FINAL REPORT

for

HRIR IMAGE RECTIFICATION

Contract No. NAS-5-9606

Prepared by

Westrex Communications
Division of Litton Systems, Inc.
New Rochelle, N.Y.

for

Goddard Space Flight Center
Greenbelt, Maryland

FINAL REPORT

for

HRIR IMAGE RECTIFICATION

Contract No. NAS-5-9606

Prepared by

Westrex Communications
Division of Litton Systems, Inc.
New Rochelle, N.Y.

for

Goddard Space Flight Center
Greenbelt, Maryland

Prepared by: H. Strickholm

Approved by: K. R. McConnell 7-15-66

ABSTRACT

This report describes the modification of an HRIR Photofacsimile Recorder to provide a rectified presentation of the HRIR picture. This simplifies interpretation and re-plotting of the recorded data onto other maps. Equipment modification involved precision cam redesign, film feed rate change and film exposure compensation. Test results verified the feasibility of rectifying the picture during readout. The picture format required discarded the horizon data. Supplementary use of this data to evaluate satellite pointing stability was deemed important by other users. A composite readout including the horizon view is recommended along with investigation of providing a fully rectified picture.

TABLE OF CONTENTS

I. HRIR Readout

II. Image Rectification

III. Design Modifications

IV. Test Results

V. Field Evaluation

VI. Conclusions

LIST OF ILLUSTRATIONS

Fig. 1	HRIR Readout
Fig. 2	Scanning Geometry
Fig. 3	Recording Geometry
Fig. 4	Recorder Geometry
Fig. 5	Light Mask Design
Fig. 6	HRIR Readout, Partial Rectification
Fig. 7	Picture Format

SECTION 1

HRIR READOUT

The NIMBUS satellite carrying the HRIR experiment produces pole-to-pole pictures with a horizon-to-horizon view of the weather and ground features below the satellite. These pictures are produced on 70mm film in a Photofacsimile Recorder at the ground acquisition station from signals sent by the satellite when it is within range of this station. An optical system in the satellite forms an infrared image of the area beneath the satellite with a small portion of the image hitting an infrared sensor. A rotating mirror sweeps this image across the infrared sensor and it "sees" in sequence elemental areas forming a narrow strip from horizon to horizon. This strip passes directly beneath the satellite. On the next rotation of the mirror, the satellite has moved and the sensor sees a strip adjacent to the previous one. The scanning is a result of the composite motion of the mirror which rotates at a uniform angular velocity, and of the satellite orbital motion about the earth. The mirror scans at right angles to the satellite velocity vector. The signal generated by this sensor is stored on magnetic tape and on command is transmitted back to the ground station reconstructing an image on film in the Photofacsimile Recorder. This received signal controls the brightness of a recording lamp which illuminates a small aperture. An image of this aperture is swept across the 70mm film in step with the horizon to horizon sweep of the image across the satellite infrared sensor. The film moves one spot width for each sweep across the film to reconstruct a picture on an element-by-element basis. Under ideal conditions the orbit is circular and the orbital velocity is constant. The resultant spacing of the scan lines on the earth surface is constant and the uniform film feed in the Photofacsimile Recorder matches the satellite orbit motion. One of these pictures is shown in Figure 1, which is a portion of a pole-to-pole strip. Figure 1 was obtained from NIMBUS I which was in an elliptical rather than circular orbit. While having the obvious advantage of providing a continuous reconstruction of the weather scene from horizon-to-horizon and pole-to-pole, without an intermediate montage of frames, this method of scanning has slant angle viewing distortion. The distortion is particularly apparent towards the horizon where the scanning goes through a tangent relation to the earth's surface and is a minimum below the satellite.

Figure 2, shows the scanning geometry along the scan line. The left side shows the satellite in the apogee position and the right side shows the scanning point in the perigee position. The scan beam in Figure 2 is shown intercepting the earth's surface at 15 degree increments of its rotation. In the apogee position of the orbit, when the scan beam is at 60 degrees, it has passed beyond the horizon and is sensing space. In the perigee position, the scan beam at 60 degrees is looking approximately 15 longitude degrees to the side of the zenith-nadir line. The altitude of the satellite has two effects upon the scanning geometry. First, it effects the horizontal distortion in terms of the arc distance along the earth's surface, and secondly it has a variable spacing of the scan lines due to the variation of orbital velocity from apogee to perigee.

Usable weather pictures are produced even with these distortions when the difference in altitude between apogee and perigee is not great. The apparent change in slant range of the picture readout and of the vertical scale along orbital track is not sufficient to be objectionable. The injection of grid points in the picture readout aids in making estimates of the magnitude of weather disturbances observed. Where more precise measurements are desired, such as in plotting the diameter of the storm or examining geographic relations of land masses, the distortions of slant viewing and vertical line spacing become important and should be removed.

SECTION 2

IMAGE RECTIFICATION

The possibilities of image rectification in existing equipment are a function of several relevant factors. The HRIR 1 and MK 2 Photo Facsimile Recorders were designed to provide a readout which has a satellite centered projection picture. This projection is shown in Figure 3 which shows the recording geometry. To the left of the zenith-nadir line the original satellite centered projection surface is shown. In this case, the geometry of the recorder was selected so that the scan beam projected on the film moved across the recording film with a uniform, linear velocity. This corresponded to the uniform angular velocity of the scanning unit in the satellite. An observer viewing the film with his eye placed above the middle of the film is able to view the image from the same projection point as the satellite scanning. The film must be formed to a cylindrical section as shown in "satellite centered projection surface". This type of projection is preferable where insufficient knowledge or specificaion exists of the parameters of satellite altitude. It has the advantage of eliminating the effects of altitude variation on the picture readout and maintains the resolution on the film at a constant figure in relation to the angular resolution of the HRIR scanner. The picture arc length S_F of the satellite centered image is projected onto the film as a film length with a proportionality factor K_S times the angular position $\emptyset$ of the satellite scanner measured against the zenith-nadir line. This projection system reserves the point-to-point relation on the picture but introduces distortions in surface scale due to variations of satellite altitude as indicated in Figure 2.

An alternate projection system is shown to the right of the zenith-nadir line in Figure 3. In this case, a scale projection surface related to the earth is used. The scalar factor is the earth surface arc length S which is projected onto the film with a proportionality constant K_E. Now, linear distances measured along the earth's surface scan line are directly projected in scale onto the film. This projection technique contains effect of the altitude H of the satellite. The arc length S sub tended by the angle Ø of the satellite scan beam is expressed by the equation shown at the bottom right in Figure 3. This equation shows the arc length at the earth surface S to be a function of the earth radius, the satellite altitude and the angle at which the scanner views the earth, with the zenith-nadir line defined as the zero angle. With a satellite orbit circular, H becomes a constant. For eccentric orbits, H becomes a function of T the time in orbital position.

The HRIR MK 1 and MK 2 Photo Recorders were designed for the satellite centered projection readout with no correction of satellite altitude or orbital velocity. This design imposes limitations on allowable modifications. Variations in orbital velocity with resultant variations of scan line spacing on the readout would require a continuously variable film feed system. This is not possible within the existing fixed gear train of the HRIR Recorders. Concurrently with a variable spacing of subsequent scan lines on the film, the vertical height of the aperture would also require adjustment to avoid overlap of successive scan lines at close spacing or underlap at wide spacing. Again, the initial equipment was designed for a fixed magnification of the physical aperture onto the film.

The line sweep of the Photo Recorder is generated by a cam action as shown in Figure 4. Rotation of the cam oscillates a mirror. A modulated light beam from the aperture is reflected from the mirror surface through a proportionate angle onto the film. The initial profile of this cam was selected to be compatible with the satellite centered projection system. The basic equations for the cam rise are shown in Figure 4. R_S and R_E are satellite and earth centered rise equations. Since the major distortions in the readout of the HRIR occur in the lateral plotting of the image points to the side of the satellite subtrack, experimentation on this contract was restricted to correcting this form of error. The plate cam design does not allow the introduction of the altitude variation.

A correction of the horizontal plotting of the picture element across the film so that the same linear distance along the scan line would represent the same scale miles, changes the spot velocity proportionally. Variations of velocity of a constant intensity spot on the film surface will result in variations of density in the developed film. A correction must therefore be introduced into the optical system which attenuates the light beam at the center of scan so the exposure is the same at the center as it is at the end of the scan. This attenuation may be accomplished by introducing a neutral density filter in front of the film. The neutral density filter would have a variation in its transmission coefficient along the scan line so that a maximum of light is transmitted at either end of the scan line and a proportionate minimum at the center. An alternate to introducting the filter is to introduce an opaque mask which effectively stops down the beam illuminating the film. This mask would dip into the beam from either the top or the bottom, blocking out a portion of the light forming the image. At the ends of the scan line the edge of the mask would be curved away so the full illumination through the optical system would fall onto the film.

With a change in the projection system used for reading out the picture data, the picture format would change to a certain degree. Analysis of the orbital separation of successive orbits, shows approximately 1,900 miles separation between successive orbits as the satellite crosses the equator. A scale factor was therefore chosen for the film so that the 54 millimeters of picture readout would correspond to 1,900 statute miles. This horizontal scale factor would provide full coverage of the earth with a small amount of overlap at the equator and successively increasing overlap as either pole is approached. This picture format would eliminate the weather from beyond that point to the horizon, on the horizon, and the space view.

SECTION 3

DESIGN MODIFICATIONS

The design of the MK 1 and MK 2 HRIR Photo Recorders limited the experiment to a correction of the slant range distortion on the photo readout. A non-linear cam profile was designed to fit the recorder optical and mechanical constants. The basic equation of this profile is shown in Figure 4 with the rise defined as r_E. The machine constants are L, the follower radius of the mirror system, and F, the focal length of the objective lens. Other constants are b, the earth radius and H, the satellite altitude. The value of the radius of a sphere of equal volume was selected for b. The satellite altitude H was selected as the design altitude of 600 nautical miles and was assumed to be fixed for the purpose of this experiment. The cam rotation, $\emptyset$, corresponds directly to the rotation of the scanning mirror in the satellite. A precision cam was designed to the theoretical equations for installation in the photo recorder in place of the existing cam.

The horizontal scale on the film was defined at 1,900 statute miles for the 54 millimeter width of readout. A new set of film feed gears was designed to provide a vertical feed proportionate to the horizontal scale factor. These gears are a pair of parallel helical gears. Gear ratios are restricted to whole number ratios. The gear ratio selected for the film feed provided an overall drive that was within one part in 10,000 of the theoretical film feed rate. This figure is far less the normal shrinkage of film in processing and is well within acceptable limits for the film feed.

A light mask was selected as the correction technique for maintaining uniform exposure across the film at constant signal level. The design approach is shown in Figure 5. An oversized scale graphic layout was made of the illuminating beam which images the picture elemental area on the scan line. The side view of Figure 5 shows the line height in exaggerated form. The plan view shows the scan line with the beam as it shifts from left to right along the scan line. The layout of the mask is shown above the plan view. An adjusting screw is placed at each end of the mask to allow it to be brought down so the mask profile would be tangent to the converging light beam at both ends of the scan position. The edge of the mask dips down into the converging light beam obscuring greater and greater portions until a maximum blocking occurs at the center of scan. An identical curvature is used for both halves of the mask. Theoretically, this type of correction of exposure along the scan line would produce uneven illumination within the image of the aperture on the film. This is shown in the side view. When the mask projects half way down, it obscures a major portion of the cone which forms the image point of the left edge of the scan line and obscures less of the converging cone for the image point which forms the opposite side of the scan line. When the line height is very small compared to the overall diameter of the base of the converging light cone, this effect is reduced. It is further reduced by selecting a position of the mask plane sufficiently far from the image plane so the back projection of scan line height represents a small fraction of the cone diameter at the masking plane.

The velocity of a spot of light across the film was computed from the basic cam equation. A correction factor was also introduced for the natural reduction in illumination when a lens is working off axis. This is the well known cosine to the fourth power law of lens illumination. The combination of these factors gave a coefficient which determined how much of the converging cone of light would require blocking off.

On the scale layout, circles were drawn for successive light beam positions and proportionate parts of the circle were deleted. The resulting composite figure of the sections of the circle then established points along the curve of the mask. A smooth curve was drawn through this layout to establish the profile of the mask. From this layout, a reduced scale drawing was made for actual manufacture of the mask to be installed in the Photo Recorder.

SECTION 4

TEST RESULTS

The HRIR Photo Recorder was received from NASA. A preliminary series of status tests were performed to establish the equipment performance in relation to its original delivered performance. No deterioration was found in the capability of the equipment to pass the previous qualification tests. The machine was then disassembled and the feed gears, new aperture, light mask assembly and precision cam were put in place.

A new test procedure was prepared to reflect the changes specified by the contract for this partial rectification experiment. The new feed gear ratio was measured in terms of film feed and performed as expected. The matching aperture was adjusted to provide the proper amount of scan line blending on the film.

The light mask assembly was installed and adjusted on the unit. Preliminary attempts to utilize a photo meter to set the exposure at the scan line did not produce valid results. Later adjustments utilized densitometer measurements of the film to correct mask position to provide nearly constant density across the film to within specifications.

The testing of the precision cam provided the greatest difficulty on this equipment. The angular velocity change of the mirror is approximately 4 to 1 with the greatest velocity occurring at the ends of the scan line just prior to the beginning of retrace and the end of retrace. Initial film results showed excessive vertical streaking on the picture. A re-analysis of the cam design tolerances and correlation of the film patterns with the surface finish of the cam, led to the conclusion that the cam tolerances should be smaller. A technical conference with the cam manufacturer and an analysis of his precision grinding equipment, indicated that the tolerances could be cut in half for the desired higher precision.

The cam was reground to the greater precision deemed necessary. Upon reinstallation of the cam in the equipment, the vertical pattern was significantly reduced. Further experimentation and introduction of damping upon the follower arm, reduced the streaking to an acceptable level on the film readout. Subsequent testing of the picture spot position against the cam rotation showed the unit met the design parameters for correcting the slant range distortion on the readout. At the completion of the testing of the equipment at Westrex, the unit was shipped for field evaluation and testing.

SECTION 6

CONCLUSIONS

The partial rectification of the HRIR Photographic readout showed up the advantages of having a simple scalar system for replotting weather information onto standard Mercator maps. While the experiment limited itself to rectification on the slant range, the equations derived for the rectification design showed it is also possible to correct for satellite altitude and orbital velocity variations. Correction of these parameters would require a redesign of the machine to allow a variable film feed to accommodate the velocity variation, a three dimensional cam which would have a continuous range of profiles to accommodate the altitude effects on a slant range distortion, and a variable magnification of the physical aperture onto the film to be consistant with the variation of line spacing due to the orbital velocity effects.

The picture formats of this experiment are shown in Figure 7, A and B. Figure 7 shows the format of the exsisting HRIR photo readout. Horizon and space data are retained with the unrectified readout due to the satellite center projection system recorded on the film. Figure 7, B shows the format utilized in the rectification experiment in which the horizontal sweep line of 1,900 statute miles was scaled to fit within the 54 millimeters of the film.

A composite readout is shown in C of Figure 7. This was not tested in this experiment. In this case the 1,900 statute miles of rectified earth is retained in the center of the picture.

A marker line is placed at the beginning and end of the rectified portion and the balance of the film is utilized to print out the unrectified data out past the horizon. This unrectified portion could utilize a satellite centered geometry to supplement the data of the rectified portion of the readout. A composite picture of this form would retain the advantage, in the center, of easy transfer of data from one graphic projection system to another. In addition, it would provide the supplementary experimental information of satellite stability performance, indicated by undulations of the horizon line, and preliminary data on the weather towards the horizon although with attendent slant range compression.

The possibilities of designing a photo facsimile recorder to rectify fully in both directions is inherent in the basic equation for the cam profile. Whether such a fully rectified readout is needed for this type of weather evaluation or the form of HRIR weather data presentation will be superceded by other systems, is dependent on the performance of many other experiments and theories in the meteorological field.

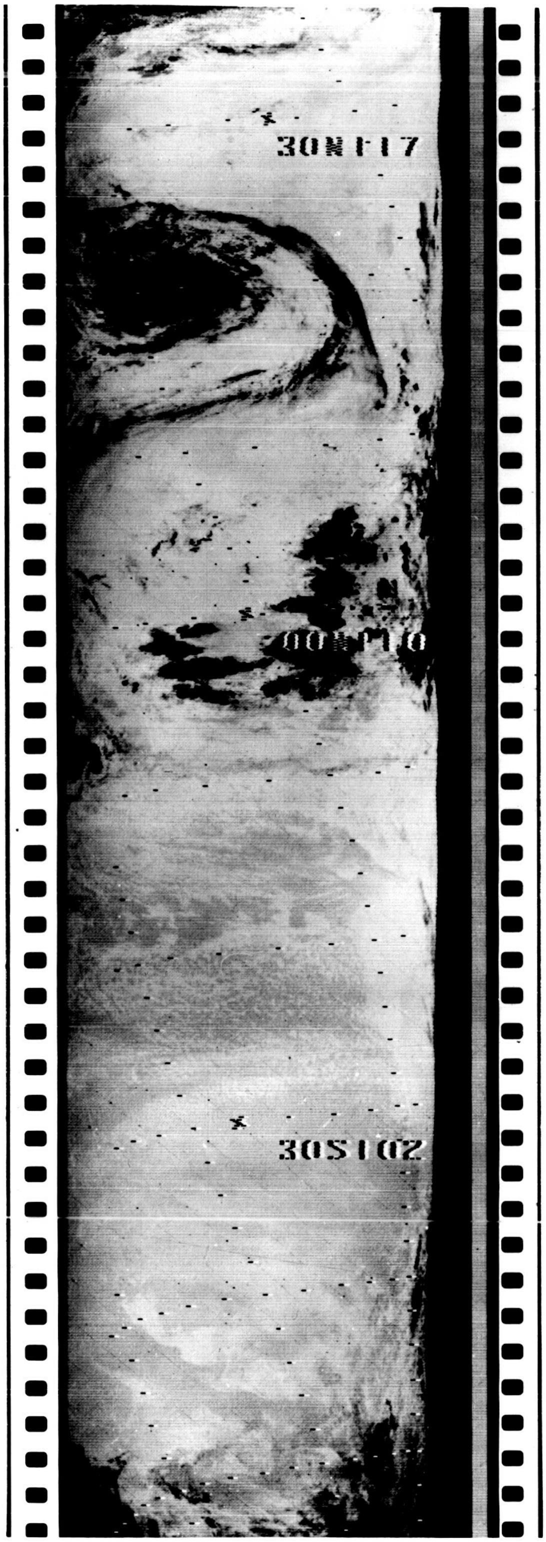


FIGURE 1. HRIR READOUT

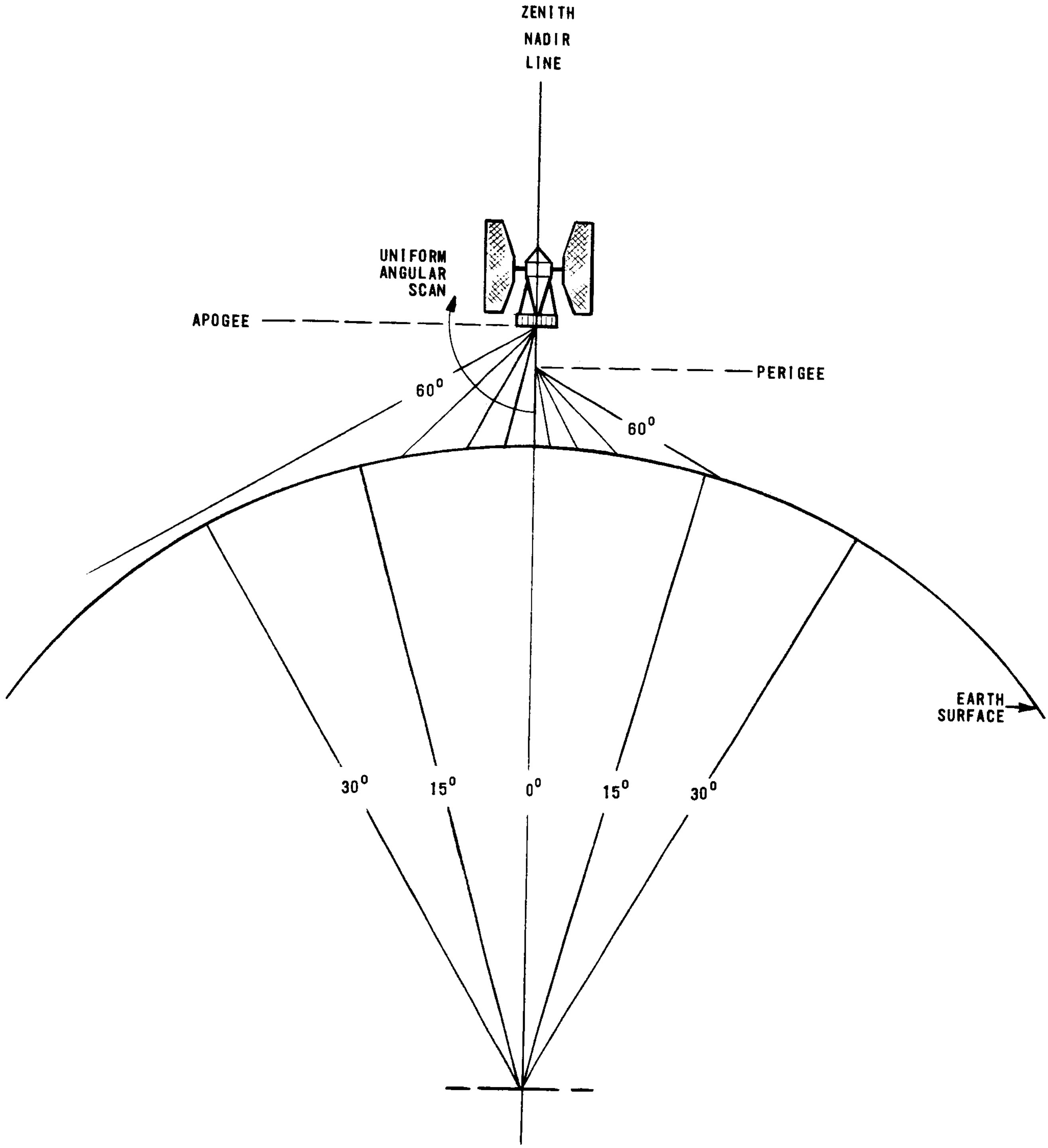


FIGURE 2. SCANNING GEOMETRY

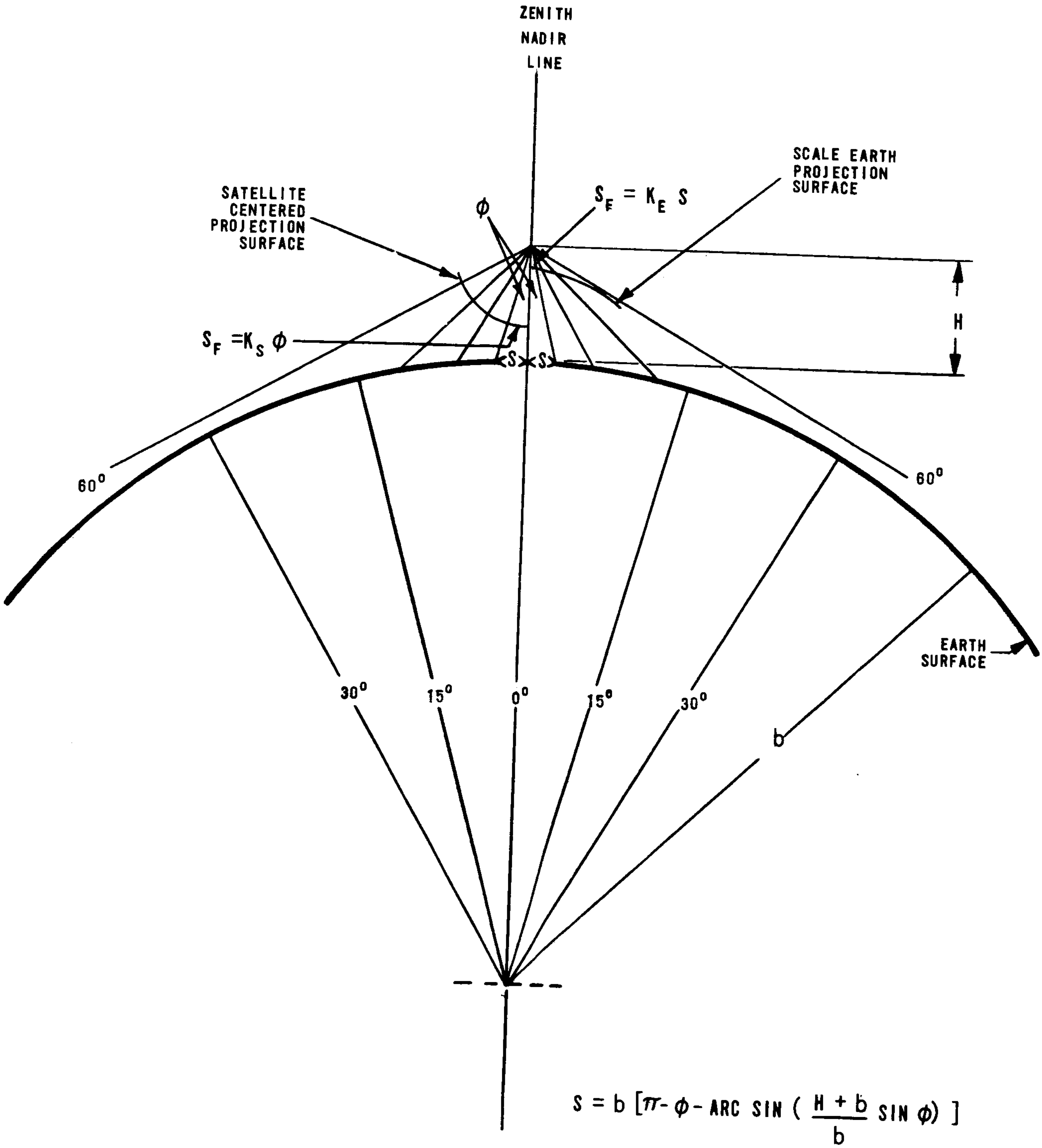
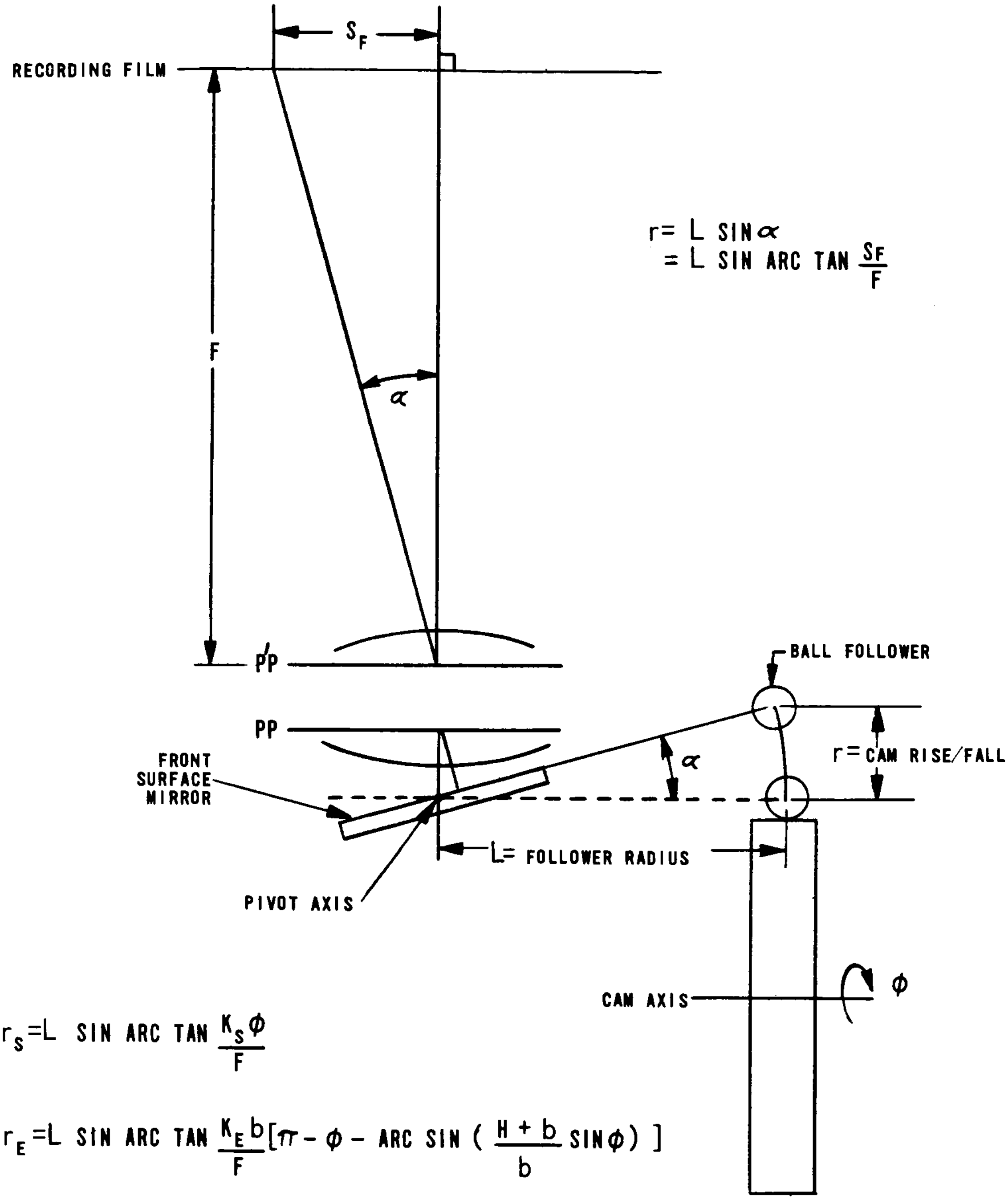


FIGURE 3. RECORDING GEOMETRY



$$r = L \text{ SIN } \alpha$$
$$= L \text{ SIN ARC TAN } \frac{S_F}{F}$$

$$r_S = L \text{ SIN ARC TAN } \frac{K_S \phi}{F}$$

$$r_E = L \text{ SIN ARC TAN } \frac{K_E b}{F}\left[\pi - \phi - \text{ARC SIN } \left(\frac{H + b}{b} \text{ SIN } \phi \right) \right]$$

FIGURE 4. RECORDER GEOMETRY

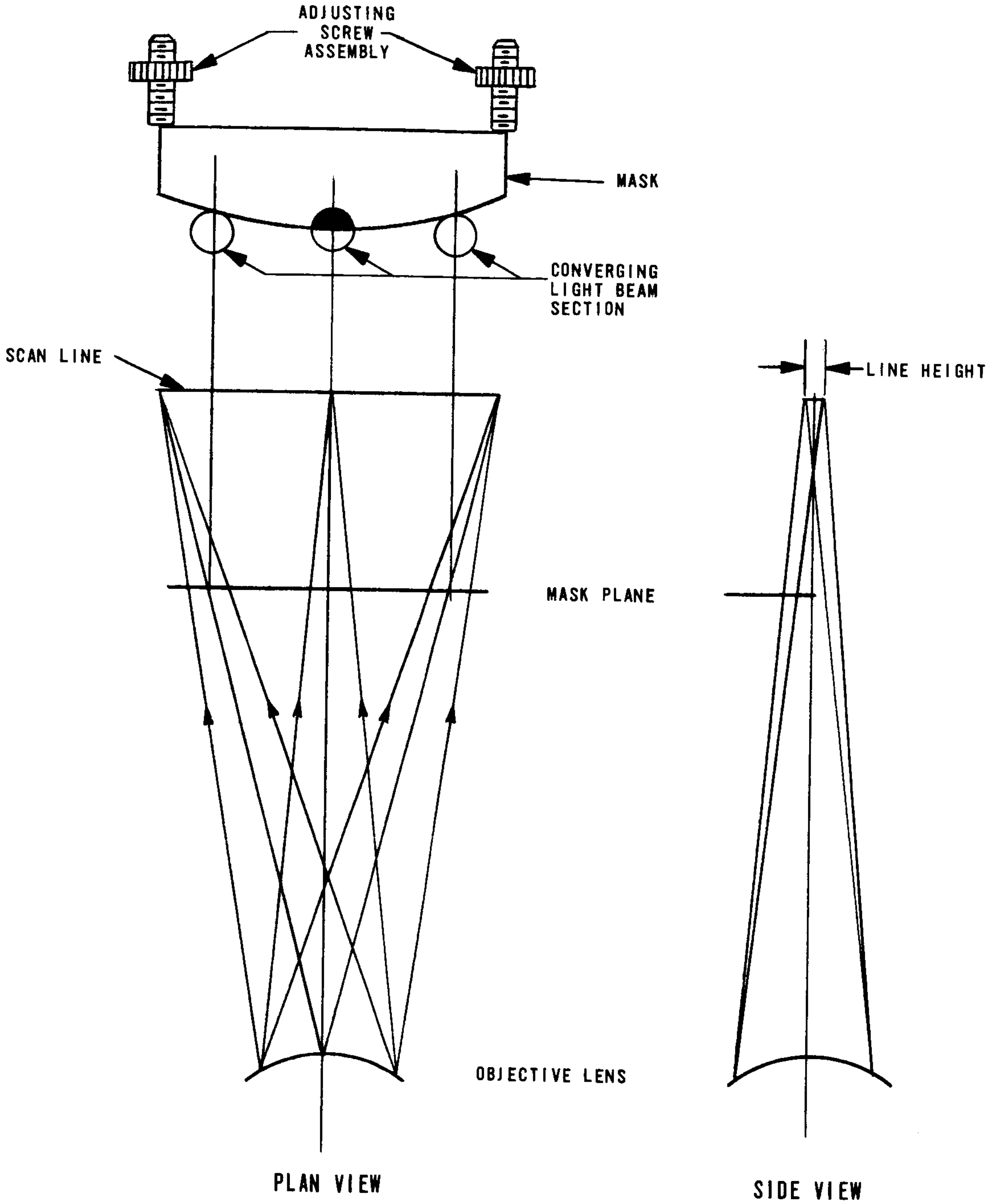
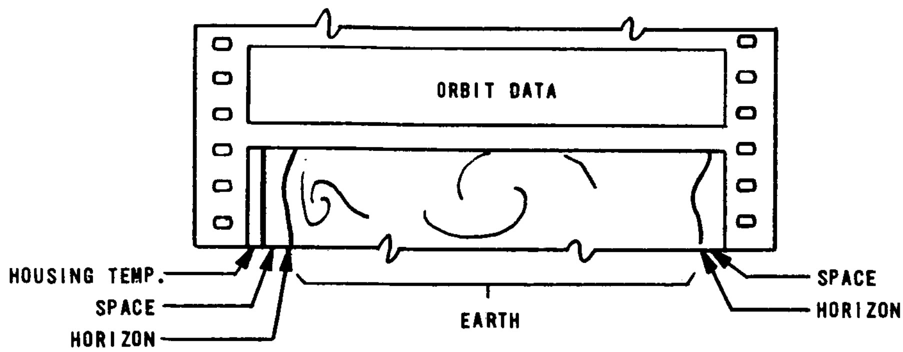
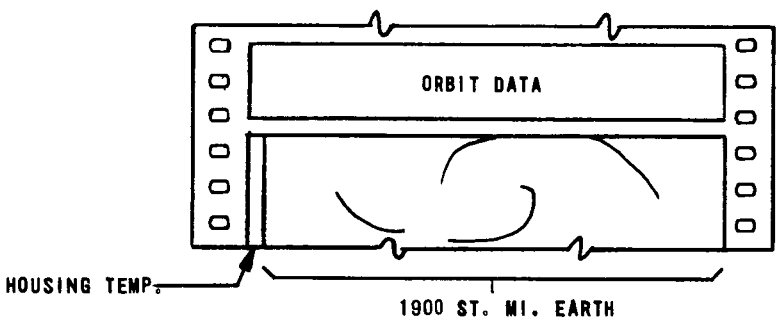


FIGURE 5. LIGHT MASK DESIGN

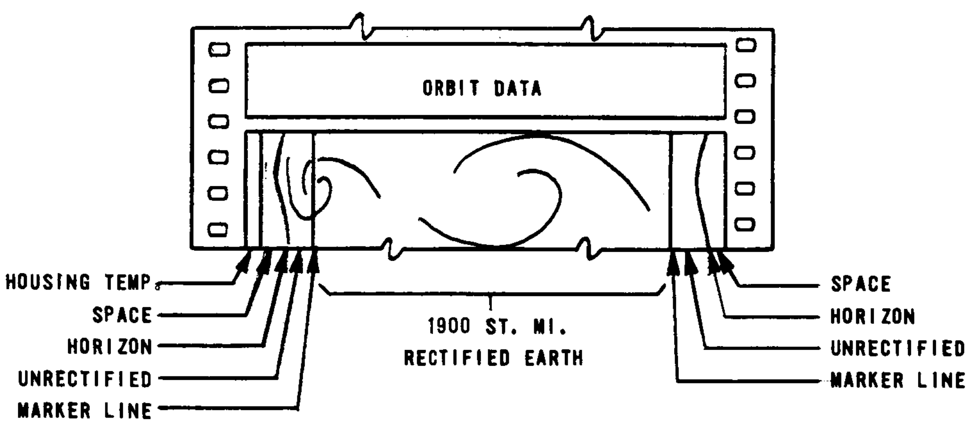
FIGURE 6. HRIR PARTIAL RECTIFIED READOUT



A. HRIR READOUT



B. HRIR PARTIAL RECTIFIED



C. HRIR COMPOSITE READOUT

FIGURE 7. PICTURE FORMAT