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CRYSPER On-Orbit Performance Prediction Model

PFA TECHNICAL REPORT NO. 10

PHOTO RECONNAISSANCE SYSTEMS DIVISION
OFFICE OF DEVELOPMENT AND ENGINEERING

BYE 15319-73

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CRYSPER ON-ORBIT PERFORMANCE PREDICTION MODEL

PFA TECHNICAL REPORT NO. 10

14 JANUARY 1974

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PUBLICATION REVIEW

This report has been reviewed and is approved.

[redacted]
Task Chairman, Headquarters

ROBERT J. KOHLER
Chairman, Post Flight Analysis Team

FOREWORD

This report documents the concepts and theory employed in the CRYSPER Computer Program. CRYSPER is an on-orbit performance prediction model for the HEXAGON camera. It models the acquisition, atmospheric, and camera performance aspects of the Sensor Subsystem, to enable the prediction of the expected on-orbit achieved ground resolved distance. This report discusses the major program subroutines, the required aspect data and the sources of that data, and summarizes some of the problems inherent in the CRYSPER Program.

There is no conclusion and/or recommendations section for the intent of this report is to describe how the CRYSPER Program works, not how valid the predictions are. The test and operational results from this program are recorded in the specific mission reports (Sensor Subsystem Post Flight Analysis, Flight Readiness, etc.).

Special credit is due [redacted] of the West Coast Project Office (WCPO) for drafting Section II, J. Avenel (BRIDGEHEAD) for Section III, and [redacted] (SSC) for Section IV.

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SECTION I

ON-ORBIT PERFORMANCE ESTIMATES

1.1 INTRODUCTION

Preflight performance predictions are made for each HEXAGON mission using the CRYSPER Program. CRYSPER predicts the on-orbit performance of the camera system in its expected operating environment. The predictions are generally two sigma low estimates of resolution in both cycles/mm in the film plane as well as the projection of that resolution to the ground resolved distance (GRD) of the recorded scene. The program has three basic sections which are linked together, each one describes a major aspect of the final system resolution. These three sections are:

A. An orbital model (SR-1) which uses as input data the orbital elements for the mission and specific characteristics of the targets. The output of this section of the program is ordered by target access and consists of the solar ephemeris as well as the geometry of each access.

B. An atmospheric model (SR-2) which uses the data generated in the previous section and computes the apparent contrast of each accessed target. It contains various haze models which have been verified by emperical measurements made during the last several years. The data bank enables this section of the program to estimate the effects of various haze levels on a geographic and seasonal probability basis.

C. A camera performance model (SR-3) which is a mathematical description of the performance characteristics of the camera system and flight vehicle. This subroutine uses the output from both of the previous subroutines as well as the film characteristics and the camera smear/optical performance data under the various operating conditions. The basic flow of data through CRYSPER is shown in Figure 1-1.

The calculation of resolution is obtained by intersecting the system modulation transfer function (MTF) with an aerial image modulation (AIM or TM) curve that describes the film characteristics under the exposure/contrast conditions prevalent during exposure, see Figure 1-2. CRYSPER has been configured to compute a table of resolution values in either cycles/mm at the film plane or ground resolved distance (GRD) in feet for a range of solar altitudes based on latitudes over the entire 120° format.

As mentioned above, the resolution predictions can be either two sigma low or median values. In the early stages of the evolution, the estimates were obtained from a Monte Carlo process in which the 96th percentile resolution was chosen from a large number of individual samples. However, the computer running time was too long. In order to shorten the time for the "worst case estimate", CRYSPER was changed to approximate the resolution from the single computation using the mean smear and defocus plus or minus (whichever was worse) the two sigma variation of these parameters. The program also has the capability to compute a median resolution value. Testing is in progress to more fully understand the meaning of a median as compared to a two sigma low prediction. CRYSPER is still being refined, and

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DATA FLOW THROUGH CRYSPER PROGRAM

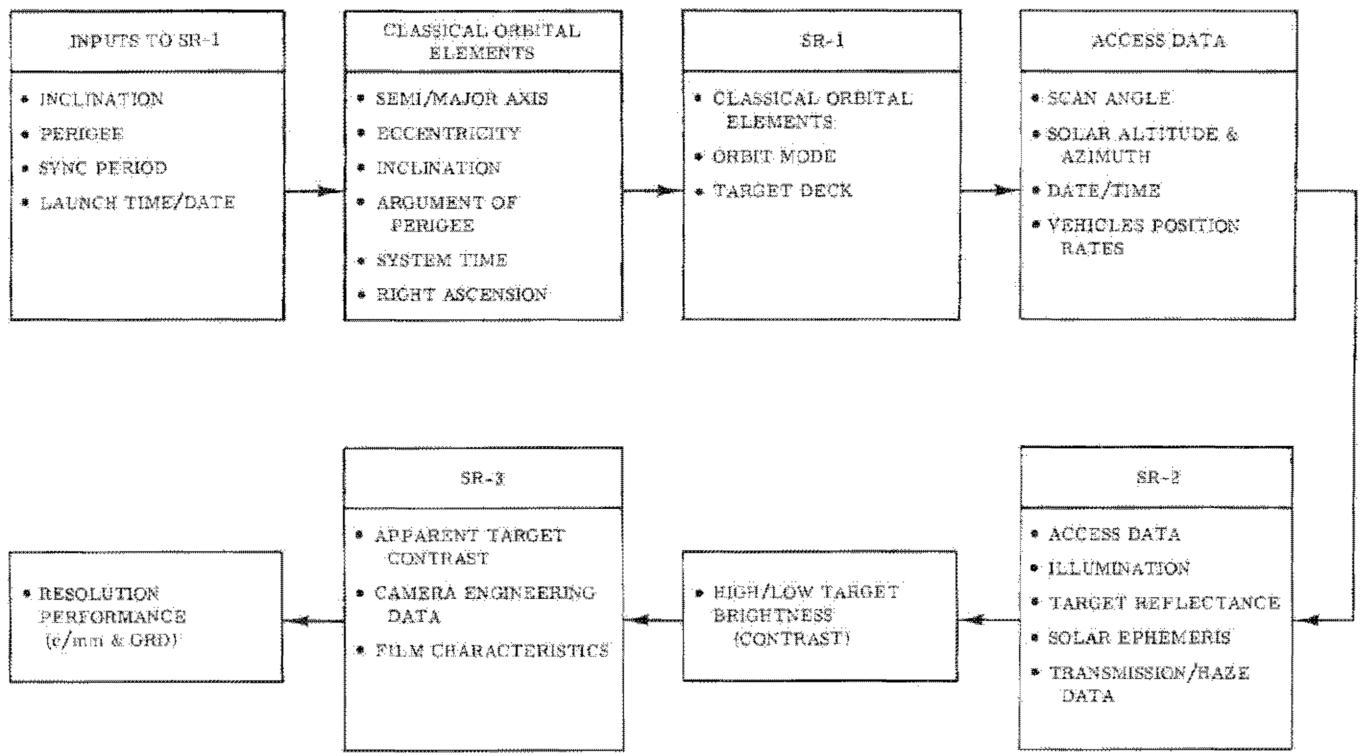

FIGURE 1-1

TM CURVE RESOLUTION PREDICTION

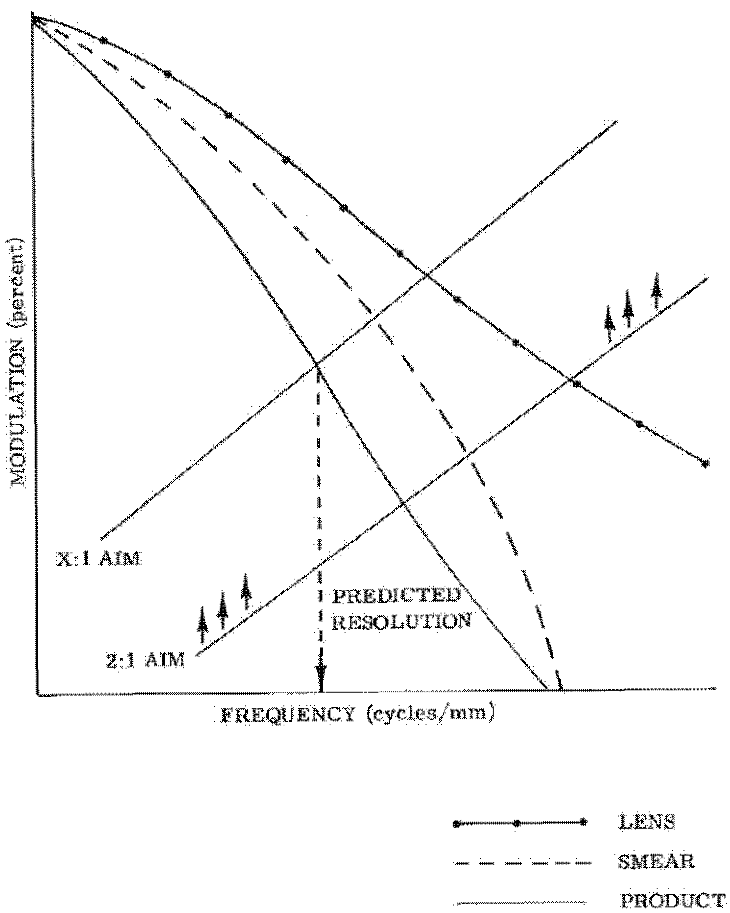

FIGURE 1-2

is expected to change as more is learned about this type of modeling through examination of actual flight photography. There will likely be further expansions in the output format of the new version of CRYSPER, referred to as KAPER.

1.2 CRYSPER CONCEPTS

During the design and test stages of building a camera system, a set of standard conditions are used that are generally based on best exposure and 2:1 apparent target contrast. This provides a stable base from which design predictions can be compared against actual test chamber results. However, these stable conditions do not exist during flight.

Each operational target is acquired under its own unique set of conditions. Even the same targets acquired on a later date can exhibit new characteristics that will influence the final achieved performance. Among the factors that are not within engineering control are the reflectances (contrast) of the targets and the haze conditions at the time of exposure. These two factors have a direct and significant influence on performance.

An effort has been undertaken to quantify these two characteristics so that the CRYSPER Program could be used to predict the GRD for accessed intelligence targets or geography with some relation to reality. The haze has been estimated as a probability distribution on a seasonal basis. The seasonal haze model is an estimate made on a statistical basis. Typical haze levels for different areas of the world can also be input. The target reflectance aspect has been handled by assigning a high-light and low-light reflectance to each COMIREX target category. These values were based on density measurements made from past reconnaissance photography. The contrast of these targets is low, the maximum being slightly above 2:1 on the ground. Intelligence target contrasts are further reduced (to 1.5:1 or lower) by the atmospheric haze.

A series of CRYSPER runs are made to estimate the performance for all HEXAGON missions. The CRYSPER output consists of the format/solar altitude tables and the target access data. The orbital elements for a particular launch are used along with the performance estimates from the Chamber A acceptance test and the latest Chamber A-2 test. Chamber A-2 provides data at only two collimator locations, whereas Chamber A has three. In order to have as much data as possible for determining the film synchronization errors as a function of scan angle, both sets of data are used. However, there are some inconsistencies in the data between these two tests.

The output used for the angle/angle resolution (cycles/mm) tables has been expanded to include GRD in feet. The computation used to convert from film plane resolution in cycles/mm to GRD takes into account the slant range and perspective conditions of the acquisitions. It is, therefore, a number that relates to horizontal objects on the ground, i.e., Controlled Range Network (CORN) tribar targets.

Mobile CORN tribar targets are photographed during domestic passes for engineering purposes.

These targets have a ground contrast of approximately 5:1, and have been useful in assessing the accuracy of on-orbit performance predictions from CRYSPER.

Separate CRYSPER runs are made in order to accommodate both the engineering and intelligence needs for resolution predictions. The engineering run uses an average haze condition and the nominal CORN tribar target reflectances of 7% and 33%. This equates to placing a CORN tribar target at each intelligence location and photographing it on "average" days. CRYSPER approximates the engineering ground based tests by controlling the major non-camera related variables and produces GRD values between 2' and 9' as the design indicates. The run for "typical intelligence targets" equates to replacing the intelligence target with a CORN tribar target that nearly matches it in contract (10-20%) and photographing it under atmospheric conditions typical of those at that time of the year. Hence, it is not uncommon to have photography of 10-15 feet GRD under these conditions even when the camera is operating according to its design.

A third type of performance prediction entitled CRYSPER/VEM resolution has been added to the standard premission predictions. This prediction is designed to relate to the VEM resolution data acquired during the PFA time period and the subsequent in-depth analyses of the mission. VEM provides an estimate of the 2:1 contrast resolution in cycles/mm, the basic performance measure of the camera system. The VEM matrix is calibrated to 2:1 contrast resolution regardless of the contrast of the edge itself. The CRYSPER atmospheric subroutines, which ultimately adjust the AIM curve for exposure and contrast are bypassed for these predictions and a constant 2:1 contrast is employed.

SECTION II

CRYSPER TARGET ACQUISITION MODEL (SR-1)

2.1 SUMMARY

The software module SR-1 determines target acquisitions and various orbital data associated with each of these acquisitions. The SR-1 model is also referred to as PANDA. Acquisitions are determined using a data base consisting of a target deck in standard CRYSPER format and a set of rev-by-rev instantaneous orbit elements of the BREAKWELL-type. Target acquisition data is determined for each orbit revolution through an iterative process using standard BREAKWELL orbit decay techniques.

Several options are available to the user in selection of the mode in which this software is to be run. The user may specify a unique rev span to be examined, a maximum obliquity to be used for target acquisition determination, or a minimum solar elevation at which acquisition data is desired. An additional option of use in post-flight evaluation of CRYSPER predictions is the capability to include in the target data the rev number on which the target was acquired. This allows the program to generate target acquisition data only for the specified rev.

The SR-1 program is written in FORTRAN for execution on an IBM 360/370 Computer having at least 150K bytes of memory plus at least 150K bytes of auxiliary disk storage. The SR-1 program will run as a stand-alone module. However, the input target data must be formatted by the CRYSPER driver or an equivalent program.

2.2 SR-1 INPUTS

SR-1 inputs consist of a target data set, an orbit element data set, and a single control card. SR-1 uses only the target latitude, longitude, and the actual rev number of acquisition from the target data set. The balance of the target data set is merely passed on for use by the SR-2 and SR-3 modules.

The orbit element data set contains two data set control records which provide mission identification and launch dates and times associated with the orbit elements. The remainder of the orbit element data set consists of BREAKWELL-type elements which provide the semi-major axis, eccentricity, inclination, argument of perigee, ascending node longitude, epoch (ascending node) time, and BREAKWELL decay factors.

The control card needed to run SR-1 provides the run identification, launch date and time, start and stop rev, maximum obliquity, minimum solar elevation, identification on orbit data set, and rev exclusive (acquisitions computed only on revs indicated on target records) indicator. If no inputs are provided for any of the above items the program selects appropriate default values and proceeds with execution. Some default examples are 0° for minimum solar elevation, 60° for maximum obliquity, etc.

2.3 SR-1 OUTPUTS

Certain data is computed and output by SR-1 for use by the SR-2 and SR-3 modules. Other SR-1 outputs are data items which are merely passed from the target data set to be used by the SR-2 and SR-3 modules.

Data items computed by SR-1 and passed for use by SR-2 and SR-3 are:

A. GMT day, month, year, and time (closest approach) of each target acquisition.

B. Satellite vehicle latitude and longitude at time of closest approach.

C. Direction of vehicle travel at time of closest approach (northbound or southbound).

D. Scan angle to target at time of closest approach.

E. Vehicle radius, oblate earth radius, and satellite altitude at point of closest approach.

F. Ratios of velocity to altitude for velocities measured along the X, Y, and Z axes (Vx/h, Vy/h and Vz/h) at the time of closest approach.

G. Satellite inertial velocity at the time of closest approach.

H. Solar elevation at the target location at the time of closest approach.

I. Rev number on which the target is acquired.

2.4 SOFTWARE DESCRIPTIONS

The SR-1 module consists of a main program and several subprograms. These programs are described below. This module has been developed by SSC/WCFO under the name of PANDA and is described in detail in BIF007/D-0041-73 dated 16 February 1973.

2.4.1 MAIN Program

This is primarily a driver for a series of subroutines. It also interprets the input control card and sets up the controlling parameters for the SR-1 execution.

2.4.2 SETELT Subprogram

This routine initially reads the orbital data set and computes a number of the frequently used parameters for each orbit revolution. Subsequent calls to this routine pick up the orbital parameters for each revolution which are used in computing target acquisitions.

2.4.3 ACQCON Subprogram

This routine reads the target deck and converts target latitudes from geodetic to geocentric. Auxiliary Routines TARACQ and SOLLY are called to determine if each target is acquired and if the solar elevation meets the minimum criteria. The FINDAT Routine is then called to assemble required output acquisition parameters and place the data on a temporary file.

2.4.4 SUMRY Subprogram

This routine prepares summary information concerning the number of acquisitions for each target within the target deck.

2.4.5 TARACQ Subprogram

This routine determines whether a target is acquired on the ascending/descending portion of an orbit. The Routines ANGLE, LOCORD and CENANG are auxiliary to performing this computation.

2.4.6 SOLLY Subprogram

This routine computes the solar elevation at the target latitude/longitude based upon the time and date of acquisition.

2.4.7 ANGEL Subprogram

This routine computes the vehicle radius, latitude, longitude, time, and orbit angle at the time of acquisition.

2.4.8 Additional Subprograms

The additional Subprograms LOCORD, EDK, CDAT, CENANG, DAOFYR, XDAT, VALCHK, GUN, and FINDAT provide auxiliary computations regarding the orbital ephemeris and target acquisitions. Each of these routines is documented fully in the 16 February 1973 PANDA software description document referenced above.

SECTION III

SPECTRAL PHOTOGRAPHIC ACQUISITION MODEL (SR-2)

3.1 SUMMARY

SR-2 is an abridged, subroutine version of the spectral photographic acquisition model, KALEIDOSCOPE. The SR-2 model is also known as KSCOPE. This model calculates atmospheric and scene radiance, including the atmospheric transmittance, relative to the geometry of acquisition.

Information on the acquisition geometry is provided by the SR-1 (orbital model) portion of the program. SR-2 then calculates contrast values and apparent luminance values for the target reflectances passed from SR-1, calculating the spectral content of the scene and atmospheric conditions according to the parameters supplied by SR-1, and including the exact spectral weighting function of the system response. System response is the combination of film sensitivity, lens transmittance, and filter transmittance in the camera system. These values are then passed to subroutine SR-3 (camera model) where, combined with data describing the system characteristics, system performance for the acquisition is calculated.

The values required by the SR-3 portion of CRYSPER are target luminance and contrast values. Target luminance is calculated by comparing the radiometric energy from the target with the energy of a known calibration source, and then scaling the integrated energy (watts/m^2) to photometric units (foot-lamberts). Contrast values are computed as the ratio of the energy of the atmospheric radiance (haze) to the effective irradiance of daylight, as modified by the spectral atmospheric transmittance. For both calculations, the values are computed relative to the exact spectral response of the Forward and Aft photographic systems. Spectral atmospheric quantities are computed for the exact geometry of acquisition, as supplied by SR-1.

3.2 SR-2 INPUTS

3.2.1 Geometry Inputs

Values describing the geometry of acquisition are required for the calculation of daylight irradiance, atmospheric radiance, and atmospheric transmittance. These values are either supplied by SR-1, or are calculated based on values supplied by SR-1. These values include:

A. Date of acquisition.
B. Time of acquisition.
C. Satellite geographic location.
D. Satellite altitude.
E. Scan angle.
F. Orbital inclination.
G. Solar altitude.

H. Solar azimuth.

I. "CATS" angle (the angle included by the camera-target and sun-target lines).

J. True zenith distance (the angle between the target zenith and the camera line of sight).

3.2.2 Target Description Inputs

SR-1 also supplies the following values which are used in computing target luminance, and in specifying atmospheric conditions (haze level):

A. Target low and high reflectivities.

B. Target type used to indicate snow surround. If snow is present, target luminances are increased by the effect of snow, and the exposure time used in SR-3 is shortened to compensate for the increased energy.

C. Haze indicator. The haze level can be input manually, or the model may be allowed to estimate the haze level as a function of the date of acquisition.

3.2.3 Spectral System Response

All energy values calculated by SR-2, and used in SR-3, are computed relative to the exact spectral response of the photographic system. These include:

A. Spectral transmittance of the lens system.

B. Spectral transmittance of the filter(s) in the optical system.

C. Spectral sensitivity of the film.

3.3 RADIOMETRIC ACQUISITION SIMULATION

The atmospheric radiance, atmospheric transmittance, and daylight irradiance models within SR-2 are of particular importance, since they constitute quasi-standards which are the basis for the energy calculations performed in the program. The following lists the parameters considered in determining these spectral quantities for a given acquisition:

A. Horizontal Plane Daylight Irradiance Model

(1) Solar altitude. Examination of measured spectral irradiance distributions indicates that, over the range of haze levels suitable for photographic acquisition, irradiance at any given solar altitude does not vary appreciably as a function of changes in atmospheric quality.

B. Atmospheric Transmittance

(1) Molecular scattering.

(2) Aerosol scattering.

(3) Absorption of atmospheric moisture.

(4) Absorption of ozone.

(5) Zenith distance of optical axis.

C. Atmospheric Radiance

(1) Transmittance level.

(2) Solar altitude.

(3) Zenith distance of optical axis (determines air mass number for calculation of spectral scatter fraction).

(4) "CATS" angle (scatter angle).

(5) Increases in radiance caused by the reflectance of the surround.

3.4 BASIC EQUATIONS

The acquisition geometry, and certain options the user may choose, are used by SR-2 in modeling the horizontal plane irradiance of daylight, atmospheric radiance, and atmospheric transmittance. The algorithms involved are quite lengthy. These algorithms are discussed later in this section. The basic equations of those terms actually passed to SR-3 are given below.

3.4.1 Target Luminance

Target luminance is calculated by comparing the energy from the target with the energy of a known calibration source (currently, a 1B Sensitometer), and by scaling the integrated energy (in watts/m^2) to foot-lamberts. Although all calculations are performed in radiometric units, this output is converted to photometric units to conform with SR-3 requirements.

$$B_a = .4210 * \pi * \frac{\int \left[\frac{Ho_\lambda * R * T_{A\lambda}}{\pi} + Nh_\lambda \right] * T_\lambda * F_\lambda * S_\lambda \, d\lambda}{\int H_\lambda * T_\lambda * F_\lambda * S_\lambda \, d\lambda}$$

where:

B_a = apparent luminance (foot-lamberts)

Ho = spectral irradiance of daylight

R = neutral target reflectance (from SR-1)

T_A = spectral atmospheric transmittance

Nh = spectral atmospheric radiance

T = spectral transmittance of the lens

F = spectral transmittance of the filter system

S = spectral sensitivity of the film

H = spectral energy of 1B Sensitometer with daylight filter

.4210 = constant, to scale to foot-lamberts

λ = wavelength (nanometers)

Apparent luminance values are calculated for both high-light and low-light target reflectance values, supplied by SR-1.

3.4.2 Contrast Values

Contrast values are computed as the ratio of the energy of the atmospheric radiance to the effective irradiance of daylight, as modified by the spectral atmospheric transmittance. The formula for calculating contrast values is:

$$C = 100 * \frac{\int \pi * Nh_\lambda * T_\lambda * F_\lambda * S_\lambda \; d\lambda}{\int Ho_\lambda * T_{A\lambda} * T_\lambda * F_\lambda * S_\lambda \; d\lambda}$$

where:

C = the contrast value

All other terms are as defined in paragraph 3.4.1. All calculations are performed for both the Forward and Aft Camera Systems and their unique geometry.

3.5 SR-2 INPUT/OUTPUT

3.5.1 SR-2 Input

In addition to the information supplied by the SR-1 portion of the program, SR-2 requires inputs describing the spectral system response and the overall exposure adjustment desired for a given run. These inputs are:

A. Spectral System Response

The user must supply the program with the following information describing the camera system:

(1) Spectral transmittance of the lens system.

(2) Spectral transmittance of the filter(s) used in the optical system. Up to three each may be specified for both the Forward and Aft Cameras.

(3) Spectral sensitivity of the film.

B. Spectral Data Library

In order to simplify the user's task and minimize the number of cards required by SR-2, a "spectral library" of spectral system data is used by the program. Data entries in the library consist of unique eight-character codes, and the wavelength-by-wavelength spectral data associated with each code. In running the program, the user only has to specify the code name for the data desired and the program will then retrieve the actual spectral values. Maintenance of the library (additions, deletions, and updates) is performed as a separate, off-line operation by BRIDGEHEAD personnel.

C. Exposure Adjustment Option

Exposure times calculated by SR-3 (camera model) are computed using a table of solar altitude versus exposure time, using linear interpolation techniques. These tables normally reflect the ideal exposure at the center of scan for any given solar altitude. On occasion, however, the user may wish to simulate over or underexposure of a mission. SR-2 incorporates the capability of specifying other than ideal exposure through the input of the $\log_{10}$ exposure adjustment desired; the exposure time calculated in SR-3 is then modified using the following equation:

$$t' = t \cdot 10^{ADJUST}$$

where:

t' = modified exposure time

t = ideal exposure time

ADJUST = $\log_{10}$ exposure adjustment

NOTE: The exposure adjustment specified in SR-2 is applied to every acquisition simulated in the run.

3.5.2 Data Passed From SR-1

The bulk of the information required by SR-2 is passed by SR-1 using a temporary data set as intermediate storage. Information read from this data set is placed in labeled COMMON storage for use by both SR-2 and SR-3. It is identified/labeled as: COMMON/XIN/RDOH, XIN, IOR, IIN.

The following information is used by SR-2:

A. Sun/Vehicle Geometry Input

(1) IIN (12) Greenwich day

(2) IIN (13) Greenwich month

(3) IIN (14) Greenwich year

(4) XIN (1) Greenwich Mean Time

(5) XIN (2) Satellite geographic latitude

(6) XIN (3) Satellite geographic longitude

(7) XIN (4) Satellite altitude normal to oblate earth

(8) XIN (5) Scan angle (positive to left of flight path, looking forward)

(9) AI Orbital inclination (not placed in COMMON for use by SR-3)

Most of these values are required as inputs to additional geometry subroutines within the SR-2 package.

These additional terms are then input to the daylight irradiance, atmospheric transmittance, and atmospheric radiance subroutines. Paragraph 3.6, "Subprogram Packages", presents a description/discussion of these additional values.

B. Target Description Inputs

(1) IIN (8) Target low-light reflectivity

(2) IIN (9) Target high-light reflectivity

C. Target Luminance Inputs

The following values of R are used in computing target luminance:

(1) IIN (10) Target type

(2) IIN (11) Target haze condition

D. Haze Level Specification Options

The scaling of the atmospheric radiance and atmospheric transmittance is based on the estimate of the atmospheric transmittance at a wavelength of 550 nanometers (T_{550}). The value of IIN (11), the target haze condition indicator, is used to specify a choice of haze level, see Table 3-1.

TABLE 3-1

HAZE LEVEL SPECIFICATION OPTIONS

IIN (11)	Haze Level/Atmospheric Transmittance	T_{550}
1	Light	.758
2	Moderate	.697
3	Heavy	.584

If IIN (11) has a value other than 1, 2, or 3, SR-2 estimates the atmospheric transmittance at 550 nanometers as a function of the date of acquisition. This estimate is based on a study of seasonal variations in haze level for several specific locations in denied areas. While the algorithm used does not provide average values for all places in the world at all times of the year, it is the best available source for estimates of the variation in the average value for the locations most appropriate in photographic reconnaissance. This algorithm is:

$$T_{550_\theta} = \frac{.63}{1 + .124 \sin(\theta - 69°)}$$

where:

T_{550} = atmospheric transmittance at 550 nanometers

$$\theta = 360° \times \frac{(\text{day of year} - 1)}{365}$$

E. Snow Correction Option

The IIN (10) target type indicator is used to indicate any special target characteristics which must be considered by the program. Currently, the only value which will cause SR-2 to perform any special calculations is IIN (10) = 2, which indicates a target covered by snow. IIN (10) = 1 indicates vegetation surround. The snow cover exposure correction applied by SR-3 is a function of solar altitude, see Table 3-2.

TABLE 3-2

SNOW CORRECTION OPTIONS

Solar Altitude Range (degrees)	Change in Exposure (stops)
0 to 10	1/3 reduction
10 to 15	2/3 reduction
15 to 90	1 reduction

This procedure provides for:

(1) The possibility that no snow will exist when snow is predicted.

(2) The radiance range at various solar altitudes.

(3) The use of a compromise exposure criterion for lower solar altitudes.

When this correction is applied, the $\log_{10}$ exposure adjustment passed to SR-3 is modified for this acquisition only by the amount specified in Table 3-2.

3.5.3 Data Passed to SR-3

Table 3-3 lists the values calculated by SR-2 and placed in labeled COMMON for use by SR-3.

TABLE 3-3

SR-2 DATA PASSED TO SR-3

Common Block	Variable Name	Value
XIN	XIN (10)	Target low-light luminance, Aft Camera
	XIN (11)	Target high-light luminance, Aft Camera
	XIN (12)	Target low-light luminance, Fwd Camera
	XIN (13)	Target high-light luminance, Fwd Camera
CFACTT	CFACTT (1)	Contrast value, Aft Camera
	CFACTT (2)	Contrast value, Fwd Camera
GLITCH	ADJUST	Log_{10} exposure adjustment

3.6 SR-2 SUBPROGRAM PACKAGES

3.6.1 Geometry

In addition to the vehicle geometry passed by SR-1, SR-2 must calculate several values involving the sun/vehicle/target geometric relationships. These are required by the subroutines which model the spectral atmospheric transmittance and radiance, and the spectral irradiance of daylight.

A. Solar Altitude

$$\sin h = \cos\phi * \cos\delta * \cos(15 * \text{TBATN}) + \sin\phi * \sin\delta$$

where:

h = solar altitude

ϕ = target latitude

δ = solar declination, a table format for day, month, and year of access

TBATN = 12 - TST (time before or after true noon)

where:

TST = true sun time

TST = GMT + Equation of time + $\theta/15$

where:

GMT = Greenwich Mean Time

Equation of Time = a numerical factor, determined from a table for the day and month

θ = target longitude

B. Solar Azimuth

Solar Azimuth is the direction toward which an observer at the target location must look to view the sun, measured clockwise from due North = 0°.

$$\tan(AZ) = \frac{-\sin(15 * \text{TBATN}) * \cos\delta * \cos\o}{\sin\delta - \sin\phi * \sin h * \cos^2 h}$$

where:

AZ = solar azimuth

All other terms are as defined in paragraph 3.6.1.A.

C. Camera-Target-Sun (CATS) Angle

The "CATS" angle is the angle between the camera-target and sun-target vectors. It is determined by the following equation:

$$\cos(\text{CATS}) = -\cos h \cdot \cos SD \cdot \cos SCN \cdot \sin OFST$$
$$- \cos h \cdot \sin SD \cdot \sin SCN$$
$$+ \sin h$$

where:

SD = solar direction. SD is found by knowing the vehicle heading and solar azimuth. SD is positive if the sun is to the right of the flight line, negative if to the left. The SD equals AZ minus the vehicle heading.

h = solar altitude

SCN = camera scan angle. SCN uses the opposite sign convention from the rest of CRYSPER, i.e., positive is to the right of the vehicle.

OFST = camera in-track offset angle. The OFST is plus if Forward-looking and minus if Aft-looking.

D. True Zenith Distance

True zenith distance is the angle between the target zenith and the camera line-of-sight. If a tangent is drawn to the earth's surface at the target point, and a perpendicular drawn to the point of tangency, the angle between the normal and the camera view angle is the true zenith distance. The equation for the true zenith distance (TZD) is:

$$TZD = \sin^{-1}\left[\frac{(H + R)\sin e}{R}\right]$$

where:

H = altitude of the vehicle

R = radius of the earth

e = camera look angle = $\cos^{-1}(\cos|OFST| \cdot \cos|SCN|)$

OFST, SCN are as defined in paragraph 3.6.1 C.

3.6.2 Radiometric Acquisition Simulation

The atmospheric and daylight irradiance models within SR-2 are of particular importance since they constitute quasi-standards which are the basis for the energy calculations performed in the program. The following is a summary of the equations used in this section of the program:

A. Horizontal Plane Daylight Irradiance Model

The calculation of a specific spectral irradiance distribution is done as follows:

(1) The following is the equation for determining the daylight-correlated color temperature for a horizontal plane (TCC), it is calculated as a function of solar altitude. The relationship is probably

not valid below a 5° solar altitude.

$$T_{CC} = 2.1428\,(h) + 5546.43$$

(h) = solar altitude in degrees

(2) On the basis of formulas recommended by the CIE[1] and as cited by Robertson[2], the daylight chromaticity coordinates are calculated as follows:

If $2000° \leq T_{CC} \leq 7000°$

then:

$$X_D = -4.5993\,\frac{10^7}{T_{CC}^3} + 2.9645\,\frac{10^6}{T_{CC}^2} + .09905\,\frac{10^3}{T_{CC}} + .244063$$

If $7000° < T_{CC} \leq 25000°$

then:

$$X_D = -2.0031\,\frac{10^9}{T_{CC}^3} + 1.8997\,\frac{10^6}{T_{CC}^2} + .24734\,\frac{10^3}{T_{CC}} + .237040$$

and:

$$Y_D = 2.870X_D - 3.000X_D^2 - .275$$

(3) Vector Scalars (M_1 and M_2) are then computed as per Robertson.

$$M_1 = \frac{-1.3515 - 1.7703X_D + 5.911Y_D}{.0241 + .2562X_D - .7341Y_D}$$

$$M_2 = \frac{.030 - 31.442X_D + 30.0717Y_D}{.0241 + .2562X_D - .7341Y_D}$$

(4) The relative spectral irradiance distribution is then found from:

$$\vec{E}_{\lambda h°} = \vec{E} + M_1\vec{V}_{1\lambda} + M_2\vec{V}_{2\lambda}$$

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(1) Nickerson, D., and Jerome, C. W., Illumination Engineering 60, p. 262, 1965.

(2) Robertson, A. R., "Computation of Correlated Color Temperature and Distribution Temperature", Journal of the Optical Society of America, Vol. 58, No. 11, pp. 1528-35, Nov. 1968.

where:

$\vec{E}_{\lambda_{h°}}$ = relative spectral irradiance for a solar altitude of h°

$\vec{\bar{E}}_{\lambda}$ = mean relative spectral irradiance curve obtained from 734 measured distributions

$\vec{V}_1, \vec{V}_2$ = characteristic vectors obtained by analysis of the 734 distributions

The value of E_{560nm} is unity for any value of solar altitude. The values for the mean curve ($\vec{\bar{E}}_{\lambda}$) and the vectors ($\vec{V}_{1_\lambda}$, $\vec{V}_{2_\lambda}$) are shown in Tables 3-4 thru 3-6.

(5) The horizontal plane absolute irradiance at 560 nanometers, in watts/meter^2/5nm, is computed from functional relationships resulting from daylight spectral irradiance measurements. The irradiance Ho_{560} is calculated from:

$$Ho_{560} = a_1 + a_2 (h° + 10) + a_3 (h° + 10)^2 + a_4 (h° + 10)^3$$

The values for the coefficients a_1 thru a_4 for various solar altitude ranges are given in Table 3-7.

TABLE 3-7

COEFFICIENT VALUES FOR SOLAR ALTITUDE RANGES

Solar Altitude Limits	Coefficients a_1	a_2	a_3	a_4
-5.00° to less than -.62°	-.17149	.08554	-.01453	.00086
-.62° to less than 15.00°	.16456	-.05812	.00501	0
15.00° to 90.00°	-1.96202	.14329	.00033	-.00001

(6) The absolute irradiance in watts/meter^2/5nm is then obtained from:

$$\vec{Ho}_{\lambda} = Ho_{560} \bullet \vec{E}_{\lambda_{h°}}$$

TABLE 3-4

SPECTRAL DISTRIBUTION OF ELEMENT MEAN

WAVE LGTH	VALUE	LOG OF VALUE	WAVE LGTH	VALUE	LOG OF VALUE	WAVE LGTH	VALUE	LOG OF VALUE
300	4.000E-04	-3.398E 00	540	1.053E 00	2.243E-02	780	6.500E-01	-1.800025
305	3.020E-02	-1.520E 00	545	1.048E 00	2.036E-02	785	6.550E-01	-1.800026
310	6.000E-02	-1.222E 00	550	1.044E 00	1.870E-02	790	6.600E-01	-1.800027
315	1.790E-01	-7.496E-01	555	1.022E 00	9.451E-03	795	6.350E-01	-1.900028
320	2.960E-01	-5.287E-01	560	1.000E 00	0.0	800	6.100E-01	-2.100029
325	4.240E-01	-3.726E-01	565	9.800E-01	-8.774E-03	805	5.720E-01	-2.400030
330	5.530E-01	-2.573E-01	570	9.600E-01	-1.773E-02	810	5.330E-01	-2.700031
335	5.630E-01	-2.495E-01	575	9.560E-01	-1.954E-02	815	5.610E-01	-2.500032
340	5.730E-01	-2.418E-01	580	9.510E-01	-2.182E-02	820	5.890E-01	-2.200033
345	5.960E-01	-2.248E-01	585	9.210E-01	-3.574E-02	825	6.040E-01	-2.100034
350	6.180E-01	-2.090E-01	590	8.910E-01	-5.012E-02	830	6.190E-01	-2.000035
355	6.170E-01	-2.097E-01	595	8.980E-01	-4.672E-02	835	6.180E-01	-2.000036
360	6.150E-01	-2.111E-01	600	9.050E-01	-4.335E-02	840	6.170E-01	-2.000037
365	6.520E-01	-1.858E-01	605	9.040E-01	-4.383E-02	845	6.140E-01	-2.100038
370	6.880E-01	-1.624E-01	610	9.030E-01	-4.431E-02	850	6.120E-01	-2.100039
375	6.610E-01	-1.798E-01	615	8.940E-01	-4.866E-02	855	6.080E-01	-2.100040
380	6.340E-01	-1.979E-01	620	8.840E-01	-5.355E-02	860	6.040E-01	-2.100041
385	6.460E-01	-1.898E-01	625	8.620E-01	-6.449E-02	865	6.030E-01	-2.100042
390	6.580E-01	-1.818E-01	630	8.400E-01	-7.572E-02	870	6.010E-01	-2.200043
395	8.030E-01	-9.528E-02	635	8.460E-01	-7.263E-02	875	5.730E-01	-2.400044
400	9.480E-01	-2.319E-02	640	8.510E-01	-7.007E-02	880	5.460E-01	-2.600045
405	9.980E-01	-8.695E-04	645	8.350E-01	-7.831E-02	885	5.220E-01	-2.800046
410	1.048E 00	2.036E-02	650	8.190E-01	-8.672E-02	890	5.170E-01	-2.900047
415	1.054E 00	2.284E-02	655	8.220E-01	-8.513E-02	895	5.110E-01	-2.900048
420	1.059E 00	2.490E-02	660	8.260E-01	-8.302E-02	900	5.050E-01	-2.900049
425	1.014E 00	6.038E-03	665	8.380E-01	-7.676E-02	905	4.890E-01	-3.100050
430	9.680E-01	-1.412E-02	670	8.490E-01	-7.109E-02	910	4.730E-01	-3.200051
435	1.054E 00	2.284E-02	675	8.310E-01	-8.040E-02	915	4.560E-01	-3.400052
440	1.139E 00	5.652E-02	680	8.130E-01	-8.991E-02	920	4.390E-01	-3.500053
445	1.198E 00	7.846E-02	685	7.660E-01	-1.158E-01	925	4.250E-01	-3.700054
450	1.256E 00	9.899E-02	690	7.190E-01	-1.433E-01	930	4.140E-01	-3.800055
455	1.256E 00	9.899E-02	695	7.310E-01	-1.361E-01	935	4.320E-01	-3.600056
460	1.255E 00	9.864E-02	700	7.430E-01	-1.290E-01	940	4.490E-01	-3.400057
465	1.234E 00	9.131E-02	705	7.540E-01	-1.226E-01	945	4.830E-01	-3.100058
470	1.213E 00	8.386E-02	710	7.640E-01	-1.169E-01	950	5.170E-01	-2.800059
475	1.213E 00	8.386E-02	715	6.980E-01	-1.561E-01	955	5.358E-01	-2.700060
480	1.213E 00	8.386E-02	720	6.330E-01	-1.986E-01	960	5.545E-01	-2.500061
485	1.174E 00	6.967E-02	725	6.750E-01	-1.707E-01	965	5.674E-01	-2.400062
490	1.135E 00	5.500E-02	730	7.170E-01	-1.445E-01	970	5.804E-01	-2.300063
495	1.133E 00	5.423E-02	735	7.440E-01	-1.284E-01	975	5.838E-01	-2.300064
500	1.131E 00	5.346E-02	740	7.700E-01	-1.135E-01	980	5.872E-01	-2.300065
505	1.120E 00	4.922E-02	745	7.110E-01	-1.481E-01	985	5.862E-01	-2.300066
510	1.108E 00	4.454E-02	750	6.520E-01	-1.858E-01	990	5.851E-01	-2.300067
515	1.086E 00	3.583E-02	755	5.640E-01	-2.487E-01	995	5.784E-01	-2.300068
520	1.065E 00	2.735E-02	760	4.770E-01	-3.215E-01	1000	5.717E-01	-2.400069
525	1.076E 00	3.181E-02	765	5.820E-01	-2.351E-01	1005	5.624E-01	-2.500070
530	1.088E 00	3.663E-02	770	6.860E-01	-1.637E-01			
535	1.070E 00	2.938E-02	775	6.680E-01	-1.752E-01			
1010	5.531E-01	-2.572E-01	1045	5.014E-01	-2.998E-01	1080	4.296E-01	-3.600080
1015	5.497E-01	-2.598E-01	1050	4.865E-01	-3.129E-01	1085	4.100E-01	-3.800081
1020	5.464E-01	-2.625E-01	1055	4.788E-01	-3.198E-01	1090	3.905E-01	-4.000082
1025	5.367E-01	-2.702E-01	1060	4.711E-01	-3.269E-01	1095	3.632E-01	-4.300083
1030	5.271E-01	-2.781E-01	1065	4.612E-01	-3.361E-01	1100	3.359E-01	-4.700084
1035	5.217E-01	-2.826E-01	1070	4.512E-01	-3.456E-01			
1040	5.163E-01	-2.871E-01	1075	4.404E-01	-3.562E-01			

TABLE 3-5

SPECTRAL DISTRIBUTION OF ELEMENT VECTOR1

WAVE LGTH	VALUE	LOG OF VALUE	WAVE LGTH	VALUE	LOG OF VALUE	WAVE LGTH	VALUE	LOG OF VALUE
300	2.000E-04	-3.699E 00	540	4.200E-02	-1.377E 00	780	-1.040E-01	-1.800094
305	2.260E-02	-1.646E 00	545	3.100E-02	-1.509E 00	785	-1.050E-01	-1.800095
310	4.500E-02	-1.347E 00	550	1.900E-02	-1.721E 00	790	-1.060E-01	-1.800096
315	1.340E-01	-8.729E-01	555	1.000E-02	-2.000E 00	795	-1.020E-01	-1.900097
320	2.240E-01	-6.498E-01	560	0.0	0.0	800	-9.700E-02	-2.100098
325	3.220E-01	-4.921E-01	565	-8.000E-03	-8.774E-03	805	-9.000E-02	-2.400099
330	4.200E-01	-3.768E-01	570	-1.600E-02	-1.773E-02	810	-8.300E-02	-2.700100
335	4.130E-01	-3.840E-01	575	-2.600E-02	-1.954E-02	815	-8.800E-02	-2.500101
340	4.060E-01	-3.915E-01	580	-3.500E-02	-2.182E-02	820	-9.300E-02	-2.200102
345	4.110E-01	-3.862E-01	585	-3.500E-02	-3.574E-02	825	-9.600E-02	-2.100103
350	4.160E-01	-3.809E-01	590	-3.500E-02	-5.012E-02	830	-9.800E-02	-2.000104
355	3.980E-01	-4.001E-01	595	-4.600E-02	-4.672E-02	835	-9.763E-02	-2.000105
360	3.800E-01	-4.202E-01	600	-5.800E-02	-4.335E-02	840	-9.726E-02	-2.000106
365	4.020E-01	-3.958E-01	605	-6.500E-02	-4.383E-02	845	-9.834E-02	-2.100107
370	4.240E-01	-3.726E-01	610	-7.200E-02	-4.431E-02	850	-9.942E-02	-2.100108
375	4.040E-01	-3.936E-01	615	-7.900E-02	-4.866E-02	855	-9.729E-02	-2.100109
380	3.850E-01	-4.145E-01	620	-8.600E-02	-5.355E-02	860	-9.517E-02	-2.100110
385	3.680E-01	-4.342E-01	625	-9.100E-02	-6.449E-02	865	-8.760E-02	-2.100111
390	3.500E-01	-4.559E-01	630	-9.500E-02	-7.572E-02	870	-8.004E-02	-2.200112
395	3.920E-01	-4.067E-01	635	-1.020E-01	-7.263E-02	875	-7.250E-02	-2.400113
400	4.340E-01	-3.625E-01	640	-1.090E-01	-7.007E-02	880	-6.496E-02	-2.600114
405	4.480E-01	-3.487E-01	645	-1.080E-01	-7.831E-02	885	-6.536E-02	-2.800115
410	4.630E-01	-3.344E-01	650	-1.070E-01	-8.672E-02	890	-6.575E-02	-2.800116
415	4.510E-01	-3.458E-01	655	-1.140E-01	-8.513E-02	895	-6.118E-02	-2.900117
420	4.390E-01	-3.575E-01	660	-1.200E-01	-8.302E-02	900	-5.661E-02	-2.900118
425	4.050E-01	-3.925E-01	665	-1.300E-01	-7.676E-02	905	-4.302E-02	-3.100119
430	3.710E-01	-4.306E-01	670	-1.400E-01	-7.109E-02	910	-2.943E-02	-3.200120
435	3.690E-01	-4.330E-01	675	-1.380E-01	-8.040E-02	915	-3.029E-02	-3.400121
440	3.670E-01	-4.353E-01	680	-1.360E-01	-8.991E-02	920	-3.116E-02	-3.500122
445	3.630E-01	-4.401E-01	685	-1.280E-01	-1.158E-01	925	-4.887E-02	-3.700123
450	3.590E-01	-4.449E-01	690	-1.200E-01	-1.433E-01	930	-6.659E-02	-3.800124
455	3.420E-01	-4.660E-01	695	-1.260E-01	-1.361E-01	935	-7.977E-02	-3.600125
460	3.260E-01	-4.868E-01	700	-1.330E-01	-1.290E-01	940	-9.294E-02	-3.400126
465	3.020E-01	-5.200E-01	705	-1.310E-01	-1.226E-01	945	-9.765E-02	-3.100127
470	2.790E-01	-5.544E-01	710	-1.290E-01	-1.169E-01	950	-1.024E-01	-2.800128
475	2.610E-01	-5.834E-01	715	-1.180E-01	-1.561E-01	955	-1.001E-01	-2.700129
480	2.430E-01	-6.144E-01	720	-1.060E-01	-1.986E-01	960	-9.785E-02	-2.500130
485	2.220E-01	-6.536E-01	725	-1.110E-01	-1.707E-01	965	-9.332E-02	-2.400131
490	2.010E-01	-6.968E-01	730	-1.160E-01	-1.445E-01	970	-8.879E-02	-2.300132
495	1.820E-01	-7.399E-01	735	-1.190E-01	-1.284E-01	975	-8.399E-02	-2.300133
500	1.620E-01	-7.905E-01	740	-1.220E-01	-1.135E-01	980	-7.919E-02	-2.300134
505	1.470E-01	-8.327E-01	745	-1.120E-01	-1.481E-01	985	-7.579E-02	-2.300135
510	1.320E-01	-8.794E-01	750	-1.020E-01	-1.858E-01	990	-7.239E-02	-2.300136
515	1.090E-01	-9.626E-01	755	-9.000E-02	-2.487E-01	995	-7.015E-02	-2.300137
520	8.600E-02	-1.066E 00	760	-7.800E-02	-3.215E-01	1000	-6.790E-02	-2.400138
525	7.400E-02	-1.131E 00	765	-9.500E-02	-2.351E-01	1005	-6.705E-02	-2.500139
530	6.100E-02	-1.215E 00	770	-1.120E-01	-1.637E-01			
535	5.200E-02	-1.284E 00	775	-1.080E-01	-1.752E-01			
1010	-6.671E-02	-2.572E-01	1045	-5.790E-02	-2.998E-01	1080	-4.498E-02	-3.600149
1015	-6.461E-02	-2.598E-01	1050	-5.817E-02	-3.129E-01	1085	-3.489E-02	-3.800150
1020	-6.300E-02	-2.625E-01	1055	-5.751E-02	-3.198E-01	1090	-2.479E-02	-4.000151
1025	-6.160E-02	-2.702E-01	1060	-5.685E-02	-3.269E-01	1095	-1.392E-02	-4.300152
1030	-6.020E-02	-2.781E-01	1065	-5.456E-02	-3.361E-01	1100	-3.050E-03	-4.700153
1035	-5.892E-02	-2.826E-01	1070	-5.227E-02	-3.456E-01			
1040	-5.763E-02	-2.871E-01	1075	-4.863E-02	-3.562E-01			

TABLE 3-6

SPECTRAL DISTRIBUTION OF ELEMENT VECTOR2

WAVE LGTH	VALUE	LOG OF VALUE	WAVE LGTH	VALUE	LOG OF VALUE	WAVE LGTH	VALUE	LOG OF VALUE
300	0.0	-3.699E 00	540	-5.000E-03	-1.377E 00	780	6.800E-02	-1.100163
305	1.000E-02	-2.000E 00	545	-4.000E-03	-1.509E 00	785	6.900E-02	-1.100164
310	2.000E-02	-1.699E 00	550	-3.000E-03	-1.721E 00	790	7.000E-02	-1.100165
315	3.000E-02	-1.523E 00	555	-1.500E-03	-2.000E 00	795	6.700E-02	-1.100166
320	4.000E-02	-1.398E 00	560	0.0	0.0	800	6.400E-02	-1.100167
325	6.200E-02	-1.208E 00	565	1.000E-03	-3.000E 00	805	6.000E-02	-1.200168
330	8.500E-02	-1.071E 00	570	2.000E-03	-2.699E 00	810	5.500E-02	-1.200169
335	8.200E-02	-1.086E 00	575	4.000E-03	-2.398E 00	815	5.800E-02	-1.200170
340	7.800E-02	-1.108E 00	580	5.000E-03	-2.301E 00	820	6.100E-02	-1.200171
345	7.200E-02	-1.143E 00	585	1.300E-02	-1.886E 00	825	6.300E-02	-1.200172
350	6.700E-02	-1.174E 00	590	2.100E-02	-1.678E 00	830	6.400E-02	-1.100173
355	6.000E-02	-1.222E 00	595	2.700E-02	-1.569E 00	835	6.463E-02	-1.100174
360	5.300E-02	-1.276E 00	600	3.200E-02	-1.495E 00	840	6.526E-02	-1.100175
365	5.700E-02	-1.244E 00	605	3.700E-02	-1.432E 00	845	6.471E-02	-1.100176
370	6.100E-02	-1.215E 00	610	4.100E-02	-1.387E 00	850	6.416E-02	-1.100177
375	4.600E-02	-1.337E 00	615	4.400E-02	-1.357E 00	855	6.580E-02	-1.100178
380	3.000E-02	-1.523E 00	620	4.700E-02	-1.328E 00	860	6.745E-02	-1.100179
385	2.100E-02	-1.678E 00	625	4.900E-02	-1.310E 00	865	7.296E-02	-1.100180
390	1.200E-02	-1.921E 00	630	5.100E-02	-1.292E 00	870	7.848E-02	-1.100181
395	5.000E-04	-3.301E 00	635	5.900E-02	-1.229E 00	875	8.313E-02	-1.000182
400	-1.100E-02	-3.625E-01	640	6.700E-02	-1.174E 00	880	8.776E-02	-1.000183
405	-9.000E-03	-3.487E-01	645	7.000E-02	-1.155E 00	885	8.653E-02	-1.000184
410	-5.000E-03	-3.344E-01	650	7.300E-02	-1.137E 00	890	8.528E-02	-1.000185
415	-6.000E-03	-3.458E-01	655	8.000E-02	-1.097E 00	895	8.922E-02	-1.000186
420	-7.000E-03	-3.575E-01	660	8.600E-02	-1.066E 00	900	9.317E-02	-1.000187
425	-1.000E-02	-3.925E-01	665	9.200E-02	-1.036E 00	905	1.026E-01	-9.900188
430	-1.200E-02	-4.306E-01	670	9.800E-02	-1.009E 00	910	1.121E-01	-9.500189
435	-1.900E-02	-4.330E-01	675	1.000E-01	-1.000E 00	915	1.106E-01	-9.500190
440	-2.600E-02	-4.353E-01	680	1.020E-01	-9.914E-01	920	1.091E-01	-9.600191
445	-2.750E-02	-4.401E-01	685	9.300E-02	-1.032E 00	925	9.591E-02	-1.000192
450	-2.900E-02	-4.449E-01	690	8.300E-02	-1.081E 00	930	8.268E-02	-1.000193
455	-2.850E-02	-4.460E-01	695	9.000E-02	-1.046E 00	935	7.312E-02	-1.100194
460	-2.800E-02	-4.868E-01	700	9.600E-02	-1.018E 00	940	6.357E-02	-1.100195
465	-2.700E-02	-5.200E-01	705	9.100E-02	-1.041E 00	945	6.160E-02	-1.200196
470	-2.690E-02	-5.544E-01	710	9.500E-02	-1.071E 00	950	5.954E-02	-1.200197
475	-2.600E-02	-5.834E-01	715	7.800E-02	-1.108E 00	955	6.313E-02	-1.200198
480	-2.600E-02	-6.144E-01	720	7.000E-02	-1.155E 00	960	6.661E-02	-1.100199
485	-2.200E-02	-6.536E-01	725	7.300E-02	-1.137E 00	965	7.131E-02	-1.100200
490	-1.800E-02	-6.988E-01	730	7.600E-02	-1.119E 00	970	7.601E-02	-1.100201
495	-1.650E-02	-7.399E-01	735	7.800E-02	-1.108E 00	975	8.102E-02	-1.000202
500	-1.500E-02	-7.909E-01	740	8.000E-02	-1.097E 00	980	8.603E-02	-1.000203
505	-1.400E-02	-8.327E-01	745	7.400E-02	-1.131E 00	985	8.932E-02	-1.000204
510	-1.300E-02	-8.794E-01	750	6.700E-02	-1.174E 00	990	9.261E-02	-1.000205
515	-1.250E-02	-9.626E-01	755	6.000E-02	-1.222E 00	995	9.439E-02	-1.000206
520	-1.200E-02	-1.066E 00	760	5.200E-02	-1.284E 00	1000	9.617E-02	-1.000207
525	-1.100E-02	-1.131E 00	765	6.300E-02	-1.201E 00	1005	9.787E-02	-1.000208
530	-1.000E-02	-1.215E 00	770	7.400E-02	-1.131E 00			
535	-7.500E-03	-1.284E 00	775	7.100E-02	-1.149E 00			
1010	9.956E-02	-1.002E 00	1045	1.101E-01	-9.583E-01	1080	1.194E-01	-9.200218
1015	1.013E-01	-9.942E-01	1050	1.108E-01	-9.556E-01	1085	1.263E-01	-8.900219
1020	1.031E-01	-9.866E-01	1055	1.113E-01	-9.533E-01	1090	1.331E-01	-8.700220
1025	1.043E-01	-9.818E-01	1060	1.119E-01	-9.510E-01	1095	1.374E-01	-8.600221
1030	1.054E-01	-9.771E-01	1065	1.137E-01	-9.443E-01	1100	1.417E-01	-8.400222
1035	1.074E-01	-9.690E-01	1070	1.154E-01	-9.377E-01			
1040	1.094E-01	-9.610E-01	1075	1.174E-01	-9.303E-01			

B. Atmospheric Transmittance

As mentioned previously, modeling of the spectral atmospheric transmittance is based on an estimate of transmittance at a wavelength of 550 nanometers (T_{550}). Paragraph C, Atmospheric Radiance, describes the methods used by SR-2 to select T_{550}, either as a nominal value or estimated as a function of the time of year. It should also be noted that the inclusion of the seasonal selection of T_{550} in Figure 3-1 presents a general flow for the calculation of spectral atmospheric transmittance.

(1) The atmospheric pressure is used to calculate the vertical atmospheric transmittance due to molecular scattering (Rayleigh). The effective atmospheric pressure is calculated using both the terrain elevation and the vehicle altitude. Since target elevation above sea level is not currently available in the data passed from SR-1, this value is assumed to be 0. The pressure is calculated from:

$$P = P_1 - P_2$$

where:

P_1 = pressure at particular terrain elevation (millibars)

P_2 = pressure at vehicle altitude (millibars)

The individual pressures (P_1 and P_2) are calculated from algorithms based on the U. S. Standard Atmosphere which are:

(a) For altitudes between 0 and 7 kilometers

$$\log P_H = -.056H + 3.0057$$

(b) For altitudes between 7 and 15 kilometers

$$\log P_H = -.066H + 3.076$$

(c) Altitudes above 15 kilometers are assumed to be zero

H = altitude (kilometers)

The vertical decadic turbidity due to molecular scattering is then calculated according to Moon's[3] formula:

$$\tau_{\lambda_p} = -\frac{.0033\ P}{1013\ \lambda^4}$$

where:

P = pressure (millibars)

λ = wavelength (microns)

(2) Transmittance due to aerosol scattering. The modeling of previous transmittance measurements with respect to mean, maximum, and minimum values of atmospheric transmittance suggests a correlation between total atmospheric aerosol concentration and the scale height of precipitable

(3) Moon, P., "Proposed Standard Solar-Radiation Curves for Engineering Use," Journal of the Franklin Institute, v. 230, Nov. 1940, pp. 587-617.

GENERAL FLOW FOR CALCULATION OF SPECTRAL ATMOSPHERIC TRANSMITTANCE

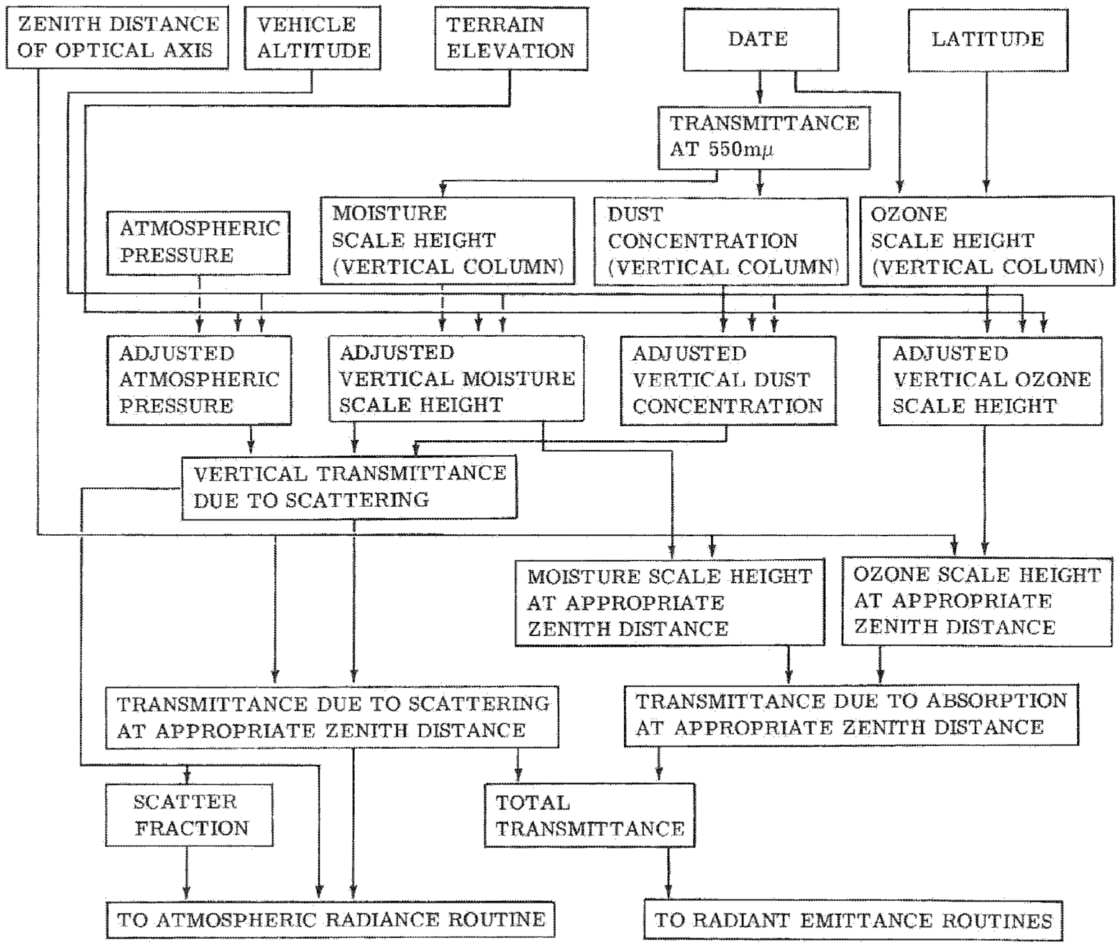

FIGURE 3-1

moisture. Analysis of weather data and the work of Nikitinskaya[4] tend to support this inference. A set of empirical relationships allow an estimate of the scale height of precipitable moisture and the atmospheric dust concentration to be made from the atmospheric transmittance at 550 nanometers. For a vertical column in the atmosphere:

$$W = 719.5757T^3 - 1349.5674T^2 + 702.7271T - 63.8732$$

$$D = 7516.8789T^2 - 14692.4648T + 7469.0195$$

where:

T = vertical transmittance at 550mμ

W = vertical scale height of precipitable moisture in millimeters

D = atmospheric dust concentration in particles/cm^3, measured in the vertical

This data is then scaled according to vehicle altitude using the profiles suggested by the Air Force Cambridge Research Laboratory (AFCRL)[5]. The scaling of these quantities with respect to terrain elevation is not possible at this time because of the limited quantity of information available; however, the model does provide for the incorporation of these quantities. The relationships are:

The moisture scale height, earth-to-space, is calculated for various altitude bands with definitions:

H = the altitude (kilometers)

W = scale height for a vertical column as previously calculated.

The algorithms are:

(a) Altitude from 0 thru 4 kilometers

$$\log_{10} W_{H-\infty} = \left[\log_{10} W \; (-.0765H + 1) - .159H\right]$$

(b) Greater than 4 to 8 kilometers

$$\log_{10} W_{H-\infty} = (.162 \log_{10} W - .534)\, H + 1.53$$

(c) Greater than 8 to 14 kilometers

$$\log_{10} W_{H-\infty} = mH - 14m - 3.0$$

where:

$$m = 1.660 (\log_{10} W)^2 + 3.104 (\log_{10} W) - 1.649$$

---

(4) Nikitinskaya, N. I., On Optical Properties of Air Masses of Different Origin, S. M. Krinov Forest-Engineering Academy, Leningrad, (Text translated by Hqs AWS personnel).

(5) McClatchey, R. A.; Fenn, R. W., Selly, J. E. A.; Volz, F. E.; and Garing, I. S.; "Optical Properties of the Atmosphere (Revised)", AFCRL-71-0279, Environmental Research Papers, No. 354, 10 May 1971.

(d) Greater than 14 kilometers

$$\log_{10} W_{H-\infty} = -.121H - 1.3$$

The vertical moisture scale height adjusted for altitude is:

$$W_v = W - W_{H-\infty}$$

The vertical decadic turbidity resulting from moisture is then given by Moon's formula:

$$T_{\lambda_W} = -\frac{.0075W_v}{20\lambda^2}$$

The dust concentration (an average of all altitudes) is calculated in a like manner using relationships fitted to AFCRL/aerosol/altitude profiles. The average number of dust particles, earth-to-space is given by:

$$D_{TOT} = \frac{4953D}{880} + 842$$

The following fractions from altitude-to-ground are:

(a) From 0 to 4 kilometers

$$D_{H_{0-5}} = \frac{D}{880} \text{ x antilog } \left[-.0179 (H-1)^2 + .12394 (H-1) + 3.48661 \right]$$

(b) Greater than 4 to 15 kilometers

$$D_{H_{4-15}} = \frac{4953D}{880} + \text{antilog } \left[-.00931 (H-1)^2 + .2719 (H-1) + .82682 \right]$$

(c) From greater than 15 to 20 kilometers

$$D_{H_{15-20}} = \frac{4953D}{880} + \text{antilog } \left[.02525 (H-1) + 2.43169 \right]$$

From the above, the average number of particles is calculated from:

$$D_H = \frac{D_{H_{a-H}}}{D_{TOT}} \bullet D$$

The vertical decadic turbidity caused by atmospheric dust is calculated using Moon's equation with a modified exponent of wavelength which seems to allow a better fit to the measured data. Moon's exponent is -0.75, the current modified value is -1.5. It is thought the average value probably lies between -1.3 and -1.5, but a conclusive value has not yet been determined. The decadic turbidity is obtained as follows:

$$T_{\lambda_D} = -\frac{.0353D_H}{800\lambda^{1.5}}$$

At this point, all the vertical decadic turbidities for scattering contributors were calculated, and the vertical atmospheric transmittance caused by scattering is calculated as follows:

$$t_{\lambda_{s_v}} = \text{antilog}_{10} \left[-(\tau_{\lambda_p} + \tau_{\lambda_w} + \tau_{\lambda_D}) \right]$$

The atmospheric transmittance due to scattering for angles other than vertical is calculated from:

$$t_{\lambda_{s_\theta}} = t_{\lambda_{s_v}}^{\text{SEC}\ \theta}$$

where:

θ = angle between the optical axis and the vertical constructed at the intersection of the optical axis and the earth's surface (True Zenith Distance). When θ exceeds 60°, Bemporad's[6] air mass numbers are used instead of SEC θ.

(3) Transmittance caused by absorption of atmospheric moisture (T_A), at a precipitable moisture scale height of 10 millimeters, is stored as BLOCK DATA in the model. Since the changes in absorption follow an error function rather than an exponential function, changes in transmittance resulting from changes in vertical scale height and look angle (True Zenith Distance) must be handled differently than scattering phenomena. A set of empirical relationships has been fitted to the AFCRL scaling data which allows these changes to be calculated. The log scaling function (y_λ) is calculated from the 10 millimeter transmittance data according to:

(a) Transmittance from 0 to .4

$$y_\lambda = 279.607910\, t_{A_\lambda}^4 - 269.130127\, t_{A_\lambda}^3 + 89.931458\, t_{A_\lambda}^2 - 14.475016\, t_{A_\lambda} + 3.479495$$

(b) Transmittance greater than .4

$$y_\lambda = -36.961121\, t_{A_\lambda}^4 + 68.905258\, t_{A_\lambda}^3 - 41.955338\, t_{A_\lambda}^2 + 5.903717\, t_{A_\lambda} + 2.937166$$

The adjusted scaling function (y_{λ_2}) is computed from the zenith distance and vertical moisture scale height.

$$y_{\lambda_2} = y_\lambda + \log_{10}(.1\, W_v\ \text{SEC}\ \theta)$$

(6) Bemporad, A., "Search for a New Empirical Formula for the Representation of Intensity of Solar Radiating with Zenith Angle," Meteerotogische Zeitschrift, Vol 24 (NASA Technical Translation), TTF-302, July 1907.

where:

W_v = millimeters of precipitable water

θ = zenith distance

The transmittance resulting from absorption by water vapor at the appropriate zenith distance is:

(a) Log scaling function equal to or less than 2.0

$$t_{\lambda_{WA_\theta}} = .0033222442\, y_{\lambda_2}^4 - .0204351731\, y_{\lambda_2}^3 - .0625828505\, y_{\lambda_2}^2 - .0872156024 y_{\lambda_2} + .93397474$$

(b) Log scaling function greater than 2.0 but less than 3.0

$$t_{\lambda_{WA_\theta}} = .0476983003\, y_{\lambda_2}^3 - .2112650275\, y_{\lambda_2}^2 - .2146139145\, y_{\lambda_2} + 1.295908928$$

(c) Log scaling function greater than 3.0

$$t_{\lambda_{WA_\theta}} = .12^{(y_{\lambda_2} - 2.0)^{2.3}} \frac{1}{y_{\lambda_2}}$$

(d) If the log scaling functions are less than (-.98457)

$t_{\lambda_{WA_\theta}}$ is set to 1.0

Vertical transmittance for an ozone scale height of 3.8 millimeters is:

$$t_{\lambda_{OA}} = 1 - .05 \left[e^{-\left[(\lambda - .59)^2 / .002686\right]} \right]$$

The vertical ozone scale height is determined from time of year and north latitude based on Godson's data. The vertical scale height (OZ_v) is then rescaled to the vehicle altitude according to a relationship derived from the AFCRL profiles:

$$\log_{10} OZ_{H-\infty} = -.05001H \log_{10} OZ_v - .00378H + \log_{10} OZ_v$$

and

$$OZ_H = OZ_v - OZ_{H-\infty}$$

where:

H = Vehicle altitude (kilometers)

OZ_v = earth-to-space vertical ozone scale height (millimeters)

$OZ_{H-\infty}$ = vehicle-to-space vertical scale height (millimeters)

OZ_H = earth-to-vehicle vertical ozone scale height (millimeters)

The transmittance at the appropriate vehicle altitude, look angle (True Zenith Distance), and vertical ozone scale height is then calculated from the vertical transmittance (earth-to-space) at a scale height of 3.8 millimeters as follows:

$$t_{\lambda_{OA_\theta}} = t_{\lambda_{OA}} \left[\frac{OZ_H \bullet SEC\,\theta}{3.8} \right]$$

where:

angle θ is as previously defined.

The total transmittance resulting from absorbers accounted for in the model is then given by:

$$t_{\lambda_{ABS_\theta}} = t_{\lambda_{WA_\theta}} \bullet t_{\lambda_{OA_\theta}}$$

The total transmittance for a given haze level, adjusted for vehicle altitude and terrain elevation at a specific look angle, is given by:

$$t_{\lambda_\theta} = t_{\lambda_{S_\theta}} \bullet t_{\lambda_{ABS_\theta}}$$

C. Atmospheric Radiance

The principal data in the atmospheric radiance model is the vertical spectral radiance data at 40° solar altitude. This information is stored in the model as BLOCK DATA for the wavelength interval of .35 to 1.1 micrometers. The vertical data at 40° solar altitude is scaled with respect to haze level as a function of the change in atmospheric vertical transmittance, then as a function of solar altitude, solar scatter angle, and the change in transmittance as a function of look angle. An estimate is also made of the effect of background reflectance on the atmospheric radiance. This estimate is based on the relationship suggested by Gordon[7]. The general scheme for calculation of spectral atmospheric radiance is shown in Figure 3-2; the atmospheric radiance at 40° solar altitude is shown in Table 3-8.

(1) Scaling of the Atmospheric Radiance With Respect to Haze Level

In general, measurements of atmospheric radiance for a day when the atmospheric transmittance remained constant indicated a proportional change in atmospheric radiance with changing solar altitude. The haze level is accounted for by scaling the vertical radiance at 40° solar altitude.

(7) Gordon, Jacqueline I., "Model for a Clear Atmosphere", Journal of the Optical Society of America, Vol 59, No. 1, Jan 1969, pp. 14-18.

GENERAL SCHEME FOR CALCULATION OF SPECTRAL ATMOSPHERIC RADIANCE

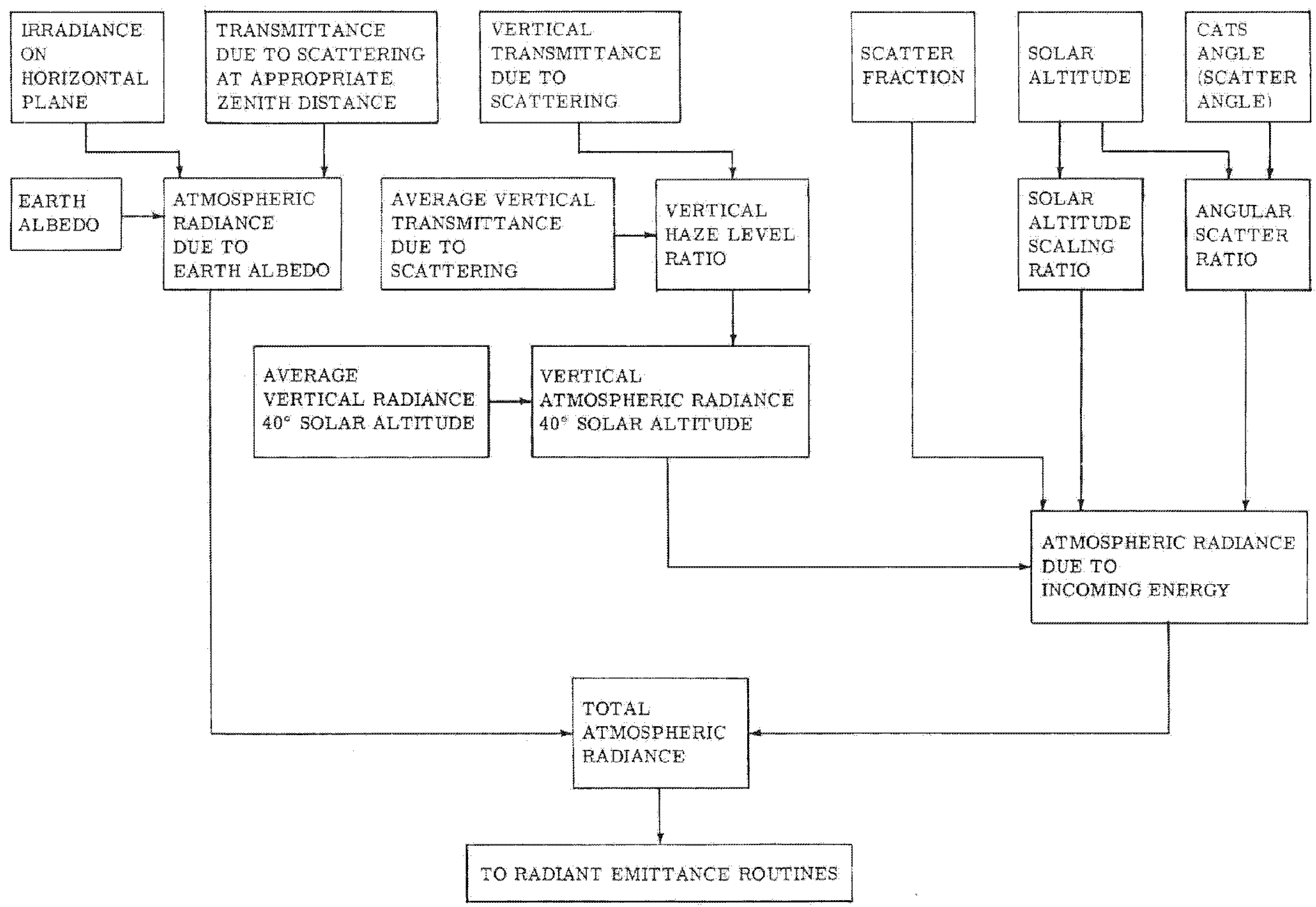

FIGURE 3-2

TABLE 3-8

SPECTRAL DISTRIBUTION OF ELEMENT NH,40DEG

WAVE LGTH	VALUE	LOG OF VALUE	WAVE LGTH	VALUE	LOG OF VALUE	WAVE LGTH	VALUE	LOG OF VALUE
350	1.820E-01	-7.399E-01	590	7.674E-02	-1.115E 00	830	1.297E-02	-1.800232
355	1.776E-01	-7.506E-01	595	7.390E-02	-1.131E 00	835	1.270E-02	-1.800233
360	1.732E-01	-7.616E-01	600	7.106E-02	-1.148E 00	840	1.243E-02	-1.900234
365	1.753E-01	-7.562E-01	605	6.886E-02	-1.162E 00	845	1.211E-02	-1.900235
370	1.775E-01	-7.508E-01	610	6.666E-02	-1.176E 00	850	1.180E-02	-1.900236
375	1.750E-01	-7.570E-01	615	6.397E-02	-1.194E 00	855	1.145E-02	-1.900237
380	1.725E-01	-7.632E-01	620	6.127E-02	-1.213E 00	860	1.109E-02	-1.900238
385	1.681E-01	-7.743E-01	625	5.944E-02	-1.226E 00	865	1.080E-02	-1.900239
390	1.638E-01	-7.858E-01	630	5.762E-02	-1.239E 00	870	1.050E-02	-1.900240
395	1.770E-01	-7.519E-01	635	5.597E-02	-1.252E 00	875	1.021E-02	-1.900241
400	1.903E-01	-7.205E-01	640	5.433E-02	-1.265E 00	880	9.921E-03	-2.000242
405	2.061E-01	-6.858E-01	645	5.289E-02	-1.277E 00	885	9.540E-03	-2.000243
410	2.220E-01	-6.537E-01	650	5.145E-02	-1.289E 00	890	9.158E-03	-2.000244
415	2.176E-01	-6.624E-01	655	5.031E-02	-1.298E 00	895	8.695E-03	-2.000245
420	2.131E-01	-6.714E-01	660	4.917E-02	-1.308E 00	900	8.233E-03	-2.000246
425	2.022E-01	-6.942E-01	665	4.818E-02	-1.317E 00	905	7.859E-03	-2.100247
430	1.913E-01	-7.182E-01	670	4.719E-02	-1.326E 00	910	7.485E-03	-2.100248
435	1.950E-01	-7.099E-01	675	4.593E-02	-1.338E 00	915	7.164E-03	-2.100249
440	1.987E-01	-7.017E-01	680	4.467E-02	-1.350E 00	920	6.844E-03	-2.100250
445	2.024E-01	-6.939E-01	685	4.232E-02	-1.373E 00	925	6.299E-03	-2.200251
450	2.060E-01	-6.861E-01	690	3.997E-02	-1.398E 00	930	5.754E-03	-2.200252
455	2.046E-01	-6.891E-01	695	3.966E-02	-1.402E 00	935	5.263E-03	-2.200253
460	2.032E-01	-6.921E-01	700	3.935E-02	-1.405E 00	940	4.772E-03	-2.300254
465	1.957E-01	-7.085E-01	705	4.004E-02	-1.398E 00	945	4.627E-03	-2.300255
470	1.882E-01	-7.254E-01	710	4.072E-02	-1.390E 00	950	4.482E-03	-2.300256
475	1.825E-01	-7.386E-01	715	3.822E-02	-1.418E 00	955	4.602E-03	-2.300257
480	1.769E-01	-7.523E-01	720	3.571E-02	-1.447E 00	960	4.722E-03	-2.300258
485	1.689E-01	-7.723E-01	725	3.396E-02	-1.469E 00	965	4.903E-03	-2.300259
490	1.609E-01	-7.934E-01	730	3.220E-02	-1.492E 00	970	5.084E-03	-2.200260
495	1.552E-01	-8.092E-01	735	3.137E-02	-1.503E 00	975	5.194E-03	-2.200261
500	1.494E-01	-3.256E-01	740	3.054E-02	-1.515E 00	980	5.304E-03	-2.200262
505	1.442E-01	-8.409E-01	745	2.525E-02	-1.598E 00	985	5.306E-03	-2.200263
510	1.391E-01	-8.568E-01	750	1.995E-02	-1.700E 00	990	5.308E-03	-2.200264
515	1.326E-01	-8.775E-01	755	1.879E-02	-1.726E 00	995	5.243E-03	-2.200265
520	1.261E-01	-8.992E-01	760	1.763E-02	-1.754E 00	1000	5.177E-03	-2.200266
525	1.229E-01	-9.106E-01	765	1.720E-02	-1.765E 00	1005	5.070E-03	-2.200267
530	1.196E-01	-9.223E-01	770	1.675E-02	-1.776E 00	1010	4.963E-03	-2.300268
535	1.158E-01	-9.364E-01	775	1.710E-02	-1.767E 00	1015	4.886E-03	-2.300269
540	1.120E-01	-9.509E-01	780	1.744E-02	-1.759E 00	1020	4.809E-03	-2.300270
545	1.085E-01	-9.645E-01	785	1.741E-02	-1.759E 00	1025	4.695E-03	-2.300271
550	1.051E-01	-9.785E-01	790	1.738E-02	-1.760E 00	1030	4.582E-03	-2.300272
555	1.006E-01	-9.973E-01	795	1.685E-02	-1.773E 00	1035	4.468E-03	-2.300273
560	9.618E-02	-1.017E 00	800	1.632E-02	-1.787E 00	1040	4.355E-03	-2.300274
565	9.259E-02	-1.033E 00	805	1.568E-02	-1.805E 00	1045	4.227E-03	-2.300275
570	8.899E-02	-1.051E 00	810	1.503E-02	-1.823E 00	1050	4.100E-03	-2.300276
575	8.550E-02	-1.068E 00	815	1.441E-02	-1.841E 00	1055	3.992E-03	-2.300277
580	8.201E-02	-1.086E 00	820	1.379E-02	-1.861E 00			
585	7.937E-02	-1.100E 00	825	1.337E-02	-1.874E 00			
1060	3.883E-03	-2.411E 00	1075	3.672E-03	-2.435E 00	1090	3.516E-03	-2.400287
1065	3.795E-03	-2.421E 00	1080	3.637E-03	-2.439E 00	1095	3.544E-03	-2.400288
1070	3.707E-03	-2.431E 00	1085	3.577E-03	-2.447E 00	1100	3.573E-03	-2.400289

This is accomplished with a relationship arrived at from measurements which indicate essentially linear changes in radiance with changes in transmittance. The scaling function (M_λ) is determined from:

$$M_\lambda = -\left[\frac{Nh_{\lambda_{\overline{40}}}}{1 - t_{\lambda_{S_{\overline{V}}}}}\right]$$

then,

$$Nh_{\lambda_{40L}} = Nh_{\lambda_{\overline{40}}} + M_\lambda \left[(t_{\lambda_{S_{V_L}}} - t_{\lambda_{S_{\overline{V}}}}\right]$$

where:

$Nh_{\lambda_{\overline{40}}}$ = average vertical haze radiance at 40° solar altitude seen through one atmosphere (watts/m^2/5mμ).

$Nh_{\lambda_{40L}}$ = vertical haze radiance at 40° solar altitude at any vehicle altitude and haze level

$t_{\lambda_{S_{V_L}}}$ = vertical transmittance due to scattering at haze level and vehicle altitude under consideration

$t_{\lambda_{S_{\overline{V}}}}$ = vertical transmittance due to scattering at average haze level through one atmosphere

(2) Scaling of the Atmospheric Radiance With Respect to Solar Altitude

The solar altitude scaling routine reflects the observed proportional change mentioned previously. The scaling function (A_{SA}) is broken down into two solar altitude ranges:

(a) Solar altitude of 5° or greater:

$$A_{SA} = .00000576(SA)^3 - .000857(SA)^2 + .04856(SA) + .06417$$

(b) Solar altitude less than 5 degrees:

$$A_{SA} = \text{antilog}_{10} \left[-.000413775(SA+10)^4 + .02003885(SA+10)^3 - .375054(SA+10)^2 + 3.336588(SA+10) - 12.891922\right]$$

where:

SA = solar altitude (degrees)

A_{SA} = scaling ratios

(3) Scaling the Atmospheric Radiance With Respect to Air Mass (Scatter Fraction)

Duntley[8] has shown experimentally that the atmospheric radiance for paths of sight other than the vertical can be corrected by calculating the ratio of the scattering fraction (1.0 - transmittance) at the angle of interest to the vertical scattering fraction. The spectrally dependent air mass correction is calculated from:

$$A_{AM_{\lambda_\theta}} = \frac{1 - t_{\lambda_{S_\theta}}}{1 - t_{\lambda_{S_V}}}$$

where:

$t_{\lambda_{S_\theta}}$ = atmospheric transmittance at any zenith angle due to scattering

$t_{\lambda_{S_V}}$ = vertical atmospheric transmittance due to scattering

(4) Scaling the Atmospheric Radiance With Respect to Angle-to-the-Sun (Scatter Angle or CATS Angle)

The angular dependence of scattering is accounted for by an empirical relationship derived from measurements of atmospheric radiance. Presently, the spectral dependence of the angular scattering is not reflected in the relationship, but is indicative of the red region of the spectrum.

The relationship gives the relative scatter at any angle ϕ to the sun. The increase or decrease in scattering relative to the vertical is obtained by calculating a ratio of scatter at the angle of interest to the scatter for a vertically down-looking angle. This is the required scaling factor, since the prime item of data in the model is for a down-looking vertical path of sight. The equations are:

(8) Duntley, S. Q.; Johnson, R. W.; Gordon, J. E.; Ground Based Measurements of Earth-to-Space Beam Transmittance, Path Radiance, and Contrast Transmittance, Technical Documentary Report No. AL-TDR-64-245, Contract AF33(657)-7739, Project No. 6220, Task No. 622009, 1965.

$$\phi_1 = 180° - CATS$$

$$\phi_2 = 90° + SA$$

then,

$$R_{1,2} = .401911 + .286959 \cos \phi_{1,2} - .0362438 \sin \phi_{1,2} + .197304 \cos 2\phi_{1,2} - .0506574 \sin 2\phi_{1,2} + .0858164 \cos 3\phi_{1,2} - .0339767 \sin 3\phi_{1,2} + .0219449 \cos 4\phi_{1,2} - .012164 \sin 4\phi_{1,2}$$

and

$$A_{ANG_\phi} = \frac{R_1}{R_2}$$

where:

CATS = the angle between the optical axis and the sun's beam where the two vectors intersect at the earth's surface. The angle is counted from 0° looking straight down the sun's beam.

SA = solar altitude

(5) Additional Haze Radiance Caused by the Earth's Reflectance

The additional haze radiance due to reflectance of daylight irradiance is estimated from an equation which is a modification of an equation developed by Gordon. This spectral radiance is calculated from:

$$Nh_{\lambda_{e_{\theta_{SA}}}} = A \cdot \frac{R_\lambda}{4\pi} (1 - t_{\lambda_{S_\theta}}) \; Ho_{\lambda_{SA}}$$

where:

$T_{\lambda_{S_\theta}}$ = transmittance at the appropriate zenith angle due to scatter

$Ho_{\lambda_{SA}}$ = daylight horizontal plane irradiance at the appropriate solar altitude

λ = wavelength (microns)

A and R_λ are explained below

The reflectance (R_λ) is calculated for both snow and an average soil type background:

R_λ for snow is:

$$R_{\lambda_s} = .4222_\lambda + .999$$

R for average soil is associated with a scaling factor "A", which will ultimately allow estimated atmospheric radiance to be brought into agreement with experimentally observed values.

From 350 to 650mμ, $R_{\lambda_e} = 1.05244\lambda - .05825$

From 650 to 1100mμ, $R_{\lambda_e} = .56965\lambda + .25557$

The present estimate of "A" for desert areas is .35 while no scaling is done for general vegetation background analysis since the average atmospheric radiance corresponds to a value of .12.

(6) Complete Expression for Atmospheric Radiance

Based on the average vertically down-looking radiance at 40° solar altitude, the atmospheric radiance for the appropriate solar altitude, azimuth angle, CATS angle, haze level, vehicle altitude, terrain elevation, and background reflectance is given by:

$$NH_{\lambda_{SA,\phi,\theta,L,e}} = (NH_{\lambda_{40L}} \bullet A_{SA} \bullet A_{AM_{\lambda_\theta}} \bullet A_{ANG_\phi}) + Nh_{\lambda_{e,\theta,SA}}$$

SECTION IV

CAMERA PERFORMANCE MODEL (SR-3)

4.1 SUMMARY

4.1.1 General Description of SR-3

SR-3 is a modified, subroutine version of the original camera performance prediction model. The original model is also known as PERFORM. This model predicts the resolution of the HEXAGON Camera System from a statistical model of possible camera degradations for each target acquisition. Camera performance is given as the limiting resolving power, which means the smallest recognizable component of a tribar target that can be identified from the developed film. Thus, this measure of performance depends not only upon the performance integrity of the camera, but also the characteristics of the film, the development process, and the interactions of the human observer combined with the transfer characteristics of the exploitation equipment.

The camera performance is characterized by the system modulation transfer function (MTF). The other factors are integrally described by the film threshold modulation (TM) curve. Resolving power, as it is calculated in SR-3, is the spatial frequency (lines/millimeter) at which the MTF and the TM curves intersect. This resolving power is also converted through geometric scaling considerations to the ground resolved distance (GRD) in feet corresponding to the given image resolving power.

The instantaneous values of the camera degradations are not known, but their statistical characteristics can be estimated. Thus, CRYSPER gives a probabilistic estimate of camera performance. The program treats two types of camera degradations as random factors, these are defocus and smear (uncompensated image motion). The resolution value output by CRYSPER corresponds either to the median values or to the mean plus two sigma worst case values of these two parameters.

The smear values are used to compute the smear MTF. The defocus values are used to choose a polychromatic optical MTF from a precomputed table. The product of these two MTFs is multiplied by the C_o (modulation reduction) factor which estimates manufacturing and thermal degradations. The result is the system MTF.

The program has the option of using either a "specification" TM curve or of choosing a TM curve from a tabulation which is exposure dependent. The resolving power is computed from the intersection of the system MTF and the TM curve. The program outputs resolution for two directions, in-track (flight direction) and cross-track (scan direction).

4.1.2 Function of SR-3 in CRYSPER

Information about the acquisition geometry and dynamics is provided by the SR-1 portion of the program. Additional data concerning contrast and apparent luminance for the specified target comes from the SR-2 section. SR-3 uses this information to calculate image motion and defocus statistics, resulting transfer functions for the camera, and resolution from the intersection of the transfer function and the threshold modulation (TM) curve. The calculated image motion and resolution values are returned to the SR-2 section for further processing.

4.1.3 Operation of SR-3

The first time (first target acquisition) that Subroutine SR-3 is called by CRYSPER, certain special functions are performed. SR-3 is first used to input some data which either subsequently remains fixed or is needed for one-time-only computations. This objective is accomplished by calling Subroutine READH which, via Subroutines INPARM and RADPRM, also outputs a summary of the input parameters in engineering units and in radian units, respectively. The other special functions of this first pass through SR-3 are to output tables of measured image velocities, the tables of the optical MTFs, and the tables of contrast uncompensated TM curves. The measured image velocities are tabulated versus scan angle and V/H (velocity-to-altitude ratio), the optical MTFs are tabulated versus defocus and field angle, and the TM curves are tabulated versus the $\log_{10}$ of the exposure. The commands that accomplish the above objectives are ignored on all subsequent passes through SR-3, and the following operations performed.

Parameters are calculated that will be needed for the conversion of camera resolution to GRD. The program then decides which of the Aft or Forward Cameras has acquired the target. Subroutine B1 is called to calculate the mean and standard deviation of the image velocity and Subroutine B2 is called to compute the mean and standard deviation of defocus. Subroutine B2 also computes the object distance (slant range-to-target) which is then used in SR-3 to calculate additional GRD conversion parameters. The camera exposure time is chosen from a tabulation of exposure time versus sun angle (above the horizon) provided separately from SR-2.

Since the exposure time set in the camera is controlled by slit width and film speed, a check is made to see that the computed exposure time falls within the range imposed by the constraints of those variables. If it is too large or too small, a new value is calculated from the appropriate extreme value of the slit width.

The target contrast at the entrance aperture of the camera is calculated from the high-light and low-light brightness values that were computed in SR-2. If the default (specification) TM curve option is chosen, then the TM curve is calculated and divided by the contrast to give the contrast compensated TM curve. If the variable TM curve option is chosen, the $\log_{10}$ of the exposure is calculated from the exposure time, high-light brightness, and optical characteristics of the camera. The $\log_{10}$ exposure is then used to select the appropriate TM curve from the table, which is then divided by the contrast to give the contrast compensated TM curve.

The mean value of image velocity from Subroutine B1 is added to the chamber measured mean. If the mean value of image motion is desired, then this value is used in Subroutine GAUSSN together with the standard deviation from B1 to produce a new distribution of image velocities which are all positive. The adjusted mean is calculated from this new distribution. If the worst case option is chosen, then the unadjusted mean is added to plus and minus two times the standard deviation giving two possible values of the worst case. Regardless of which option is chosen, the value of image velocity is multiplied by the exposure time to produce the image smear.

A similar procedure is followed with defocus. The differences are that no measured values are used, data comes from Subroutine B2, and the defocus value is used to determine a defocus index with which the proper optical MTF can be chosen. When the worst case option is chosen, the mean minus two sigma is the value used as the worst case.

The worst case image smear is chosen as that one of the two worst case candidates which has the greatest absolute value. The smear transfer function (linear smear assumed) is calculated from the smear. The optical MTF is computed in Subroutine AVGMTF, where the MTFs for the given field angle are averaged over a defocus range determined from the defocus index described above and the film tilt. The system MTF is then computed as the product of the smear MTF, the C_o factor, and the optical MTF.

The intersection of the system MTF and the contrast compensated TM curve is found by linear interpolation between those portions of the two curves which are closest to the intersection. The result is the estimated camera resolving power in lines per millimeter. The equivalent ground resolution (GRD) in feet is then computed from the camera resolving power, taking altitude and slant range distances defined by format location into account.

All of the preceding operations are performed for both the in-track and cross-track directions. Finally, the geometric mean GRD is calculated from the two GRD values. This entire procedure can be repeated if the performance of both cameras is required. The results of the SR-3 calculations are passed to Subroutine SR-2 for output.

4.1.4 Image Velocity Determination in Subroutine B1

The mean value of image velocity that Subroutine B1 calculates is what the mean value would be if the camera was exactly as designed and it operated optimally. This mean value is also called the fixed known image velocity. The main reason that the fixed known value is not zero is that the image motion compensation (IMC) systems (the film speed and platen skew angle) were designed to remove on-orbit image velocity only on the optical axis (0° field angle), which is the major axis of the photographic format.

The fixed known value is computed in B1 from the altitude, Vx/h (in-track), Vy/h (cross-track), scan angle, field angle, and stereo angle. First the film speed is computed; then the platen skew angle and its rate of change. The fixed known value is determined as the difference between the image motion that would occur if there were no IMC systems and the compensating effect of the IMC systems.

The standard deviation of the image velocity is computed as the resultant of a list of randomly fluctuating errors which are expected to occur during camera operation on-orbit. One of these terms represents the standard deviation of the motion that was measured in the chamber (sync-flash test) and, thus, represents the errors in manufacturing and calibrating the camera.

4.1.5 Defocus Determination in Subroutine B2

Subroutine B2 calculates a fixed known value of defocus. The fixed known defocus is computed from the variation in focus due to the object distance which changes with scan angle. The standard deviation is computed as the resultant of a list of randomly fluctuating errors which are expected to occur during camera operation on-orbit.

4.2 BASIC EQUATIONS

4.2.1 Background

The original version of SR-3 was a Monte Carlo simulation of camera performance. Random values of resolution were generated from random values of image motion and defocus. These random values of resolution were arranged into an empirical cumulative distribution from which various statistics could be calculated. This Monte Carlo simulation was repeated for each acquisition.

The Monte Carlo approach had to be abandoned because the computing time was prohibitive. Consequently, the current version of SR-3 calculates values of resolution which correspond to certain statistics of the perturbing random variables (image motion and defocus). However, the computed resolution values do not have any statistical significance. For instance, the resolution value corresponding to the mean values of both image motion and defocus is not necessarily the mean value of resolution. It simply corresponds to the mean value of the perturbing parameters, but its statistical meaning is not specifically known.

4.2.2 Explanation of Basic Equations

A. Ground Resolved Distance (GRD)

Subroutine SR-3 calculates the camera resolution in lines per millimeter/cycles per millimeter and also the corresponding ground resolved distance (GRD) in feet. The calculated value of GRD is defined as the distance on a plane tangent to the surface of the spherical earth at the object which corresponds to the projection of a given photographic resolution element in the camera's focal plane.

Mathematically:

$$g_x = \frac{cp}{fL_x}\sqrt{\frac{1-\lambda^2 \cos^2\theta \sin^2\phi}{\cos\beta}},$$

$$g_y = \frac{cp}{fL_y}\sqrt{\frac{1-\lambda^2 \sin^2\theta}{\cos\beta}}$$

where:

subscript x = in-track

subscript y = cross-track

subscript g = GRD (feet)

subscript p = object distance/slant range (nautical miles)

This object distance is defined by

$$p = R\ (\lambda \cos \alpha - \cos \beta)$$

where:

$$\cos \beta = \sqrt{1 - \lambda^2\ (1 - \cos^2 \alpha\ )}$$

$$\cos \alpha = \cos \theta \ \cos \phi$$

$$\lambda = 1 + h/R$$

and

R = earth radius (nautical miles)

h = satellite altitude (nautical miles)

f = camera focal length (1524 millimeters)

θ = half stereo angle (10 degrees)

ϕ = scan angle

c = feet per nautical mile

L = camera resolution (lines per millimeter)

B. Camera Resolving Power

The camera resolving power as it is defined in SR-3 is that value of the spatial frequency in lines per millimeter at which the system MTF intersects the film TM curve. Each of these two functions are stored in the computer for 14 equidistant spatial frequencies from 20 to 280 lines per millimeter. Denote these values of spatial frequency as K_i ($i = 1, 2, \ldots, 14$), and denote the corresponding MTF values and TM values as T_i and A_i respectively. Then, the resolution (L) is by the following linear interpolation:

$$L = K_{j-1} + (K_j - J_{j-1})\ (T_{j-1} - A_{j-1})/ \left[T_{j-1} - A_{j-1} + A_j - T_j \right];$$

where j is the smallest value of i for which A_i is larger than T_i.

C. Film Threshold Modulation (TM)

Subroutine SR-3 has the option of using either the "specification" TM curve that is used by the PERFORM Program or a TM curve that varies with $\log_{10}$ exposure. If the PERFORM option is chosen, the contrast uncompensated TM curve is generated from the following:

$$A_i = .1\ (K_i/190)^{1.22}$$

where:

K = spatial frequency (cycles/mm)

If the variable option is chosen, then the contrast uncompensated TM curve is chosen from a tabulation of TM curve versus $\log_{10}$ exposure, see Table 5-4. The chosen curve has an implicit log exposure value that is closest to the actual log exposure for the particular acquisition.

In either case, the contrast uncompensated TM curve is divided by the contrast modulation to produce a contrast compensated TM curve which is then intersected with the system MTF to find system resolving power.

D. Log Exposure

The value of log exposure that is used to select the proper variable AIM curve is given by:

$$\log E = \log_{10}\left[10.764\, t_s\, t_e\, B_2\, (.001)/(36P_f)\right]$$

where:

t_s = system transmission

t_e = exposure time (milliseconds)

B_2 = maximum apparent luminance of target

P_f = filter factor

thus, this value of log exposure corresponds to the maximum exposure that is to be expected for the acquisition.

E. Contrast Modulation

The contrast modulation (C) is calculated from:

$$C = \frac{B_2 - B_1}{B_2 + B_1}$$

where:

B_1 = the minimum apparent luminance of the target

B_2 = the maximum apparent luminance of the target

F. System MTF

The system MTF is defined as the following product:

where:

$$T = C_o T_s T_o$$

C_o = the modulation reduction factor which estimates manufacturing and thermal degradations of the optical system

T_s = image motion (smear) MTF

T_o = optical system MTF

G. Image Motion MTF

CRYSPER assumes linear image motion. Thus, the image motion MTF is:

$$T_s = \sin(\pi sK)/(\pi sK)$$

where:

s = the image displacement (smear) in microns

k = spatial frequency (cycles/micron)

H. Smear

The smear, since it is assumed to be linear, is:

$$s = \dot{x}\, t_e$$

where:

$\dot{x}$ = image velocity (microns/millisecond)

t_e = exposure time (milliseconds)

I. Exposure Time

The actual exposure time is determined by the film speed and the slit width. For a post-mission run, the exposure time is calculated from:

$$t_e = w/V_f$$

where:

t_e = exposure time (milliseconds)

w = slit width (inches)

V_f = film speed (inches/milliseconds)

For a premission run, an optimum exposure time is chosen from a tabulation of exposure time versus sun angle (elevation of sun above horizon). The expected sun angle for an acquisition is used to pick the appropriate exposure time from the table by linear interpolation.

However, the actual exposure time is limited by constraints on the size of the slit width. If the calculated value of t_e exceeds these limits, then it is redefined as the appropriate limiting value (either $.08/V_f$ or $.91/V_f$).

J. Optical MTF

Optical MTFs are tabulated versus field angle and defocus. The field angle index (i) runs from 1 to 5, and has the following relationship with the field angle:

i	1	2	3	4	5
field angle (degrees)	-2.5	-2	0	2	2.5

The defocus index (j) runs from 1 to 41, and represents defocus values in microns of from ± 40 in steps of 2. Defocus (D) represents a displacement parallel to the optical axis of the position of the recorded image from a reference focal plane.

The problem is one of two dimensional interpolation. The field angle (ϕ) is used to choose a value of i according to the following scheme:

if:

$\phi < -2.26$	$i = 1$
$-2.26 \le \phi < -1.01$	$i = 2$
$-1.01 \le \phi < 1.0$	$i = 3$
$1.0 \le \phi < 2.25$	$i = 4$
$2.25 \le \phi$	$i = 5$

There is a measured maximum value of the deviation of the point of best focus from the tilted film plane. It is maximum with respect to field angle. Corresponding to the maximum deviation is a shift of $\pm$ n values of the defocus index j.

Denote the MTF with indices i and j as T_{ij}. Then the following average (with respect to defocus) values are calculated:

$$T_{av1} = \frac{1}{(2n+1)} \sum_{\ell = j-n}^{j+n} T_{i\ell}$$

$$T_{av2} = \frac{1}{(2n+1)} \sum_{\ell = j-n+1}^{j+n+1} T_{i\ell}$$

where:

$$d_j \le d \le d_{j+1}$$

Then the optical MTF (T_o) is computed from:

$$T_o = \frac{d - d_j}{d_{j+1} - d_j} \quad T_{av2} + \left[1 - \left(\frac{d - d_j}{d_{j+1} - d_j}\right)\right] T_{av1}$$

K. Statistical Transformation

Both smear and defocus are assumed to be Gaussian (normal) random variables. Subroutine SR-3 has the option of calculating either (1) a mean ± 2 sigma worst case, or (2) a mean. The mean option transforms the original random variable to its absolute value, then calculates the median from that distribution and assigns to the median the sign of the mean of the original random variable. Thus, the mean option produces a median of the absolute value of smear and defocus.

The worst case option chooses either the mean +2 sigma or the mean -2 sigma of the original random variable, whichever has the greater absolute value.

L. Defocus

The mean value of defocus in millimeters is calculated from:

$$D_m = .001 (D_n - D_a)$$

where:

D_m = the focal shift due to object distance variation.

D_n = focal shift in microns due to the nominal object distance adjusted for field position.

D_a = the focal shift in microns due to the actual object distance. D_a is calculated from:

$$D_a = \frac{1253.3}{p}$$

where:

p = the object distance/slant range (nautical miles)

and

the constant 1253.3 represents the nominal focal length squared in units of microns times nautical miles.

The standard deviation of defocus is calculated from:

$$D_\sigma = .001 \sqrt{\sum_{i=1}^{10} D_i^{\;2}}$$

where:

D_i = the defocus errors (microns). These errors are listed in Table 4-1.

TABLE 4-1

DEFOCUS ERRORS

Error Number	Error Description
1	Platen roller run out
2	Film thickness and lift-off variation
3	Film flutter
4	Film mean unflatness
5	Thermal effects in platen
6	Thermal effects in optics
7	Uncertainties in expansion coefficients
8	Dimensional stability in metering rods
9	Final focus adjustment
10	Shift in primary mirror (after launch)

M. Image Velocity

The two main contributors to the gross image motion for the HEXAGON System are the satellite velocity and the scan rate of the optical bars. The film is driven at a variable speed to compensate for the cross-track component of the gross image velocity and the orientation of the film varies to compensate for the in-track component of the gross image velocity. If the IMC systems are operating perfectly, then the residual image velocity will be a fixed (zero standard deviation) known quantity. The fixed known errors in the in-track ($\dot{x}_{f.k.}$) and cross-track directions ($\dot{y}_{f.k.}$) are calculated from:

$$\dot{x}_{f.k.} = \Bigg\{ f\left[-\frac{V_x}{h}\cos^2\theta\cos\phi - .5\frac{\dot{h}}{h}\sin 2\theta\cos\phi\right] + x\left[.5\frac{V_x}{h}\sin 2\theta\,(1+\cos^2\phi) - .5\frac{V_y}{h}\cos\theta\sin 2\phi + \frac{\dot{h}}{h}(\sin^2\theta - \cos^2\theta\cos^2\phi)\right] + \frac{x^2}{f}\left[\frac{V_y}{h}\sin\theta\sin\phi\right]\Bigg\} S - V_f\sin\psi,$$

$$\dot{y}_{f.k.} = \Bigg\{ f\left[.25\frac{V_x}{h}\sin 2\theta\sin 2\phi + \frac{V_y}{h}\cos\theta\cos^2\phi - .5\frac{\dot{h}}{h}\cos^2\theta\sin 2\phi\right] + x\left[-\frac{V_x}{h}\sin^2\theta\sin\phi - \frac{V_y}{h}\sin\theta\cos\phi + .5\frac{\dot{h}}{h}\sin 2\theta\sin\phi\right]\Bigg\} S - f\dot{\phi} + X\dot{\psi} - V_f\cos\psi,$$

where:

f = camera focal length (inches)

θ = camera half-stereo angle (radians)

ϕ = camera scan angle (radians)

$\left.\begin{matrix} \frac{V_x}{h} \\ \frac{V_y}{h} \\ \frac{\dot{h}}{h} \end{matrix}\right\}$ = in-track, cross-track, and vertical components, respectively, of the normalized (with respect to altitude) apparent ground velocity

S = a spherical earth correction

$\dot{\phi}$ = scan angle rate

V_f = film speed

Ψ = platen skew angle with respect to optical bar

$\dot{\Psi}$ = skew angle rate

x = field position (inches)

The spherical earth correction is calculated from:

$$S = 1/\left\{c\left(1 + \left[1 - \sqrt{1-\lambda t \quad (2+\lambda)}\,\right]/\lambda\right)\right.$$

where:

$c = \cos^2\theta \ \cos^2\phi$

$t = \tan^2\theta \ \tan^2\phi$

$\lambda = h/R$

R = earth radius (NM)

h = altitude (NM)

The IMC commands ($\dot{\phi}$, Ψ, $\dot{\Psi}$, V_f) are calculated from:

$$\dot{\phi} = K\frac{V_x}{h}$$

$$\Psi = \frac{\cos^2\theta \ \cos\phi}{K}\left[1 - \frac{4.23418}{2R(V_x/h)}\tan^2\phi\right]$$

where the expression in the square brackets is an approximation to the spherical earth correction.

$$\dot{\Psi} = -\frac{\dot{\phi}\cos^2\theta \ \sin\phi}{K}\left[1 + \frac{4.2318}{R(V_x/h)}\left(1 - \frac{1}{2}\sin^2\phi\right)\Big/\cos^2\phi\right]$$

$$V_f = -f\dot{\phi} + \left[f\left(.25\frac{V_x}{h}\sin 2\theta \quad \sin 2\phi \quad + \frac{V_y}{h}\cos\theta \quad \cos^2\phi\right.\right.$$

$$\left.\left. -.5\frac{V_x}{h}\ \frac{\cos^4\theta \quad \cos^2\phi}{K}\right)\right]$$

where the expression in the square brackets is called the film velocity modulation. The constant K has the value $\pm 20\pi$, depending on which camera data is being processed.

The reason that the fixed known errors are not identically zero is that the IMC commands are approximations to what one would ideally like them to be. For instance, the gross image motions vary with field position, and it is impossible to vary the film velocity as a function of field position. All of the IMC commands are designed to compensate only at 0° field position.

The fixed known image velocity is added to the mean image velocity that was measured in the chamber ($\dot{x}_c$) to find the mean value of the image velocity on-orbit:

$$\dot{x}_m = \dot{x}_{f.k.} + \dot{x}_c$$

$$\dot{y}_m = \dot{y}_{f.k.} + \dot{y}_c$$

The standard deviation of the image velocity is found from perturbing the fixed known equations and the standard deviation of the chamber measurements. There are 30 image motion error sources which are each assumed to have zero mean and a specified two sigma value, see Table 4-2.

TABLE 4-2

IMAGE MOTION ERROR SOURCES

Error Number	Description of Error
1	Alignment optical bar-to-vehicle attitude reference (pitch)
2	Alignment optical bar-to-vehicle attitude reference (roll)
3	Alignment optical bar-to-vehicle attitude reference (yaw)
4	Alignment projected optical axis-to-scan axis
5	Alignment optical axis-to-scan axis (pitch)
6	Alignment optical axis-to-scan axis (roll)
7	In-track slit position
8	Cross-track slit position
9	Vehicle attitude rate (pitch)

TABLE 4-3 (CONT'D)

Error Number	Description of Error
10	Vehicle attitude rate (roll)
11	Vehicle attitude rate (yaw)
12	Alignment optical axis-to-scan axis (yaw)
13	Vehicle attitude error (pitch)
14	Vehicle attitude error (roll)
15	Vehicle attitude error (yaw)
16	Scan angle error
17	Focal length error
18	Skew angle position
19	Skew angle error
20	Flat mirror angular rate (pitch)
21	Flat mirror angular rate (roll)
22	Flat mirror angular rate (yaw)
23	Optical bar angular rate (pitch)
24	Optical bar angular rate (roll)
25	Optical bar angular rate (yaw)
26	Film speed synchronization
27	Film speed modulation
28	V_x/h error
29	V_y/h error
30	Lateral film speed

NOTE: The "vehicle angular rate" category represents the resultant of two errors (vehicle attitude rate and vehicle angular vibrations).

Some of these errors do not exist in the chamber, i.e., vehicle attitude errors and rates. The program uses a budgeted value for the two sigma for each of these error sources. The remaining error sources exist both in the chamber and on-orbit. The two sigma value for each of these error sources is assumed to be the same on-orbit as in the chamber. However, the chamber measurements result in an overall two sigma value, not the two sigma values for each of the error sources. Thus the overall two sigma value measured in the chamber in the in-track direction is assigned to the lateral film speed error and the overall two sigma value measured in the chamber in the cross-track direction is assigned to the film speed synchronization error. The two sigma values of the remaining error sources that exist both in the chamber and on-orbit are set to zero.

The lateral film speed error and the film speed synchronization error were chosen for this purpose because the image motion due to these error sources has the same magnitude as the error sources, and because the resulting image velocity in each case acts entirely in the required direction (in-track for the lateral error, and cross-track for the synchronization error).

The total image velocity error due to these error sources is a linear combination of the error sources.

$$\dot{\xi} = \sum_{i=1}^{30} f_i E_i$$

$$\dot{\eta} = \sum_{i=1}^{30} g_i E_i$$

are the in-track and cross-track components of the total image velocity error. The constants f_i, g_i are the partial derivatives of the fixed known errors with respect to the ith error source:

$$f_i = \left. \frac{\partial \dot{x}_{f.k.}}{\partial E_i} \right|_{E_i = 0}$$

$$g_i = \left. \frac{\partial \dot{y}_{f.k.}}{\partial E_i} \right|_{E_i = 0}$$

Under the assumption that the E_i are independent random variables with means $\mu(E_i)$ and variances $\sigma^2(E_i)$, the mean and variance of $\dot{\xi}$ and $\dot{\eta}$ are:

$$\mu(\dot{\xi}) = \sum_{i=1}^{30} f_i \, \mu(E_i) = 0$$

$$\mu(\dot{\eta}) = \sum_{i=1}^{30} g_i \, \mu(E_i) = 0$$

$$\sigma^2(\dot{\xi}) = \sum_{i=1}^{30} f_i^2 \, \sigma^2(E_i)$$

$$\sigma^2(\dot{\eta}) = \sum_{i=1}^{30} g_i^2 \, \sigma^2(E_i)$$

Since $\dot{\xi}$ and $\dot{\eta}$ are not necessarily independent, their covariance is calculated from

$$\sigma_{\xi \eta} = \sum_{i=1}^{30} f_i g_i \sigma^2 (E_i)$$

The correlation coefficient is thus:

$$p = \frac{\sigma_{\xi \eta}}{\sigma(\dot{\xi}) \ \sigma(\dot{\eta})}$$

In summary, the mean and standard deviation of the in-track image velocity are $\dot{x}_m$ and $\sigma(\dot{\xi})$, and the mean and standard deviation of the cross-track image velocity are $\dot{y}_m$ and $\sigma(\dot{\eta})$.

Since the image velocity is the sum of many contributing random variables, we assume that the image velocity is a bivariate Gaussian random variable in which case the "mean $\pm 2\sigma$" values $\dot{x}_t$, $\dot{y}_t$ can be calculated from

$$\dot{x}_t = \dot{x}_m \pm 2\sigma(\dot{\xi})$$

$$\dot{y}_t = \dot{y}_m \pm \left[p + \sqrt{1 - p^2} \right] 2\sigma(\dot{\eta})$$

where:

p = the correlation coefficient.

4.3 STRUCTURE OF SR-3

The SR-3 routine consists of a main program (Subroutine SR-3) and several subsidiary subroutines. Data is passed between subroutines via labeled COMMON.

4.3.1 Main Program (SR-3)

Subroutine SR-3 contains a set of control variables to set the flow of logic for various options. These control variables are presented in Table 4-3. This angle/angle table has the option to quickly run through the program to obtain a tabulation of resolution versus sun angle and scan angle for a "typical" target under "typical" conditions.

The primary function of this main subroutine is to process the control variables and to call the subsidiary subroutines which do the actual calculations. These subsidiary subroutines are JUMP1, MAIMC1, B1, B2, SMEAR1, EXPTIM, SYSTF, READH, GAUSSN, AVGMTF, INPARM, RADPRM.

TABLE 4-4

SR-3 CONTROL VARIABLES

Variable Name	Variable Value	Description
IBR	10	Subscript for Aft Camera data
	12	Subscript for Forward Camera data
IBRR	1	Subscript for Aft Camera output
	2	Subscript for Forward Camera output
JUMP	0	First pass for new engineering data
	1	Any subsequent pass
JUMPZ	1	First call to Subroutine SR-3
	0	Any subsequent call
J10RB	0	Premission run
	1	Post mission run
LBRR	1	Subscript for Aft Camera data
	2	Subscript for Forward Camera data
LQQQZ	1	Using the -2 sigma defocus setting
	2	Using the +2 sigma defocus setting
	3	Using the mean defocus setting
MAIMC	0	Use PERFORM (specification) TM curve
	1	Use tabular TM curve
MMEAN	0	Two sigma worst case
	1	Mean case
MRTEST	0	Angle/angle table or premission
	1	Post mission and doing two sigma worst case
	2	Post mission and doing mean case
SUNTT	0	Building an angle/angle table
	1	Processing an access

4.3.2 Description of Subsidiary Subroutines

A. Subroutine JUMP1

This subroutine is called from Subroutine SR-3 only when the control variable JUMP has the value 0. It is used to initialize and update engineering data. This is primarily accomplished by calls to Subroutines READH and MAIMC1. JUMP1 also inputs the exposure time versus sun angle tables, outputs the optical MTF headers, and the PERFORM (specification) TM curve if it is used.

(1) Subroutine READH

Subroutine READH which is called from JUMP1 inputs various camera descriptors, the optical MTFs, the defocus and image velocity error budgets, and the chamber measurements of the image velocity mean and two sigma values. Subroutine READH also calls Subroutines INPARM and READPRM.

(a) Subroutine INPARM

Subroutine INPARM outputs a summary of the camera descriptors, and the defocus and image velocity error budgets in engineering units.

(b) Subroutine RADPRM

Subroutine RADPRM outputs the same data as does Subroutine INPARM, but here the image velocity error budget has been converted to radian units, where appropriate.

(2) Subroutine MAIMC1

This subroutine is called either from Subroutine JUMP1 or from Subroutine SR-3. It is called only when the control variable MAIMC has the value 1 which is when the tabular TM curves are required. If Subroutine MAIMC1 is called from Subroutine JUMP1, these tabular TM curves are output. If it is called from Subroutine SR-3, then for an initializing pass (JUMP = 0), the tabulation of chamber measured mean and two sigma image velocity is output. If JUMP is not zero, then the proper entries are chosen from that table according to the values of Vx/h and scan angle; and the log exposure is calculated, from which the proper TM curve is chosen.

B. Subroutine B1

Subroutine B1 calculates the mean and one sigma image velocity both in-track and cross-track for either camera. The calculation procedure is described in paragraph 4.2.2.M.

C. Subroutine B2

This subroutine calculates the mean and one sigma defocus for either camera. The calculation procedure is described in paragraph 4.2.2.L. B2 also determines the slant range (object distance) which is used in GRD computations.

D. Subroutine EXPTIM

Subroutine EXPTIM determines the exposure time for each access by a method described in paragraph 4.2.2.I.

E. Subroutine SMEAR1

This subroutine computes the mean or the two sigma worst case smear (image displacement) both in-track and cross-track for each camera. In a two sigma worst case, both mean ± 2 sigma are calculated and it is then determined which has the greater magnitude. SMEAR1 also uses the defocus to choose a pointer for the optical MTF array. SMEAR1 calls Subroutine GAUSSN.

(1) Subroutine GAUSSN

Subroutine GAUSSN performs the statistical transformation to get a new mean as described in paragraph 4.2.2.K.

F. Subroutine SYSTF

This subroutine calculates the image motion MTFs, determines the appropriate optical MTFs, and computes the resulting system MTFs. SYSTF calls subroutine AVGMTF.

(1) Subroutine AVGMTF

Subroutine AVGMTF uses the averaging technique described in paragraph 4.2.2.J to determine a representative optical MTF.

G. Subroutine LINES

This subroutine intersects the system MTF with the TM curve to find the camera resolution in lines per millimeter and the corresponding GRD. For each of the quantities the geometric mean of the in-track and cross-track values is also found.

SECTION V

DATA REQUIREMENTS

5.1 SUMMARY

Each of the three subroutines have specific inputs needed to drive CRYSPER. SR-1 needs the orbital elements for the selected case to be flown. SR-2 requires the target deck, solar ephemeris, haze data, transmission values and reflectances in addition to the output of SR-1. SR-3 uses the SR-2 contrast output with the camera parameters to predict the resultant resolution.

The SR-3 inputs are derived from ground tests conducted at many stages of the camera assembly and test phases. These inputs are the measured values or estimates of the performance levels of the camera components. The inputs to CRYSPER are not necessarily the optimum values but values that are indicative of the way the mission is being flown. For example, the peak focus determined from the chamber collimator data is not necessarily used for flight. The chamber value of focus will be modified to achieve the best average performance across the full format. This defocus value from peak focus at the collimator locations is input to CRYSPER, which reduces the on-axis MTF and lowers the appropriate net predicted resolution level. Smear values are also adjusted or balanced to achieve optimum performance over the total format rather than at a specific location within the format. This is the way missions are flown, and is also the philosophy used to assess mission performance by the PFA Team and users.

5.2 INPUTS

The inputs needed to run CRYSPER are listed by originator or appropriate designee. The inputs should be sent to Headquarters at the time they are generated. As has been the case in the past, CRYSPER runs were delayed due to failure of one or more originators to send their inputs in a timely fashion. This problem centers around their failure to realize that CRYSPER is a predictor and thus used extensively prior to actual flights.

5.2.1 Data Obtained From SPO/SSC

The following inputs are received from SPO/SSC:

A. Field curvature from Chamber D or Chamber A-2 tests.

B. Table of corrections to the calculated mean value of smear in both the flight and scan direction (CDADD and CFADD). Table of two sigma values of film velocity synchronization errors (BIM-26). Table of two sigma values of lateral film motion errors, (BIM-30). Tabular entries are for a range of Vx/h values from .020 to .055 per second in increments of .005 per second and a range of scan angles from -60° to +60° in increments of 10 degrees.

C. Defocus value in microns for the on-axis points (INPUT-12).

D. Tilt of focal plane in microns at the plus three inch field position (INPUT-13).

E. Film mean unflatness (DE-4).

F. Film tilt range in microns.

G. Filter to be used and its transmission as a function of wavelength.

H. The following sun angle/scan angle table data: date of the table, altitude of the vehicle, and low-light and high-light reflectances of the targets to be run, e.g., 7% and 33%, 10% and 20%, etc.

I. Orbit number and list of engineering changes whenever on-orbit adjustments are made.

5.2.2 Data Obtained From BRIDGEHEAD

The following inputs are received from BRIDGEHEAD:

A. Table of exposure times by solar altitude for each optical set and filter.

B. The following additions to the spectral library: element name, filter, optical bar number, and the corresponding 181 spectral array values.

C. Low-light and high-light reflectivity for specific intelligence target types.

5.2.3 Data Obtained From AFSPPF or SSC

The following input is received from either AFSPPF or SSC:

A. Microdensitometer readings of interferograms obtained during the 70° Chamber D tests for the five field angles (0°, ±2.0°, and ±2.5°).

5.2.4 Data Obtained From SSC

The following data inputs are received from SSC:

A. First and final focus offset and increment in microns.

B. The 23 measured aberration coefficients and the residual root mean square. It should be noted that the measured coefficients can be used to compute polychromatic MTFs in lieu of the AFSPPF/SSC microdensitometer readings.

C. The 23 design aberration coefficients at a wavelength of 6328Å.

D. The 23 design aberration coefficients for the 17 wavelengths from 3900Å to 7100Å in increments of 200Å.

E. Gravity coefficient corrections to the aberration coefficients.

NOTE: Data from input items A, C, D, and E above is required for each optical set and each filter to be processed for the five field angles (0°, ±2.0°, and ±2.5°).

5.2.5 Data Obtained From WCFO

A. Orbital elements for candidate orbits to be processed.

B. Orbital elements for post mission analysis studies.

5.2.6 Data Obtained From User

A. Target deck.

B. Haze type, snow condition, and high-light and low-light reflectivity, if specific conditions are to be studied.

5.3 VARIABLES USED IN CRYSPER

It is the desire or concept of the program originators to model every possible error or error source in the HEXAGON System. Although presently there are no means for determining the error associated with every possible source, provisions have been made in CRYSPER to input a value for all error possibilities. Unless some anomalous condition occurs which justifies assigning a value to the error, the error is assumed to be effectively zero. In cases where a vehicle experiences excessive yaw, the best estimate of the yaw error can be input to CRYSPER. CRYSPER will then determine the effective loss in performance due to this variable.

There is a performance prediction program for Chamber A resolution called PERFORM. Many of the input variables used in CRYSPER are the same as used in PERFORM. To maintain continuity, the variables used for both programs are identical. However, not all the variables used in PERFORM are used in CRYSPER. Rather than eliminate them from this report and have discontinuities, the variables associated only with PERFORM are designated as NA (not applicable). Inputs 25 thru 28 are orbital elements computed in SR-1 and are also designated NA.

5.3.1 Engineering Data Used by the CRYSPER Program (INPUT)

Table 5-1 lists the engineering data used by the CRYSPER Program.

TABLE 5-1

"INPUT" ENGINEERING DATA UTILIZED BY CRYSPER

INPUT	Description of Data or Error	Budget	CRYSPER Program
1	Number of samples	100	NA
2	Resolution percentile for summary output	96%, 50%, 4%	NA
3	Contrast ratio	2.0	Computed from target apparent brightness
4	Modulation reduction factor	.94	Changes for each optical bar
5	Optical system focal length	60"	60" or actual
6	Film type	1414	1414 or actual
7	Film TM curve constant KO	190.0	190.0
8	Film TM curve power	1.22	1.22
9	First focal plane position	-0.04mm	-0.04mm
10	Focal plane position increments	0.002mm	0.002mm
11	Number of focal plane positions	41	41
12	Defocus value for on-axis points	10	10

TABLE 5-1 (CONT'D)

INPUT	Description of Data or Error	Budget	CRYSPER Program
13	Tilt of focal plane for 3" field position	0.0	Changes for each optical bar
14	First field position for resolution calculations	-2.5°	NA
15	Field position increment	1	NA
16	Number of field positions	5	5
17	First scan angle for resolution calculations	60°	NA
18	Scan angle increment	-15°	NA
19	Number of scan angles	3	NA
20	Input tape description first field position	-2.5°	-2.5°
21	Field position increment	1.0°	1.0°
22	Number of field positions	5	5
23	Number of focal points	41	41
24	Average target brightness	600 ft-lamberts	Computed from target reflectance
25	Perigee altitude	82.0 NM	NA
26	Apogee altitude	144.0 NM	NA
27	Perigee latitude	55° North	NA
28	Orbit inclination	96.0°	NA

5.3.2 Focus Errors Two Sigma Values (DE)

Table 5-2 lists the focus error data used by the CRYSPER Program.

TABLE 5-2

FOCUS ERROR DATA UTILIZED BY CRYSPER

(Two Sigma Values)

DE (I)	Description of Data or Error	Budget (microns)	CRYSPER Program
1	Platen roller run out	1.0	0.0
2	Film thickness and lift-off variation	3.7	0.0
3	Film flutter	2.2	0.0

TABLE 5-2 (CONT'D)

DE (I)	Description of Data or Error	Budget (microns)	CRYSPER Program
4	Film mean unflatness	2.2	Results of dynamic focus test
5	Thermal effects in platen	3.7	0.0
6	Thermal effects in optics	6.8	0.0
7	Uncertainties in expansion coefficients	4.5	0.0
8	Dimensional stability of metering rods	1.4	0.0
9	Final focus adjustment	3.0	0.0
10	Shift in primary mirror (after launch)	3.0	8.0

5.3.3 Image Motion Errors - Two Sigma Values (BIM)

Table 5-3 lists the image motion error data used by the CRYSPER Program.

TABLE 5-3

IMAGE MOTION ERROR DATA UTILIZED BY CRYSPER

BIM (I)	Description of Error	Budget	CRYSPER Program
1	Align OB to vehicle attitude ref (P)	.00292 radian	0.0
2	Align OB to vehicle attitude ref (R)	.00166 radian	0.0
3	Align OB to vehicle attitude ref (Y)	.00146 radian	5.02 minutes
4	Align projected optical axis normalized to scan angle marks	.000145 radian	0.0
5	Align optical axis to scan axis (P)	.000034 radian	0.0
6	Align optical axis to scan axis (R)	.000034 radian	0.0
7	Δx slit position	.01 inch	0.0
8	Δy slit position	.02 inch	0.0
9	Vehicle attitude rate (P)	.000314 rad/sec	.013 degree/sec
10	Vehicle attitude rate (R)	.000314 rad/sec	.013 degree/sec
11	Vehicle attitude rate (Y)	.000314 rad/sec	.013 degree/sec
12	Vehicle optical axis to scan axis (Y)	.000034 radian	7.0 seconds
13	Vehicle attitude error (P)	.00977 radian	.56 degree
14	Vehicle attitude error (R)	.00977 radian	.56 degree
15	Vehicle attitude error (Y)	.01169 radian	.67 degree

TABLE 5-3 (CONT'D)

BIM (I)	Description of Error	Budget	CRYSPER Program
16	Scan angle error	.000291 radian	0.0
17	Focal length error	.0074 inch	0.0
18	Skew angle position	.00006 radian	0.0
19	Skew angle error	.00013 radian	0.0
20	Mirror angle rate (P)	.000126 radian/sec	0.0
21	Mirror angle rate (R)	.000126 radian/sec	0.0
22	Mirror angle rate (Y)	.000126 radian/sec	26.0 seconds/sec
23	OB angle rate (P)	.000126 radian/sec	0.0
24	OB angle rate (R)	.000126 radian/sec	0.0
25	OB angle rate (Y)	.000126 radian/sec	26.0 seconds/sec
26	Film velocity synchronization	.053 inch/sec	2σ cross-track smear measurement
27	Film velocity modification	.013 inch/sec	0.0
28	Vx/h error	.00027 radian/sec	.00027 radian/sec
29	Vx/h error	.00003 radian/sec	.00003 radian/sec
30	Lateral film velocity	.02 inch/sec	2σ in-track smear measurement
CD	In-track smear measurement	0.0	Add in-track smear measurement
CF	Cross-track smear measurement	0.0	Add cross-track smear measurement

5.4 OUTPUTS

The initial version of CRYSPER computed resolution for specific targets. While this capability still exists, it is not the most used output. CRYSPER has been configured to compute a table of resolution values in either cycles/mm at the film plane or ground resolved distance (GRD) in feet for a range in solar altitudes based on latitude over the entire 120° format. These tables have been used in all flight readiness reports and REBOUND-231 Messages.

The basic output of the CRYSPER Program is a listing of the inputs, intermediate calculations and values, angle/angle tables, and resultant predictions for specific targets that can potentially be acquired.

The input values are listed at the beginning of the CRYSPER run. The intermediate calculations and final predictions follow and are listed in the order in which they appear in a normal CRYSPER run. Examples of some of these outputs are shown as Tables 5-4 thru 5-9.

A. Uncompensated TM Curve Table (Table 5-4).

B. Exposure Table Versus Solar Altitude (Table 5-5).

C. Angle/Angle Table for Mean Resolution (cycles/mm) of Each Camera and the Mean of Both Cameras Together (Table 5-6).

D. Angle/Angle Table for Mean Reciprocal Resolution (cycles/mm) (Table 5-7).

E. Angle/Angle Table for Mean Resolution (GRD-feet) (Table 5-8).

F. Target Acquisition Listing and Predictions for Selected Revs (Table 5-9).

TABLE 5-4

UNCOMPENSATED TM CURVE TABLE

SPATIAL FREQUENCY CYCLES/MM	LCGE												
	-1.080	-0.980	-0.880	-0.780	-0.680	-0.580	-0.480	-0.390	-0.280	-0.190	-0.080	0.020	0.120
1.	0.012	0.023	0.024	0.024	0.024	0.024	0.025	0.025	0.027	0.030	0.033	0.034	0.038
20.	0.014	0.024	0.025	0.024	0.024	0.025	0.026	0.026	0.027	0.031	0.034	0.035	0.039
40.	0.020	0.027	0.027	0.026	0.026	0.027	0.028	0.028	0.030	0.033	0.037	0.039	0.043
60.	0.030	0.033	0.030	0.029	0.029	0.030	0.031	0.032	0.034	0.038	0.042	0.044	0.048
80.	0.044	0.040	0.036	0.034	0.034	0.035	0.036	0.037	0.040	0.044	0.048	0.052	0.056
100.	0.062	0.050	0.042	0.040	0.039	0.040	0.042	0.044	0.047	0.052	0.057	0.061	0.066
120.	0.084	0.062	0.051	0.046	0.045	0.047	0.049	0.052	0.056	0.062	0.068	0.073	0.079
140.	0.110	0.076	0.060	0.055	0.053	0.055	0.057	0.061	0.067	0.074	0.080	0.086	0.093
160.	0.140	0.093	0.071	0.064	0.061	0.064	0.067	0.072	0.079	0.087	0.094	0.102	0.110
180.	0.174	0.111	0.083	0.074	0.071	0.074	0.078	0.084	0.093	0.103	0.110	0.120	0.128
200.	0.212	0.132	0.097	0.086	0.082	0.085	0.091	0.098	0.108	0.120	0.128	0.140	0.150
220.	0.254	0.154	0.113	0.098	0.093	0.098	0.104	0.113	0.125	0.139	0.148	0.162	0.173
240.	0.300	0.179	0.129	0.112	0.107	0.112	0.119	0.126	0.143	0.159	0.170	0.187	0.199
260.	0.350	0.205	0.147	0.128	0.121	0.127	0.135	0.148	0.164	0.182	0.194	0.213	0.226
280.	0.404	0.234	0.167	0.144	0.136	0.143	0.153	0.167	0.186	0.206	0.218	0.242	0.254

TABLE 5-5

EXPOSURE VERSUS SOLAR ALTITUDE TABLE

FILTER: WRATTEN 2E AFT CAMERA (P)
MISSION(1207) SET(010)

SOLAR ALTITUDE IN DEGREES	EXPOSURE TIME IN SEC
2.0	.01580
4.0	.00944
6.0	.00694
8.0	.00529
10.0	.00429
12.0	.00357
14.0	.00309
16.0	.00275
18.0	.00247
20.0	.00225
24.0	.00192
30.0	.00161
34.0	.00146
40.0	.00130
50.0	.00104
60.0	.00081
70.0	.00076
80.0	.00007
90.0	.00059

FILTER: WRATTEN 12 FORWARD CAMERA (A)
MISSION(1207) SET(010)

SOLAR ALTITUDE IN DEGREES	EXPOSURE TIME IN SEC
1.0	.01650
2.0	.00118
3.0	.00894
4.0	.00720
5.0	.00630
7.0	.00492
10.0	.00374
12.0	.00324
15.0	.00275
20.0	.00224
25.0	.00193
30.0	.00173
35.0	.00158
40.0	.00148
50.0	.00127
60.0	.00113
70.0	.00103
80.0	.00095
90.0	.00088

TABLE 5-6

ANGLE/ANGLE TABLE FOR MEAN RESOLUTION OF EACH CAMERA AND BOTH CAMERAS COMBINED

(cycles/mm)

TYPICAL RESOLUTION OBTAINABLE FROM EACH CAMERA SYSTEM (IN LINES/MM) FOR VARIOUS SUN AND SCAN ANGLES

(0 CENTER 120 SCAN)

	LAT	SUN \ SCAN	-60	-50	-40	-30	-20	-10	0	10	20	30	40	50	60
	65	1	42	48	51	53	55	58	60	57	55	53	51	48	42
	60	6	44	50	52	54	57	60	63	60	58	55	53	49	42
	55	11	66	70	73	75	78	81	84	81	79	76	72	67	59
	50	16	82	88	90	93	96	99	102	101	99	96	92	87	78
AFT CAMERA	45	22	94	101	103	105	107	110	113	112	111	109	106	102	92
	35	32	108	117	118	120	122	124	127	127	127	126	125	121	110
SSN 010 CSN 38B	25	42	118	127	129	130	132	133	136	136	137	137	136	132	121
	15	52	129	139	142	141	141	143	144	145	146	146	148	143	131

(0 CENTER 120 SCAN)

	LAT	SUN \ SCAN	-60	-50	-40	-30	-20	-10	0	10	20	30	40	50	60
	65	1	44	49	51	52	52	52	52	52	51	50	49	47	43
	60	6	49	54	56	56	56	56	55	54	53	52	50	48	44
	55	11	72	77	79	80	80	80	79	79	78	77	75	73	67
	50	16	85	92	94	95	94	94	94	93	93	92	91	89	83
FORWARD CAMERA	45	22	96	102	104	104	103	104	103	103	103	102	101	99	94
	35	32	109	115	116	115	115	114	114	114	115	115	115	114	109
SSN 010 CSN 31A	25	42	118	123	124	123	122	121	121	121	122	123	124	123	118
	15	52	126	131	131	130	129	128	128	129	130	131	132	131	127

MEAN RESOLUTION OF THE TWO OPTICAL SYSTEMS IN LINES/MM

(0 CENTER 120 SCAN)

	LAT	SUN \ SCAN	-60	-50	-40	-30	-20	-10	0	10	20	30	40	50	60
	65	1	42	48	51	52	53	54	55	54	52	51	49	47	42
	60	6	46	51	53	54	56	57	58	56	55	53	51	48	42
	55	11	68	73	75	77	78	80	81	79	78	76	73	69	62
	50	16	83	89	91	93	94	96	97	96	95	93	91	87	80
SSN 010(A AND B)	45	22	94	101	103	104	104	106	107	107	106	105	103	100	92
	35	32	108	115	116	117	118	118	120	120	120	120	119	117	109
CSN 38B ,CSN 31A	25	42	118	124	126	126	126	126	128	128	129	129	129	127	119
	15	52	127	134	136	135	134	135	135	136	137	138	139	136	128

PARAMETERS ASSOCIATED WITH THE LAST ENTRY INTHE RIGHT HAND COLUMN OF THE TABLE

TARGET LATITUDE D M S	REFLECTANCE HIGH	REFLECTANCE LOW	TARGET SUN TYPE	HAZE COND	SOLAR AZI-MUTH	DATE D M Y (DA CR)	RDOH	INERTIAL VELOCITY (FT/SEC)	SATELLITE LAT (DEGREES)	SATELLITE LONG (DEGREES)	SAT ALT (NM)	OBLATE EARTH RADIUS	SATELLITE TO EARTH CENTER(NM)	VXOH	VYOH
14 39 23	20	10	1	4	186.53	14 12 73	0.00018	25694.04	15.1548	27.687	89.6 +	3443.1 =	3532.7	0.0457	0.00269

TABLE 5-7

ANGLE/ANGLE TABLE FOR MEAN RECIPROCAL RESOLUTION (cycles/mm)

TYPICAL RESOLUTION OBTAINABLE FROM EACH CAMERA SYSTEM (RECIPROCAL OF LINES/MM TIMES TEN)

(0 CENTER 120 SCAN)

	LAT	SUN	SCAN -60	-50	-40	-30	-20	-10	0	10	20	30	40	50	60
	65	1	0.238	0.208	0.196	0.188	0.182	0.172	0.167	0.175	0.182	0.189	0.196	0.208	0.238
	60	6	0.227	0.200	0.193	0.185	0.175	0.167	0.159	0.167	0.172	0.182	0.189	0.204	0.238
	55	11	0.152	0.143	0.137	0.133	0.128	0.123	0.119	0.124	0.127	0.132	0.139	0.149	0.170
	50	16	0.122	0.114	0.111	0.108	0.104	0.101	0.099	0.099	0.101	0.104	0.109	0.115	0.128
AFT CAMERA	45	22	0.106	0.099	0.097	0.095	0.093	0.091	0.088	0.089	0.090	0.092	0.094	0.098	0.109
	35	32	0.093	0.086	0.085	0.083	0.082	0.081	0.079	0.079	0.079	0.079	0.080	0.083	0.091
SSN 010 OSN 38B	25	42	0.085	0.079	0.078	0.077	0.076	0.075	0.074	0.074	0.073	0.073	0.074	0.076	0.083
	15	52	0.078	0.072	0.070	0.071	0.071	0.070	0.069	0.069	0.068	0.068	0.068	0.070	0.076

(0 CENTER 120 SCAN)

	LAT	SUN	SCAN -60	-50	-40	-30	-20	-10	0	10	20	30	40	50	60
	65	1	0.227	0.200	0.196	0.192	0.192	0.192	0.192	0.192	0.196	0.204	0.204	0.213	0.232
	60	6	0.204	0.185	0.179	0.179	0.179	0.179	0.182	0.185	0.189	0.192	0.200	0.208	0.227
	55	11	0.138	0.130	0.127	0.125	0.125	0.125	0.127	0.127	0.128	0.130	0.133	0.137	0.149
	50	16	0.118	0.109	0.106	0.105	0.106	0.106	0.106	0.108	0.108	0.109	0.110	0.112	0.121
FORWARD CAMERA	45	22	0.11	0.10	0.10	0.10	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.10	0.11
	35	32	0.09	0.09	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.09
SSN 010 OSN 31A	25	42	0.08	0.08	0.08	0.08	0.08	0.08	0.07	0.07	0.07	0.07	0.07	0.08	0.08
	15	52	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08

MEAN RESOLUTION OF THE TWO OPTICAL SYSTEMS IN LINES/MM

(0 CENTER 120 SCAN)

	LAT	SUN	SCAN -60	-50	-40	-30	-20	-10	0	10	20	30	40	50	60
	65	1	0.24	0.21	0.20	0.19	0.19	0.19	0.18	0.19	0.19	0.20	0.20	0.21	0.24
	60	6	0.22	0.20	0.19	0.19	0.18	0.18	0.17	0.18	0.18	0.19	0.20	0.21	0.24
	55	11	0.15	0.14	0.13	0.13	0.13	0.12	0.12	0.13	0.13	0.13	0.14	0.14	0.16
	50	16	0.12	0.11	0.11	0.11	0.11	0.10	0.10	0.10	0.11	0.11	0.11	0.11	0.12
SSN 010(A AND B)	45	22	0.11	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.09	0.10	0.10	0.10	0.11
	35	32	0.09	0.09	0.09	0.09	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.09	0.09
OSN 38B ,OSN 31A	25	42	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
	15	52	0.08	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.08

PARAMETERS ASSOCIATED WITH THE LAST ENTRY INTHE RIGHT HAND COLUMN OF THE TABLE

TARGET LATITUDE D M S	REFLECTANCE HIGH	LOW	TARGET SUN TYPE	HAZE COND	SOLAR AZI-MUTH	DATE D A	M O	Y R	ROOH	INERTIAL VELOCITY (FT/SEC)	SATELLITE LAT (DEGREES)	LONG	SAT ALT (NM)		OBLATE EARTH RADIUS		SATELLITE TO EARTH CENTER(NM)	VXCH	VYOH
14 39 23	20	10	1	4	186.53	14	12	73	0.00018	25694.04	15.1548	27.687	89.6	+	3443.1	=	3532.7	0.0457	0.00269

TABLE 5-8

ANGLE/ANGLE TABLE FOR MEAN GROUND RESOLVED DISTANCE RESOLUTION

(GRD-feet)

TYPICAL RESOLUTION OBTAINABLE FROM EACH CAMERA SYSTEM (IN FEET) FOR VARIOUS SUN AND SCAN ANGLES

(0 CENTER 120 SCAN)

	LAT	SUN \ SCAN	-60	-50	-40	-30	-20	-10	0	10	20	30	40	50	60
	65	1	29.11	16.47	11.77	9.25	7.83	6.96	6.61	7.07	7.84	9.22	11.75	16.72	29.39
	60	6	27.23	15.66	11.29	8.87	7.48	6.61	6.11	6.60	7.37	8.71	11.12	15.92	28.57
	55	11	17.88	10.87	7.92	6.32	5.40	4.84	4.52	4.79	5.31	6.25	7.96	11.40	19.95
	50	16	14.25	8.55	6.31	5.02	4.32	3.89	3.67	3.81	4.18	4.87	6.17	8.63	14.89
AFT CAMERA	45	22	12.24	7.36	5.45	4.40	3.81	3.45	3.28	3.38	3.68	4.24	5.27	7.29	12.47
	35	32	10.35	6.23	4.63	3.76	3.27	3.00	2.87	2.93	3.15	3.59	4.41	6.03	10.22
SSN 010 OSN 38B	25	42	9.39	5.68	4.22	3.45	3.02	2.77	2.66	2.72	2.90	3.30	4.02	5.50	9.25
	15	52	8.70	5.24	3.87	3.22	2.83	2.62	2.53	2.58	2.75	3.12	3.73	5.11	8.61

(0 CENTER 120 SCAN)

	LAT	SUN \ SCAN	-60	-50	-40	-30	-20	-10	0	10	20	30	40	50	60
	65	1	28.10	16.23	11.64	9.43	8.25	7.69	7.55	7.80	8.51	9.82	12.21	16.92	28.74
	60	6	24.65	14.44	10.50	8.60	7.58	7.11	7.02	7.28	8.00	9.28	11.62	16.11	27.59
	55	11	16.50	9.93	7.25	5.95	5.25	4.90	4.81	4.96	5.41	6.21	7.70	10.58	17.73
	50	16	13.72	8.18	6.01	4.94	4.37	4.09	4.02	4.12	4.45	5.07	6.24	8.50	14.03
FORWARD CAMERA	45	22	11.96	7.30	5.38	4.45	3.94	3.67	3.60	3.68	3.96	4.54	5.54	7.50	12.28
	35	32	10.24	6.35	4.73	3.92	3.48	3.27	3.21	3.26	3.49	3.93	4.76	6.41	10.36
SSN 010 OSN 31A	25	42	9.40	5.87	4.40	3.66	3.26	3.06	3.00	3.05	3.25	3.65	4.40	5.89	9.44
	15	52	8.88	5.57	4.18	3.48	3.10	2.91	2.85	2.90	3.08	3.46	4.17	5.56	8.89

MEAN RESOLUTION OF THE TWO OPTICAL SYSTEMS IN LINES/MM

(0 CENTER 120 SCAN)

	LAT	SUN \ SCAN	-60	-50	-40	-30	-20	-10	0	10	20	30	40	50	60
	65	1	28.60	16.35	11.71	9.34	8.04	7.32	7.07	7.42	8.17	9.52	11.98	16.82	29.07
	60	6	25.91	15.04	10.89	8.74	7.53	6.86	6.55	6.93	7.68	8.99	11.37	16.02	28.07
	55	11	17.18	10.39	7.58	6.13	5.32	4.87	4.66	4.87	5.36	6.23	7.83	10.98	18.81
	50	16	13.99	8.37	6.16	4.98	4.34	3.99	3.84	3.96	4.31	4.97	6.20	8.57	14.46
SSN 010(A AND B)	45	22	12.10	7.33	5.42	4.43	3.87	3.56	3.43	3.53	3.82	4.39	5.40	7.40	12.37
	35	32	10.29	6.29	4.68	3.84	3.38	3.13	3.03	3.09	3.32	3.76	4.58	6.22	10.29
OSN 38B ,OSN 31A	25	42	9.39	5.77	4.31	3.55	3.14	2.91	2.83	2.88	3.07	3.47	4.21	5.69	9.34
	15	52	8.79	5.40	4.02	3.35	2.96	2.76	2.68	2.73	2.91	3.29	3.94	5.33	8.75

PARAMETERS ASSOCIATED WITH THE LAST ENTRY INTHE RIGHT HAND COLUMN OF THE TABLE

TARGET LATITUDE D M S	REFLECTANCE HIGH	REFLECTANCE LOW	TARGET SUN TYPE	HAZE COND	SOLAR AZI-MUTH	DATE D A	DATE M O	DATE Y R	RDOH	INERTIAL VELOCITY (FT/SEC)	SATELLITE LAT (DEGREES)	SATELLITE LONG (DEGREES)	SAT ALT (NM)		OBLATE EARTH RADIUS		SATELLITE TO EARTH CENTER(NM)	VXOH	VYOH
14 39 23	20	10	1	4	186.53	14	12	73	0.00018	25694.04	15.1548	27.687	89.6	+	3443.1	=	3532.7	0.0457	0.00269

(ALL TABLES CALCULATED USING MTFS CORRESPONDING TO 0.0 FIELD POSITION

TABLE 5-9

TARGET ACQUISITION LISTING AND PREDICTIONS FOR SELECTED REVS

TARGET IDENT		REV	DATE DA/MO/YR	TIME (GMT) HR MN SC	OBLIQ (DEG)	ALT (NM)	SLANT RANGE (NM)	SOLAR ELEV (DEG)	FWD GRD (FT)	AFT GRD (FT)	REFL %
PK	7A1944	56	14/12/73	7 8 39	-64	89.1	215.6	37	13.0	13.3	10/20
PK	2C0962	56	14/12/73	7 8 10	-57	89.2	174.5	35	8.9	8.9	10/20
PK	7A1943	56	14/12/73	7 7 56	-45	89.3	130.6	34	5.4	5.3	10/20
PK	2C1445	56	14/12/73	7 7 47	-56	89.4	169.4	33	8.5	8.5	10/20
UR	3P0023	56	14/12/73	7 5 35	-63	90.8	219.1	24	15.2	15.6	10/20
UR	3B0036	56	14/12/73	7 1 57	28	94.6	109.8	9	6.9	7.1	10/20
UR	3B0037	57	14/12/73	8 30 41	-23	94.6	104.9	9	6.2	6.7	10/20
UR	6A0175	57	14/12/73	8 28 9	-41	98.2	134.5	0	12.6	12.9	10/20
EG	2C1045	58	14/12/73	10 7 29	63	89.0	209.6	41	11.8	11.8	10/20
EG	2A0058	58	14/12/73	10 6 7	7	89.1	91.2	36	3.1	2.8	10/20
IS	1E0284	58	14/12/73	10 5 34	64	89.3	218.4	33	13.7	13.7	10/20
IS	1C0056	58	14/12/73	10 5 32	62	89.3	206.4	33	12.3	12.2	10/20
UR	9P0005	58	14/12/73	10 2 44	0	91.1	92.5	22	3.6	3.2	10/20
UR	9P0006	58	14/12/73	10 2 39	43	91.1	127.2	22	5.9	5.7	10/20
UR	1J0013	58	14/12/73	10 2 38	-22	91.2	99.9	22	4.0	3.9	10/20
UR	9A0200	58	14/12/73	10 2 27	21	91.3	99.9	21	4.0	3.8	10/20
UR	9P0003	58	14/12/73	10 2 26	-10	91.3	94.1	21	3.7	3.5	10/20
UR	9P0004	58	14/12/73	10 2 22	36	91.4	115.9	20	5.1	4.9	10/20
UR	6B0180C	58	14/12/73	10 2 8	-51	91.6	152.3	20	8.1	8.2	10/20
UR	6B0180B	58	14/12/73	10 2 4	-52	91.7	154.9	20	8.4	8.5	10/20
UR	6A0124A	58	14/12/73	9 59 59	-19	94.0	100.9	11	5.2	5.4	10/20
UR	6A0181A	58	14/12/73	9 59 46	41	94.2	127.2	10	8.3	8.8	10/20
UR	1G0001A	58	14/12/73	9 57 43	-43	97.0	136.6	2	9.6	13.0	10/20
GE	9P0001	59	14/12/73	11 29 38	-46	92.9	138.9	14	7.6	8.2	10/20
PO	9P0002	59	14/12/73	11 29 31	26	93.0	105.6	14	5.1	5.0	10/20
UR	6B1148	59	14/12/73	11 28 30	62	94.2	216.0	9	23.2	26.9	10/20
FR	1G0052	60	14/12/73	12 59 5	60	92.2	195.6	17	14.1	14.6	10/20
FP	3A0005A	65	14/12/73	20 40 34	-65	104.2	267.8	83	14.7	15.1	10/20
CH	4A0005A	70	15/12/73	3 51 33	-60	89.2	188.1	36	10.1	10.2	10/20
KN	7A2402B	70	15/12/73	3 49 25	-43	90.0	126.5	27	5.4	5.4	10/20
UR	1G0026A	70	15/12/73	3 48 20	64	90.7	226.4	22	17.0	17.4	10/20
CH	3B0085	71	15/12/73	5 20 40	31	89.1	106.5	37	3.9	3.5	10/20
CH	3B0087D	71	15/12/73	5 19 57	55	89.3	162.6	34	7.8	7.5	10/20
CH	3F0106A	71	15/12/73	5 19 55	50	89.3	144.5	33	6.4	6.0	10/20
CH	3B0086A	71	15/12/73	5 19 48	57	89.3	172.4	33	8.8	8.5	10/20
MG	6A0179A	71	15/12/73	5 17 29	-62	90.4	203.6	24	13.2	13.5	10/20
UR	3B0015	71	15/12/73	5 15 9	-60	92.5	198.0	14	15.2	16.0	10/20
UR	3B0039	72	15/12/73	6 42 38	65	93.9	238.5	8	31.6	37.5	10/20
UR	3B0036	72	15/12/73	6 42 52	-48	93.6	144.8	10	10.1	11.4	10/20
UR	1A0019RA	73	15/12/73	8 14 10	34	91.1	112.4	20	4.9	4.7	10/20
UR	1A0019RB	73	15/12/73	8 14 10	34	91.1	112.0	20	4.9	4.7	10/20
UR	1A0019RC	73	15/12/73	8 14 9	34	91.1	112.0	20	4.9	4.7	10/20
UR	1A0019H	73	15/12/73	8 14 8	38	91.1	118.5	20	5.4	5.2	10/20
UR	1A0019RD	73	15/12/73	8 14 9	33	91.1	111.4	20	4.9	4.7	10/20
UR	1A0019RE	73	15/12/73	8 14 9	33	91.1	110.5	20	4.8	4.6	10/20
UR	1A0019RF	73	15/12/73	8 14 8	35	91.1	114.1	20	5.1	4.9	10/20
UR	3B0037	73	15/12/73	8 11 35	-63	93.7	224.0	10	24.5	27.1	10/20
UR	6A0175	73	15/12/73	9 9 2	-62	96.9	225.7	0	35.5	36.4	10/20

TOP SECRET-HEXAGON

BYE 15319-73
Handle via Byeman
Controls Only

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SECTION VI

PROBLEM AREAS

6.1 MANAGEMENT

CRYSPER is a difficult program to maintain and manage. In addition to its size, it consists of three main subroutines each authored by a separate organization. Even small changes require a significant amount of care, time, and coordination. The data base for each run is enormous. The inputs are derived at various states in the assembly and test sequence of the camera system. The tests are performed at both SSC and SVIC, and the data reduced by several organizations. Many of the input values to CRYSPER are available a year or more prior to flight. The final input, which is normally the orbit case, may not be selected until the month prior to flight. The bookkeeping of the available inputs is a task in itself. Too many times, data being sent from one organization to another neither is timely nor complete. Consequently, at a time when CRYSPER could be used for mission planning, it can still be waiting proper inputs.

6.2 PERFORMANCE LEVEL

The performance predictions produced by CRYSPER should agree with the actual performance levels measured postflight, and indeed the correlation has been reasonable based on the missions flown to date. However, there are often inconsistencies related to the predictions and how they were derived. CRYSPER normally predicts two sigma low estimates based on smear. The cross-track actuals agree very well with the two sigma low predictions, indicating that the magnitude of smear being used in the program is correct. However, the in-track actuals are slightly higher than the predictions. This raises the question as to whether the smear function within the program is modeled correctly. If the median option for CRYSPER is used, vice the two sigma low smear, the predictions for both in-track and cross-track are higher than the measured performance level. The use of smear as measured in the chamber and the nature of the smear (albeit linear, non-linear, or whatever) is a continuing study.

6.2.1 Lens MTF Mismatch

The polychromatic lens MTFs obtained from interferograms in Chamber D do not provide the same field curvature and astigmatism data obtained from a fully assembled camera tested photographically in the vacuum chambers. It is not clear at this point in time which set of data is closer to the truth. Both sets of data are acquired in a gravity environment. However, the interferogram data can be adjusted for the gravity free environment of flight, while the photographic chamber data cannot. The photographic chamber data takes into account the focus effects due to film curl, while the interferogram data does not. At this time, CRYSPER configured lens MTF data can only be obtained from the interferograms.

6.2.2 Preflight Field Angle Predictions

While the program has the capability to predict resolution for any one of five field angles, it is not possible to predict the field angle location of a target before flight. The preflight predictions generally made before flight are for the center portion of the field; the MTFs for the 0° and ±2° field position are averaged. This is, in general, the portion of the format that is of slightly better performance than the rest. On occasion, predictions have been made for a particular field position if it appears as though there is a unique problem that may cause excessively poor quality. Post flight predictions can be made for field angles closer to those positions at which targets are acquired. These types of predictions are generally for CORN tribar targets where the coordinates have been measured. Intelligence targets could be run against CRYSPER, if desired, through use of the MPR predicted coordinates or the OAK reporting. These approaches are not generally used; and at present the software to handle large volumes of this type of data does not exist.

6.2.3 Smear Data Versus Scan Angle

The program is currently configured to use as input data, smear values (mean and two sigma) for both directions of each camera as a function of Vx/h and scan angle. There are unique aspects in the camera design that change the smear characteristics as a function of scan angle length and center. This means, for example, that a 30° scan sector taken from an angle/angle table run for 120° of scan will have been run with incorrect smear values. There are 16 possible scan angle/scan center conditions available. The updated version of CRYSPER known as KAPER is being configured to use data for each of these conditions and compute 16 sets of angle/angle tables. One remaining difficulty in obtaining the smear data for all conditions is that chamber data is obtained for only three collimator locations. Interpolation and some extrapolation is used to fill in the rest of the table. If large differences between chamber or test runs occur, then it occasionally caused discontinuities in the resolution values as a function of scan.

6.2.4 Mathematical Description of Smear As a Function of Performance

CRYSPER has been programmed with two simplifying assumptions about the camera system's smear characteristics: (1) it is linear, and (2) it is normally distributed. While these are probably reasonable assumptions, there are often cases when it is clearly not appropriate. Chamber data has been obtained on some camera systems that indicate skewed frequency distribution of smear. Line target images have on occasion been significantly distorted, indicating non-linear smear. While the frequency of these effects has decreased as the systems have matured, they are still present to some degree. Electromechanical analysis from TM data indicates that there are several periodic disturbances that occur randomly or as a function of a particular mode of operation, e.g., drive capstan dither. These smear conditions are not modeled in CRYSPER per se. If the magnitude of the smear can be determined, the mean smear values can be increased by that amount and additional CRYSPER runs will show the decrease in performance due to that smear. This is not a very efficient measure, and should only be used when a large amount of photography is affected.

6.2.5 Target Reflectance Inadequately Modeled

Data pertaining to two aspects of the target reflectance characteristics that are in need of improvement are the absolute reflectance of intelligence targets and the degree of specularity. CRYSPER presently contains a look-up table format containing estimates of reflectances by COMIREX category. The information for this table is a combination of real data from measurements of mission photography and a good deal of guesswork. On the average, the data is probably near correct but it is most assuredly not absolute for specific targets. In addition, the effective reflectance of ground targets varies as a function of factors that are not related to the target, e.g., snow surround and reflections from nearby clouds can cause significant changes in the apparent target appearance. CRYSPER contains no modeling for the degree of target specularity. This area requires the most work. Such effort is currently underway by BRIDGEHEAD under the sponsorship of the CCB (Photographic R&D).

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