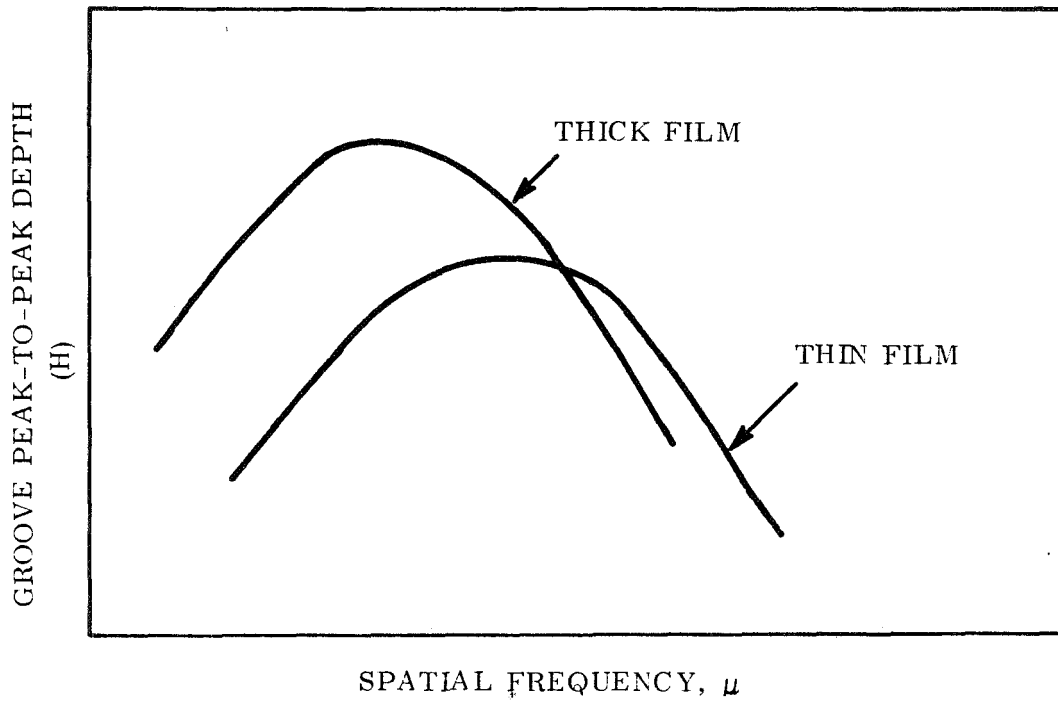
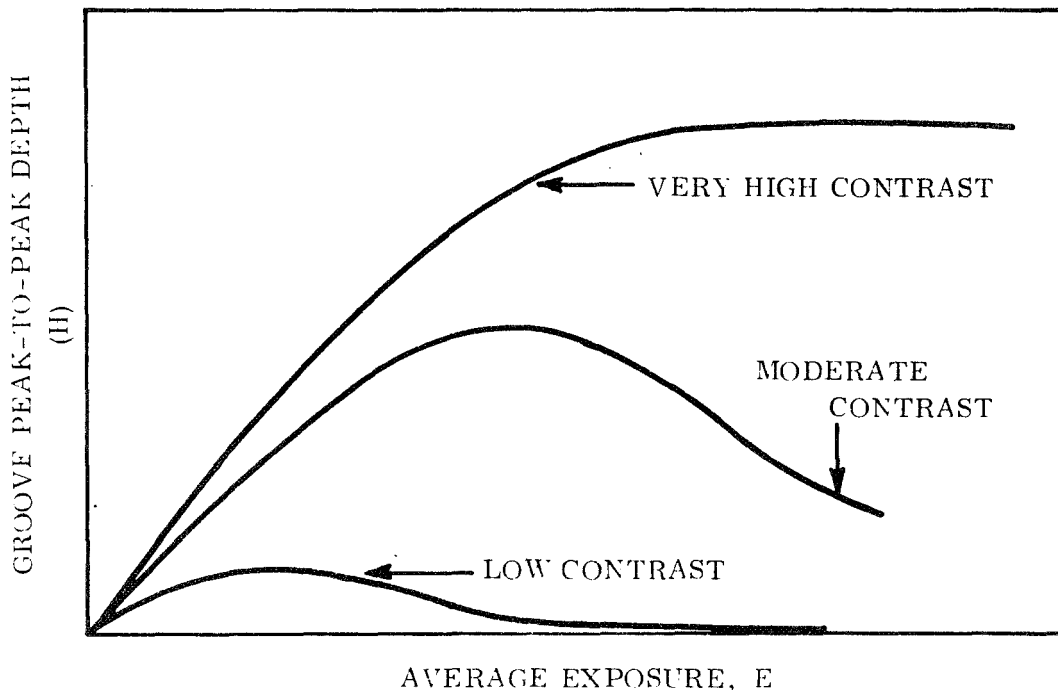Figure B-3. Typical Deformation Response of Photoplastic to Spatial Frequency

Figure B-4. Typical Deformation Response of Photoplastic
As a Function of Exposure

To make a performance evaluation of both types, one must then determine some measure of groove "modulation efficiency." This corresponds to the proportion of light being refracted (or reflected) and which contributes to the Fourier transformed image. This can be calculated, for the case of extended images, on the basis of the diffraction response of a sinusoidally modulated groove. This modulation in terms of intensities is proportional to the squares of Bessel Functions of the first kind having groove depth as the independent parameter, with the diffraction order corresponding to the function order.

Figure B-2 also summarizes the response in terms of contours of equal modulation efficiency on the spatial frequency-exposure energy plane for both reflective (R) and transmissive (T) PPR. This same data can be now displayed as MTF as a function of exposure (Figure B-5). As previously discussed, for the case of extended objects, the low frequency rolloff can be eliminated by means of a screen.

Although reflective deformable media look attractive relative to the transmissive version of the same media, one must be greatly concerned with achieving adequate flatness of the media. As expected, this is much more critical for a reflective media than a transmissive media. Several investigators have tackled this problem. Inability to achieve adequate flatness may limit the usefulness of a reflective input media.

B.1 Noise Considerations

A consideration of photodeformable specific noise effects is required to predict the recognition response in terms of signal-to-noise ratio of the photodeformable for the present application. Several sources of system noise exist which determine the required photodeformable modulation level to produce the desired signal-to-noise ratio. Some of the principal sources of noise are summarized below:

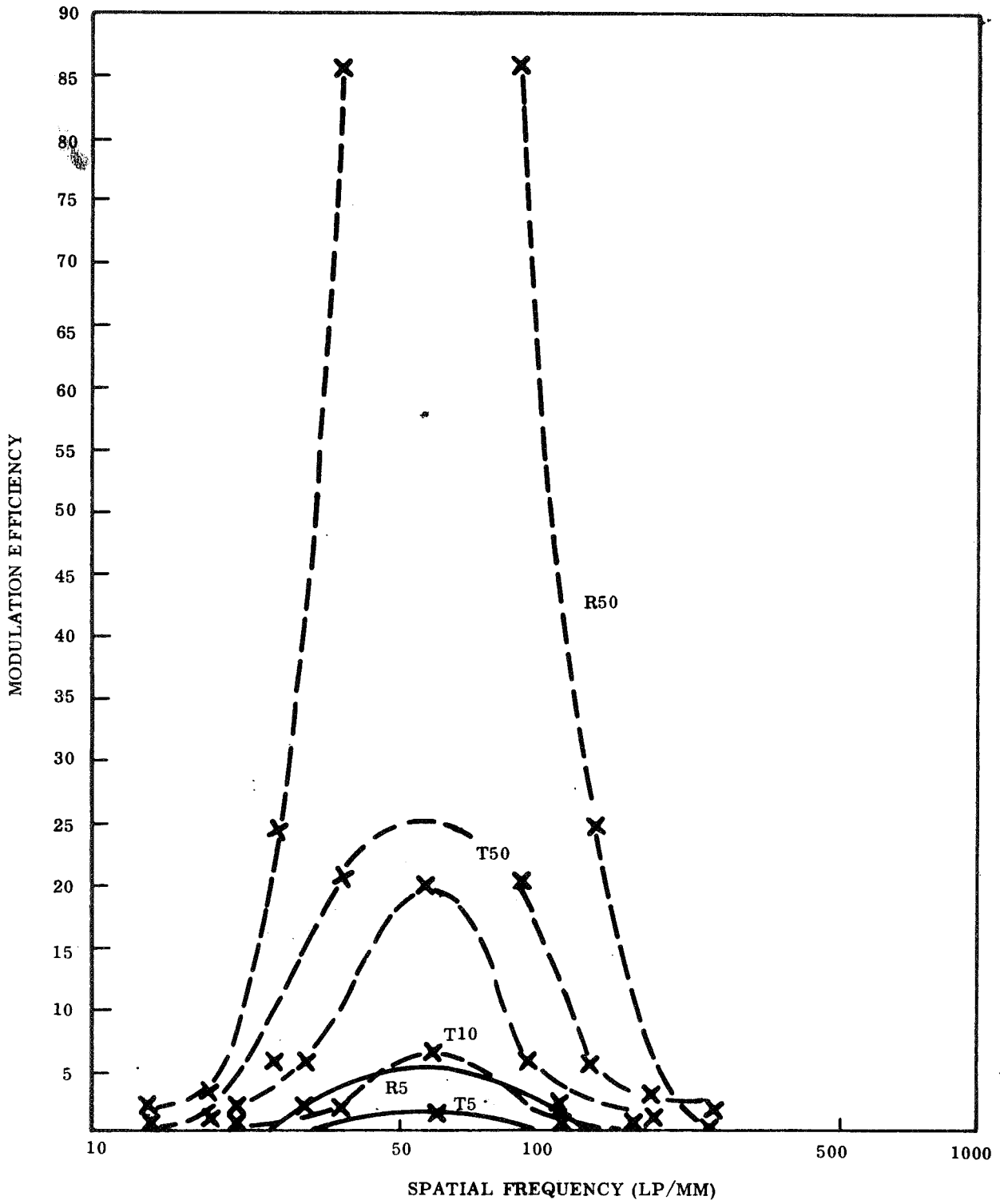|	Reflective Photodeformable	Transmission Photodeformable
Noise Sources on Exposing	Imperfections in the camera system. Dispersion noise due to non-uniformity of photoconductor.	Same
Noise Sources on Recognition	Initial surface profile noise. (Generally rather low frequency). Imperfections in reflective coating.	Initial surface profile noise (generally rather low frequency). Optical imperfection in base (base and bulk effects). Scattering in photoconductive layer.

Figure B-5. MTF for Transmissive (T) and Reflective (R) PPR Type 334
as a Function of Energy Level in Microjoules/cm^2 (5, 10, 50μj/cm^2)

We notice that all those sources of noise which appear to be common to both transmission and reflective photodeformable are subject to the same relative gain (about 3:1 advantage over reflective) considerations as related to the signal gain. Hence, we can say that the reflective system would have a relative signal-to-noise advantage if, and only if, the noise resources which the two systems do not have in common are less for the reflective system. Although one can conjecture that this should be so, further experiments are needed to demonstrate this.

GE experience indicates that these noise resources may be typically equivalent to a groove depth of about 0.02 micron (corresponding to a modulation efficiency of about 0.5 percent for the transmission system and about 2 percent for the reflective system). Hence, one would expect that it would be necessary, in the case of extended images, to have a sufficiently high signal energy level so that signal deformations will be significantly greater than equivalent deformations due to noise.

Consider next the differences involved in recording star images with photodeformables. This has already been discussed somewhat in Section 5. In the case of stars, we have no interest in recording low spatial frequencies. It is evident that a screen is probably of no value. Consequently, we might be inclined to use a very thin film in order to capture the high spatial frequencies associated with star fields. On the other hand, there is a tendency to use thicker films to take advantage of certain image blooming as discussed in Section 5. (Note that star image blooming is not necessarily a disadvantage, if it can be accomplished symmetrically.)

Both GE and Xerox have produced a photodeformable which separates the photoconductor layers and the "rheological layer" (i.e., thermoplastic). One objective is to achieve higher spatial frequencies, but sometimes at the expense of lower groove depth. Although the frequency response may have been improved, it is not evident that, because of reduced signal modulation level, recognition performance in terms of signal-to-noise ratio would be improved.

To complete the discussion of photoplastics, we present in Figure B-6 a typical spectral response of a photoplastic. This spectral response appears to have no disadvantage with respect to stellar photography for the present purposes.
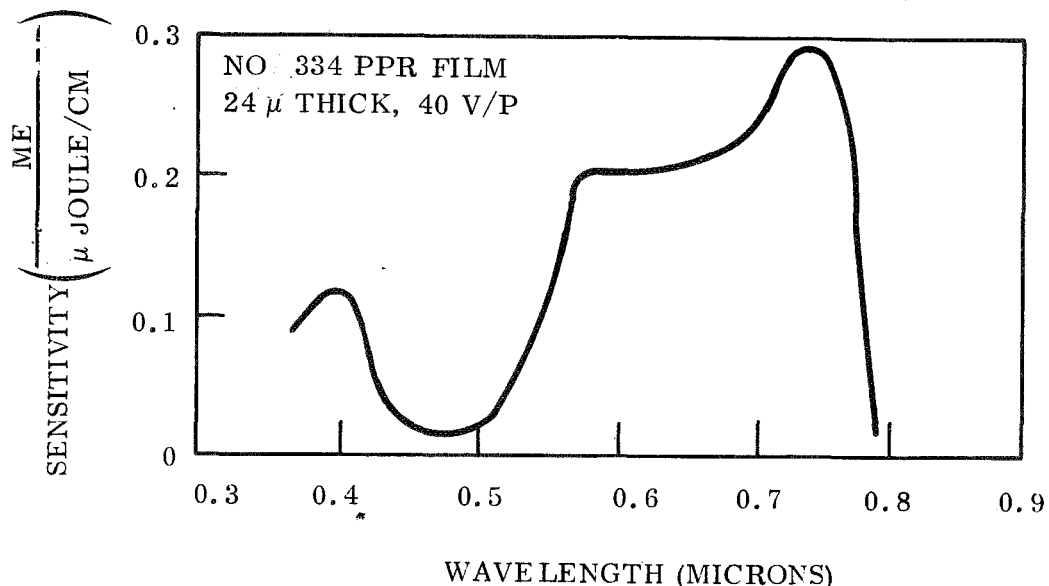

Figure B-6. Spectral Response of a Typical Photodeformable

APPENDIX C

EXPERIMENTAL EVALUATION OF STAR IMAGES ON
POLAROID DIAPOSITIVE

C.1 General

As discussed in Section 7.0, rapid process silver halide imaging media of
the type exemplified by Polaroid diapositive (Types 46L and 146L) appear to have
potential merit for the present application.

It was decided to conduct some experiments to determine the feasibility of
using this type of media and rapid processing (e.g., 1 sec) for the present application.

Both the medium contrast (Type 46L) and the high contrast (Type 146L)
versions of these films were used in these experiments. However we will con-
centrate our discussion of the experiments on the high contrast version of the trans-
parency media because of its apparent potential for much shorter development times.

These experiments with the Polaroid media which are described here in-
cluded star field recognition with a coherent optical correlator. As discussed below,
these experiments have demonstrated in the laboratory the potential of using this media
to achieve recognition with signal-to-noise ratios as high as about 300:1 after a de-
velopment time as short as 1 sec. This is accomplished with the application of a
moderate degree of heating of the medium.

C.2 Tests of Polaroid Film 146L with Star Fields

This experiment was similar to earlier experiments with Type 46L film
except Type 146L film was used. The same 4 by 5 glass transparency was used,
Ursa Major 49, which has the Right Ascension line 9 hours 30 minutes through the
center of the field. This star field with two designated areas A and B are shown in
Figure C-1.

The same area was used for the filter, designated as Area B and the same
filter, No. 2767, was used.

C.3 Exposure Latitude

As might be expected, this high contrast emulsion has a shorter latitude of
exposure than 46L film. One stop overexposure usually resulted in lack of density in
the sky background and the appearance of pinholes with resultant higher than normal
noise leakage. One stop underexposure resulted in star images that were gray rather

than clear and resulted in a weaker than normal signal. These effects may be different under more realistic conditions and are not to be accepted as final or limiting.

C.4 Variation in Development

Transparencies given normal exposure and development produced good images, reasonably sharp with clear stars and a fairly dense and uniform background. When the development at room temperature was reduced to 5 seconds, the density was less and minor tearing of the emulsion began to appear. When the film and camera were heated 20 to 30 minutes at $40^{\circ}C$, development time could be reduced to 1 second with no sign of tearing, but with some loss of density and uniformity of the sky background. (Note: It should not be inferred that such long term heating of camera and film would be required in a practical space application as it is only necessary to ensure heating of the film.)

C.5 Post Treatment

None of the transparencies used in this test were given any kind of post treatment, nor did they seem to need it. The transparencies developed at room temperature were damp for a minute or two, but this seemed to make no difference in the correlation tests. A fresh transparency was tested as rapidly as possible after processing, and then left in place to dry for an additional 15 minutes. The air temperature was 74° F and the humidity 45 percent. There was no appreciable change in the intensity of the correlation image or its appearance after drying.

Actually, the measured correlation signal with these stars fluctuates constantly. The large optical bench system being used has a 20-foot air path and variations in air temperature cause the diffracted light to be deviated slightly and fall on different areas of the filter so that the signal varies plus or minus 2 percent in about 3 second cycles. This effect is especially noticeable with point images such as stars. It could be greatly reduced or eliminated by:

1. Using a shorter system

2. Enclosing the system
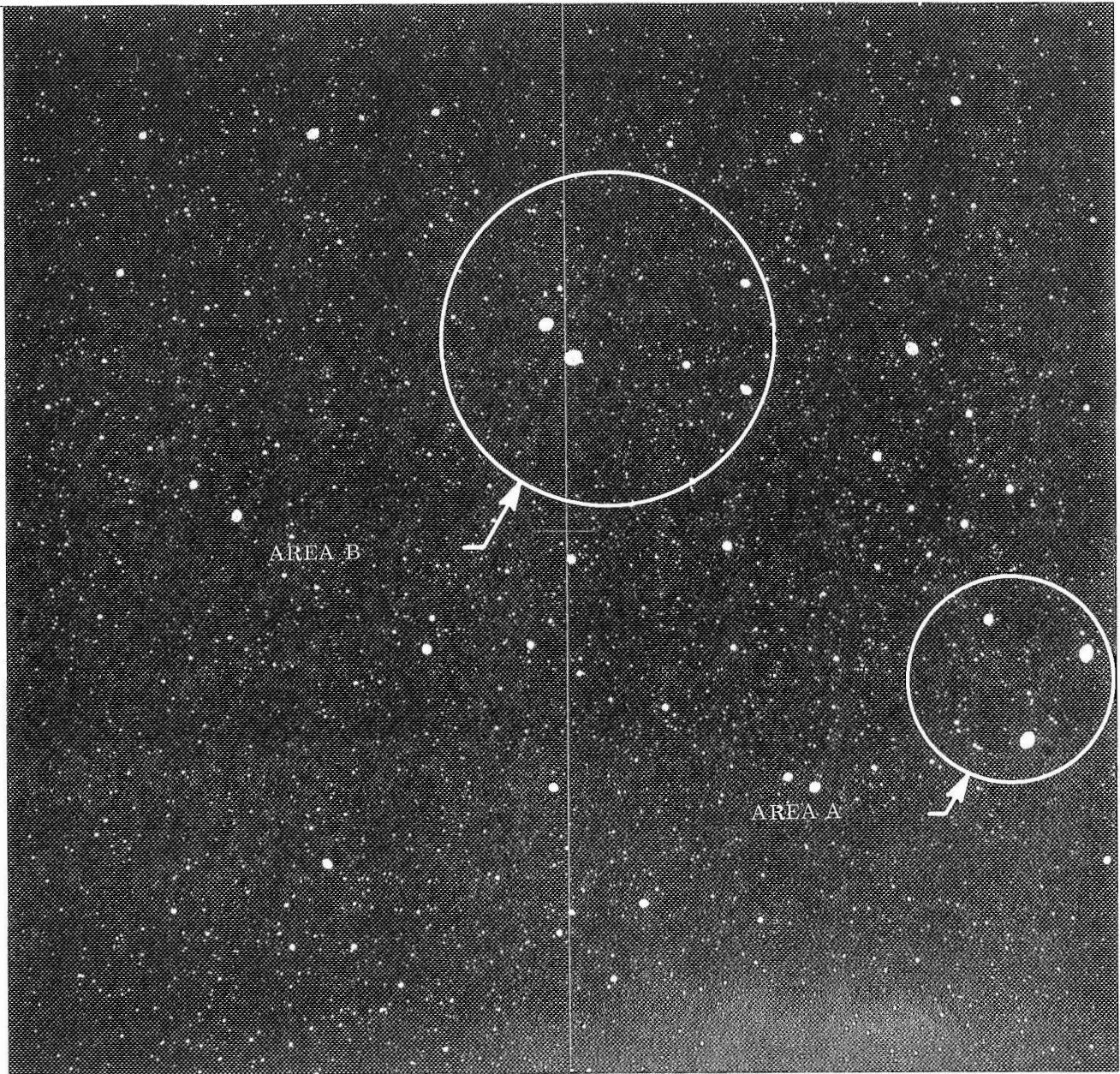
3. Evacuating the air

4. Better temperature control

Figure C-1. Star Field Ursa Major 49

C.6 Results

In the following table, Roll A was an old roll of film, part of which had been used for heating tests. This film had been heated 2 hours at 41°C, cooled and used at room temperature. The other exposures were made on normal film.

Polaroid 146L
Tests with Filter No. 2767 for Area B (Ursa Major)

Input Image Media	Signal	Noise	
Microflat Plate	100	0.3	
146L f 8 1/4 sec	216	0.5	Roll 1, 15 sec development
146L f 8 1/8 sec (too dense)	56	0.5	Roll 1, 15 sec development
146L f 8 1/4 sec	180	3.0	15 sec dev.
146L f 9 1/4 sec	100	1.0	15 sec dev.
146L f 8 1/8 sec	135	1.0	15 sec dev.
146L f 8 1/8 sec (small tear at edge, low density)	44	7.0	5 sec dev.
146L f 8 1/8 sec (low density)	67	1.5	Heat 20 min, 40°C dev. 1 sec
146L f 8 1/8 sec	95	4.0	Heat 25 min, 40°C dev. 1 sec
146L f 8 1/4 sec	100	4.0	Heat 30 min, 40°C dev. 1 sec
146L f 8 1/4 sec	160	1.0	Heat 30 min, 44°C dev. 1 sec
146L f 8 1/4 sec	200	1.0	Heat 30 min, 44°C dev. 1 sec
146L f 8 1/4 sec	200	1.0	Heat 40 min, 44°C dev. 1 sec
146L f 8 1/4 sec	230	0.8	Heat 40 min, 44°C dev. 1 sec

C.7 Comments

The best results were obtained on an old roll of film (Roll 1) which had previously been put through heat tests.

The signal obtained on some of the Polaroid films was greater than the Microflat plate. This is believed due to the fact that the Microflat plate was denser than optimum and the star images slightly gray.

The noise of the Polaroid films was always higher than the Microflat plates.

The shorter exposure latitude of 146L film makes the exposure and development more critical than on low contrast 46L film.

The signal values are on the same basis as those reported earlier and are higher than any signals obtained with 46L, but the noise is also higher.

C.8 Tests of Polaris Fields

Two different areas, A (containing large star images) and B (mostly small star images), were tested.

Polaris Area A

Input	Signal	S/N	Filter
Microflat plate	240	480:1	2724
146L	2000	200:1	2724

Polaris Area B

Input	Signal	S/N	Filter
Microflat plate	95	184:1	2736
146L	100	100:1	2736

C.9 Tests of Polaris Series

In this test, a transparency of the Polaris field on a 146L film heated 2 hours to 44°C and developed 1 second was compared to a Microflat plate using a series of filters. All these filters were of Area A, but with successively weaker stars retouched out of the object used to make the filter.

Polaris Area A Series

Input	Stars Remaining	Filter	Signal	S/N
Microflat	229	2724	240	480:1
146L	229	2724	2000	200:1
Microflat	189	2796	200	400:1
146L	189	2796	400	200:1
Microflat	146	2801	240	400:1
146L	146	2801	440	200:1

Polaris Area A Series (Cont'd)

Input	Stars Remaining	Filter	Signal	S/N
Microflat	63	2811	240	400:1
146L	63	2811	320	200:1
Microflat	43	2833	340	340:1
146L	43	2833	200	100:1
Microflat	22	2853	250	170:1
146L	22	2853	200	150:1
Microflat	13	2861	180	180:1
146L	13	2861	200	100:1

The results using 146L followed the same trend as those on Microflat plates. In most cases the S/N was lower on Polaroid film due to irregularities in the film and possibly other effects such as grain.

The Polaroid transparency used was the best of three made under practically identical conditions. The other two transparencies were tested only with the No. 2724 filter and, while they all looked the same to the eye, the others showed weaker signals and more noise. The amount of variation was about the same as we obtained in various tests of the Ursa Major area.

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APPENDIX E
"NEW TECHNOLOGY" APPENDIX

"After a diligent review of the work performed under this contract, no new innovation, discovery, improvement or invention was made".