MCR-76-564

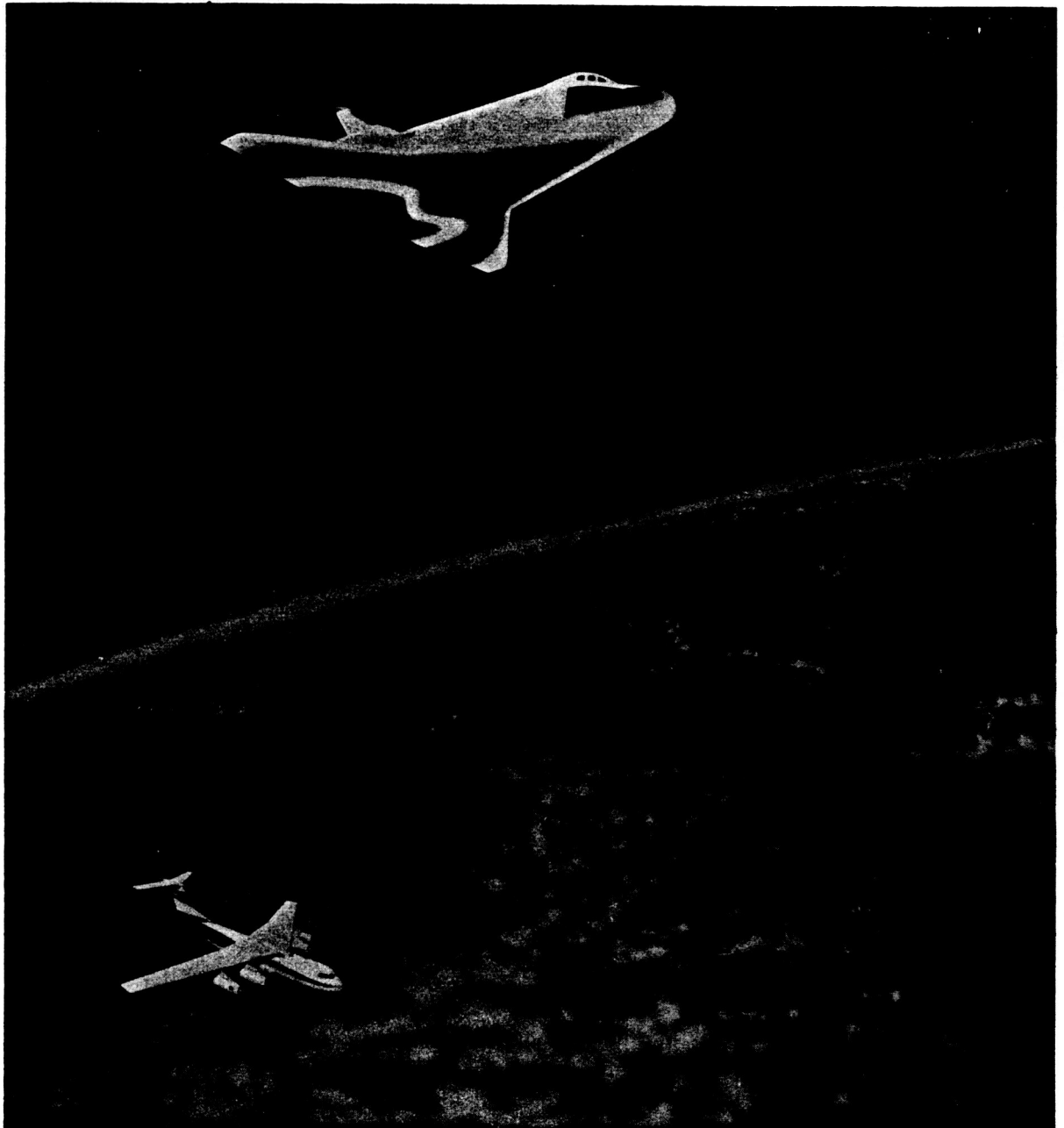Contract NAS2-9381

Task 1

Final
Report

August 1977

Infrared Imagery
of Shuttle (IRIS)

MARTIN MARIETTA

MCR-76-564

Contract NAS2-9381

Final
Report

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Task 1

**INFRARED IMAGERY
OF SHUTTLE
(IRIS)**

Approved

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SUMMARY

_____

The feasibility of remote high resolution infrared imagery of
the Shuttle Orbiter lower surface during entry to obtain accurate
measurements of aerodynamic heat transfer has been demonstrated.
Such images can be taken from an existing aircraft/telescope sys-
tem (the C141 AIRO) with minimum modification or addition of sys-
tems using available technology. These images will have a spatial
resolution of 1 meter or better and a temperature resolution of
2.5% for temperatures between 800 and 1900 K. Data reconstruction
techniques will provide a geometrically and radiometrically cor-
rected array on addressable magnetic tape ready for display by
NASA.

Schedule considerations dictate a timely start on FY1978 to mesh
with the first Shuttle Orbiter test flights in late 1979 and early
1980 and additional work in the form of subsystem breadboards is
recommended to prove principle before system construction.

CONTENTS

Figure

INTRODUCTION

Early in 1976 NASA-Ames Research Center expressed an interest in the Infrared Imagery of heated surfaces such as the Shuttle Orbiter during reentry. Necessary information to substantially reduce the weight and cost of thermal protection systems of future space transportation systems could result from accurate flight data on: (1) the lower surface heating rate distribution, (2) the location of boundary-layer transition, and (3) location and extent of flow separation in front of control surfaces. This imaging would be obtained by an appropriate telescopic sensor system mounted in one or more chase aircraft stationed appropriately along the Shuttle reentry ground track.

Initially, an approach was taken to fly the chase aircraft perpendicular to the Shuttle flight direction to maximize the viewing time (cross track approach). It became apparent that within the maximum viewing time (10 to 20 sec), no significant surface temperature changes would occur precluding the desire for multiple images. In addition, the angular rates between the Shuttle and chase aircraft became complex and were excessive, requiring major redesign of any telescope stabilization system.

At this point, NASA-Ames Research Center undertook an in-house study and generated an approach where the chase aircraft flew parallel to the Shuttle ground track (along-track approach). Since multiple images or integration times in excess of a few microseconds were unnecessary, the streak camera idea was introduced. (See Ref. 1 and Fig. 96). The streak camera, as it applies here, is a linear array of detectors at the image plane of a telescope. The detectors are sampled at a rate compatible with image motion to obtain a desired resolution. Tracking of the object is unnecessary as long as the object passes through the field-of-view of the telescope. One image is obtained for each linear array of detectors.

The feasibility study contract was then awarded. NASA directed the contractor to undertake the study based on the in-house findings. These tasks included: (1) An IR technology survey to investigate the current state of sensor technology; (2) a preliminary design of all subsystems with regard to environment, power, and support requirements; (3) a system performance describing the end-to-end capabilities of the design including error sources; and (4) a cost and schedule assessment for the design, fabrication, assembly, installation, and support during the first six Shuttle development flights. The purpose of this report is to summarize the results of the above analysis.

The objective of the experiment is to obtain high resolution (1 meter or better) surface maps of the Shuttle Orbiter lower and side surfaces with a temperature accuracy of at least 2.5% during peak heating, flap deflection, and transitional heating periods of the reentry profile. This information is required to verify computational predictions and experimental extrapolations to provide data for possible TPS block changes.

Predicted temperature distribution and transition points for the Shuttle Orbiter reentry profile 14414 are shown in Figures 1 through 4. All six Orbital Flight Test (OFT) reentry profiles are expected to have similar temperature distributions, However, the time from entry when these events occur will be different. Maximum temperatures on the windward and side surfaces are not expected to exceed 1900 K and are generally above 600 K during the time period of interest.

Implications associated with the experiment cover many facets. First, as shown in Figure 5, are the variations in Shuttle Orbiter altitude, velocity, angle-of-attack and bank angle which must be accommodated (Ref. 2). The key points of interest during the reentry (peak heating, flap deflection, and transitional heating) correspond to a given time from entry for a given reentry profile. Figure 5 data are for reentry profile 14414. OFT 1, 2 and 3 profiles are slightly different (Ref. 3). As an example, peak heating occurs at T = 400 sec for orbit reentry 14414 and at T = 282 sec for OFT 1. (Refer to the appendix for OFT 1 reentry trajectory data.) This corresponds to a Shuttle Orbiter altitude of 74.3 km, a velocity of 7.16 km/sec, an angle-of-attack of 40° and a bank angle of 74°. To obtain accurate, high-resolution data with one system for these varying conditions requires a versatile observing platform and data system.

The second consideration is associated with the expected radiation from the Shuttle Orbiter. At temperatures ranging from 600 to 1900 K, a black body will have its radiation peak between 1.5 and 4.8 micrometers. For these temperatures, the wavelengths for which the first derivative of radiant energy with temperature is a maximum occur between approximately 1.3 and 2.7 micrometers. This suggests that the optimum detector/filter response should be about 2 micrometers with a limited spectral bandwidth.

Thirdly, the requirement for at least 1 meter resolution at a maximum range of 75 km implies an angular resolution of 1.7 arcsec with foreshortening from the nonnormal aspect of the surface to the line-of-sight of 40° maximum. At a wavelength of 2.0 micrometers, a diffraction-limited telescope would require an aperture

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SHUTTLE ORBITER MAXIMUM TEMPERATURE CONTOURS

FIG. I

REENTRY PROFILE
14414
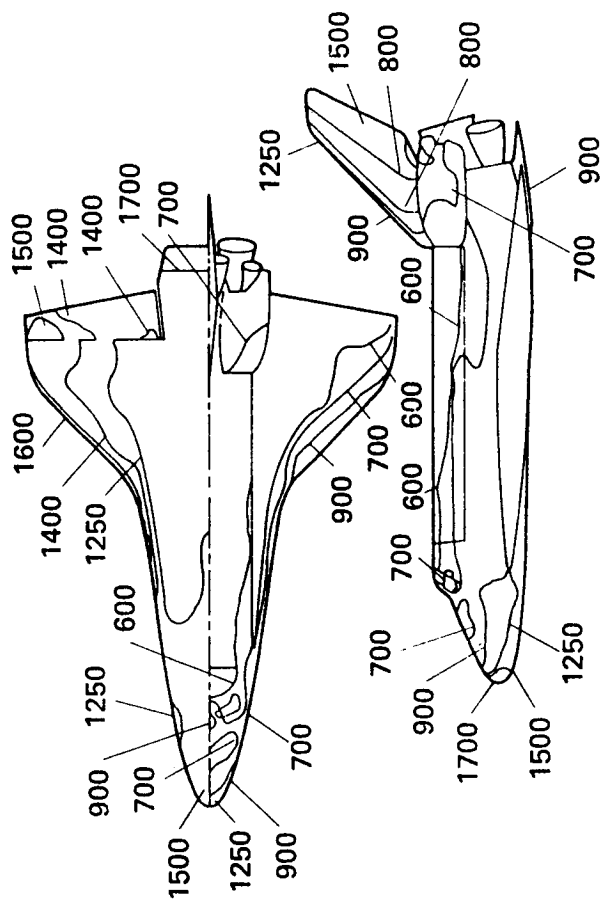
NOTE: ALL TEMPERATURES IN K

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SHUTTLE ORBITER CENTERLINE TEMPERATURE DISTRIBUTIONS

FIG. 2

REENTRY PROFILE
14414

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SHUTTLE ORBITER BODY FLAP JUNCTURE TEMPERATURE DISTRIBUTION   FIG. 3

REENTRY PROFILE
14414
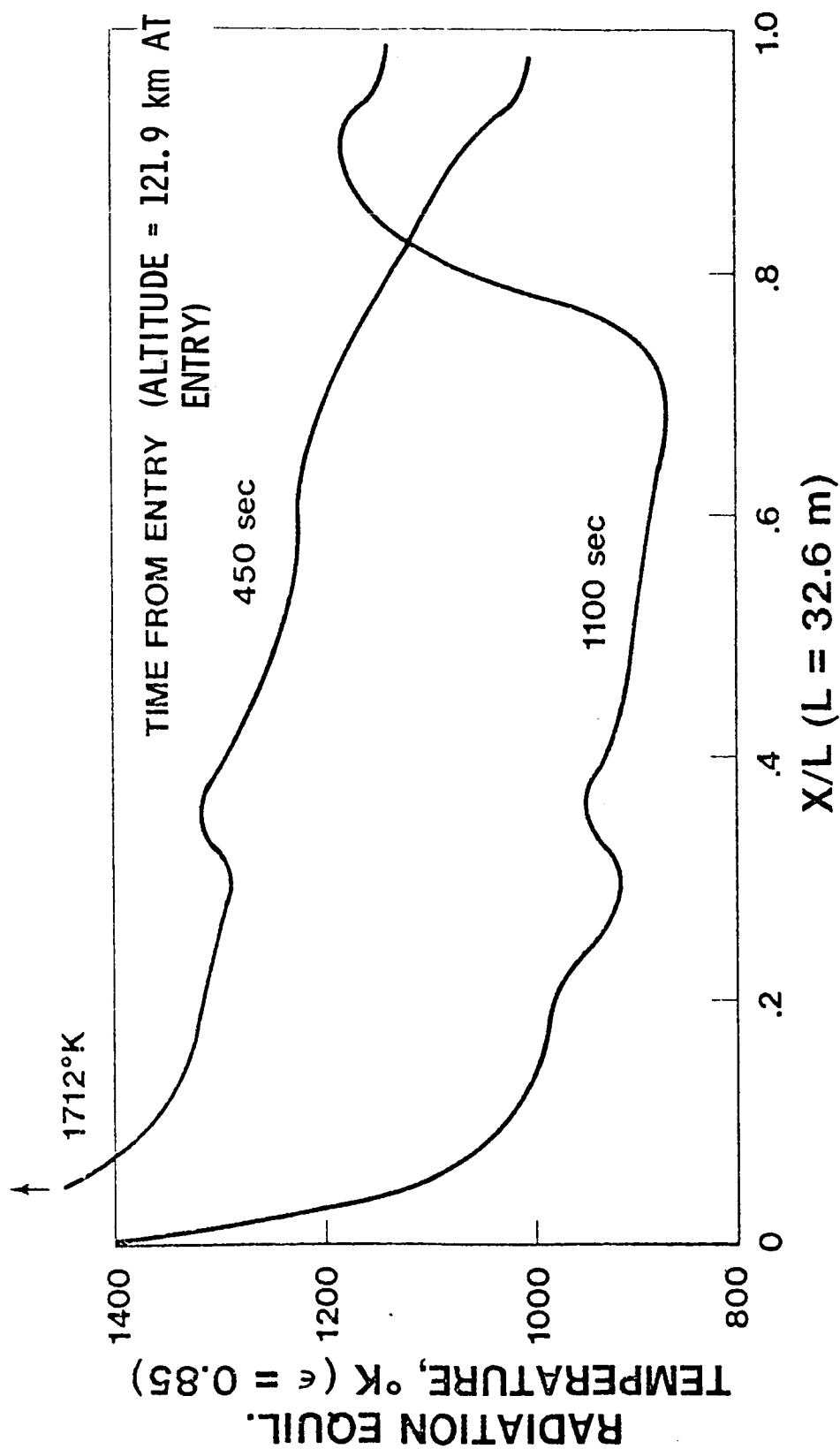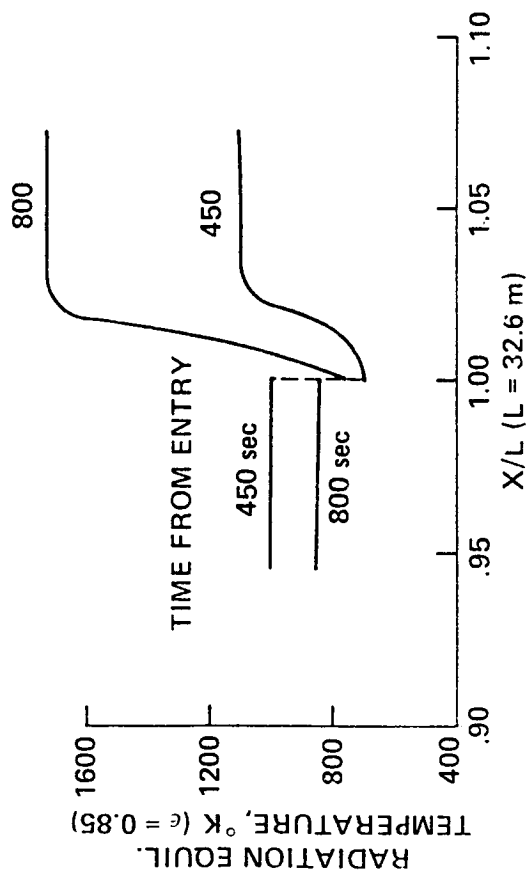
MARTIN MARIETTA

SHUTTLE ORBITER CENTERLINE TRANSITION LOCATION

FIG. 4

REENTRY PROFILE
14414

END OF TRANSITION

START OF TRANSITION

TIME FROM ENTRY, sec

1500

1000

500

0   .2   .4   .6   .8   1.0

X/L (L = 32.6 m)

VELOCITY, km/sec

BANK ANGLE, deg

ALTITUDE, km

ANGLE OF ATTACK, deg
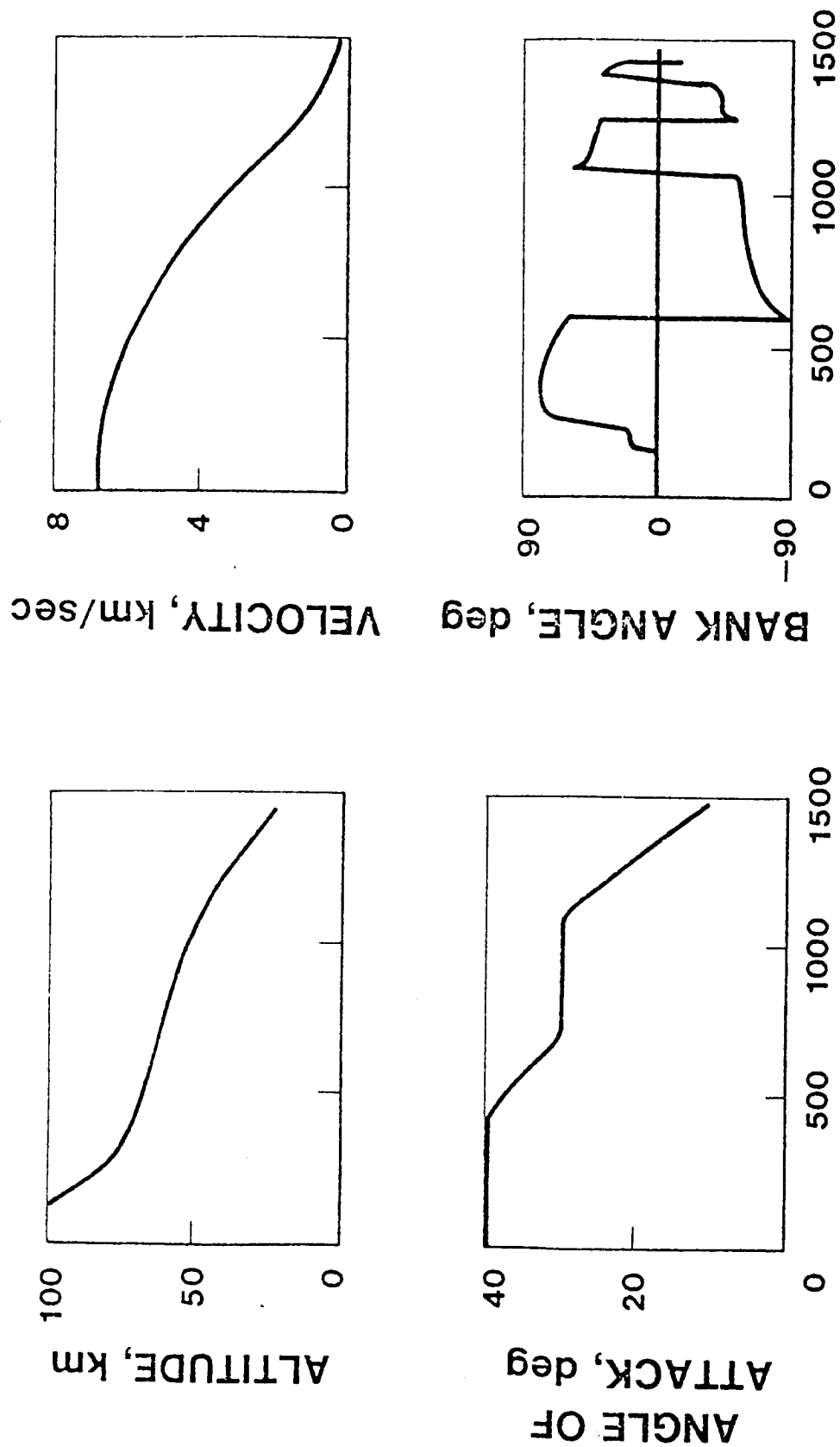
TIME FROM ENTRY, sec

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of at least 30 cm. Considering other degrading factors such as atmospheric effects, finite detector elements, image motion and the unavailability of a perfect diffraction limited telescope, an aperture of 60 to 100 cm is suggested.

In addition to the desirability of observing each OFT at a unique position along the reentry path, a verification of system performance before OFT 1 is necessary. A test flight using an aircraft that can simulate expected angular rates, temperatures, and angular size will provide the verification. The only candidate aircraft found that approaches these requirements is the YF-12 flying at an altitude of 24.4 km at 1.03 km/sec.

Finally the aircraft should be capable of a cruising altitude of 14 km (above most atmospheric water). This is arrived at by considering the wavelength requirements for maximum sensitivity to the expected temperature range of 1.5 to 2.5 micrometers. The versatility required of the observing platform is to ensure proper position with respect to the Shuttle Orbiter for a variety of reentry conditions. In addition, this aircraft must have the capacity for a telescope with an aperture of 60 to 100.
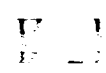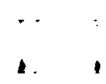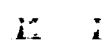
Four candidate observing platforms were considered, including one ground-based station.

ARPA Maui Optical Station - The ground-based station studied was the ARPA Maui Optical Station (AMOS), MT Haleakala, Hawaii. This facility has a 1.6-meter aperture telescope capable of tracking up to 6.6°/sec (Ref. 4). This feature would allow either formatted data or the streak camera approach to be used. The aperture available provides excessive signal to the point that image integration is not an advantage (the main reason for formatted data). The streak camera technique is quite suitable and would provide excellent data on the Shuttle Orbiter when it is within 200 to 300 km of the station. Beyond this range, the resolution required cannot be met. This is the major disadvantage of the ground-based platform because it cannot accommodate the variety of geographical positions necessary to observe the Shuttle at prescribed points in its reentry profile. Finally, the temperature data taken at an altitude of 3 km will not be accurate due to fluctuations in the water content of the atmosphere. Figure 6 represents the atmospheric transmission from AMOS and shows strong water absorption bands in the 1.5 to 2.5 micrometer region of the spectrum. The AMOS facility does not appear to be a viable candidate observing platform for this experiment.

Convair 990 - The NASA Convair 990 meets many of the basic requirements of this experiment (Ref. 5). It can be positioned optimally. A telescope that might be placed on board (see Fig. 7) is compatible with the streak camera but cannot be of sufficient aperture. The available window size (45 cm) and location (65° above water line) limit the resolution on the Shuttle Orbiter to between 2 and 5 meters. Figure 8 represents the expected MTF of a redesigned, 45-cm aperture telescope that could be used on the C990. This candidate observing platform is marginal at best and would require substantial internal modifications including a completely new gimbal platform within the aircraft.

Lear Jet - The NASA Lear Jet also meets many of the general requirements of an observing platform (Ref. 6). Its altitude and geographical range are adequate. As in the Convair 990, the resolution obtained by the Lear Jet is limited by the size and position of observing windows. The maximum aperture telescope that could be used is 30 cm at an elevation of 25° above waterline resulting in a maximum Shuttle surface resolution of 1.5 to 2 meters. The Lear Jet is more favorable than the Convair 990 for lower surface viewing even though the available telescope aperture is less because the window elevation allows viewing of the Shuttle at an angle closer to the Shuttle lower surface normal. For

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ATMOSPHERIC TRANSMISSION – AMOS GROUND STATION

FIG. 6

ZENITH ANGLE = 60°
H_1 = 3KM
H_2 = 75KM

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WAVELENGTH (μM)

% TRANSMITTANCE

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CONVAIR 990 ACQUISITION & DATA SYSTEM   FIG. 7

TELESCOPE

TRUSS

GIMBALS

ACQUISITION SCOPE

65° EL. WINDOWS

SEAT RAILS
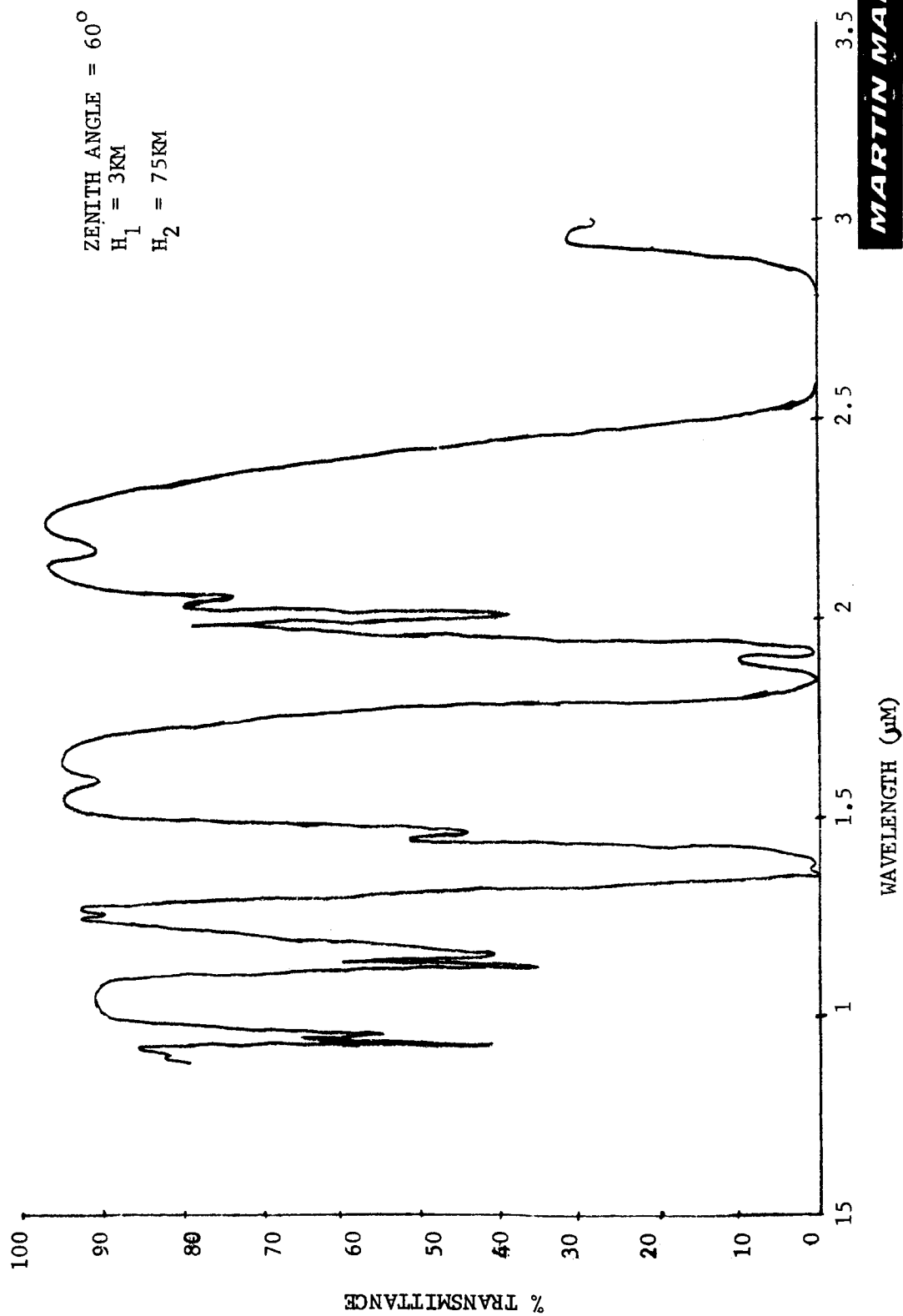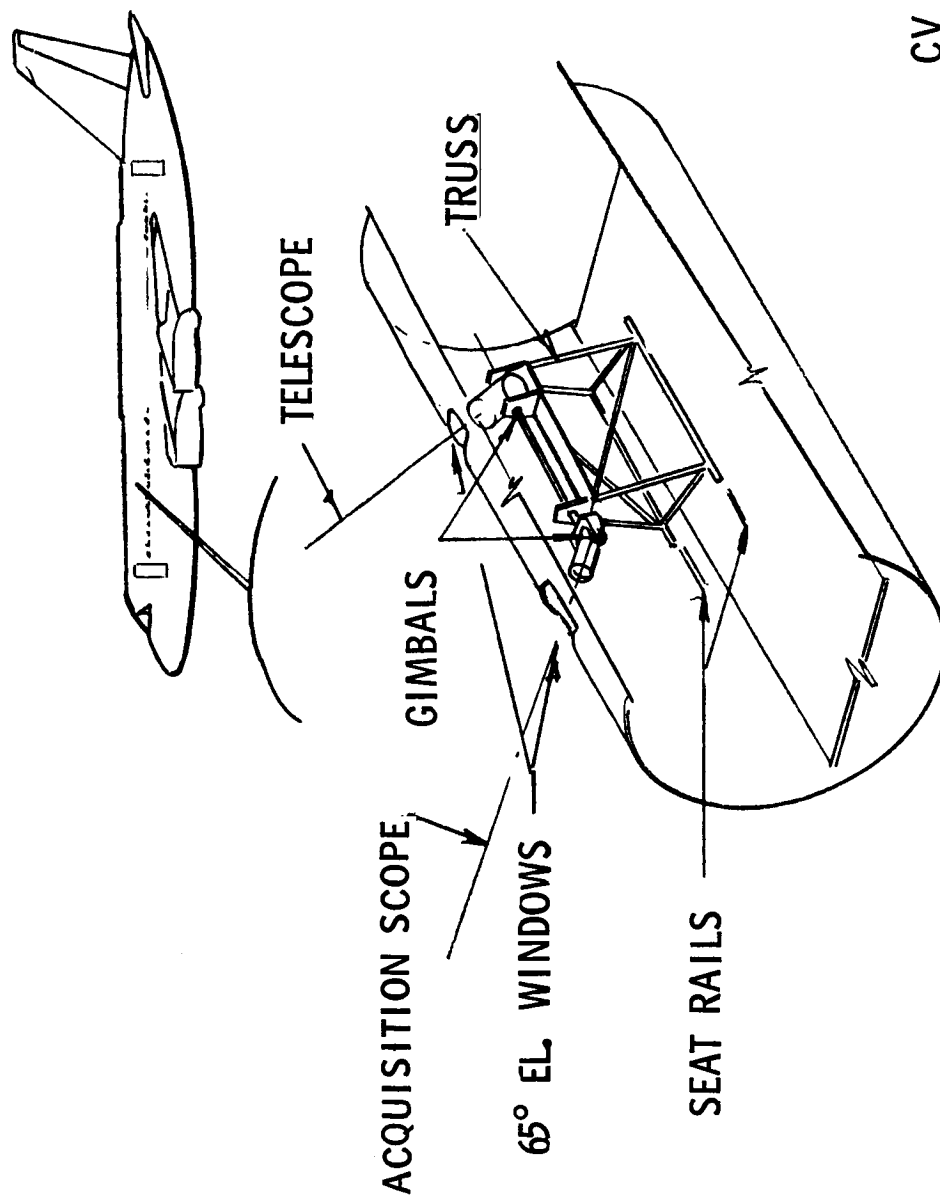
CV 900 ACQUISITION
SYSTEM

CONVAIR 990. MTF (EXPECTED) OF 45 cm TELESCOPE

FIG. 8

REDESIGN 45.7 cm APERTURE TELESCOPE TO f/25

FL = 11500 mm

$\beta = 9 \times 10^{-5}$ RAD = .054 CY/ARC SEC

ALL OTHER

OPTICS

CUTOFF = 11.1 ARC SEC = 5.38×10^{-5} RAD

MTF

CY/ARC SEC

14
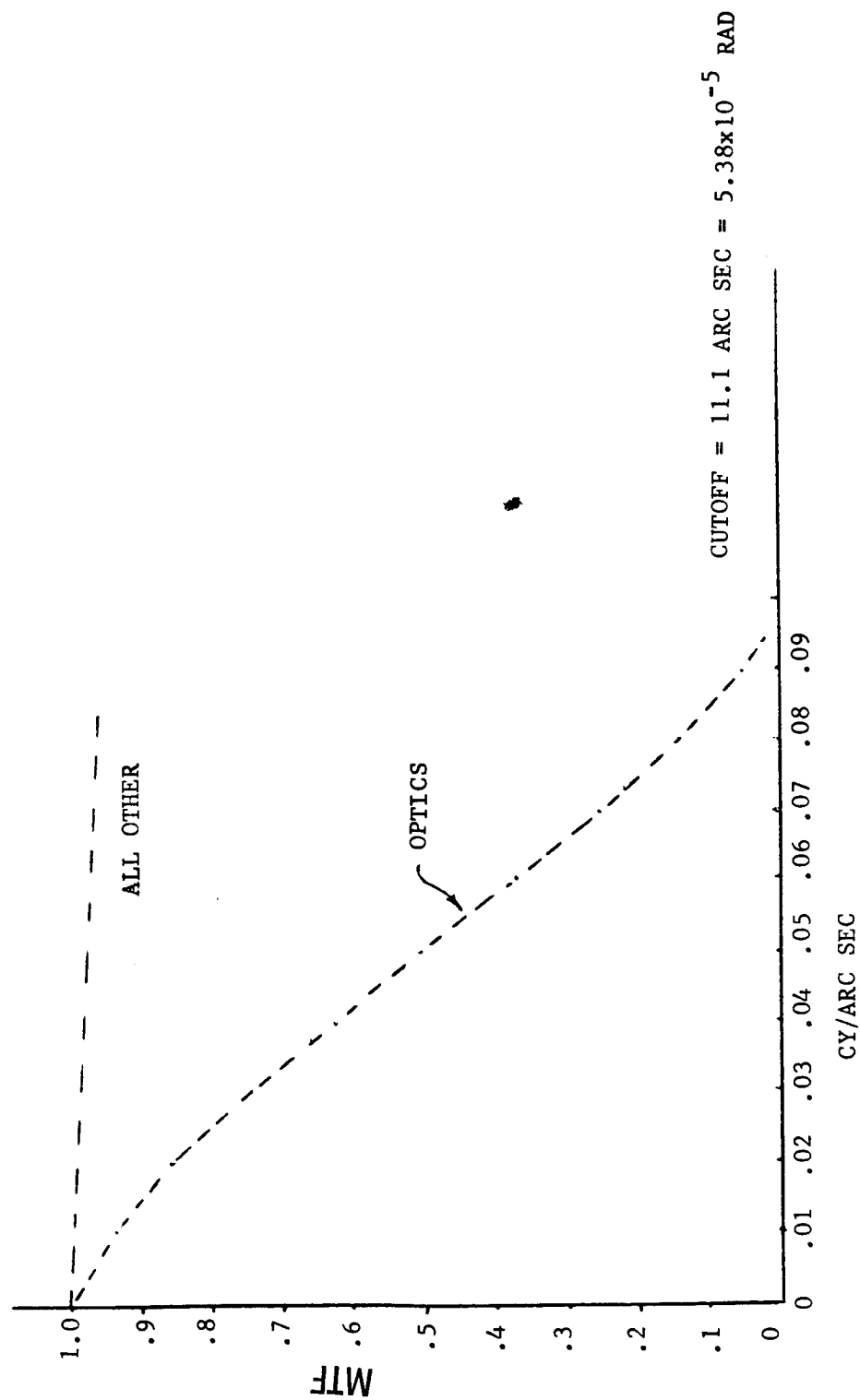
viewing of the side surfaces, the Convair 990 may be the preferred of these two aircraft. The telescope stabilization system on-board the Lear Jet is unique because it can provide elevation rates up to 50°/sec. This allows the acquisition system to be part of the main telescope since the response to an error signal can be corrected within the field-of-view of the guide telescope (see Fig. 9). Other candidate platforms require a complete separate acquisition system. This candidate then is also marginal; however, it would require fewer modifications because a 30-cm telescope and stabilization system are currently installed in the Lear Jet.

C141 - The NASA C141 Airborne Infrared Observatory (AIRO) meets all the requirements of locatability and altitude. The 91.5-cm telescope on-board will provide a Shuttle surface resolution of 1 meter or better (see Fig. 10). In most high temperature regions, the resolution will approach 0.7 meters for the longest range condition (peak heating) and approach 0.5 meters for shorter range conditions (Ref. 7). In addition, the telescope elevation is adjustable between +35 and +75° above waterline and can be optimized for each Shuttle Orbiter reentry condition. The on-board stabilization and telescope drive systems are adequate. No modifications are required other than gain adjustments on some servoloops. This aircraft is the only candidate with an on-board system control and data handling computer (HP2100). The streak camera technique is directly adaptable to the telescope similar to current IR experiments. The only modifications required are to mount an acquisition system on the telescope head ring. It will not interfere with any operation of the telescope and does not have to be removed for other experiments. The aircraft and telescope facilities are best suited for this experiment.

In the remainder of this report it is assumed that the NASA C141 AIRO is the observing platform.

ACQUISITION AND IMAGING GEOMETRY   LEAR JET

FIG. 9

SHUTTLE FLIGHT PATH

ACQUISITION = 2.25°

RANGE = 142.7 AT 282 SEC
117.6 AT 544 SEC
95.1 AT 791 SEC
68.4 AT 922 SEC

ELEVATION 25°

FLIGHT
PATH
LEAR JET

ACQUISITION TO DATA TAKE = .78 SEC AT 282 SEC
.82 SEC AT 544 SEC
1.0 SEC AT 791 SEC
1.13 SEC AT 922 SEC

ELEVATION DRIVE RATE 50°/SEC

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3.75°

2.25°

6°

40mm

GUIDE TELESCOPE FOV

FIG. 10

AIRBORNE OBSERVATORY

TELESCOPE
CONTROL
CONSOLE

ADAMS

SPOILER

TELESCOPE

17
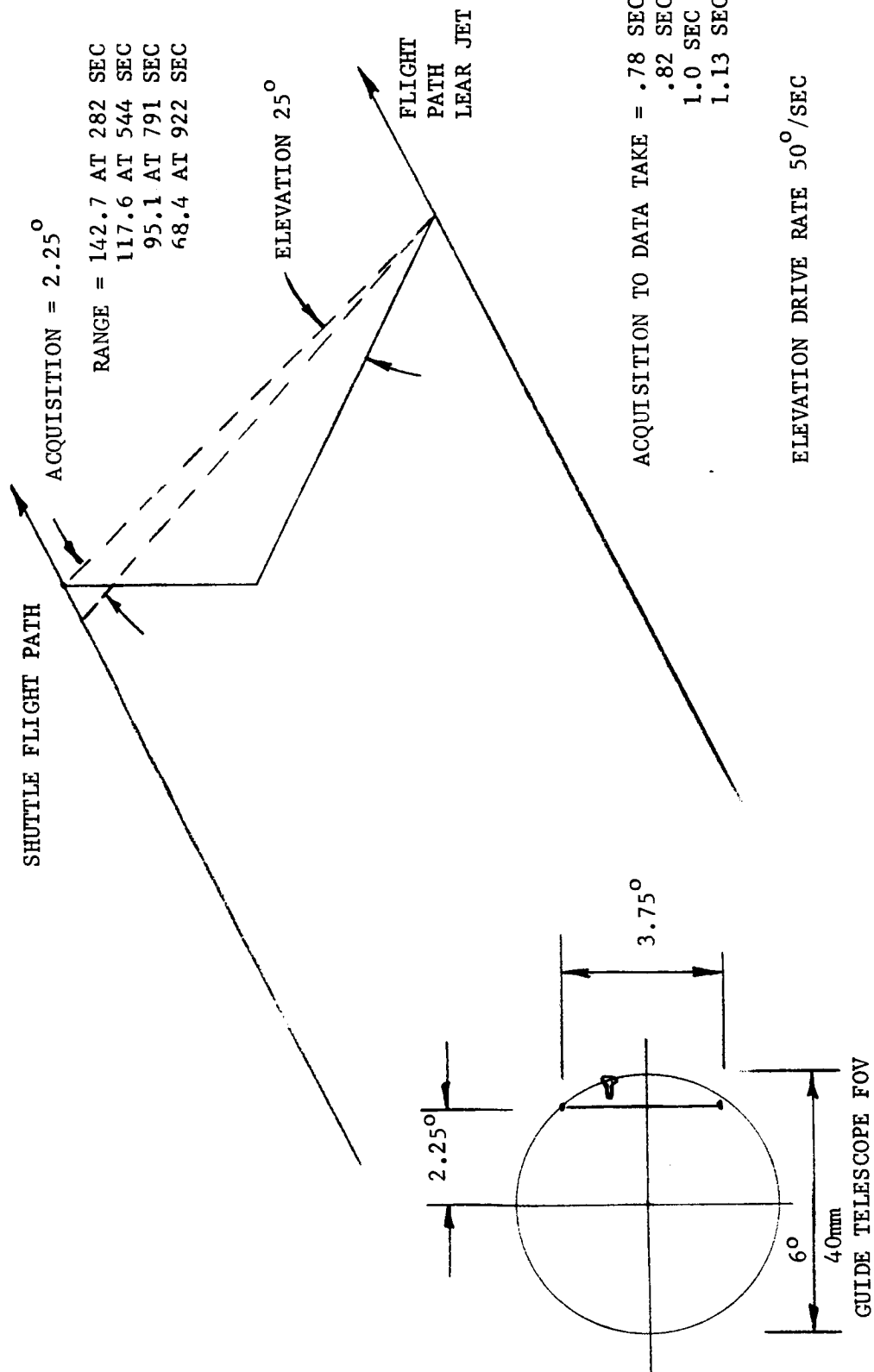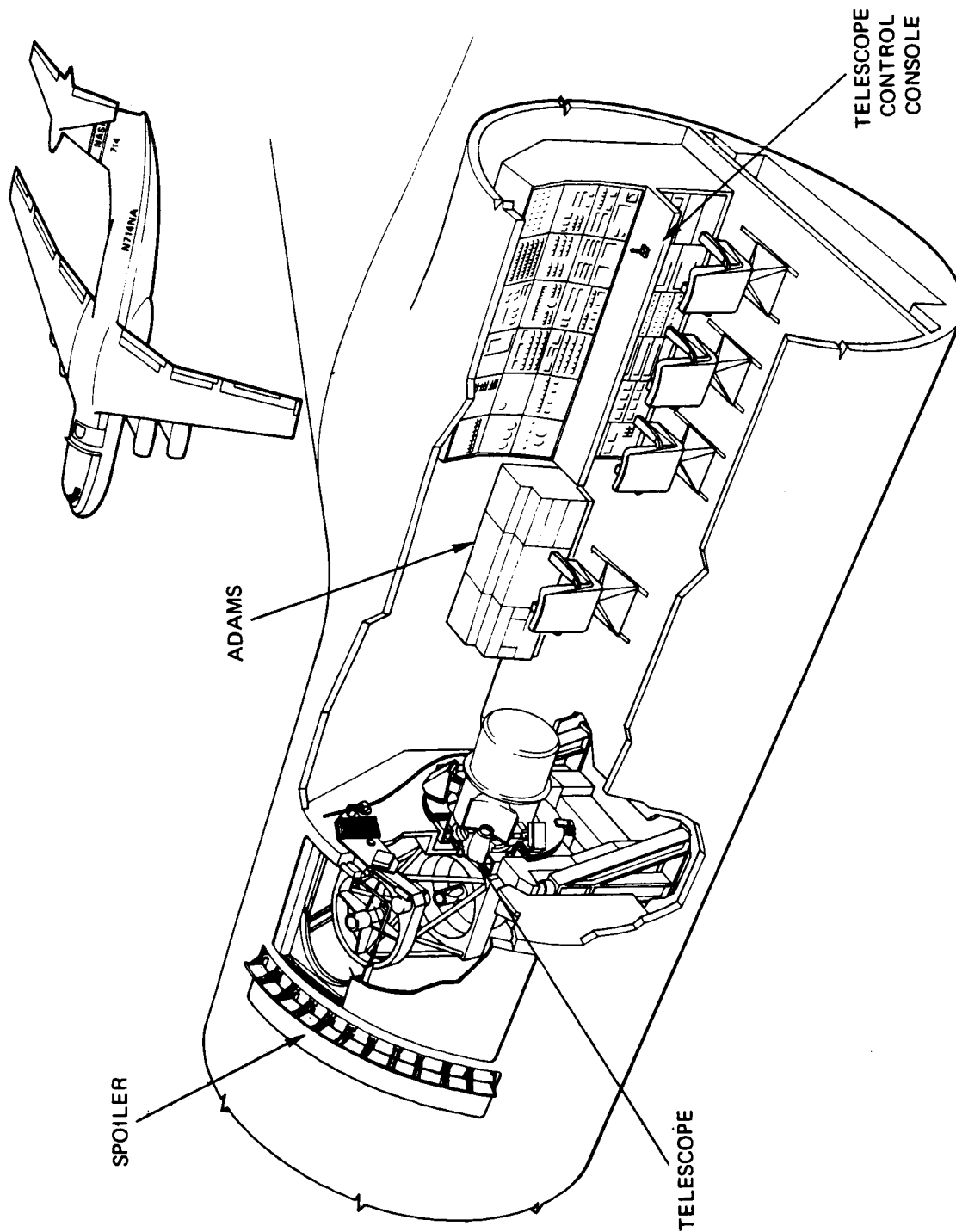
As discussed previously, the basis for the streak camera is: the object must fly through the telescope field-of-view (FOV), preferably the center of the field, within some reasonable tolerance. The FOV of the AIRO is 14 arcmin. To minimize the number of detectors required, it was stipulated that the Shuttle image pass within the center 5 arcmin of the telescope FOV.

The design requirements of the acquisition system are: (1) find the Shuttle while accounting for its uncertainty in position with respect to the aircraft, (2) lock-on the Shuttle and track it thereby providing an elevation error to the main telescope drive system, and (3) maintain this lock untils the Shuttle image passes within ±2.5 arcmin of the telescope line-of-sight. This can be accomplished by mounting the acquisition system on the main telescope with the gimbal axis 90° to both the telescope elevation axis and line-of-sight. As the telescope is driven in elevation based on the error signal received from the acquisition system, both move in elevation reducing the error signal.

The uncertainty of the Shuttle position with respect to aircraft position and the maximum range of elevation adjustment dictates the FOV of the acquisition system to be 9°. The cross track error of the Shuttle can be 15 km and the altitude error 3 km when the acquisition range is at least 90 km. The along-track error of the Shuttle is of no concern when flying parallel to the Shuttle.

The design chosen for the acquisition system is an infrared refracting lens that provides an image of the 9° field on a rotating reticle. Behind the reticle is a condensing lens and a cryostat-cooled indium antimonide detector. The whole system is mounted on a gimbal axis that is 90° to both the telescope elevation axis and the telescope line-of-sight. The rotation around this axis by the acquisition system is called acquisition angle.

The acquisition angle required is governed both by: (1) the first point the Shuttle can be detected at based on signal-to-noise, and (2) the time required to move the telescope through the maximum elevation change required. Figure 11 depicts the maximum acquisition angle available before interfering with aircraft structure. Based on the 9° FOV of the acquisition system, the maximum motion allowed in elevation is 4.5°. The maximum elevation rate for the existing elevation drive with electrical modification is 0.33°/sec. This provides 13.5 sec plus a 6 sec contingency or 20 sec of acquisition time. The maximum acquisition angle that can be accommodated based on the highest angular rates is 62° (see Appendix). This is compatible with the available acquisition angle of 65° at a telescope elevation angle of 55°. Figures 12 and 13 show the acquisition system design.

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ACQUISITION GEOMETRY – C141

FIG. II

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ACQUISITION SYSTEM

FIG. 12

ACQUISITION SYSTEM

FIG. 13
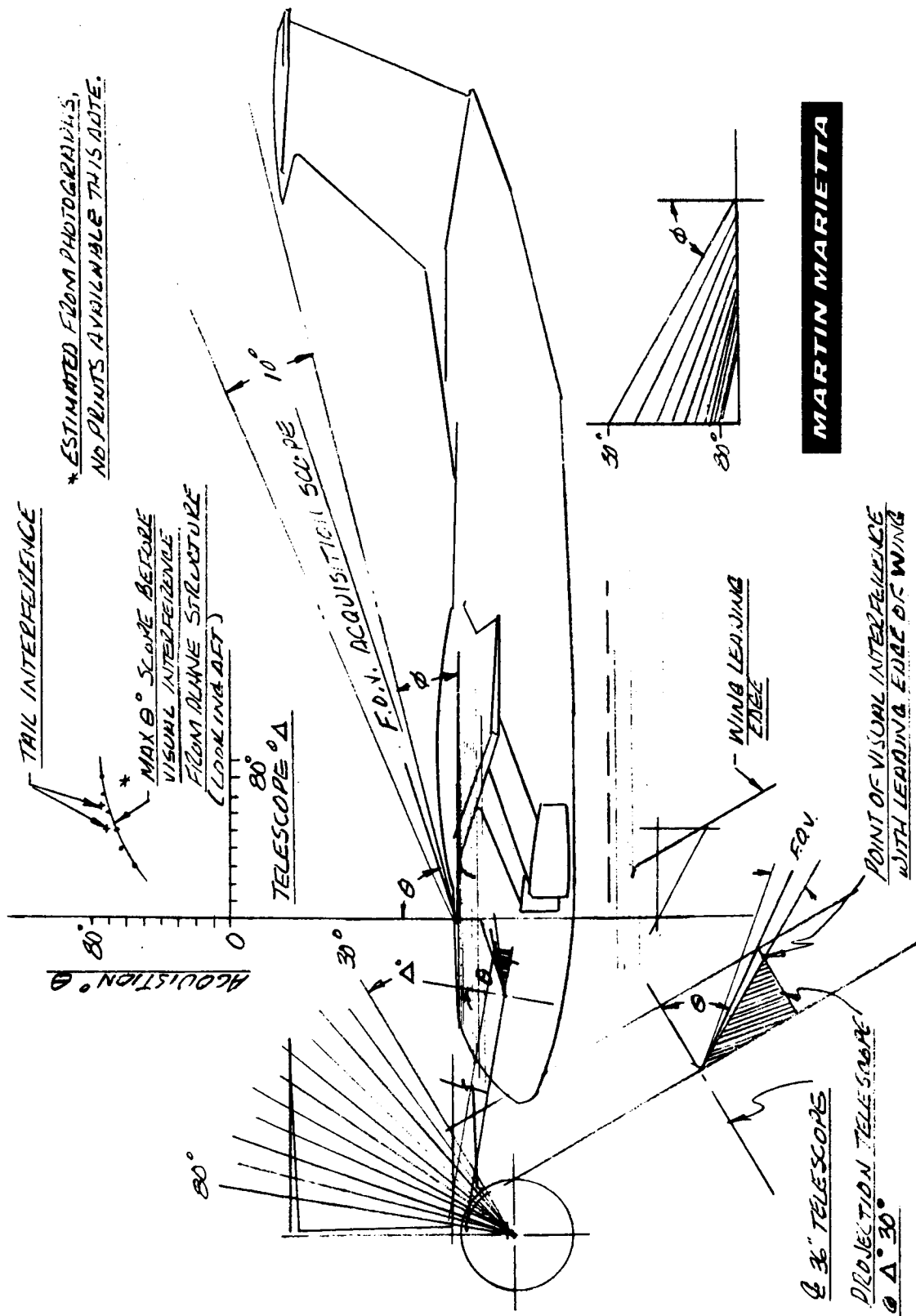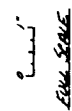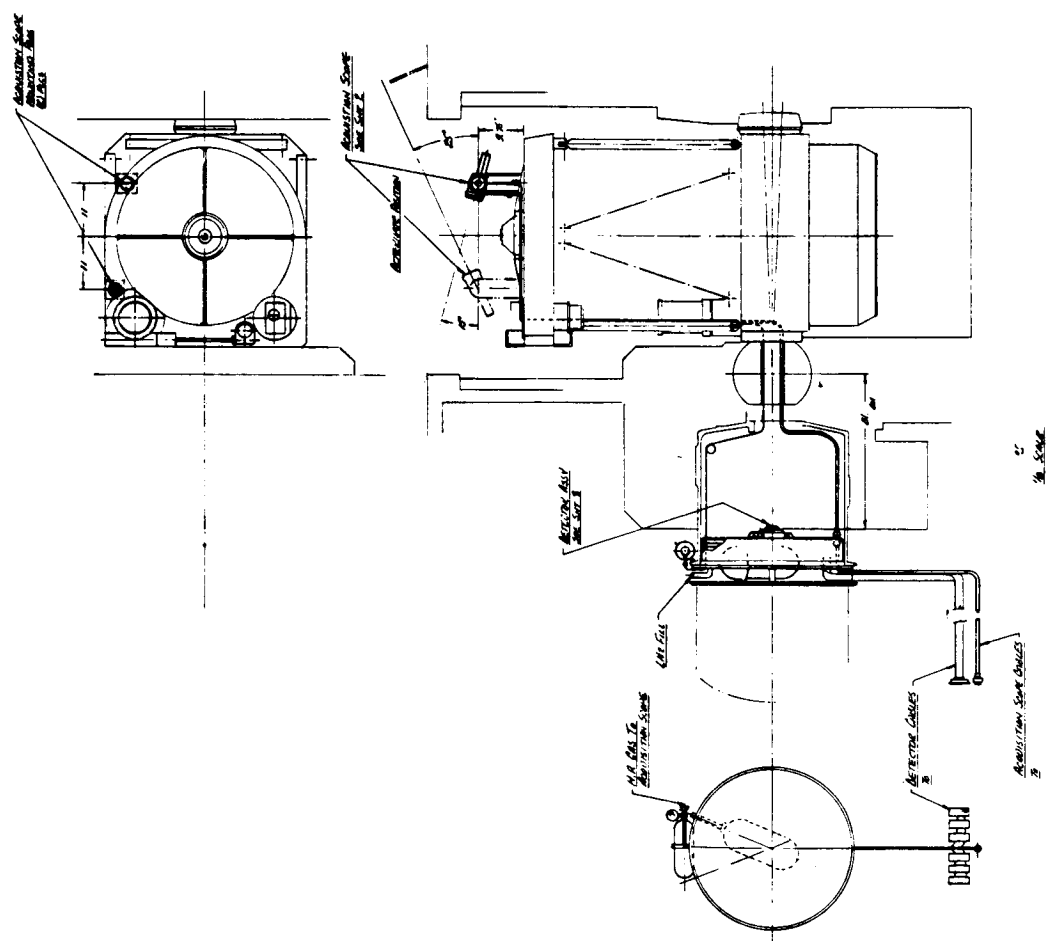
Telescope - The major components of the telescope are the collector lens system, a reticle that modulates the energy received from the target and acts as a spatial filter, a condenser lens that images the aperture on an Indium Antimonide (InSb) detector, and an optical filter. Other significant components are a nitrogen gas Joule-Thompson cryostat, optical switches, tachometer, and a brushless motor.

The telescope drive components include a motor, tachometer, and a resolver.

Reticle - The reticle shown in Figure 14 was designed specifically for the requirements of the Shuttle infrared imaging system. In the system, elevation and azimuth tracking requirements are quite different. Elevation accuracy is a driving function in determining the number of detectors required in the focal plane. Large azimuth errors are tolerable as long as the Shuttle remains in the tracking telescope's field-of-view. In the present design, we will actually bias in an error to keep the Shuttle off the reticle center (where there is no signal). Determination of the Shuttle vertical (elevation) position will be accomplished by the zero and 180° phase crossing of the opaque portion of the reticle by the Shuttle image.

The modulation by the reticle is by discrete frequencies. The radial position of the target image is determined by the frequency of modulation received by the detector. The center ±0.5° is broken up into four discrete regions that vary from three to nine times the reticle rotation rate; the next 1.0° is designed to be 11 times the rotation rate. The last 3.0° are at 13 times the rotation rate. The center portion of the reticle is broken up into several increments to aid in servosystem design. The spoke width is set up to be greater than two Shuttle image lengths, including diffraction limit blur circle for the closest predicted crossing distance.

Detector and Filter - Indium Antimonide (InSb) is the detector chosen to be used in the acquisition tracking telescope. By reducing the long wavelength background irradiation to very low levels using a cooled bandpass filter, specific detectives, D*, values of up to 3×10^{12} will be arrived at for a 4.5-mm diameter detector. The detector will be cooled with a Joule-Thompson cooler to 90 K. The combination of high D* and good frequency response (necessary for accurately determining elevation errors) narrowed the choice to the reliable InSb detector.

TRACKING SCOPE ROTATING RETICLE

FIG. 24

ENLARGED DETAIL

1°

9°

24
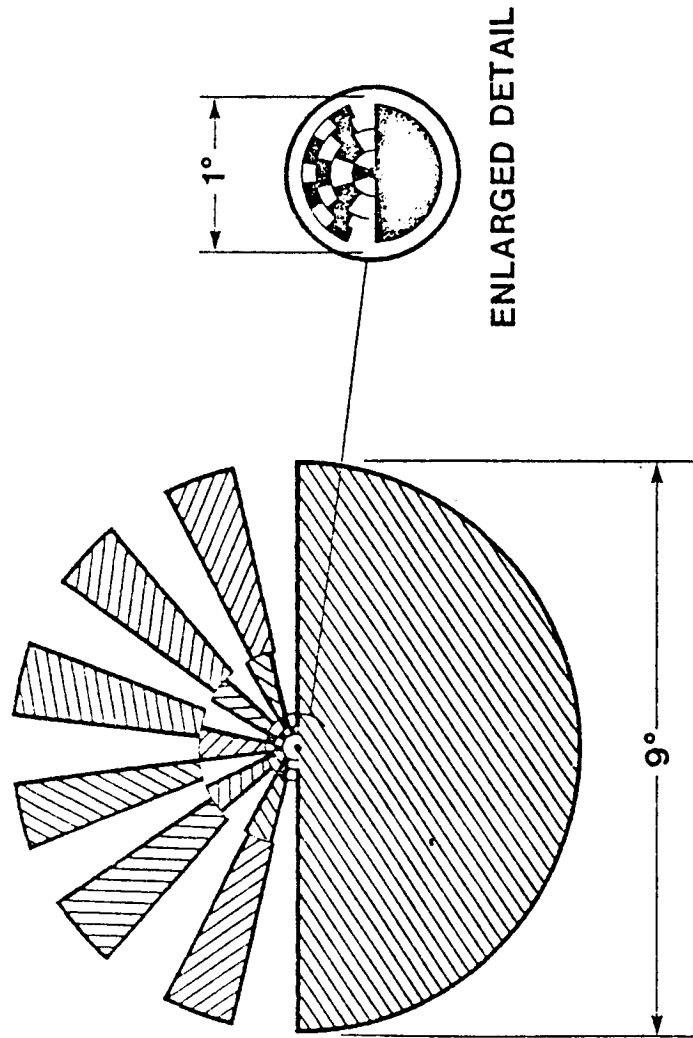
The cooled bandpass filter (Fig. 15) (1 to 2.6 micrometer) serves to reduce background irradiation and therefore detector noise. It was also determined that any target signal lost in the region beyond 2.6 micrometers is not a serious loss due to excellent signal-to-noise (S/N) values for the present system. In addition, this limit significantly eases the optical design complexity. The 1 micrometer lower wavelength limit serves to adequately reduce the solar background but aids in acquiring stars during boresighting operations (see calibration section, page 55).

Signal-to-Noise (S/N) - Figure 16 shows the system parameters for reference and the acquisition signal-to-noise (S/N) values for the listed conditions. These predicted S/N values are exceptionally good; they assure target acquisition within the telescope field-of-view. Such high S/N values ease the burden on the electronics and software system in the processing of error signals.

The servo system required to enable the acquisition system to perform its function is described in the following paragraphs. Portions of this servosystem are part of the AIRO telescope. stabilization system and only require slight modification. Figure 17 shows an overall block diagram of the acquisition and stabilization system as designed for this task, using as much existing capability as possible.

There are six major loops to consider for the C141 system.

Azimuth Telescope Stabilizing Loop - This existing loop will stabilize the telescope in azimuth and will provide an inertial hold (see Fig. 18). It will provide the initial pointing system with an incremental bias on pointing angle. It may be required to provide a low bandwidth centering function in its ±2° travel at initialization.

LOS Telescope Stabilizing Loop - Presently an operator observes a TV CRT to center the LOS axis manually via a joy stick. This function will be refined with a closed-loop servo using an angular pick-off similar to the AZ and EL system (see Fig. 19). This axis should remain centered to within 1/2 to 1/4 degree at initialization. The actual value of this error must be fed to the Elevation Initialization as a bias.

Azimuth and Elevation Tracking Loops (4 Loops) - Figures 20 and 21 show these loops. The existing system capability was evaluated as to maximum torquing accelerations and rates (see Fig. 22). The elevation axis has a maximum acceleration of $3.77°/sec^2$ which is adequate. The elevation gyro package is capable of torquing the gyro at 3°/s and is presently electronically limited to slew at 225 arcsec/sec. For our application, this should be increased to 0.5°/sec by electronic mods.

ACQUISITION SYSTEM - FILTER

FIG. 15

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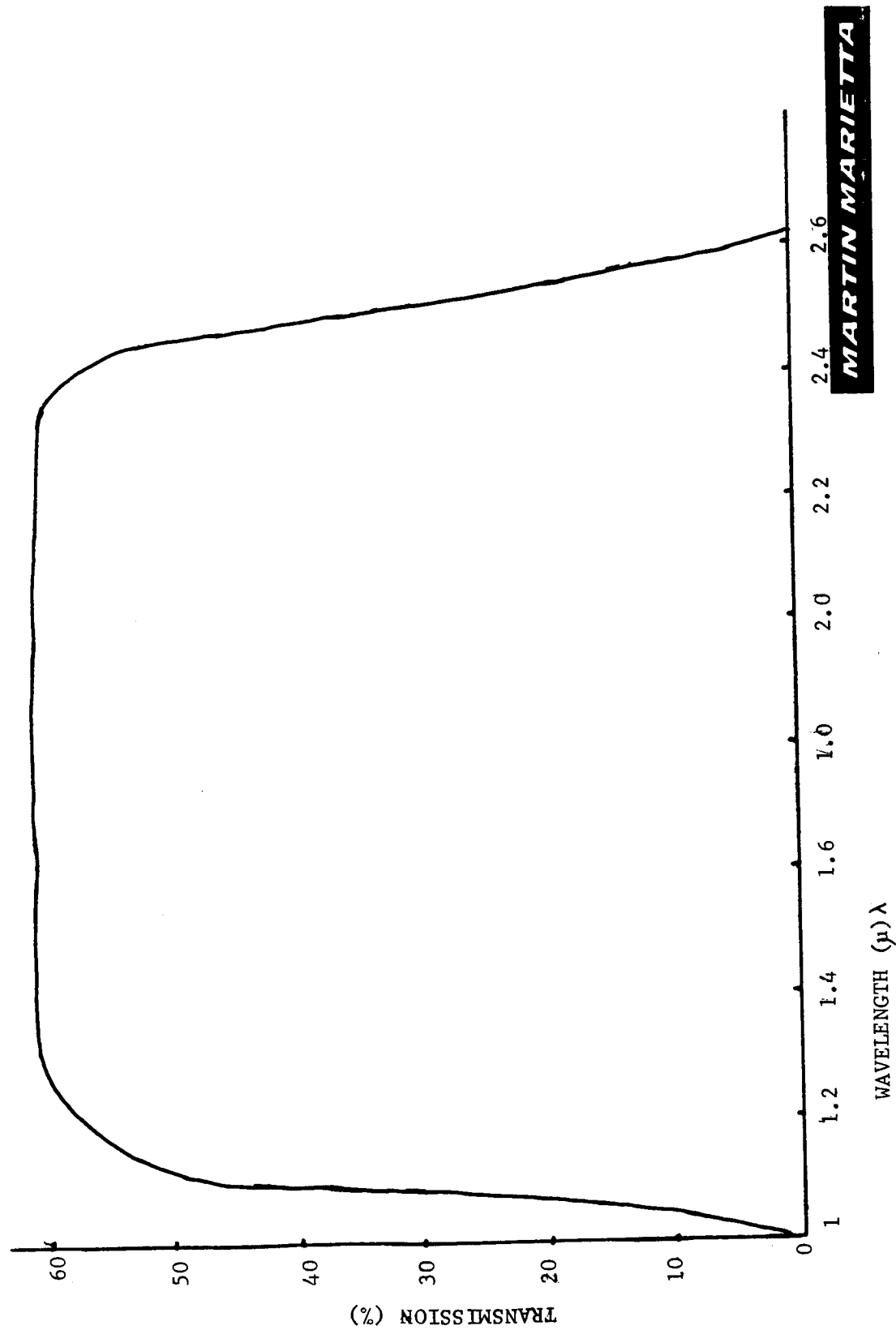
ACQUISITION AND TRACKING SYSTEM PARAMETERS

FIG. 16

SYSTEM PARAMETERS

COLLECTOR DIAMETER	62.5 mm
FOCAL LENGTH	125 mm
DETECTOR DIAMETER	4.5 mm
ELECTRICAL BANDWIDTH	25Hz
DETECTOR	InSb
$\lambda_1 = 1.0\mu$ $\lambda_2 = 2.5\mu$	
DETECTOR TEMP	$\approx 77^{o}K$
FOV	9°
SHUTTLE AREA	362 METER^2
YF-12 AREA	70 METER^2
C = 0.3*	

* DERATING FACTOR

ACQUISITION PARAMETERS

TIME FROM REENTRY OFT-1 (SEC)	282	544	791	922	YF12
MEAN TEMPERATURE	$1250^{o}K$	$1100^{o}K$	$1000^{o}K$	$1050^{o}K$	$700^{o}K$
RANGE	162KM	131KM	92KM	72KM	30KM
SIGNAL TO NOISE	2680	1900	2065	4580	200

ACQUISITION & STABILIZING SYSTEM   C141

FIG. 17

TORQUERS
AZ,EL, ⊥
EXIST.

AIR
BEARING

ONBOARD
STABILIZING
SYSTEM

EXIST.

NAV UNIT
LTN 51

EXIST.

WWV TIME REFERENCE

EXIST.

GYROS
AZ,EL,⊥

DETECTOR SIGNAL

AZ ENCODER, TAC

AZ TORQUER

EL ENCODER,

OR TILT ANGLE

AZ ENCODER

ELEVATION
SLEW

SIGNAL

ACQUISITION
CONTROLLER

ROLL,AZ
REFERENCE

TIME
REFERENCE

KEYBOARD
INPUT

DISPLAY

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FIG. 18

AZ SERVO LOOP (91.5 cm TELESCOPE)

- POSITION NULL ADDITION TO MAINTAIN AZ CENTERED
- PRESENTLY BEING DONE BY TRACKER SCOPE SIGNAL

TORQUER

GYRO

M

$$\frac{1}{J_{AZ} S}$$

$\dot{\theta}$

θ_{AZ}

ANGLE PICKOFF

DISPLAY

COMPUTER
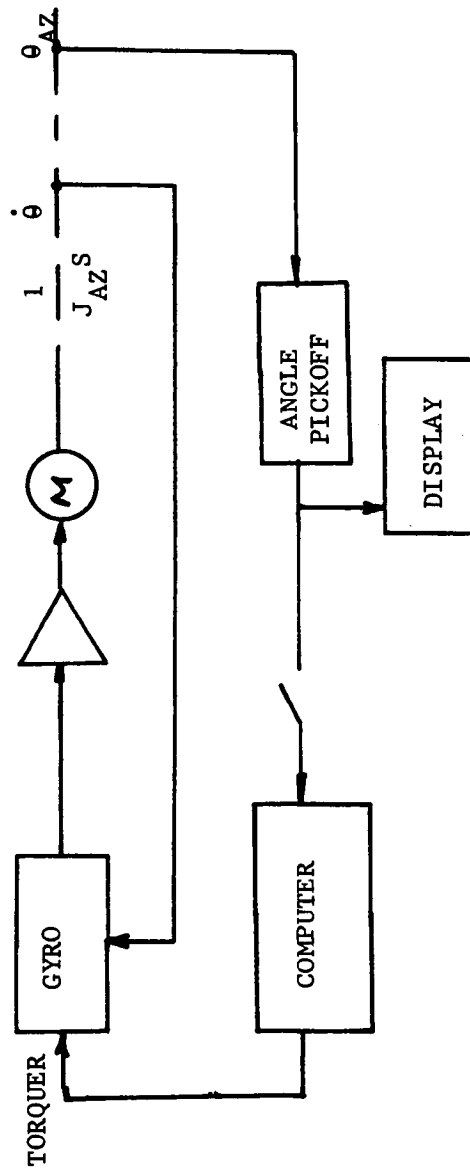
REQUIRED

*ADD SOFTWARE TO CLOSE POSITION LOOP
ALL HARDWARE EXISTING

29

FIG. 19

LOS SERVO LOOP (91.5 cm TELESCOPE)

POSITION NULL TO MAINTAIN LOS CENTER
PRESENTLY DONE BY OPERATOR OBSERVING TV DISPLAY
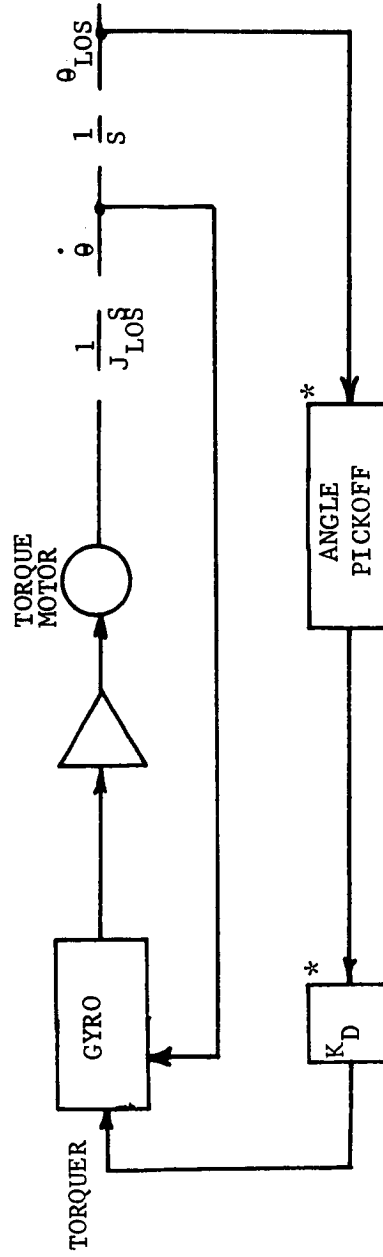
REQUIRED

*ANGLE PICKOFF (SIMILAR TO EXISTING AZ, EL)
 *COMPUTER INPUT   } OR ANALOG HARDWARE
 *COMPUTER OUTPUT
 *SOFTWARE

AZ TRACKER SERVO LOOP (NEW ACQUISITION TRACKER)   FIG. 20

o   SERVO TRACKER TO FOLLOW SHUTTLE IN AZIMUTH
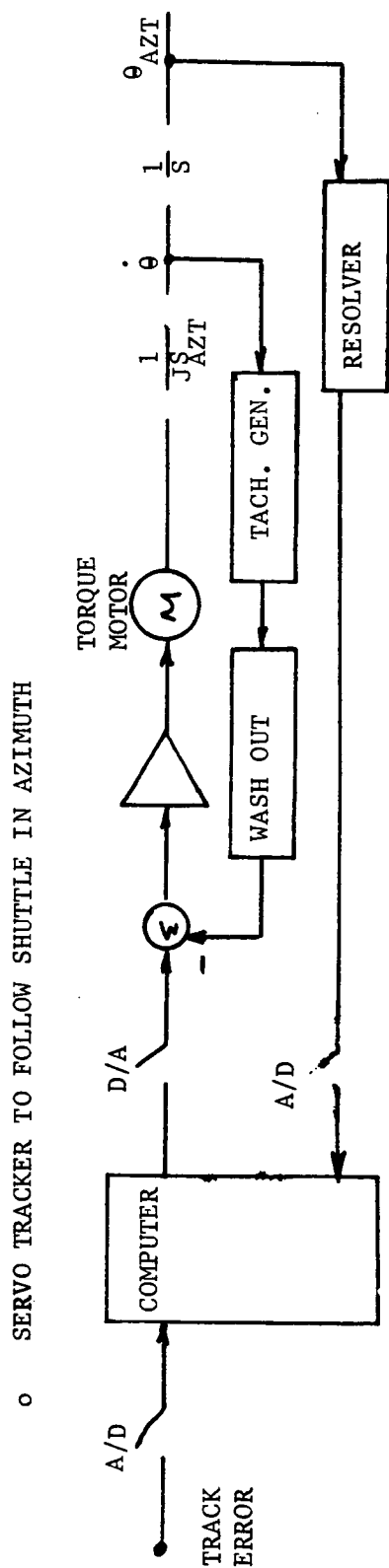
REQUIRED

*ALL ANALOG HARDWARE
*SOFTWARE TO CLOSE LOOP AND SET INITIAL POSITION

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ELEVATION SERVO (91.5 cm TELESCOPE)

FIG. 21

o ELEVATE TELESCOPE TO NULL TRACK SCOPE EL ERROR

o MAINTAIN STATOR RING IN CENTER OF TRAVEL VIA EXISTING JACK SCREW

o MAINTAIN WINDOW IN CENTER OF TRAVEL VIA EXISTING DRIVE
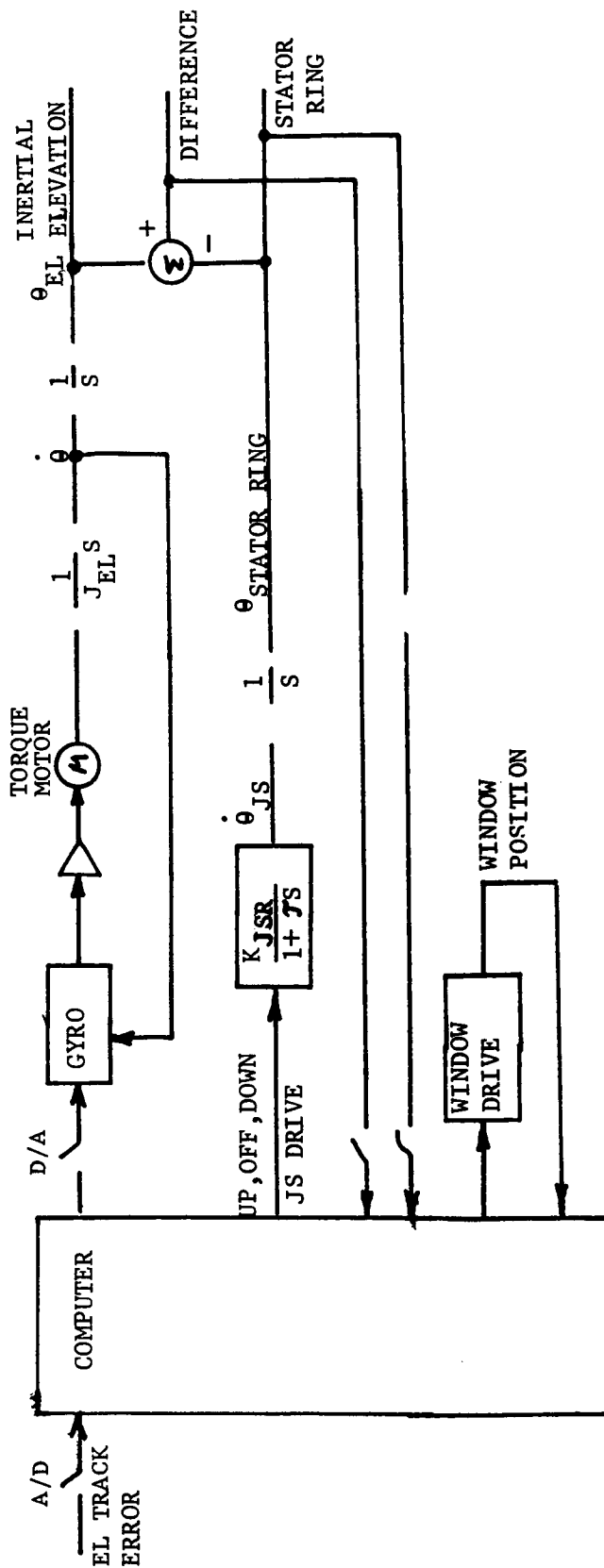
REQUIRED

*EL TRACK ERROR INPUT

*STATOR RING POSITION INPUT

*WINDOW POSITION INPUT

*JACK SCREW COMMAND OUTPUT

*WINDOW COMMAND OUTPUT

*SOFTWARE TO HANDLE ABOVE AND SET INITIAL POSITION

FIG. 22

ACCELERATION AND RATE CAPABILITIES

○ MAX TELESCOPE ACCELERATION

$$EL\ T/J = \frac{25' LB}{380SF^2} \rightarrow 3.769\ °/S^2$$

$$AZ\ T/J = \frac{25}{945} \rightarrow 1.515\ °/S^2$$

$$LOS\ T/J = \frac{25}{835} \rightarrow 1.715\ °/S^2$$

- - - - - - - - - - - - - - - - -

○ MAX GYRO TORQUE RATE
   3°/S @ .7° STOP
   ELECTRONICS PRESENTLY LIMIT TO 255 S/S

- - - - - - - - - - - - - - - - -

○ MAX JACK SCREW RATE
   ≈ .39°/S

- - - - - - - - - - - - - - - - -

○ MAX WINDOW RATE*
   ≈ .27°/S

   *THERE IS APPROXIMATELY ± 1° DEGREE EXTRA OPENING

The jack screw or stator ring and port movement were clocked at 0.39°/sec and 0.27°/sec respectively. These two servos will be driven from the computer so as to maintain center of the stabilizing system and window port. A deadband of 1/2° appears feasible to maintain center and not pick up aircraft motion. The slew rates appear to be compatible with the mission requirements. The angular sensor for a stator ring servo will be the existing elevation sensor. The sensors for the window port will be the existing window port elevation sensor, plus the stator ring elevation sensor, plus the stator ring elevation pot. The azimuth tracker loop will be accomplished by an analog rate loop and a digital position loop. The conflicting requirements of large tracking rates and low-limit cycle activity about the sensor deadband require a wash out filter on the rate feedback. An angular encoder is required to achieve accurate initial pointing.

The elevation servo will operate much as it does now with the tracker scope elevation signal being used instead of the present tracker signal. With the present system, a settling time of 5 sec is required after the initial slew rate (see Fig. 23).

Simulation of Azimuth and Elevation Control - A computer simulation code of aximuth and elevation dynamics was written to determine overall system response. Figure 24 shows elevation motion of the telescope which operates at maximum rate until elevation error reaches roughly 1/2°. The system then tends to settle for 5 sec to the final value of elevation. Figure 25 is the elevation rate. Humps indicate crossing of the center bands of the acquisition reticle.

As the main telescope is moving, the stator ring must follow to maintain the torque motors in their ±2° operating range. Figures 26 and 27 show this motion. Upon reaching 1/2 degree error between the main telescope and stator ring, Figure 26 shows the stator ring slewing at maximum rate until this error is once again within the 1/2 degree band. Figure 28 shows the difference between stator ring and main elevation. At first the main telescope out travels the stator ring, then the stator ring catches up. This condition is worst-case in that the error peaks at 2°.

The aximuth gimbal on the tracking scope picks up the Shuttle at roughly 70° aft of perpendicular to the aircraft. Figures 29 and 30 show azimuth angle and rate. Jumps in Figure 30 show the system moving between reticle bands.

Figure 31 shows the image motion in the reticle plane in azimuth and elevation. This case is for an initial error of 5° in elevation and 1 degree in azimuth. (System initially pointing below and aft of the Shuttle). Figure 32 shows the same plot but with the system initially pointing below by 2° and forward by 4° of the Shuttle.

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ACQUISITION, TRACK & SETTLE TIMING VS. MAX SLEW RATES   FIG. 23

DEGREES ERROR

SECONDS TO DATA TAKE

JACK SCREW RATE 1/3°/SEC

STAB SYSTEM LINEAR RANGE

REVISED SLEW RATE 1/2°/s

EXISTING STAB SYSTEM MAX RATE .071°/s = 255 s/s

MAIN FOV .8°

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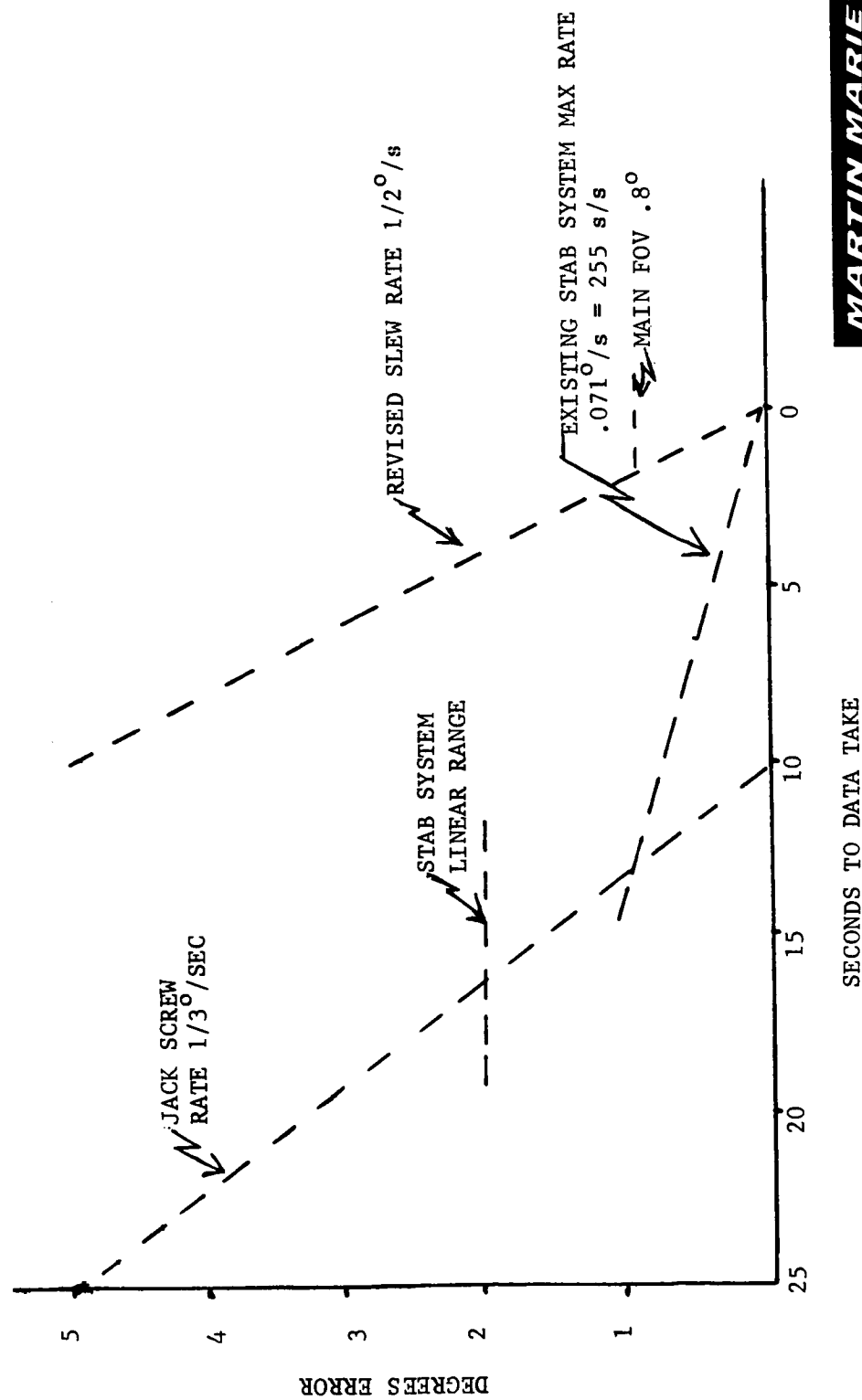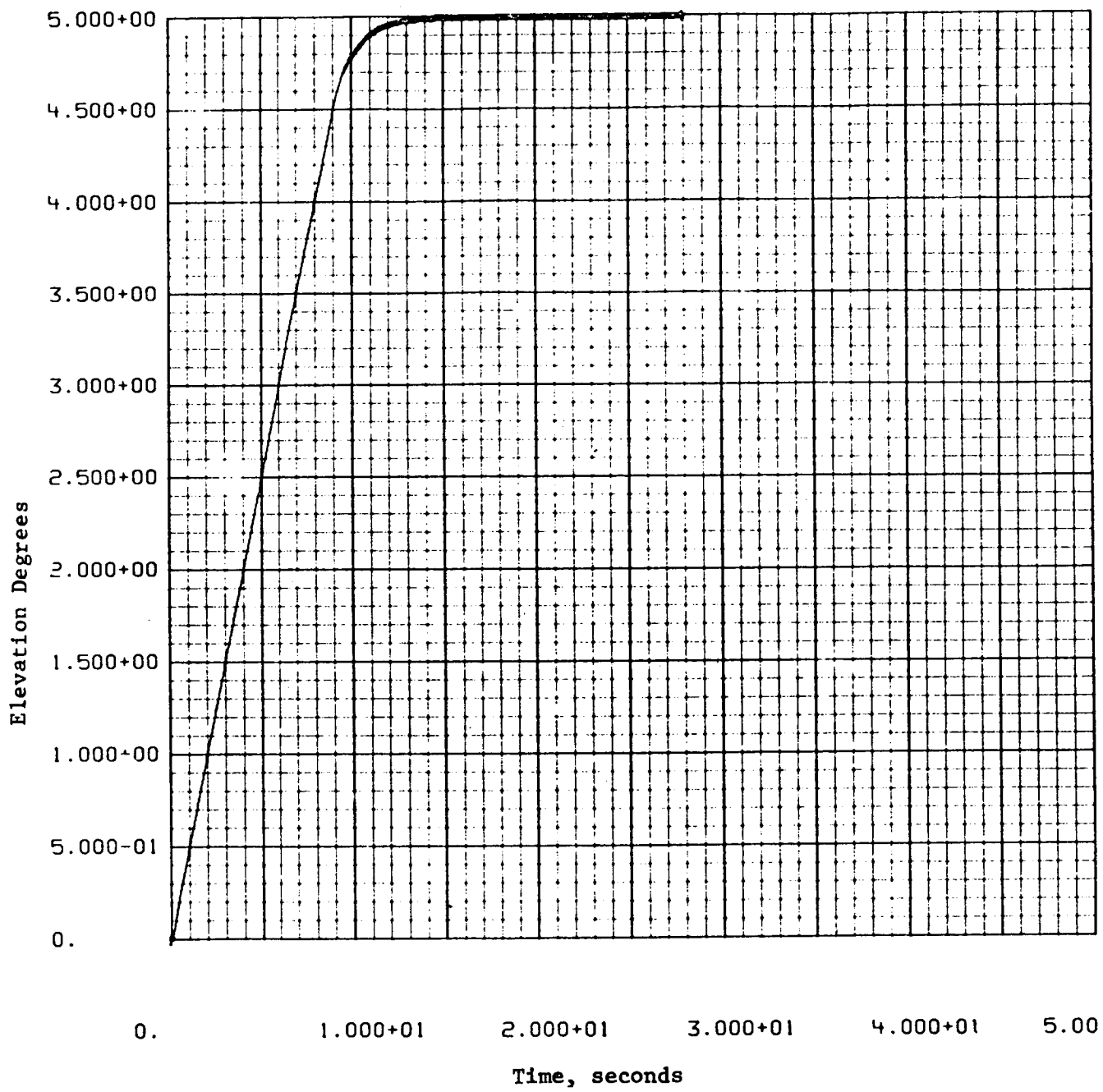
SIMULATION OF EL AND AZ CONTROL
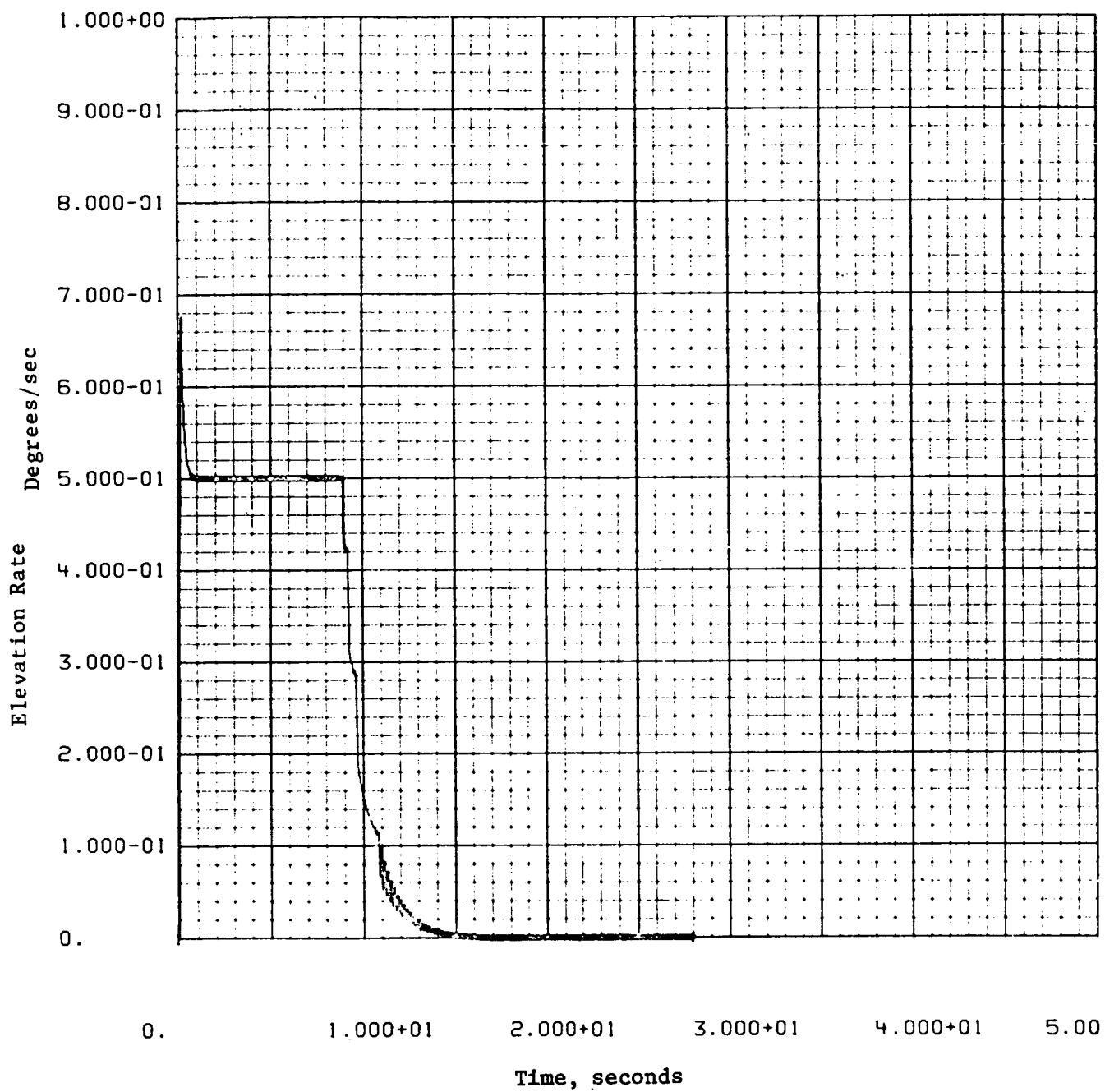
Figure 24

SIMULATION OF EL AND AZ CONTROL
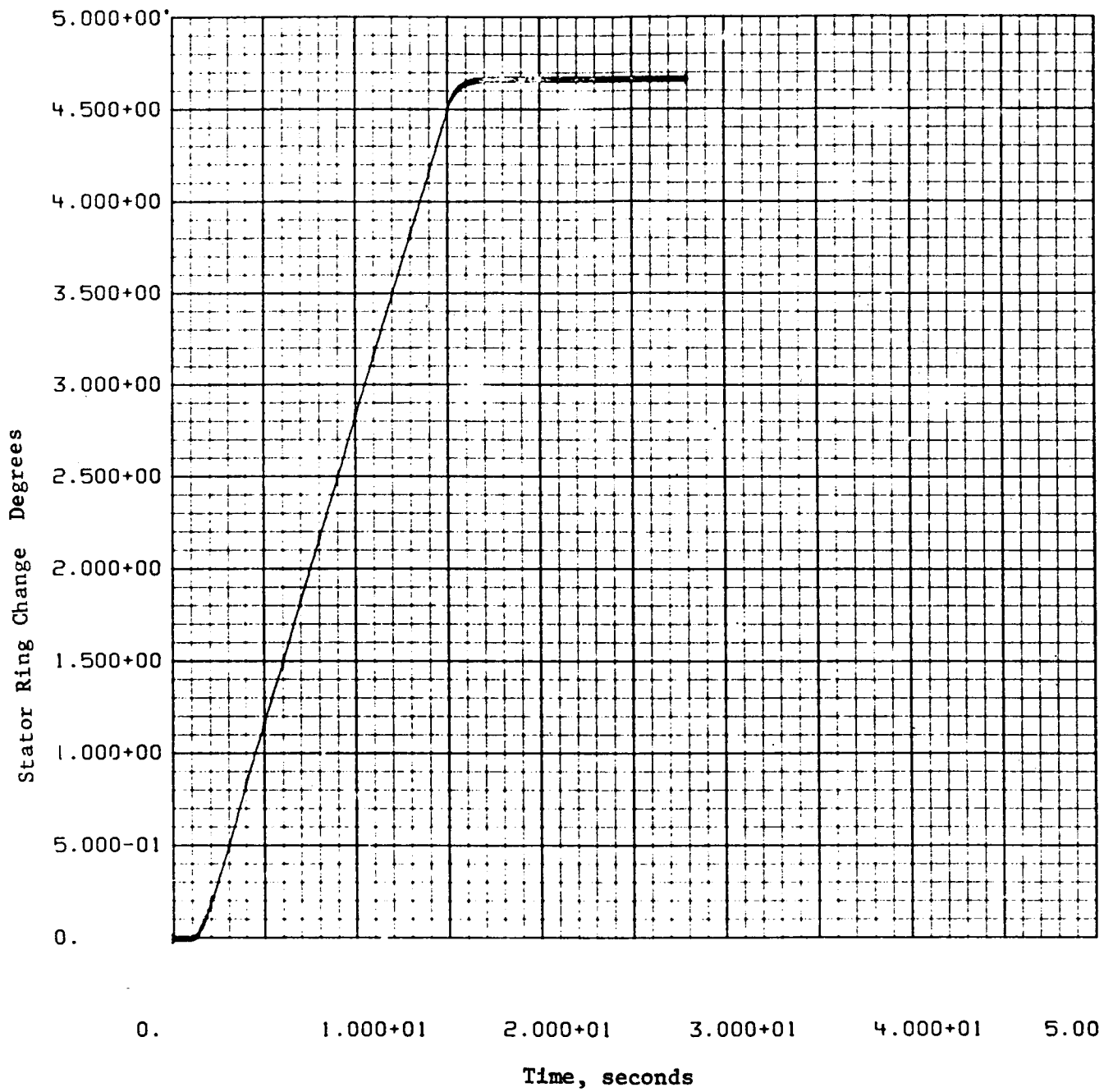
Figure 25

SIMULATION OF EL AND AZ CONTROL

Figure 26

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1   SIMULATION OF EL AND AZ CONTROL

Figure 27

SIMULATION OF EL AND AZ CONTROL

Figure 28

SIMULATION OF EL AND AZ CONTROL

Figure 29

41

SIMULATION OF EL AND AZ CONTROL

Figure 30

42

Az Reticle Error Degrees

SIMULATION OF EL AND AZ CONTROL

Initial Condition
EL error = +5°
AZ error = +1°

Figure 31

43
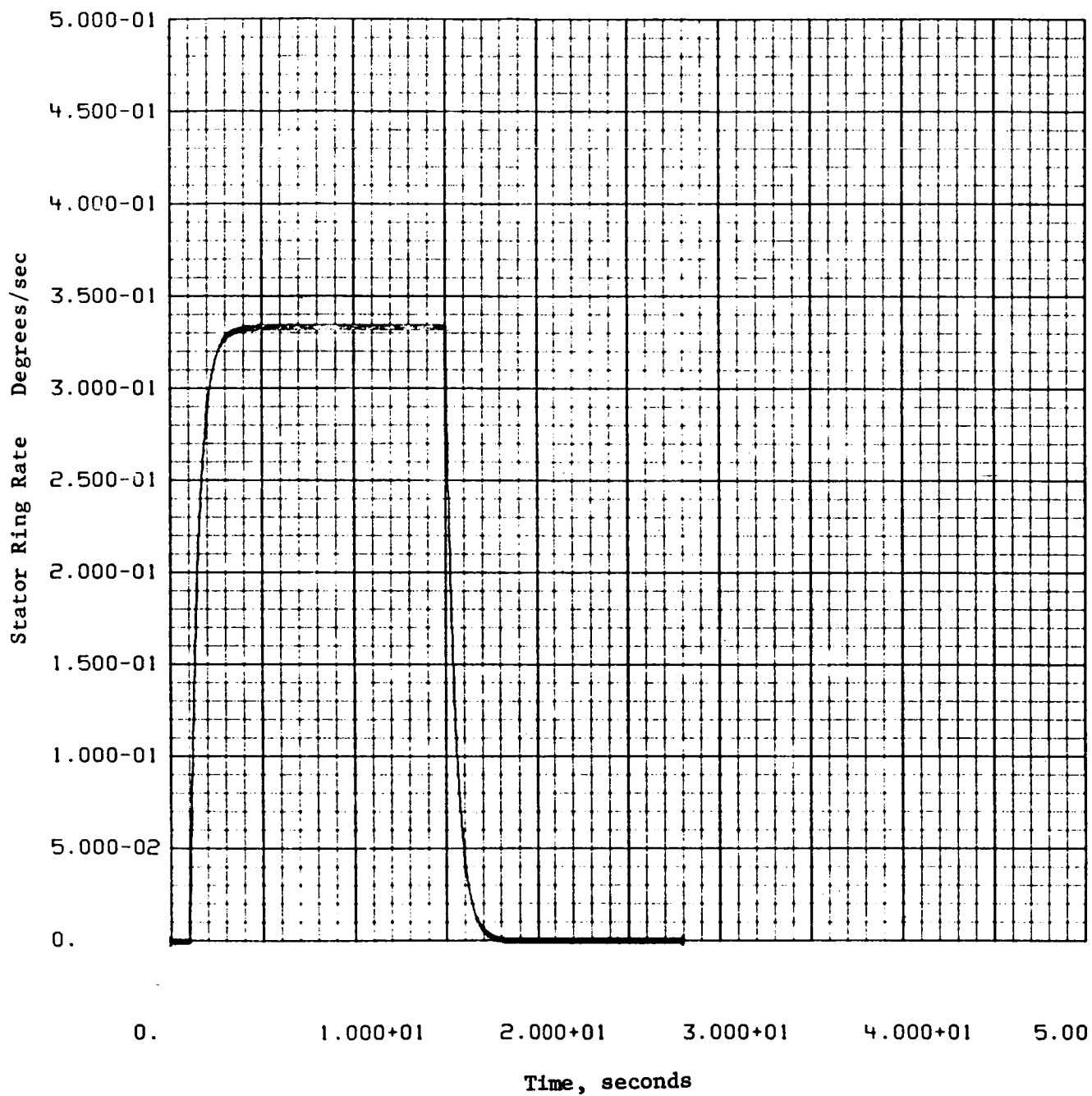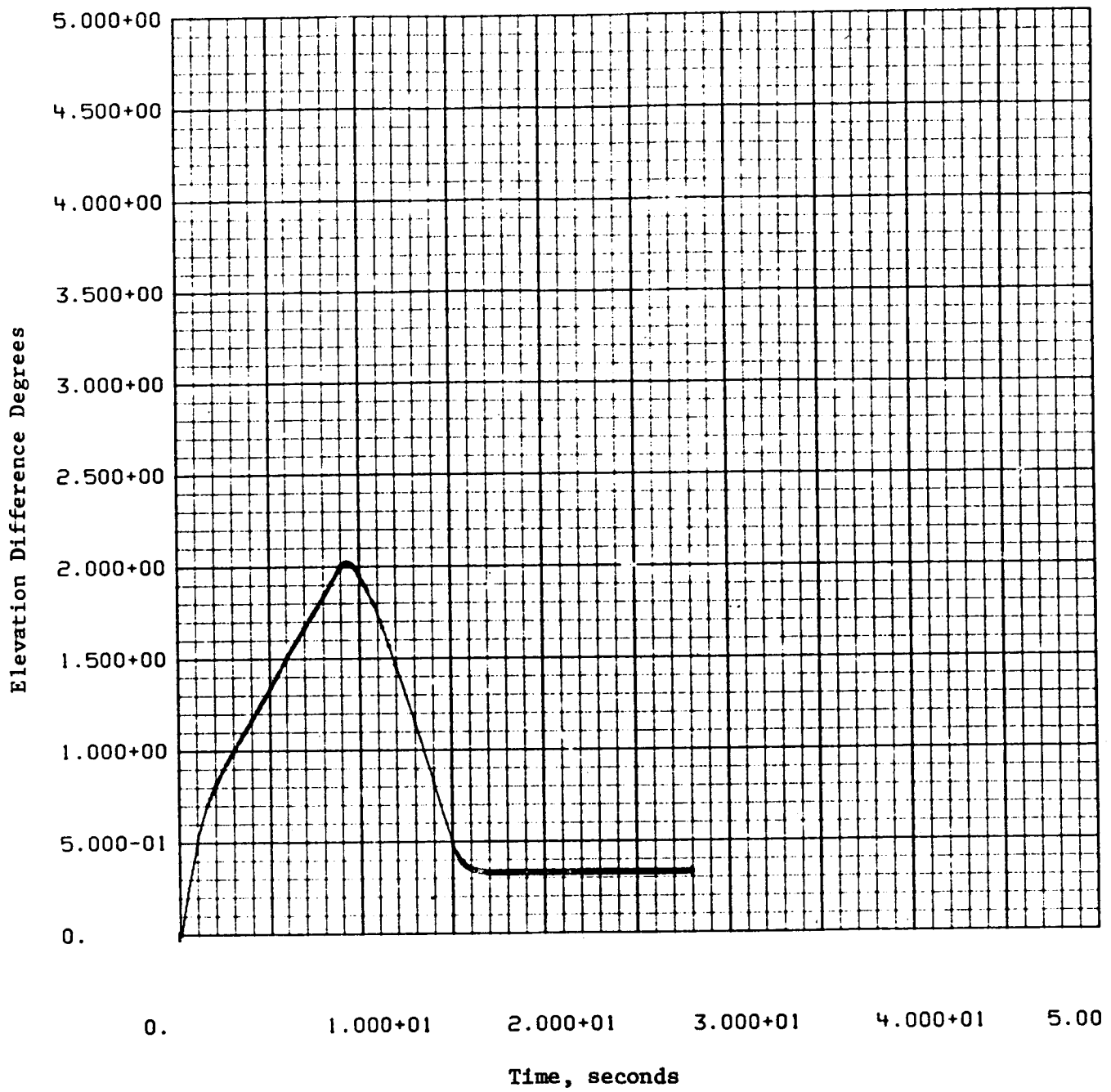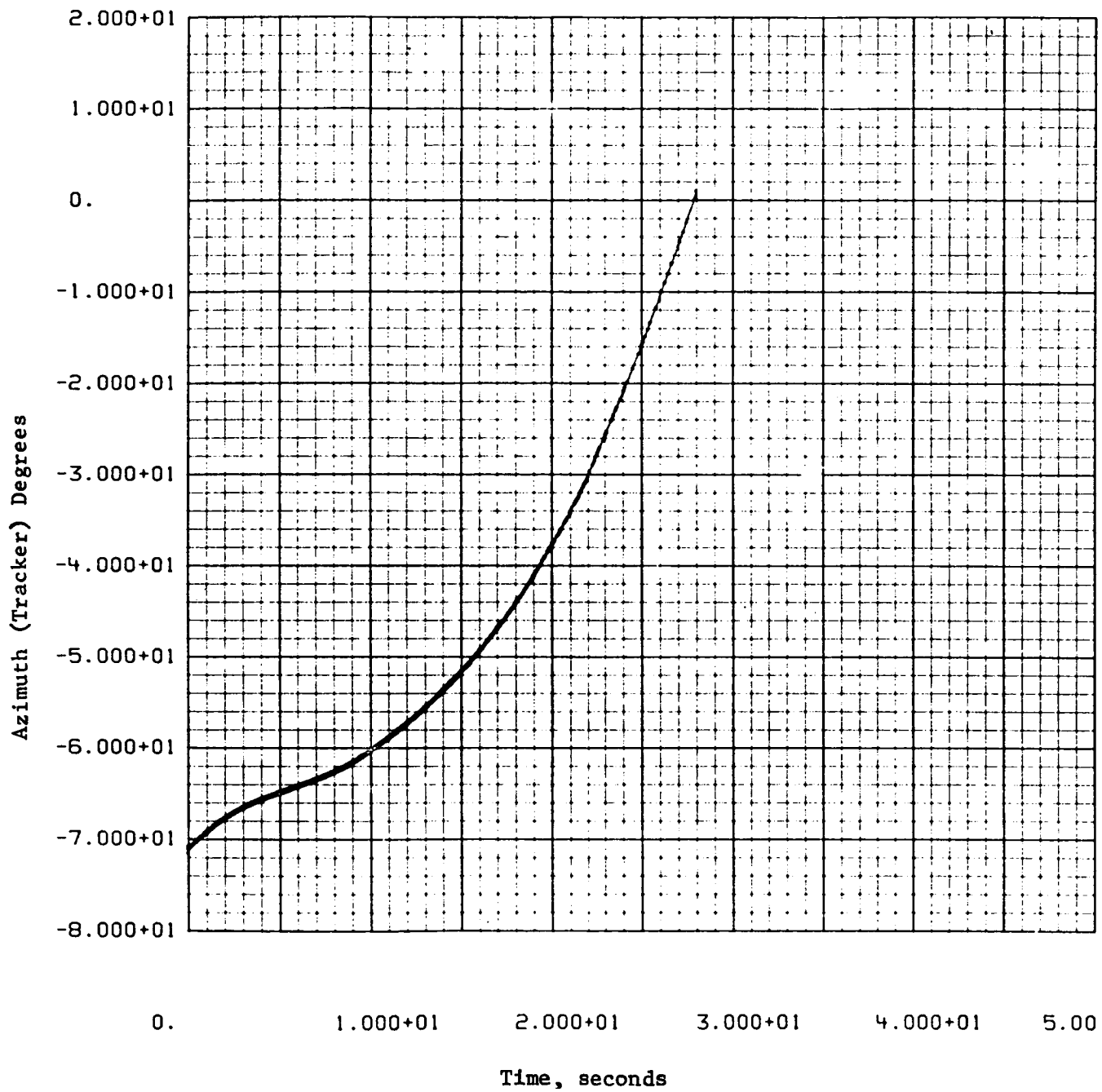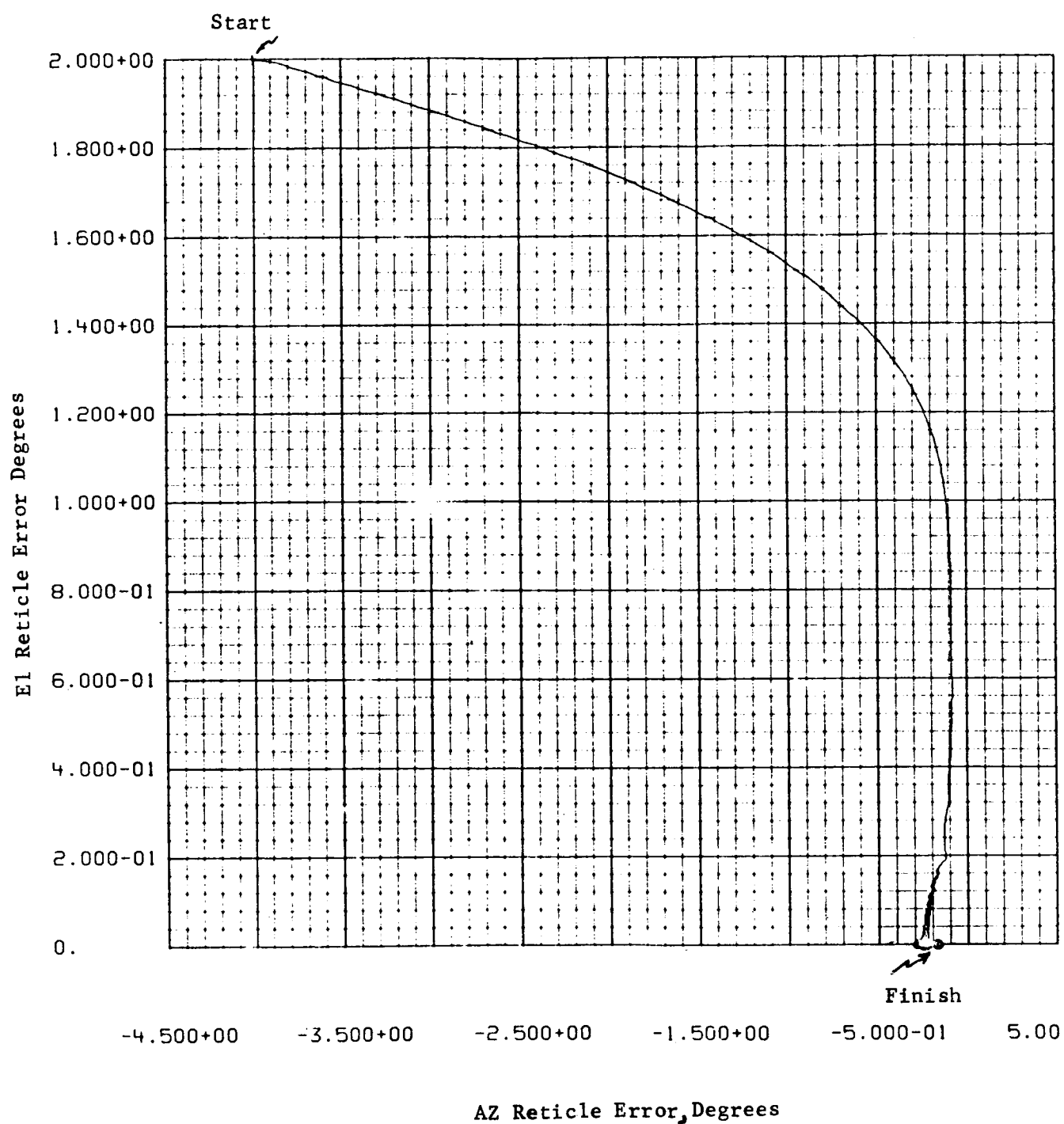
SIMULATION OF EL AND AZ CONTROL

Initial Condition
EL error = $+2^{\circ}$
AZ error = -4°

Figure 32

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Initial pointing of the acquisition and tracking scope will be
accomplished as follows. Predicted Shuttle entry azimuth will
be compared to the sum of plane heading, telescope AZ and acquisi-
tion scope AZ. The difference will be used to torque the scope
servo. Predicted Shuttle entry elevation will be compared to
the sum of plane roll angle, telescope El, stator ring elevation
and LOS angle correction. The difference will be used to elevate
the telescope servo and stator ring. At the time of go-ahead,
determined by predicted Shuttle entry time versus WWV time stand-
ard, the acquisition scope will be positioned and begin tracking
(see Fig. 33).

Acquisition Scope Errors - Sensor errors in azimuth are mainly due
to reticle radial quantization of 7 arcmin per band. The eleva-
tion axis must be much more precise. Errors are broken down into
point source errors and finite image size errors (Fig. 34). Point
source errors are as follows. An off-the-shelf lens will give a
resolution of 82.2 arcsec, while a special-built lens will reduce
this resolution to approximately 15 arcsec. Boresite alignment
will probably be around 30 arcsec and may be reduced by calibra-
tion procedures that may be corrected partially by an electronics
bias. A reasonable reticle resolution will be 7 arcsec. Detec-
tor response may be tailored, but a reasonable value is 16 arcsec
from a 25 kc bandwidth. Demodulation errors appear to be bounded
by the outer clock band resolution. A refined fiber optics light
source for this should yield 7 arcsec accuracy. Errors from the
finite image size are difficult to evaluate at present. At worst,
this should be 75 arcsec, but with an extra signal processing this
should reduce to 14 arcsec. The HP 2100 will be required to handle
this task and would act as the demodulator (see Fig. 35). A bread-
board of the system will be needed to establish firm error numbers;
however, at present, RSS errors of 41 arcsec in elevation appear
feasible.

ADAMS - Servo Interface - It appears feasible to use the ADAMS
system for much of the servoprocessing. This will be accomplished
by coding one HP2100 for servofunctions. The unit will be over-
seen by the ADAMS executive processor. It is expected that the
executive will handle CRT terminal input and output and act as a
monitor and parameter input. The interface to the servoprocessor
will be via an electronics box furnishing the signals not already
existing in the ADAMS. Figure 36 lists the existing and addi-
tional signals required. The repetition rate will be based on
the basic acquisition sample rate of 50 sps. One HP2100 appears
adequate to handle the coding and computation requirements. This
approach should be extremely flexible and allow modifications and
revisions, as required, without last minute hardware changes.
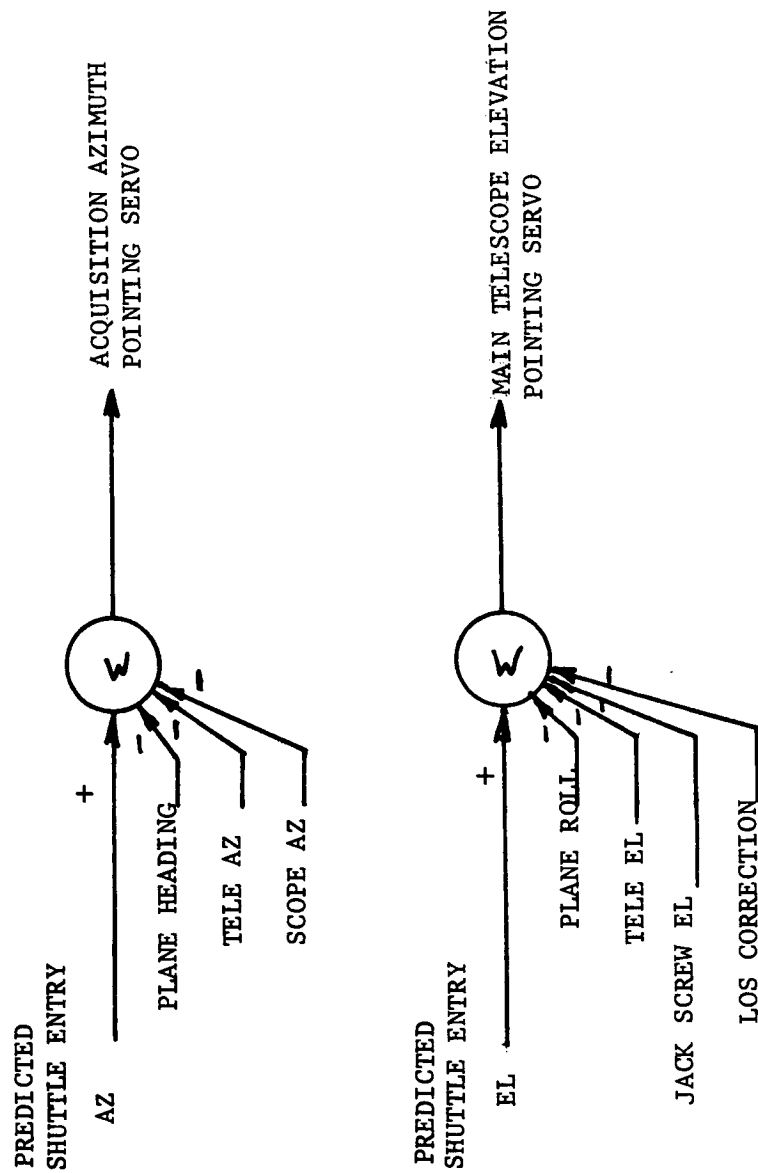
PREDICTED
SHUTTLE ENTRY

AZ

+

PLANE HEADING

TELE AZ

SCOPE AZ

ACQUISITION AZIMUTH
POINTING SERVO

PREDICTED
SHUTTLE ENTRY

EL

+

PLANE ROLL

TELE EL

JACK SCREW EL

LOS CORRECTION

MAIN TELESCOPE ELEVATION
POINTING SERVO

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FIG. 34

TRACKING SCOPE ELEVATION ERRORS

POINT SOURCE ERRORS

	PRELIM.		REFINED
OPTICS	82.2 s	REV LENSE	15 s
BORE SITE	30 s		30 s
RETICLE	7 s		7 s
DETECTOR RISE	8 s	LOWER BW	16 s (25KC)
DE MOD	29 s	REFINE	7 s
		LIGHT SOURCE	

FINITE IMAGE SIZE ERROR   75 s → COMPUTER PROCESS 14 s

Σ 89 s, RSS 41 s

TRACKER DEMOD & INTERFACE

FIG. 35

HP2100

$\theta' = \frac{1}{2}\{\theta_E + \theta_B - \pi\}$

$EL = R \cdot SIN\theta' + BIAS$

$AZ = R \cdot COS\theta' + BIAS$

50 hz

$\theta_B, 2^{12}$

θ_E

SAMPLE θ_B, θ_E

$R, 2^4$

COUNT & BUFFER

COUNT PULSES

FREQ. REFERENCE

72 KC

DIGITAL LOGIC

RETICLE

CLOCK

BAND

ZERO REFERENCE

THRESHOLD

T

THRESHOLD LEVEL

UP, DOWN COUNT

DET.

D/A

SPEED REGULATOR

MOTOR

M

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ADAMS INTERFACE SERVO (HP2100)　　　　　　　　　　FIG. 36

INPUTS

TRACKER AZ RESOLVER
TRACKER DATA: θ, R
ACQ SUCCESSFUL DISCRETE

STATOR RING POSITION A/D
PORT POSITION A/D
LOS POSITION

EXISTING

AZ, EL POSITION
NAV DATA: HEADING ANGLE
ROLL ANGLE
TIME
PITCH ANGLE
ALTITUDE

OUTPUT

D/A TRACKER AZ TORQUER
D/A LOS SIGNAL
2 BIT STATOR RING DRIVE SIGNAL
2 BIT PORT DRIVE SIGNAL

EXISTING

D/A ELEVATION TORQUER
D/A AZIMUTH TORQUER

HP2100

EXECUTIVE

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The design requirements for the Image Plane System are:

1) maintain a state-of-readiness until the Shuttle image enters any detector field-of-view,

2) be compatible with the 91.5 cm f/13.5 telescope image plane but autonomous in performance,

3) provide redundancy, and finally

4) provide adequate signal output to the data handling system under the worst-case encounter parameters with either the Shuttle or YF-12 calibration aircraft.

The streak camera approach to infrared imaging of the Space Shuttle imposes the following general requirements on the image plane detector array system:

1) The resolution elements (each detector) must be consistent with the target resolution requirements (e.g., 0.050 mm);

2) The image must be contiguous (no space) in the streak direction;

3) The detector must respond to grey body radiation in the temperature range from 600 to 1900 K;

4) The detector-filter combination must be in a wavelength region so that the first derivative $\left(\dfrac{dW}{dT}\right)$ is large enough to yield the required Shuttle temperature resolution, i.e., 5% (2½% design goal).

The time constant of the detectors must be short enough not to be a major contributor to limiting the spatial resolution of a 40-microsec detector element crossing (i.e., the 40-microsec element crossing time will be at least five time constants of the detector).

The first task undertaken was to determine the best available IR sensor compatible with the experiment objectives.

The requirement of measuring the radiance from a rapidly moving target with portions ranging from 600 to 1900 K presents constraints limiting the choice of detectors. The short wavelength region was chosen for maximum temperature resolution; however, it could not be too short or it would be insensitive to the lower temperatures. An array of detectors was necessary because of the measurement's short duration.

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The selection of detectors considered and some of their characteristics are as follows:

Detector	Sensitivity	Detector Temperature, K	Response	Wavelength Range, μm
Lead Sulphide	D* 5×10^{11}	193	2 msec	0.6 to 3
Silicon	D* 10^{12}	300	1 μsec	0.3 to 1.1
Pyroelectric Vidicons	D* 10^9	300	10 msec	Thermal only
Lead Selenide	D* 3×10^{10}	77	20 μsec	1 to 4.5
Indium Arsenide	D* 5×10^{11}	77	5 μsec	1 to 3
Mercury/Cadmium/Telluride	D* 2×10^{10}	77	0.5 μsec	8 to 15
Indium Antimonide	D* 3×10^{11}	77	0.5 μsec	1 to 5.5

The requirements include a spectral response from 1 to 3 micrometer, a D* above 1×10^{11} and a response time of 1 microsec or faster.

Only indium antimonide meets all the requirements necessary for the detector and can be manufactured in an array format.

Detector Array - To reduce cost and complexity of the detector system, a major goal was to reduce the number of detectors. By adding up the tracking uncertainties and using the worst- (largest image) case trajectory, it was found necessary to have approximately 320 detector in a linear array. Taking a conservative approach, 40 detectors were added to each end bringing the total to 400. For the 2nd row, it was determined that 200 detectors would meet the requirement if the RSS of the error sources is used.

Detector Array and Filter - The detector arrays shown in Figure 37 consist of two linear InSb (PV) arrays in the image plane. One array contains 400 detectors, the other 200 detectors. The 200-element array is added for redundancy. As shown in the enlarged view, each detector element is 0.002 in. (0.050 mm) square with a crosstrack spacing of zero. Because of measurement conditions, namely that the Shuttle image will cover only a portion of either array, it is possible to reduce the number of leads leaving the focal plane by connecting two or more detectors together. A scheme for connecting three detectors together, thereby reducing the total number of leads to 200, is shown in Figure 41, Data Handling Schematic.

The filter shown in Figure 38 is designed to accomplish three tasks. It significantly reduces background irradiation and therefore the noise. It cuts off a major absorbtion band thus easing the data reduction problems. And finally, it reduces the irradiation (on the short wavelength side) from the higher target temperatures to reduce the dynamic range. This allows (as discussed later) a better quantization of the lower target temperatures using a 12-bit system.

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FIG. 37

PRIMARY TELESCOPE IMAGE PLANE

IMAGE PLANE

SENSOR ARRAY

ENLARGED VIEW

14 arc min

TRACKING ERROR 3 arc min

.002"

.004

FIG. 38

C141 IMAGING SYSTEM

PROPOSED FILTER

FILTER CHOSEN TO AVOID ATMOS-
PHERIC ABSORBTION BANDS AND
ALSO TO LIMIT THE DYNAMIC RANGE
OF THE INCIDENT RADIATION.

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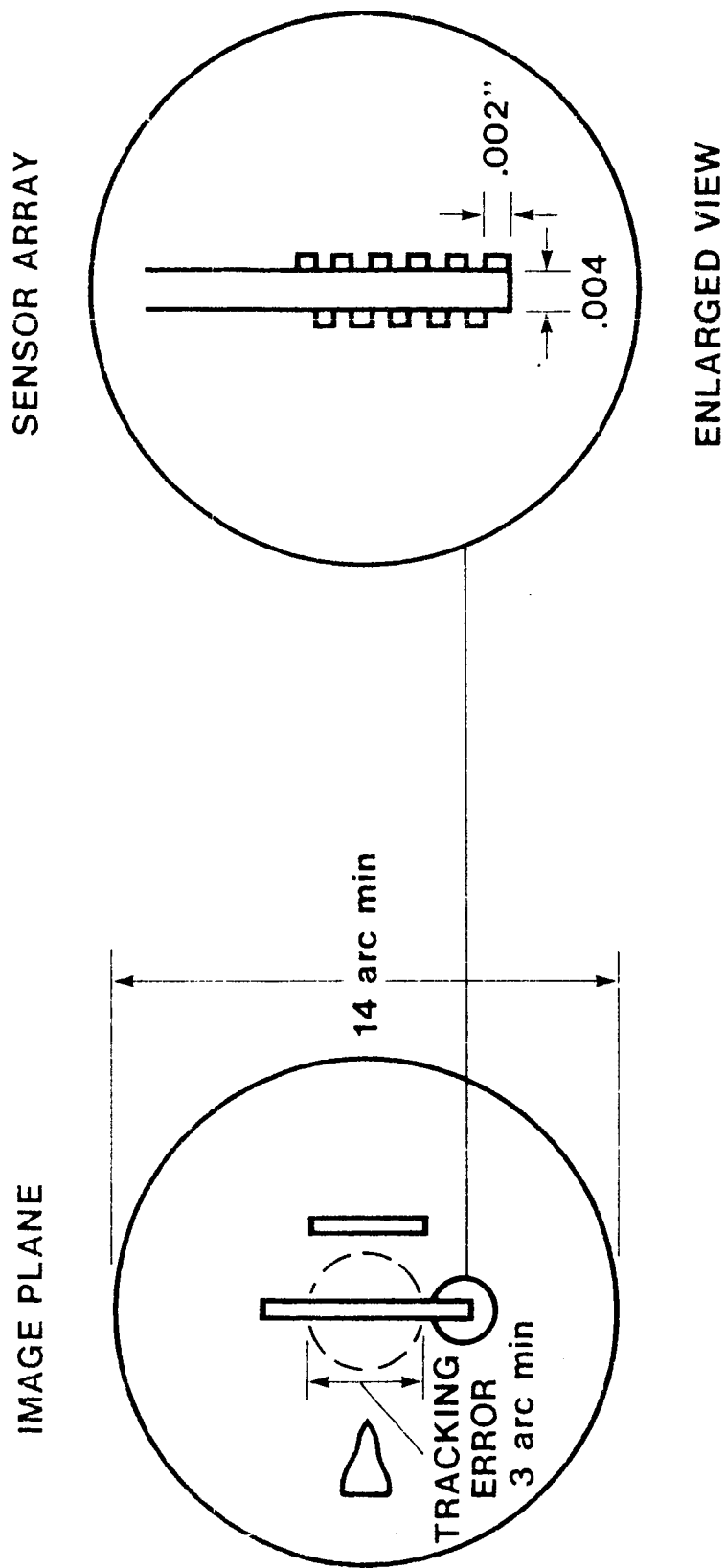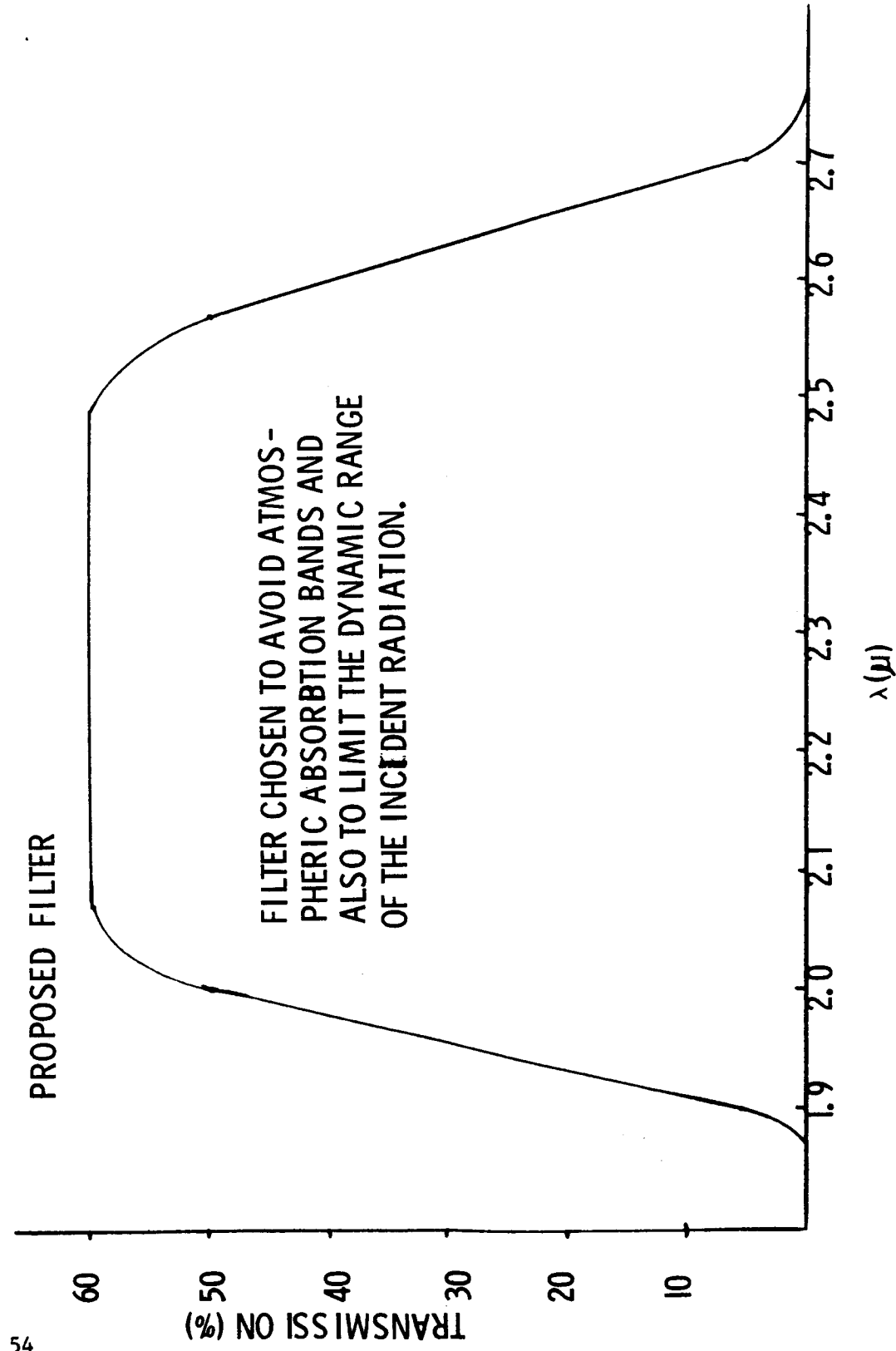
Dewar Assembly - The Dewar assembly shown in Figure 39 is an approach to housing the detector array and amplifier assemblies to the main telescope while keeping the seal integrity of the airplane-to-telescope interface.

The detector array is located at the focal plane of the main telescope. The Dewar is designed to cool the detector arrays and the bandpass optical filter. The detector leads will pass through the Dewar walls and then through hermetic seals to the amplifier boards located in the area around the Dewar. The amplifier board mounting system will allow easy access for troubleshooting and board changing.

Calibration of Detector Array - For an extended source, if the F-number is kept the same, then the following relationship exists (subscript A = telescope and subscript B = auxillary calibration system).

$$K_A D_A^2 \theta_A = K_B D_B^2 \theta_B$$

where

$K_{A,B}$ is the optical transmission of each system.

Using the system shown in Figure 40, we will illuminate approximately 137 detectors at each position setting. The procedure would be to mount the Dewar/detector array to the calibration system as shown and move the collector lens in a stop-and-take-data scheme. This procedure would be repeated for a number of source temperatures. It would use the entire amplification and data taking system. After the Dewar is mounted to the main telescope, there will be an electronic check capability of all amplifier gains.

Preliminary Prep/Flight Procedure - Following installation of the acquisition and imaging system in the C141 AIRO, a preflight alignment is necessary. This can be accomplished in the AIRO hanger using the calibration test equipment as follows:

1) Mount the blackbody source/collimator in the hanger so it can be viewed by the telescope/acquisition system. (Maximum image size is 1 arcmin.)

2) Acquire and lock-on with the acquisition system.

3) Electrically bias the acquisition system error signals in evaluation and aximuth until the 1 arcmin image is centered on the 400 element array of the image plane system.

FIG. 39

DEWAR ASSEMBLY

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DETECTOR CALIBRATION

FIG. 40

DETECTOR ASSEMBLY

DETECTOR

LENS X-Y
ADJUSTMENTS

BLACK BODY

OFF AXIS PARABOLIC
MIRROR
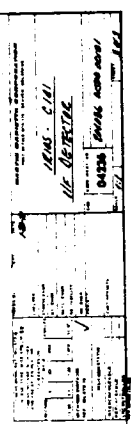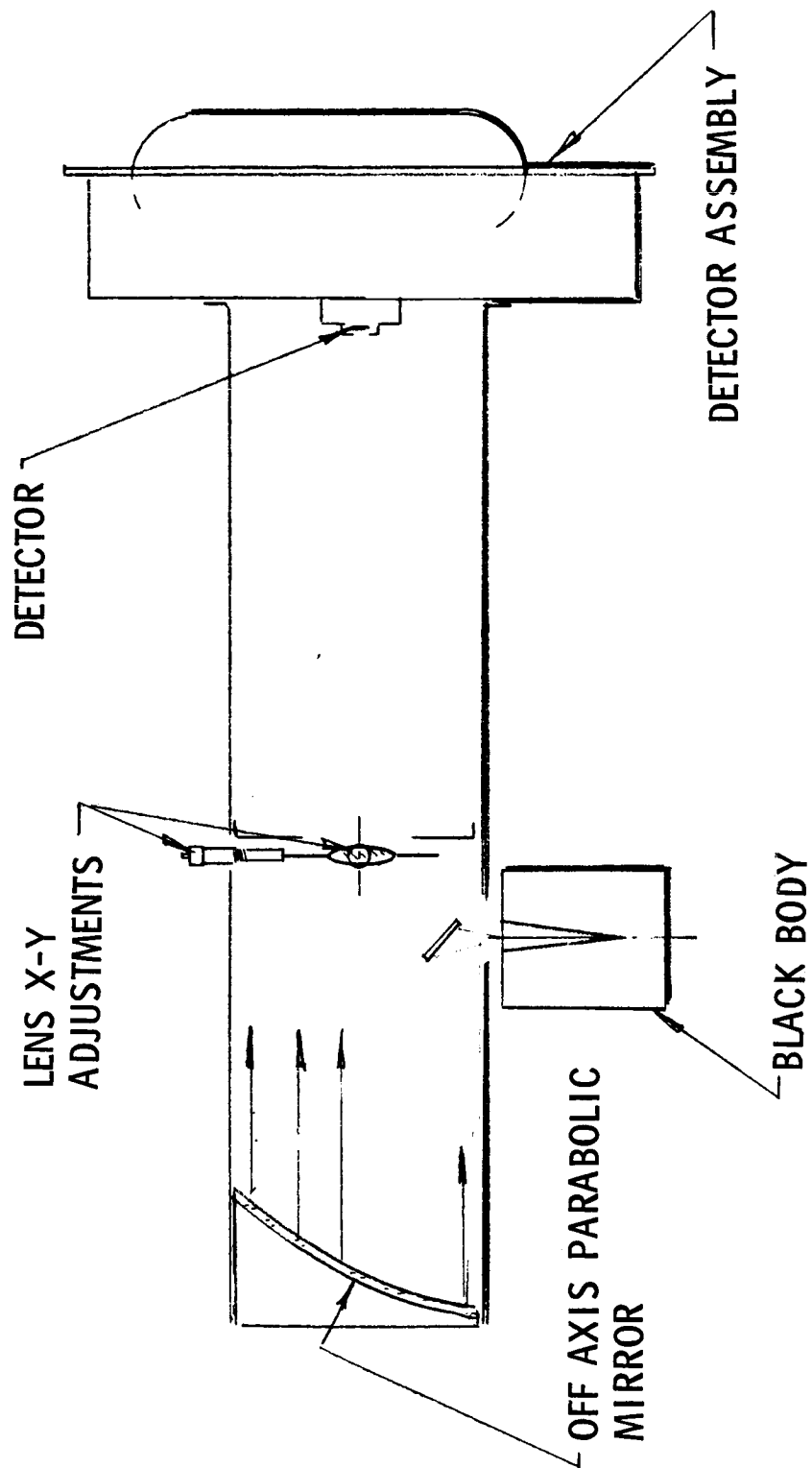
Verification of alignment at altitude is desired and can be accomplished using a star. The procedure would be similar to that described above. During preflight preencounter alignment procedures, it is planned to obtain optical boresighting between the acquisition system and main telescope by viewing a star. The system sensitivity of the main telescope imaging system is approximately 10^{-14} W/cm^2. For the acquisition system, it is approximately 2×10^{-12} W/cm^2. Several stars and planets have spectral irradiances in the range of 2 to 5×10^{-12} in the 1.0 to 2.5 micrometer region that will be usable as boresight targets. Another aspect of the system concerns focus and depth-of-focus. After boresighting on a star, the main telescope must be refocused to properly view the Shuttle. A focus shift of at least 2 mm is required at the focal plane. This may be accomplished by movement of the secondary mirror. The depth-of-focus of the system is given by

$$\delta = F\beta(f/\#)$$

where

F = Focal Length

$\beta = 7\times10^{-6}$ rad

$f/\# = 13.5$

Depth-of-focus (δ) then is 1.12 mm or about half the required focus shift. This means the required accuracy for focusing the telescope is only 2 ± 1 mm at the focal plane. Any adjustments required would compensate for thermal and aerodynamic distortion at altitude.

After alignment verification is made, the procedure for data taking is as follows:

1) Slew acquisition telescope to forward or aft acquisition angle depending on flight direction with respect to Shuttle.

2) Slew main telescope to nominal elevation angle for data pass.

3) Put acquisition system in stand-by/armed (reticle active but azimuth servo in hold).

4) Position C141 on ground track appropriate for particular data point.

5) Set time sequence with respect to anticipated Shuttle intercept.

6) At time of anticipated Shuttle acquisition (T = 25 sec), verify acquisition system switched from stand-by/armed to track.

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7) By T = 10 sec, verify acquisition system switched from track to lock.

8) Data system is automatically armed by acquisition lock.

9) Verify data system data acquired condition and dump to tape.

_____

Design Requirements - In its simplest form, the Data Handling
System is required to: (1) interface the 600 indium antimonide
detectors that form the two linear detector arrays in the focal
plane of the C-141 main telescope, and (2) provide to the C-141
ADAMS computer all the information produced during the passage
of a single Shuttle image across the detector arrays. The de-
sign requirements come from two different sources. The first
set of requirements derive from the selection of a detector
type, the associated array geometry, and the image size dictated
by the telescope optics and the Shuttle flight path relative
to the C-141. These elements are covered in other parts of this
report but they drive design requirements in the data system.
The second source of design requirements is the final desired
form of the information gathered by this system. Those require-
ments involve parameters like measurement range and resolution.
Each of these two kinds of design requirements are treated as
follows:

a. *Design Requirements Imposed by Interface Hardware Detectors-*
Each diode detector is a current transducer that will convert
IR flux to current. The baseline detector will produce approxi-
mately 0.8 nanoamp of current at a radiance representing 600 K
and 1.17 microamp at 1700 K. At the maximum Shuttle temperature
of 1900 K the output current is 2.75 microamp. For design pur-
poses the first stage amplifiers must handle a current of 0 to
2.75 microamp ±10%. The detector is a current generator in
parallel with a 10^8 ohm resistance. Operation of the detector
will be in the zero voltage mode so that neither detector source
resistance or capacitance is a major concern in the design.
Also, detector noise is not a major factor in the design. The
feedback resistor in the first current amplifier is the major
source of noise. A significant design requirement involves the
constraining of the detector to amplifier wiring so that the
cable capacitance is not modulated by aircraft vibration or
sound. The detector-to-amplifier wiring is by far the most sus-
ceptible point in the signal processing path. Extreme case
must be taken to eliminate stray electric or magnetic fields
or currents in this wiring. An element of difficulty could be
encountered here because all the detectors are single ended;
providing their signals against a common ground reference. This
means that none of the methods of common mode noise rejection
can be used in this design. The noise sources must simply be
kept from reaching this critical front-end circuitry.

The detector geometry and Shuttle image size (see Fig. 41) permits the 600 detectors to be segmented into 100 element arrays that are grouped into three sets of 200 each. The corresponding detectors in each set are then wired together to reduce the number of signal channels to 200. This is possible because the Shuttle image is small enough and the array is large enough because of tracking uncertainties, such that the Shuttle image can pass over only one detector of any parallel groups of three on any one pass. No problem is anticipated from paralleling detectors.

ADAMS - The ADAMS is a data processing system built around a pair of HP2100 computers. Their peripherals exists on the C-141 aircraft/ therefore, they will be used to checkout the detector data handling system and to write the detector output onto computer tape. The ADAMS will also issue operating mode commands to the data system, display calibration data, and perform the most important data present test. These design requirements will be expanded in the data system description section.

b. Design Requirements Generated by the Project - The temperature range is 600 to 1900 K. This range requirement is actually included in the current output specified from the detector but a measurement accuracy/resolution was not treated. A measurement accuracy of 2½% of full scale is desired; however, it is not a meaningful concept due to the extreme nonlinear nature of the measurement. Instead of setting a requirement, analysis of the measurement and the possible methods of implementing the measurement led to the conclusion to digitize the measurement and to digitize down into the noise level. The overall system signal-to-noise ratio will not be known until the system is built and installed on the aircraft. The lower noise limit is set by the thermal noise in the feedback resistor around the 1st stage amplifier. Analysis shows this to be in the order of at least one significant bit for 12-bit encoding. Therefore 12-bit encoding is specified as a design requirement.

The frequency response amplifier also has a somewhat arbitrary design requirement. The 3 dB down-point is to be at 50 kHz or greater. The sample rate for A/D conversion is not set by the frequency response number but by a requirement to keep the pixels square. An analysis of all Shuttle passes indicates pixel rate between 10,000 and 20,000 per sec with some margin. That is the design requirement for the measurement sample rate. Further study may indicate that a slew rate criteria will be more appropriate than a frequency response criteria but that is not clear at this time.

DATA HANDLING SCHEMATIC

FIG. 41

6M BITS/SEC

500K SAMPLES/SEC

A/D

SAMPLE & HOLD

MX

BUFFER MEMORY

DATA SYSTEM CONTROL

TAPE

HP2100

2 x 10^6 BIT RAM

20 MX, S&H, A/D

200 AMP

600 DETECTORS

SHUTTLE IMAGE

1
10
101
201
210
301
400

1
10
101
200

63
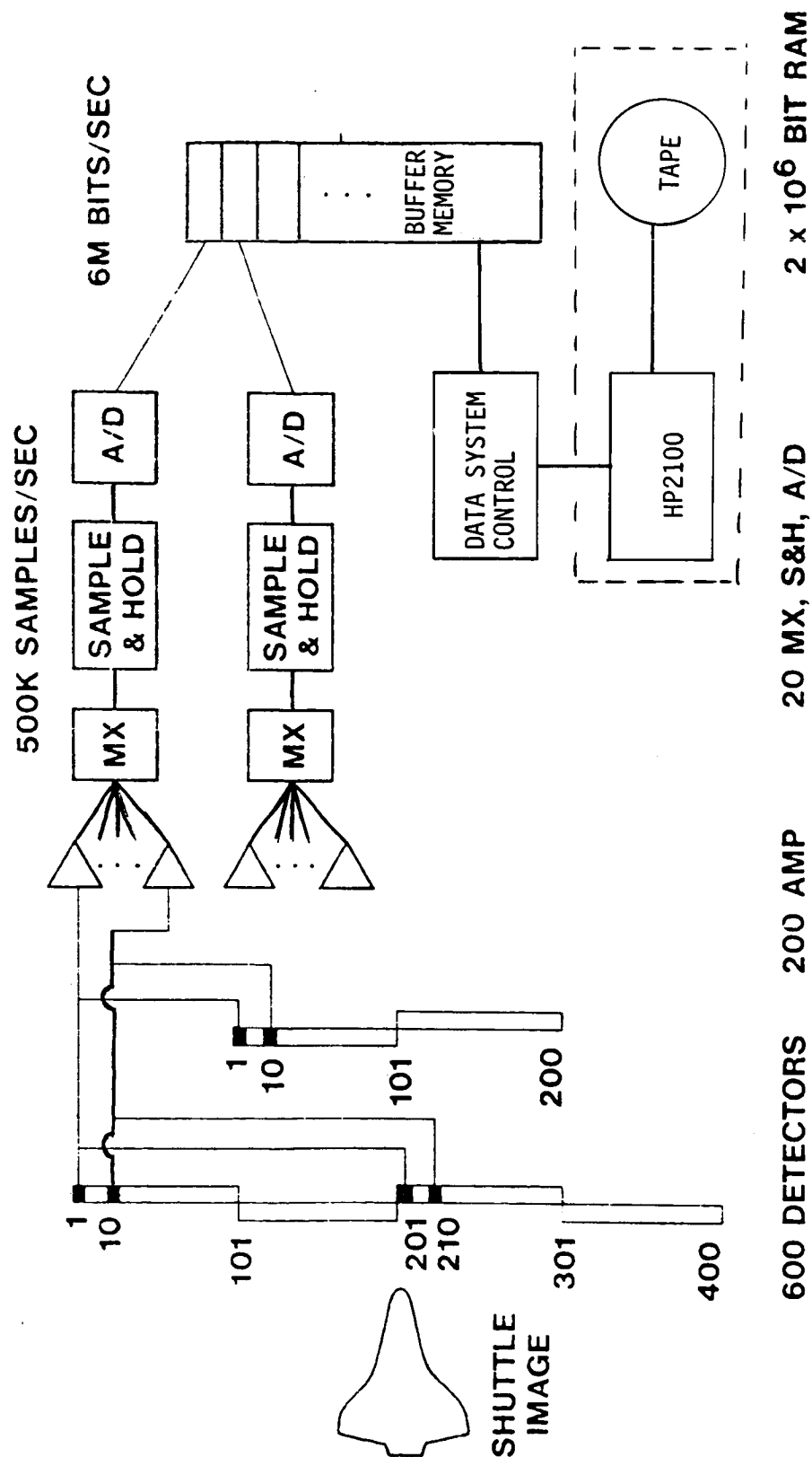
The total throughput data rate is simply the maximum sample rate (20,000) times the number of channels (200) times the word length (12) or 48 mbs. Note that this rate never really occurs in the system because the data are handled in many parallel channels, with each channel running at a much lower rate. The ability to change the system clock is another somewhat arbitrary design requirement that must be established. The design requirement is that the system clock must allow operation of the system within 5% of any A/D sampling rate desired between 10,000 and 20,000 samples/sec (sps) on a given channel. A data storage requirement can be arrived at based upon the highest pixel rate and the longest Shuttle pass. That is, 15901 sps for 13.82 msec or 527,404 bits. As a design requirement, a memory of at least twice this size is specified to allow for the storage of a block of data and its subsequent test by the ADAMS for Shuttle image content, during the period that the second block of data is being written.

Data Handling System Design - This section describes the baseline system design arrived at during the study but does not attempt to justify the system.

Overall Design Description - Figure 42 shows the overall flow of information from the Space Shuttle to the C-141 telescope through the detectors and into the data system. The data are accumulated in the data system buffer and then read into the ADAMS computer and written onto computer tape. The figure clearly shows the system interfaces; however, it must be remembered that the ADAMS is an intrinsic part of the functional system and what is referred to in this report as a data handling system is only a part of a system and will not function in a flight mode without the ADAMS.

Figure 41 is a more detailed data flow schematic and shows the paralleling of the 600 detectors into 200 analog measurement channels. Each measurement has a 1st stage amplifier and a 2nd stage amplifier. The outputs of the 200 2nd stage amplifiers are assigned by groups of 10 to 20 different but identical multiplexer, sample and hold, and A/D modules. These data modules will be purchased as complete operating systems. The Datel DAS250 system has been baselined for this module. The outputs of the 20 data system modules are read into the 1 megabit Static Ram Memory. The memory is accessed by the ADAMS system through the data system control unit. That access is either in the test-for-data mode where only selected channels are tested to see if data are present during the actual Shuttle pass or access is in a mode where the entire contents of memory are read into the ADAMS and placed on tape, or displayed.

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TEMPERATURE INFORMATION FLOW

FIG. 42

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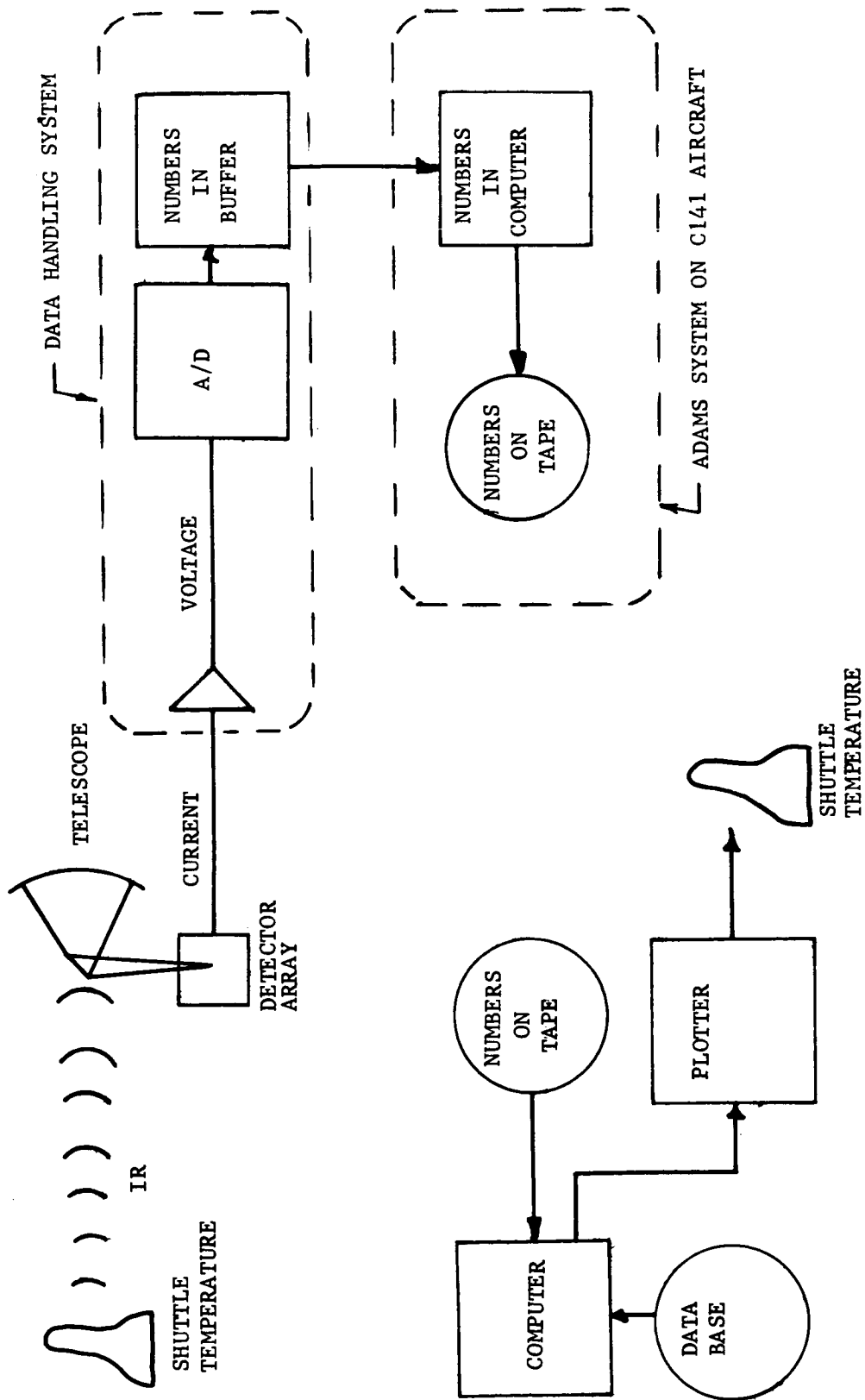
<u>Detailed Design</u> - A detailed design was not performed in this
phase but some material exists that will be useful in the detail-
ed design phase.

a. Measurement Amplification - Specific amplifiers were not se-
lected but a firm decision to use operational amplifiers was
made. Some discussions of the amplifier channel follow.

The detector size and type has been established in other portions
of this study. Based upon the detector characteristics and some
typical FET input amplifier characteristics, the amplifier input
signal is 0.8 nanoamp at 600 K and 3.0 microamp at 1900 K. With
a 10^6 ohm feedback resistor in the first amplifier, its output
voltage will be 0.8 mV to 3.0 V. The second stage of amplifica-
tion will produce 2.6 mV to 10 V. By calculation, and with a
safety factor of 3, the noise at the output of the second ampli-
fier is 1 mV peak.

This sets the minimum size for the resolution element. If that
element were twice the peak-to-peak noise, then it would be 4
mV or one part out of 2500. Ten-bit encoding is 1/1024, 11 is
1/2048, and 12 is 1/4096. It is apparent that encoding beyond
12 bits will not increase the information provided by the measure-
ment. For instance, if a 0- to 10-V signal is digitized to 13
bits, the least significant bit will represent slightly more
than 1 mV but it will change continuously due to the 2-mV peak-
to-peak system noise, and therefore will provide no useful in-
formation. The following table shows the delta temperature
represented by the noise voltage as a function of temperature.
It is not a single number because of the extreme nonlinear na-
ture of this measurement. See Figure 43.

Temperature, K	NEΔT, K
600	13
700	4
800	2
900	1

A second major consideration is the temperature resolution *de-
sired*. Two numbers have been used, 5% of reading as a require-
ment and 2½% of reading as a goal. Because of the nonlinear
measurement response, the measurement is most difficult to make
at 600 K. At that temperature, 30° must be resolved to meet the
requirement and 15° is desirable. A 10-bit conversion of the
600 to 1700 K measurement range yields only about 48 K resolu-
tion at 600 K. Either an increase in the digitizing level or a
decrease in measurement range is necessary to meet the 5%, 30 K
criterion. Encoding to 11 bits meets the 5% criterion and en-
coding to 12 bits meets the 2½%, 15-K criterion. It should be

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TEMPERATURE VERSUS COUNTS

FIG. 43

COUNTS

1000

900

800

700

600

500

400

300

200

100

600   700   800   900   1000   1100   1200   1300   1400   1500   1600   1700
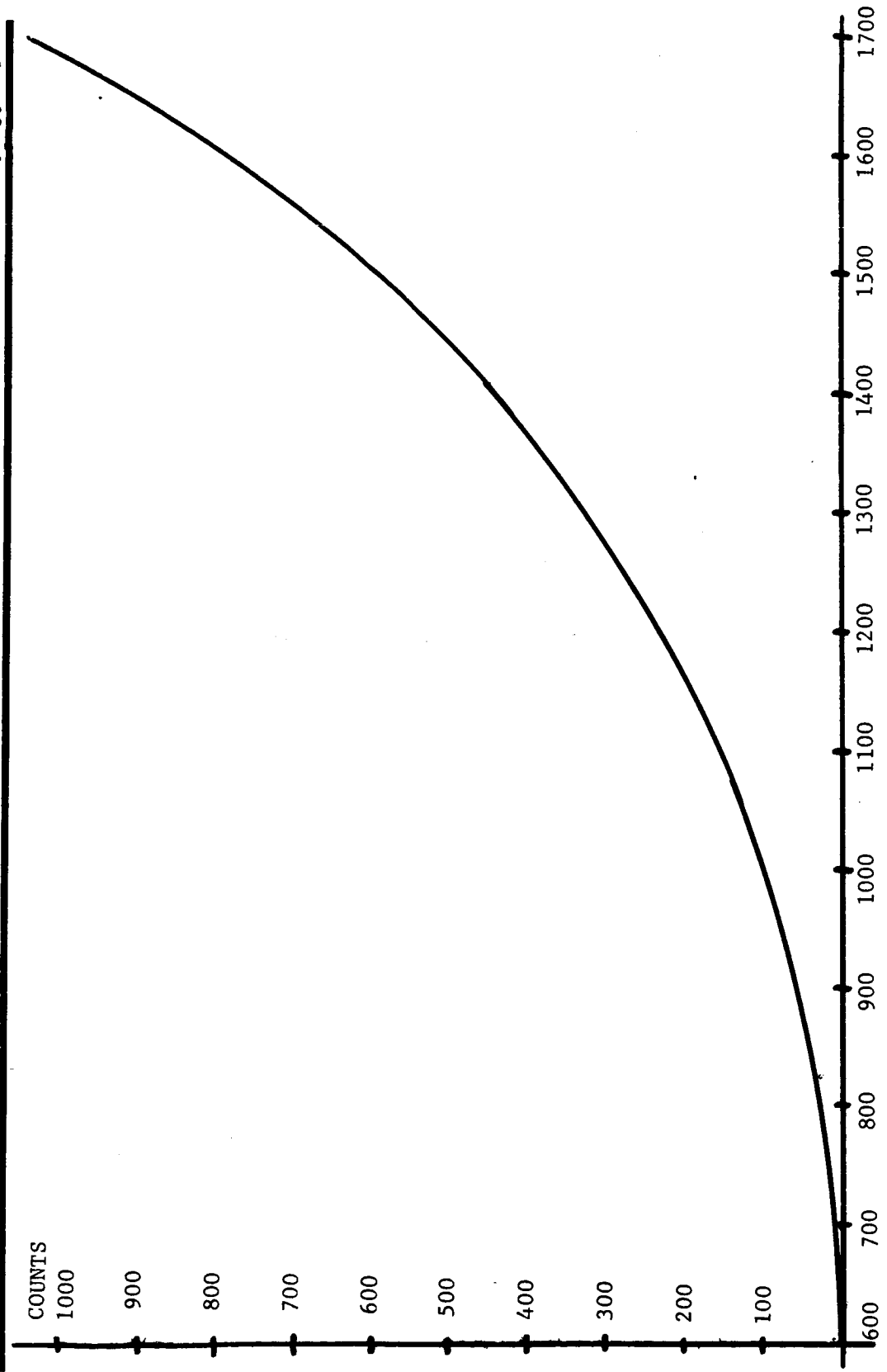
TEMPERATURE   K

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remembered that 15 K resolution is approximately the same ampli-
tude as the calculated system noise of 13 K. Again, the conclu-
sion is that 12-bit encoding is desirable.

Some effort was expended trying to make the measurement more
linear. This type of problem has been solved previously by us-
ing a transistor for the feedback resistor around the first
measurement amplifier. Its effective resistance is an inverse
function of the feedback current. This produced a logarithmic
measurement response relative to radiation flux and a more
nearly linear response relative to temperature. Unfortunately,
discussions with the design people involved indicated that it
would not be possible to increase the frequency response of that
type of circuit to that required in this application. Another
approach is to make two or more measurements out of each measure-
ment and expand the scale of each; however, neither of the
above approaches looks feasible for this task.

The basic conclusion reached is that two linear operational am-
plifiers are required for each measurement. The 1st stage ampli-
fier should be a high quality, low noise, FET input amplifier
operating as a transimpedance or current amplifier. The most
serious concern when using this amplifier is the gain bandwidth
product required and the desirability of a very flat gain curve
over the information bandwidth. The second stage of amplifica-
tion appears to be very straightforward and any number of ampli-
fiers can do this job.

b. Datel DA5250 Data Module - This module will accept 16 single-
ended measurements at a throughput rate of 250,000 sps with each
sample converted to a 12-bit number. The following table sum-
marizes its major characteristics.

Number of Channels	16
Input Type	Single-Ended
Input Voltage Range	0 to +10 V
Input Impedance	100 MΩ
Channel Addressing	4-bit code
Address Logic Compatibility	DTL/TTL
Resolution	12 bits
Nonlinearity Maximum	1/2 LSB
Maximum Error at Maximum Throughput	0.025%
Temperature Coefficient Maximum	40 ppm/°C
No Missing Codes	0 to 70°C
Throughput Rate Maximum	250,000 kHz
Acquisition Time	2 μsec
Conversion Time	2 μsec
Aperture Time	20 nsec
Output Coding	Binary and 2 Complement
Voltages Required	±15V, +5V
Package Size	12.7x11.4x3.8 cm
Operating Temperature Range	0 to 70°C

The use of this existing data system module greatly simplifies
the design of the overall system and is very cost effective.
The specifications listed for this module are remarkable and if
maintained in the system design will be transparent in the
end-to-end measurement transfer function.

c. *Static Memory* - A specific memory was not selected but the
EM&M SEMS12 memory which is off-the-shelf could do this job. It
is a 16K by 18-bit unit. At least four memories are required
to support the total bit rate and storage requirement. More
design must be done to thoroughly understand the best approach
to implementing the memory. Each memory module is approximately
16.2x22.8x3.5cm and weighs 1.68 kg.

d. *Memory Save Criteria* - In addition to the two other interest-
ing characteristics of this system, the high data rate and the
relatively small amount of information generated, a third
characteristic exists. That is, it is not exactly known when
the information will be generated. If a very large storage
medium such as magnetic tape was available, then the system would
simply be turned on well ahead of time and run until it was
verified that the Shuttle pass had occurred. With the selection
of electronic memory for storage, because it reduces cost, it
is necessary to develop a method of testing these data for the
presence of Shuttle information so that the system can be
stopped when it is verified that two complete Shuttle images are
stored. Because of the computing power available in the ADAMS
system, such a test is possible.

With digitized data, a redundancy removal or threshold detection is easy except that the system runs fast. A substantial amount of hardware would be required to process all these data in any manner. A possible way around this problem is to use two buffer memories and write them alternately. Then test a few selected channels and times and determine if Shuttle information is present. If it is, then that memory is saved and the next memory is saved and then the system is stopped. The minimum sampling array that is guaranteed to obtain at least one sample containing Shuttle data is derived below.

Legend:

A Sample Matrix Line Spacing

B Active Line Length

A&B are measured in detectors or samples
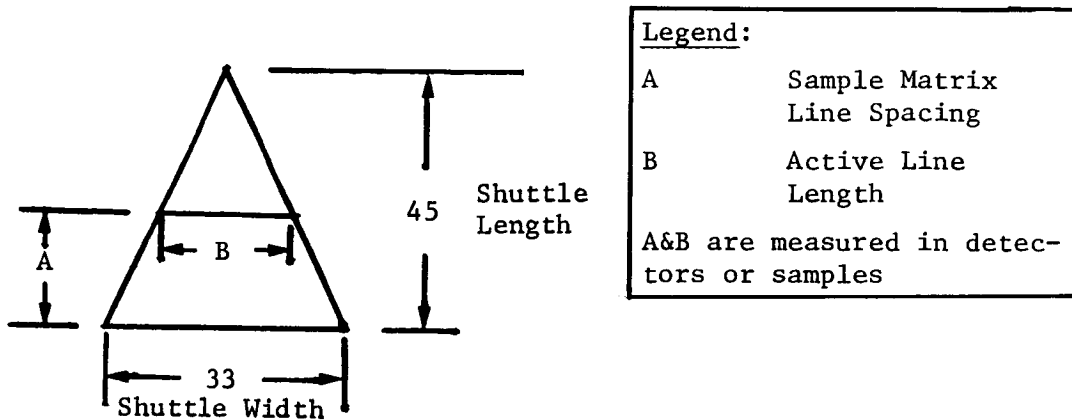
$$B = 33 - \frac{33}{45} A$$

Let N = number of detectors in the sampling rectangle

$$N = AB = A \left(33 - \frac{33}{45} A \right)$$

$$\frac{dN}{dA} = 33 - \frac{33 \times 2}{45} A = 0$$

A .= 22.5 = 22 samples   B = 16.87 = 16 detectors

The result is then for the smallest Shuttle image, every 22nd sample of every 16th detector must be tested. This is the minimum test that will guarantee the detection of Shuttle data if there are no bad detectors or noise affects anywhere in the system. Using the new baseline of 200 detectors in the first array, the test rate for the data from one array is:

$$\text{Test Rate} = \left(\frac{200}{16} + 1 \right) \frac{15558}{22} = 13.5 \ (707.18) = 9547 \text{ tests/sec}$$

A test must occur every 108.8 microsec on an average. The ADAMS HP2100A can do a memory cycle in 980 nanosec and execute most of its instructions in 1.96 microsec. A potential program might involve reading the ambient outputs of the detectors selected for data test, adding the threshold criteria to the ambients and storing the table. When the data-take starts, data to be tested must be read into the arithmetic unit, the criteria number must be read from the criteria table, a subtraction must be performed, and a test of equal to or greater than zero performed. If the result is less than zero, the computer will continue to test, if greater than zero it will generate a memory save signal. The time involved for a single test appears to be equal to two memory cycles and two instruction times or 5.88 microsec. In 108.8 microsec, eighteen tests should be performed where one is the minimum that will detect data. The conclusion reached is that it is feasible to use the HP2100A in the ADAMS to perform the data test.

e. *Electronic Calibration* - A good set of ambient measurement outputs are obtained in this system by its nature. It would appear worthwhile to check the ambients against a criteria stored in the computer and provide violations to the system engineer. In addition, it appears desirable to perform a gain check through each channel by injecting a calibration current into the first amplifier. Again the results of that check should be available. These calibration data would be stored on tape and used during data reduction. One calibration step would probably be adequate, but several would be desirable.

f. *Checkout* - Because of the relatively few times this system will be used, it would seem proper to do a fair amount of manual checkout using conventional test equipment. This is particularly true of steady-state functions like power supply voltage. As detailed design proceeds, careful attention should be paid to bringing out test points on each box that will allow the detection of a malfunctioning box.

A second level of checkout involves the use of a computer. The computer tests would verify that all storage locations are properly addressed and that all bits in each location are working. Every bit of each A/D could be tested if an additional calibration source is used at the A/D inputs.

The calibration sequence itself provides a good overall system checkout.

g. *Controls and Displays* - Power system controls and displays are probably all that are required as part of the data system. All other controls and displays should be adequately provided by the ADAMS and test equipment.

The imaging system performance has been analyzed from the radiation source to the data storage point and includes the following effects; Shuttle flow field, atmospheric, aircraft flow field, telescope optics, image stabilization, detector, and background.

The Shuttle flow field was synthesized by computer modeling (see Fig. 44). The Orbiter shock layer model for two points in the reentry trajectory is shown in Figure 45. Results from this analysis are given in Figures 46 and 47. Figure 46 shows pressure, temperature, and standoff distance of the shock layer as a function of station along the Shuttle undersurface. Figure 47 illustrates the radiative equilibrium temperature also as a function of station.

Figures 48 and 49 depict the variation in heat flux at the Shuttle wall with heat flux at the shock layer and the contribution of energy (line structure) due to self-radiation of the shock layer $\left(Q_{IS}\right)$. In all cases the energy density emerging from the shock layer is almost identical with that on the Shuttle wall $\left(Q_{CW} = Q_{CS}\right)$ indicating no effects due to the shock layer in the region of 0.5 to 6.2 micrometers. Variations of pressure by a factor of 1.5, temperature by a factor of 1.25, and density by a factor of 3 also indicated no difference between the Shuttle-radiated energy and that at the shock layer. Spatial resolution effects were also assessed by evaluating the modulation transfer function of the interviewing bow shock. Figure 50 indicates no modulation loss down to a spatial frequency corresponding to one arcsec.

The atmospheric effects include transmission as a function of wavelength (Ref. 10) and spatial resolution losses from upper atmospheric turbulence. Figure 51 depicts the atmospheric transmittance as a function of wavelength from an aircraft altitude of 12.5 km looking upward 35° from the zenith. No appreciable losses occur in the wavelength band from 1.5 to 2.5 micrometers that has been chosen as optimum for Shuttle radiative energy transfer.

The modulation transfer function of the upper atmosphere is shown in Figure 52. It has been described by Hufnagel and Stanley (Ref. 9) and by Farhat and Decon (Ref. 11). The atmospheric structure constant (Ref. 12) has been evaluated numerically between 12.5 and 70 km for one case and 12.5 and 40 km for case two. The associated zenith angles for Case 1 corresponds to conditions found early in the Shuttle reentry profile and Case 2 to the later, lower altitude conditions. The atmospheric effects have a significant effect on the system performance. Increasing the aircraft

ORBITER NOSE REGION MODELS

FIG. 44

α = 42°

30°

R_n

~11°

~1°

Sta.
1120

(x/L = 0.125)

Spherical Nose

α	R_n
30°	121.5 cm
42°	168.0 cm
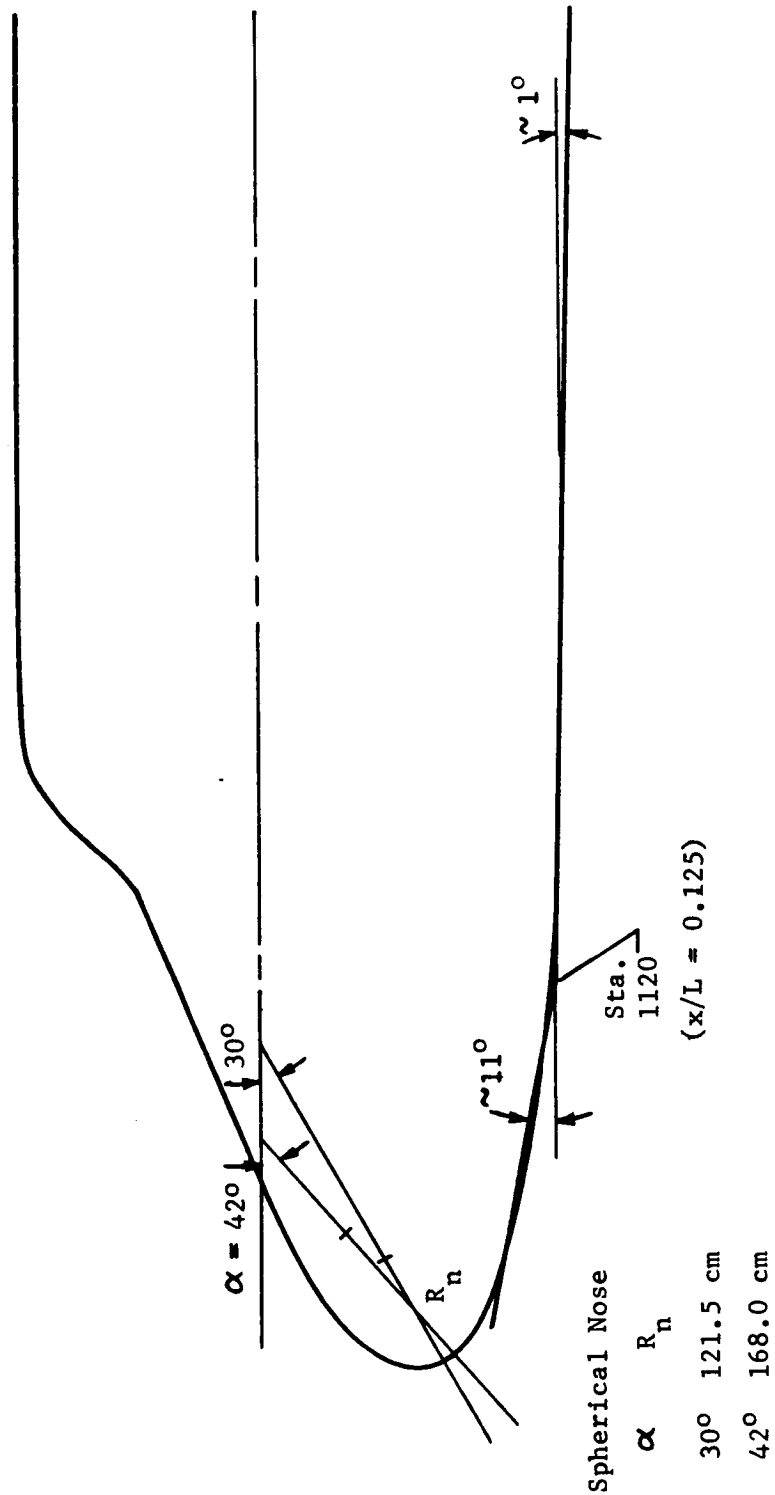
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ORBITER SHOCK LAYER MODELS

FIG. 45

Orbiter trajectory 14414.1

Traj. time 450 s

Dual cone model

$R_n = 166$ cm
$\theta_{c1} = 52.5°$
$\theta_s = 55.2°$

Sing. cone model

$R_n = 316$ cm
$\theta_{c2} = 42.5°$
$\theta_s = 44.6°$

Traj. time 1200 s

Dual cone model

$R_n = 125$ cm
$\theta_{c1} = 41.8°$
$\theta_s = 46.5°$

Sing. cone model

$R_n = 234$ cm
$\theta_{c2} = 31.8°$
$\theta_s = 35.5°$

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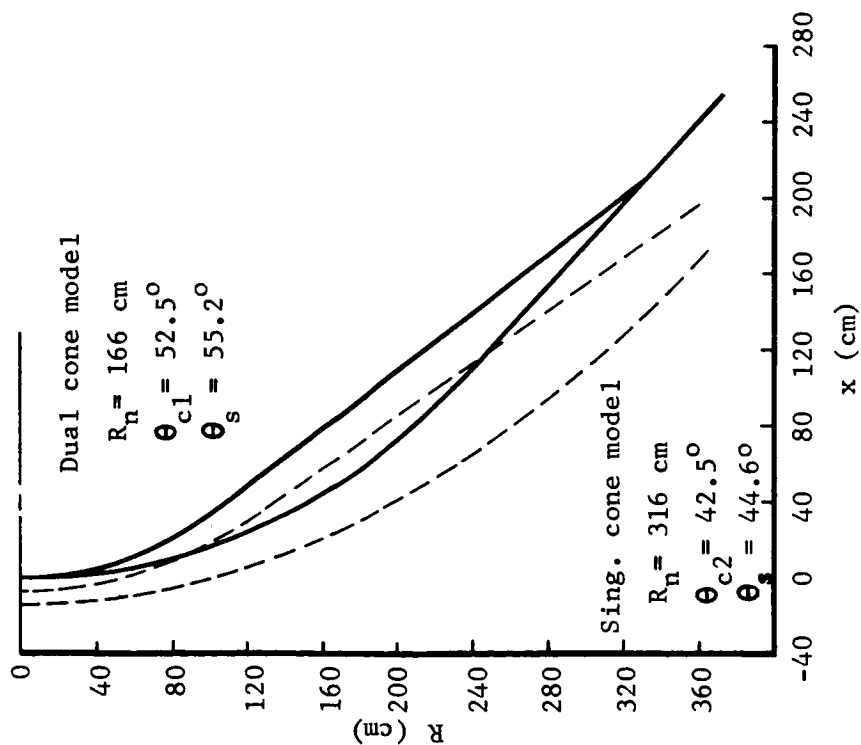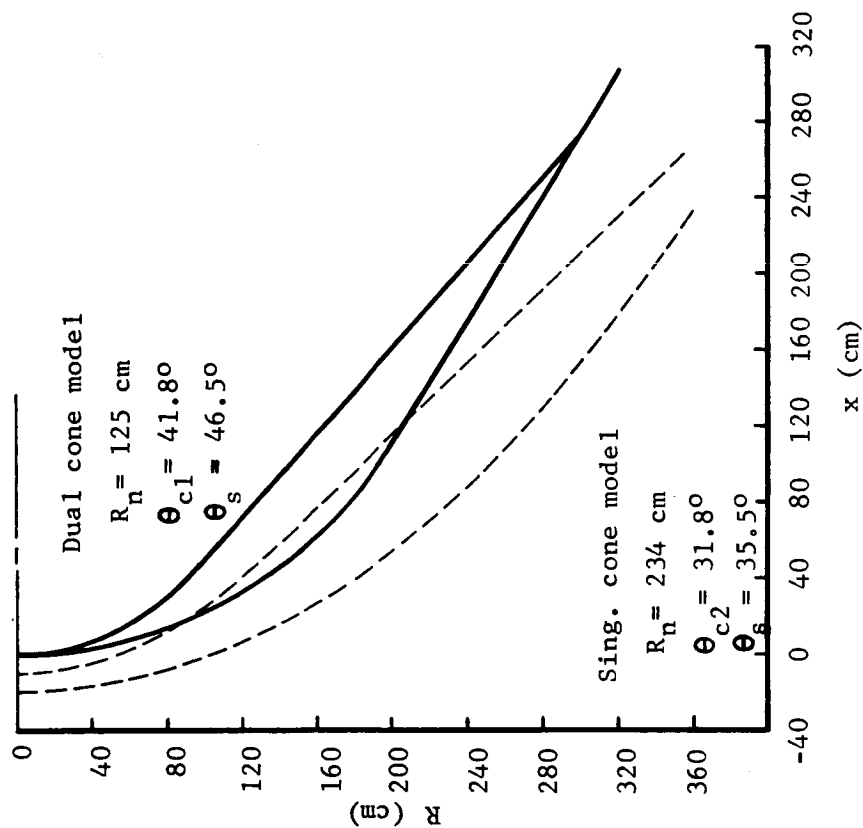
TRAJECTORY CONDITIONS & SHOCK LAYER PROPERTIES FIG. 46

Orbiter trajectory 14414.1

Trajectory Parameters		Nose Cap	Sta. 1120 x/L = 0.125	Sta. 1200 x/L = 0.200	Sta. 1400 x/L = 0.400	Sta. 1600 x/L = 0.600	Sta. 1800 x/L = 0.800	Sta. 1996 x/L = 1.000
t = 450 s Z = 74.5 km V = 7.5 km/s α = 41.5°	P_s (atm)	0.0247	0.0165	0.0120	0.0120	0.0120	0.0120	0.0120
	T_s (°K)	5969	5377	4951	4951	4951	4951	4951
	δ_s (cm)	7.25	28	37	61	85	109	133
t = 800 s Z = 63.8 km V = 5.7 km/s α = 32.8°	P_s (atm)	0.0547	0.0283	0.0183	0.0183	0.0183	0.0183	0.0183
	T_s (°K)	5465	4064	3004	3004	3004	3004	3004
	δ_s (cm)	7.50	34	43	65	88	111	134
t = 1200 s Z = 49.4 km V = 3.1 km/s α = 30.8°	P_s (atm)	0.0960	0.0485	0.0306	0.0306	0.0306	0.0306	0.0306
	T_s (°K)	3057	2313	1682	1682	1682	1682	1682
	δ_s (cm)	10.97	46	62	104	145	187	229

ORBITER WINDWARD ℄ RADIATIVE EQUIL. TEMPERATURES   FIG. 47

Orbiter trajectory 14414.1

$\dot{Q} = 0.85 \, \sigma \, T_{RE}^4$

Time from Entry
450 s
800 s
1000 s
1200 s

T_{RE} (°K)

x/L

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Orbiter trajectory 14414.1

Traj. Time(s)		Nose Cap	Sta. 1120 x/L = 0.125	Sta. 1200 x/L = 0.200	Sta. 1400 x/L = 0.400	Sta. 1600 x/L = 0.600	Sta. 1800 x/L = 0.800	Sta. 1996 x/L = 1.000
450	$\dot{Q}_{Cw}$ (w/cm²)	41.0	15.7	16.2	13.4	10.0	9.32	4.83
	$\dot{Q}_{Cs}$ (w/cm²)	41.0	15.7	16.2	13.4	10.0	9.33	4.84
	$\dot{Q}_{Ls}$ (w/cm²)	3.2×10^{-5}	2.2×10^{-6}	1.0×10^{-7}	1.7×10^{-7}	2.4×10^{-7}	3.1×10^{-7}	3.7×10^{-7}
800	$\dot{Q}_{Cw}$ (w/cm²)	36.3	11.2	9.32	8.23	5.91	5.52	2.70
	$\dot{Q}_{Cs}$ (w/cm²)	36.3	11.2	9.32	8.23	5.91	5.52	2.70
	$\dot{Q}_{Ls}$ (w/cm²)	7.3×10^{-6}	4.2×10^{-10}	9.2×10^{-15}	1.4×10^{-14}	1.9×10^{-14}	2.4×10^{-14}	2.9×10^{-14}
1200	$\dot{Q}_{Cw}$ (w/cm²)	11.9	3.62	4.27	2.33	7.11	7.73	5.58
	$\dot{Q}_{Cs}$ (w/cm²)	11.9	3.62	4.27	2.33	7.11	7.73	5.58
	$\dot{Q}_{Ls}$ (w/cm²)	1.0×10^{-13}	$\sim 10^{-19}$	$\sim 10^{-26}$	$\sim 10^{-26}$	$\sim 10^{-25}$	$\sim 10^{-25}$	$\sim 10^{-25}$

Constant property shock layer using post shock conditions.

Frequency range 2.5 ev to 0.2 ev (0.5 μm to 6.2 μm).

$\dot{Q}_{Cw}$ = Heat flux at the shuttle wall. (Continuum)

$\dot{Q}_{Cs}$ = Heat flux at the shock layer. (Continuum)

$\dot{Q}_{Ls}$ = Heat flux at the shock layer. (Line Structure)

EFFECT OF SHOCK LAYER PROPERTIES ON $\bar{C}$ RADIATIVE HEAT FLUX   FIG. 49

Orbiter trajectory 14414.1
Trajectory time 450 s after entry.

Variation		Nose Cap	Sta. 1200 x/L = 0.200	Sta. 1600 x/L = 0.600	Sta. 1996 x/L = 1.000
$P = 1.5P_s$	$\dot{Q}_{Cw}$ (w/cm^2)	41.0	16.2	10.0	4.83
	$\dot{Q}_{Cs}$ (w/cm^2)	41.0	16.2	10.0	4.84
	$\dot{Q}_{Ls}$ (w/cm^2)	6.1×10^{-5}	2.0×10^{-7}	4.7×10^{-7}	7.4×10^{-7}
$T = 1.25T_s$	$\dot{Q}_{Cw}$ (w/cm^2)	41.0	16.2	10.0	4.84
	$\dot{Q}_{Cs}$ (w/cm^2)	41.0	16.2	10.0	4.86
	$\dot{Q}_{Ls}$ (w/cm^2)	2.5×10^{-2}	1.7×10^{-4}	3.9×10^{-4}	6.2×10^{-4}
$\delta = 3.0\delta_s$	$\dot{Q}_{Cw}$ (w/cm^2)	41.0	16.2	10.0	4.84
	$\dot{Q}_{Cs}$ (w/cm^2)	41.0	16.2	10.0	4.85
	$\dot{Q}_{Ls}$ (w/cm^2)	9.7×10^{-5}	3.1×10^{-7}	7.1×10^{-7}	1.1×10^{-6}

MTF – BOW SHOCK

$$T = e^{\frac{-4\pi^2 S^2}{\lambda^2}} + \frac{f^2}{K^2 + f^2}$$

where

$$S = \frac{3 \times 10^{-6}\, \rho M^2}{1 + .1\, M^2}$$

See Reference (8)

T = Modulation
K = $\delta/10\lambda R$
f = Spatial Frequency
M = Mach no.
δ = Shock Wave Standoff or Boundary Layer Thickness
ρ = Pressure Ratio (6.8 x 10^{-5} from Sea Level to 70 KM)
R = Focal Length

Mach No. = 4
Pressure Ratio @ $\frac{70KM}{12KM}$ = 1.8 x 10^{-5}
Boundary Layer δ = 100 cm
Wavelength λ = 2x10^{-4} cm
Focal Length R = 1236.2 cm

f cy/arc sec	T Modulation
0	.999
.06	
.12	
.18	
.24	
.30	
.36	
.42	
.48	
.54	
.60	
.66	
.72	
.78	
.84	
.90	

FIG. 50

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ATMOSPHERIC TRANSMITTANCE (C14I)

FIG. 51

AIRCRAFT ALTITUDE = 12.5 KM
— SHUTTLE ALTITUDE - 74.3 KM   ANGLE FROM ZENITH = 35°
---SHUTTLE ALTITUDE = 43.9 KM   ANGLE FROM ZENITH = 55°

WAVELENGTH (μm)

% TRANSMITTANCE

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MTF – ATMOSPHERIC TURBULENCE .FIG. 52

$$T = e^{-\frac{1}{2}D}$$

$$D = 2.91 \; \frac{4\pi^2}{\lambda^2} \; (f\lambda R)^{5/3} \; SEC \; \alpha \int c_n^2$$

$$\Sigma \epsilon_n^2 = 3.96 \times 10^{-12} \quad \Sigma C_n = 3.98 \times 10^{-12}$$
$$\alpha = 55° \qquad \alpha = 35°$$

$$R = 1236.2 \; cm$$
$$\lambda = 2 \times 10^{-4} \; cm$$

f/CY/MM	f/cy/arc/sec	$T_{\alpha=35°}$	$T_{\alpha=55°}$
0	0	1.0	1.0
1	.06	.969	.956
2	.12	.904	.867
3	.18	.821	.756
4	.24	.728	.637
5	.30	.631	.520
6	.36	.536	.412
7	.42	.446	.318
8	.48	.365	.239
9	.54	.293	.175
10	.6	.232	.125
11	.66	.180	.087
12	.72	.138	.060
13	.78	.104	.040
14	.84	.077	.026
15	.90	.056	.017

f = Spatial Frequency
T = Modulation
λ = Wavelength
R = Focal Length
α = Angle from Zenith
C_n = Atmospheric Structure Constant as a Function of Altitude

altitude from 12.5 to 14 km raises the MTF about 2%. Fortunately as the zenith angle increases, the range decreases such that the overall transfer function improves at lower altitudes.

The aircraft flow field or boundary layer is similar in analyses to that done for the Shuttle. Figure 53 again shows little effect.

The telescope on-board the NASA C141 is the 91.5-cm aperture f/13.5 Cassegrain system. The optical parameters for this telescope were obtained from the *C141 AIRO Users Handbook* and input to the Polypagos Optical Analysis Program (Ref. 13). The resulting MTF is shown in Figure 54. An energy-detected option in the computer program indicated 77.7% of the energy in the point spread function would be detected by a 50 x 50 micrometer detector. A graphical representation of the point spread function of the telescope is shown in Figure 55 and the MFT in Figure 56. The transmission efficiency of the optics at 2 micrometers is approximately 85% with three reflections.

Light falling on the detectors at the Cassegrain focal plane as a function of time is subject to the telescope stabilization jitter. The loss of contrast due to image motion has been discussed by Rosznau (Ref. 14). Figure 57 shows no effect due to the short exposure time per pixel (40 μsec). For the C141 the telescope jitter is a maximum of 2 arcsec at an 8-Hz bandwidth. This corresponds to an image motion at the focal plane over that period of 6×10^{-7} mm.

The detector MTF, due to its physical size, is given by Seyrafi (Ref. 15) as a straight line function for square apertures and is shown in Figure 58.

The required electrical bandwidth for the front-end electronics is given by:

FREQ (Hz) = (A) (f)

where A is the maximum angular image rate and f is spatial frequency. To minimize the effect of the 3 dB rolloff, the frequency response was pushed out three time constants to provide 95% accuracy. The resulting bandwidth, as a function of spatial frequency, is shown in Figure 59 with 95% accuracy. The MTF of the electrical bandwidth has a negligible effect.

The calculated background irradiance at the 91.5-cm telescope entrance aperture and the acquisition telescope aperture at an altitude of 12 to 14 km is shown in Figure 60. The irradiance from the target for the worst-case (600 K) is still several orders of magnitude above any background source. The acquisition system does see scattered sunlight as a high signal; however, due to its uniformity compared to the Shuttle image, the background is

MTF – BOUNDARY LAYER

$$T = e^{-4\pi^2 \frac{S^2}{\lambda^2}} + \frac{f^2}{K^2 + f^2}$$

$$S = \frac{3 \times 10^{-6}\,\delta\rho M^2}{1 + .1\,M^2}$$

$$K = \delta/10\lambda R$$

M = Mach no.
δ = Shock Wave Standoff
ρ = Pressure
λ = Wavelength
R = Focal Length
f = Spatial Frequency

BOUNDARY LAYER

m = .9
δ = 5 cm
ρ = .27 @ 12 KM
λ = 2x10^{-4} cm
R = 1236.2 cm

f cy/arc sec	$T_{Boundary\ Layer}$
0	1
.06	.991
.12	.991
.18	
.24	
.30	
.36	
.42	
.48	
.54	
.60	
.66	
.72	
.78	
.84	
.90	

FIG. 53

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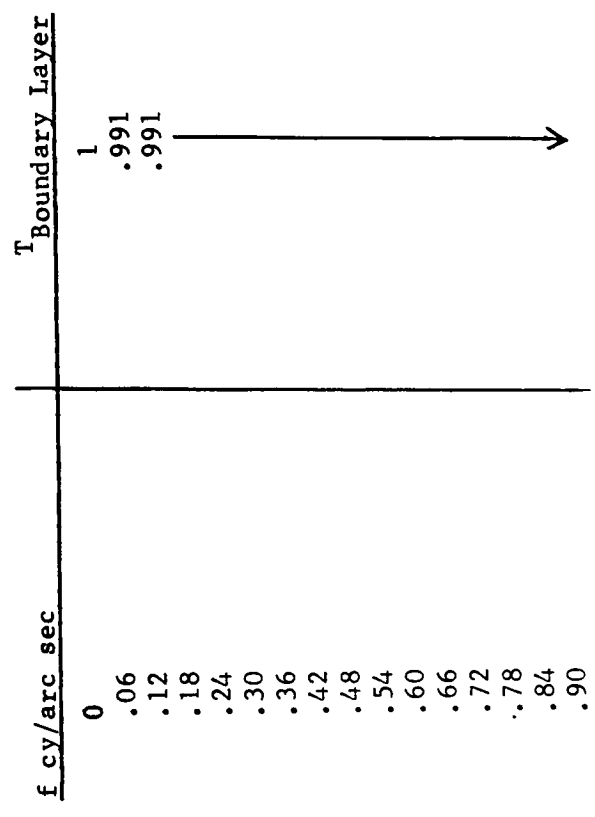
FROM POLYPAGOS COMPUTER PROGRAM

$f_{CY/MM}$	T
0	1.0
1	.95
2	.90
3	.85
4	.79
5	.77
6	.73
7	.70
8	.66
9	.61
10	.57
11	.54
12	.51
13	.49
14	.46
15	.45

36-IN. AIRBORNE, NO CORRECTOR
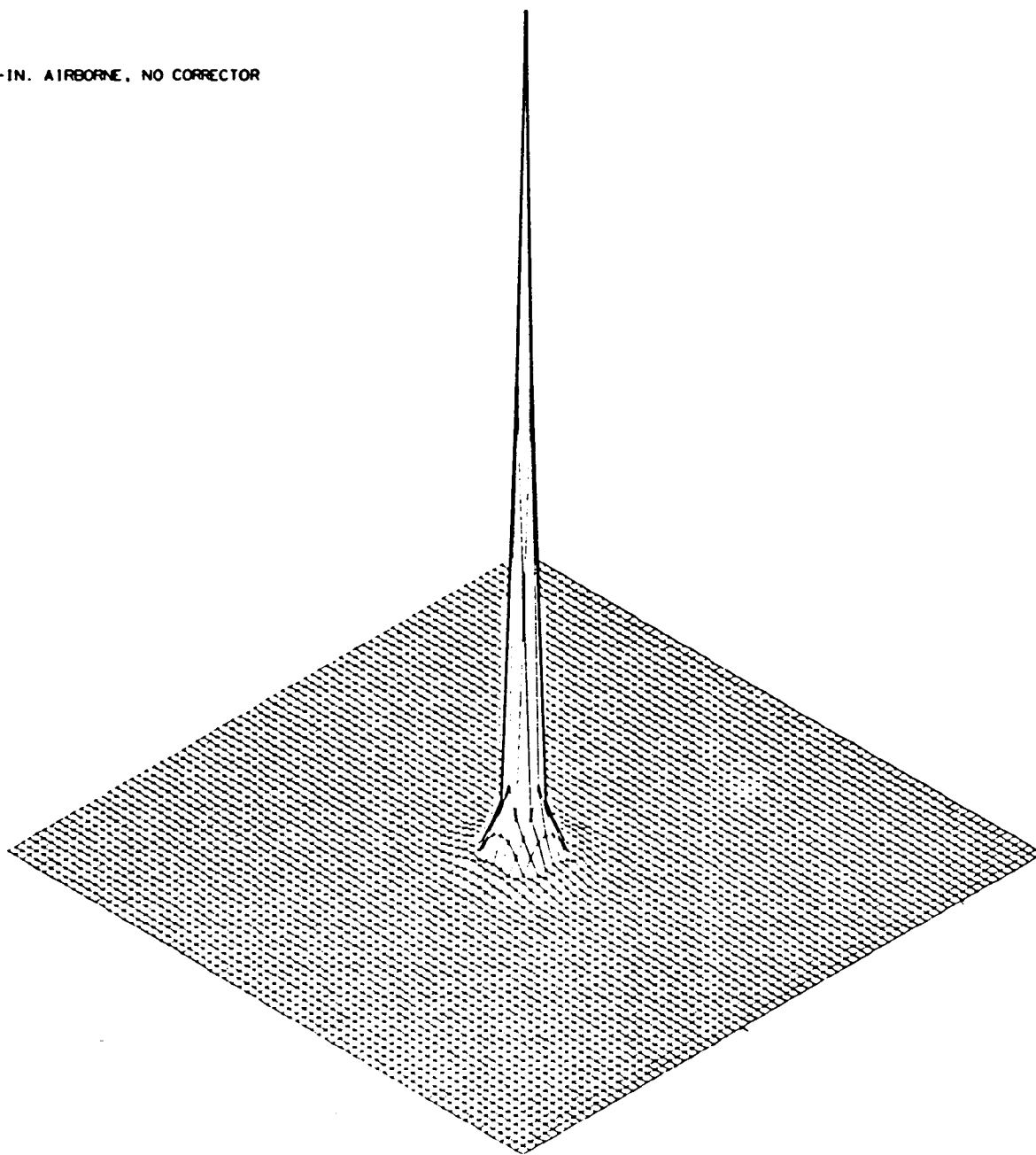
PSF K = 0.000

91.5 cm TELESCOPE
POINT SPREAD FUNCTION
FIG. 55

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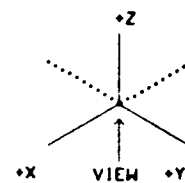
36-IN. AIRBORNE, NO CORRECTOR
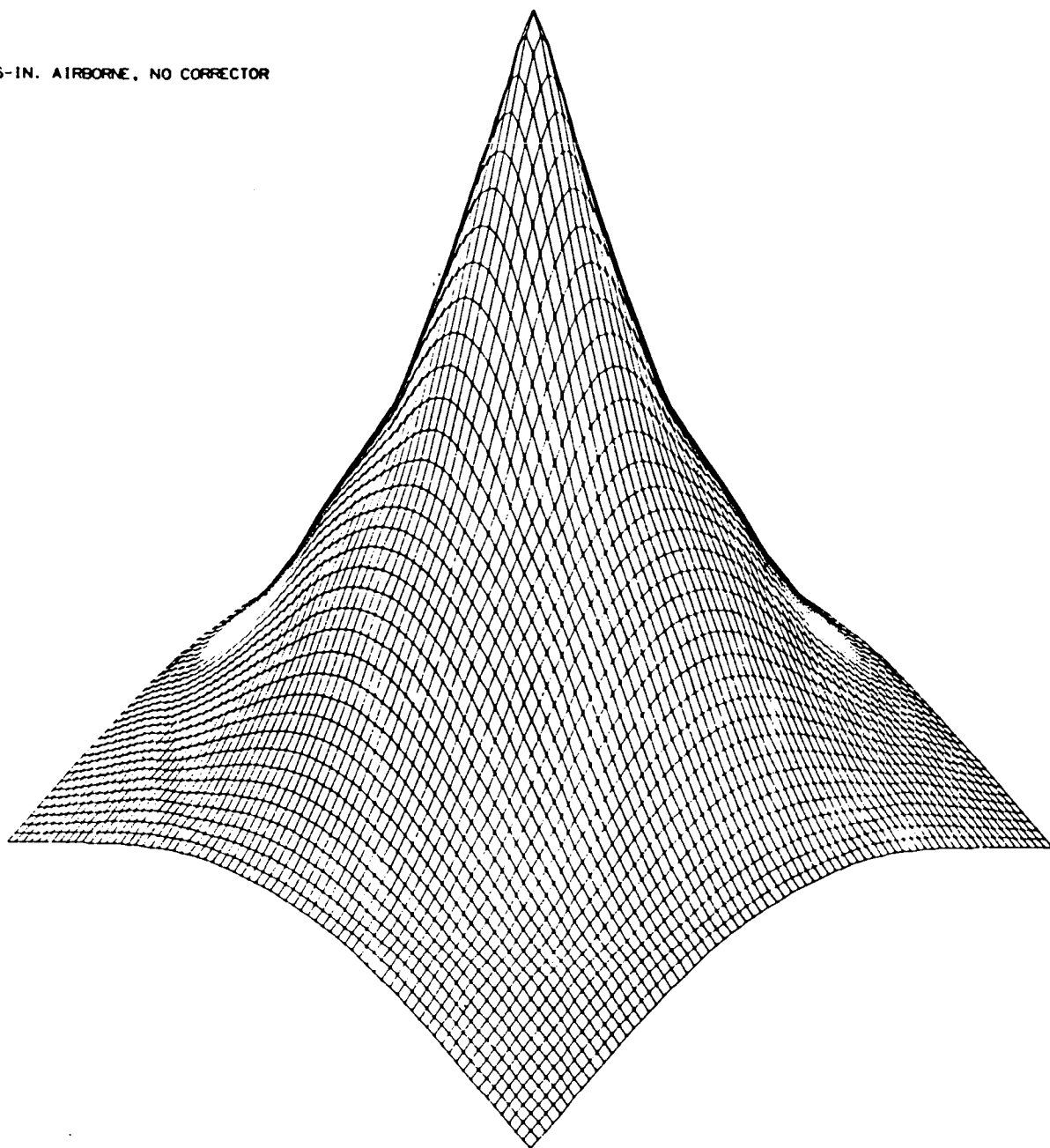
MTF K = 0.000

91.5 cm TELESCOPE
MTF

FIG. 56

+Z

+X   VIEW   +Y

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MTF – IMAGE MOTION

FIG. 57

$$T = e^{-2\pi^2 a^2 K^2}$$
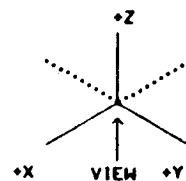
T = Modulation

$\alpha = 6 \times 10^{-7}$ mm   Maximum Image Motion for Short Exposure

K = Spatial Frequency

f CY/MM   T

1.0

0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

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MTF - DETECTOR   FIG. 58
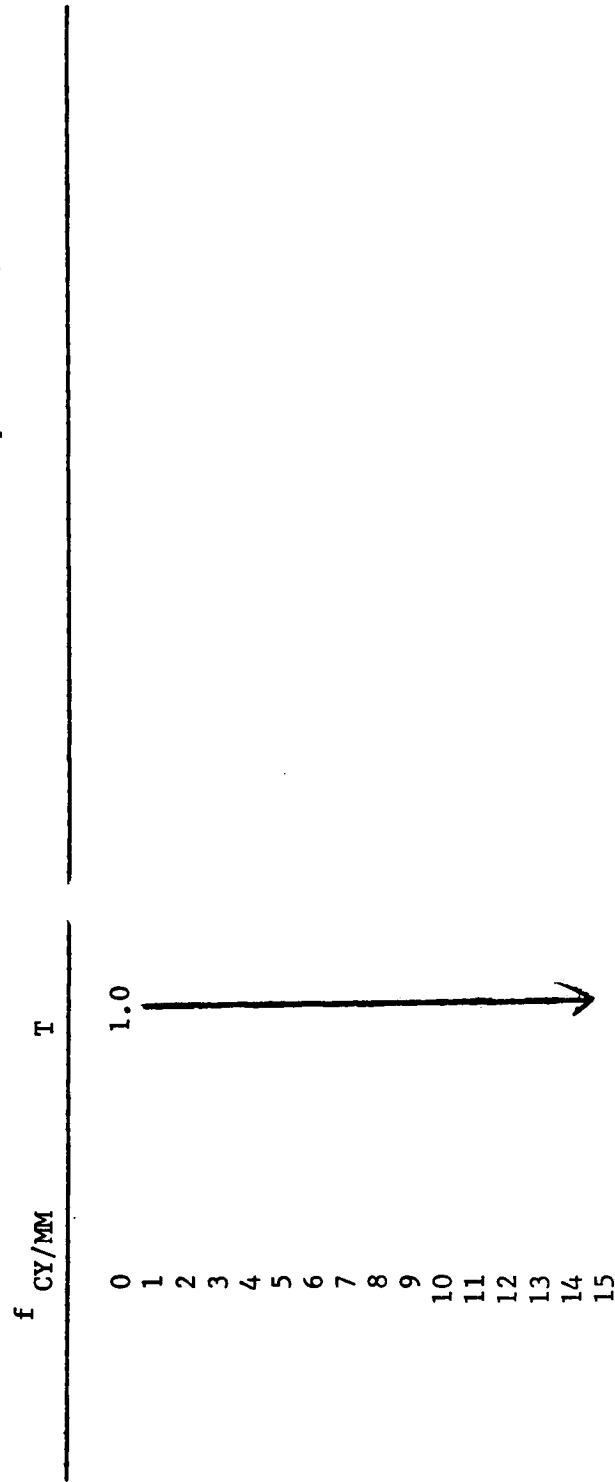
$$T = 1 - {}^{a}/1/_{K}$$

a = .05 mm Detector Size

K = Spatial Frequency

$f_{CY/MM}$	T
0	1.0
1	.95
2	.90
3	.85
4	.80
5	.75
6	.70
7	.65
8	.60
9	.55
10	.50
11	.45
12	.40
13	.35
14	.30
15	.25

ELECTRICAL BANDWIDTH

FIG. 59

$FREQ = (A)(f)$ A = MAXIMUM ANGULAR IMAGE RATE = 19983 ARC SEC/SEC

f CY/ARC-SEC	FREQ(Hz) 3 db POINT	FREQ X 3 TIME CONSTANTS FOR 95% ACCURACY (Hz)
0	0	0
.06	1199	3597
.12	2398	7194
.18	3597	10791
.24	4796	14388
.30	5995	17985
.36	7194	21582
.42	8393	25129
.48	9592	28776
.54	10791	32373
.60	11990	35970
.66	13189	39567
.72	14388	43164
.78	15587	46761
.84	16786	50358
.90	17985	53955
.96		

BACKGROUND IRRADIANCE AT ENTRANCE APERTURE

FIG. 60

	IRRADIANCE FROM TARGET	ATMOS. EMISSION	SCATTERED SUNLIGHT
ACQUISITION SYSTEM (T = 1100°K) RANGE = 131 KM $\Delta\lambda$ (1.0 TO 2.5) FOV 9°	5.9×10^{-9} Watts/cm^2	1.2×10^{-15} @ -60°C Watts/cm^2	5.4×10^{-8} Watts/cm^2
IMAGING SYSTEM $\Delta\lambda$ (1.9-2.6) (T = 600°K)	8.5×10^{-14} Watts/cm^2	3.3×10^{-24} Watts/cm^2	4.7×10^{-17} watts/cm^2

COMPARING TARGET TO BACKGROUND IRRADIANCE WE FIND THAT ONLY IN THE ACQUISITION SYSTEM DOES ANY COMPONENT OF BACKGROUND (SCATTERED SUNLIGHT) CAUSE CONCERN. BY AC COUPLING THE DETECTOR TO AMPLIFIER SYSTEM WE VERY EFFECTIVELY ELIMINATE ANY SIGNIFICANT CONTRIBUTION FROM UNIFORM BACKGROUND.

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rejected. AC coupling then eliminates scattered sunlight as a
signal source.

The summation of all effects governing MTF and ultimately spatial
and temperature resolution is shown in Figure 61. Since only the
atmospheric loss changes and the amount is not significant, all
conditions of viewing are similar concerning MTF.

The NEΔT for zero spatial frequency has been calculated for all
temperatures and is shown in Figure 62 using 12-bit encoding. In
an imaging system, however, modulation loss does occur. The sys-
tem MTF shown previously is used to modify the NEΔT as follows to
obtain minimum resolvable temperature as a function of temperature
and spatial frequency:

$$MRT\ (k, \Delta T) = \frac{NE\Delta T\ (0\ Spatial\ Freq)}{MTF\ (k)}$$

The MRT is shown in Figure 63 for several temperatures.

Spatial Resolution - Given the system MTF and the parameters for
viewing the Shuttle in each case, the spatial resolution can be
obtained. Spatial resolution is simply the reciprocal of spatial
frequency times the range divided by the cosine of the angle be-
tween the line-of-sight and the Shuttle underside normal. (see
Appendix.) This is shown in Figure 64. Also, using data pre-
sented in Figure 63, both the spatial and temperature resolution
can be obtained for any case.

Figure 65 is a composite of the spatial resolution and minimum
resolvable temperature for maximum range with the system perfor-
mance bounded. The data can be processed to enhance either spa-
tial resolution or minimum resolvable temperature at the expense
of the other within the bounds defined by design goals. As an
example, if the minimum temperature in a frame of data were
1000 K, the ΔT could be allowed to slide to 2.5% improving spatial
resolution or vice versa. Figure 66 is the same composite for
the minimum range condition. Here much lower temperatures are
resolvable within the system bounds.

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FIG. 61

ΣMTF

BOW SHOCK
BOUNDARY LAYER
IMAGE MOTION
ELECTRICAL BANDWIDTH

TELESCOPE
OPTICS

DETECTOR

ATMOSPHERE (35° – 12 TO 70 KM)

ΣMTF

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SPATIAL FREQUENCY CY/ARC-SEC

MODULATION
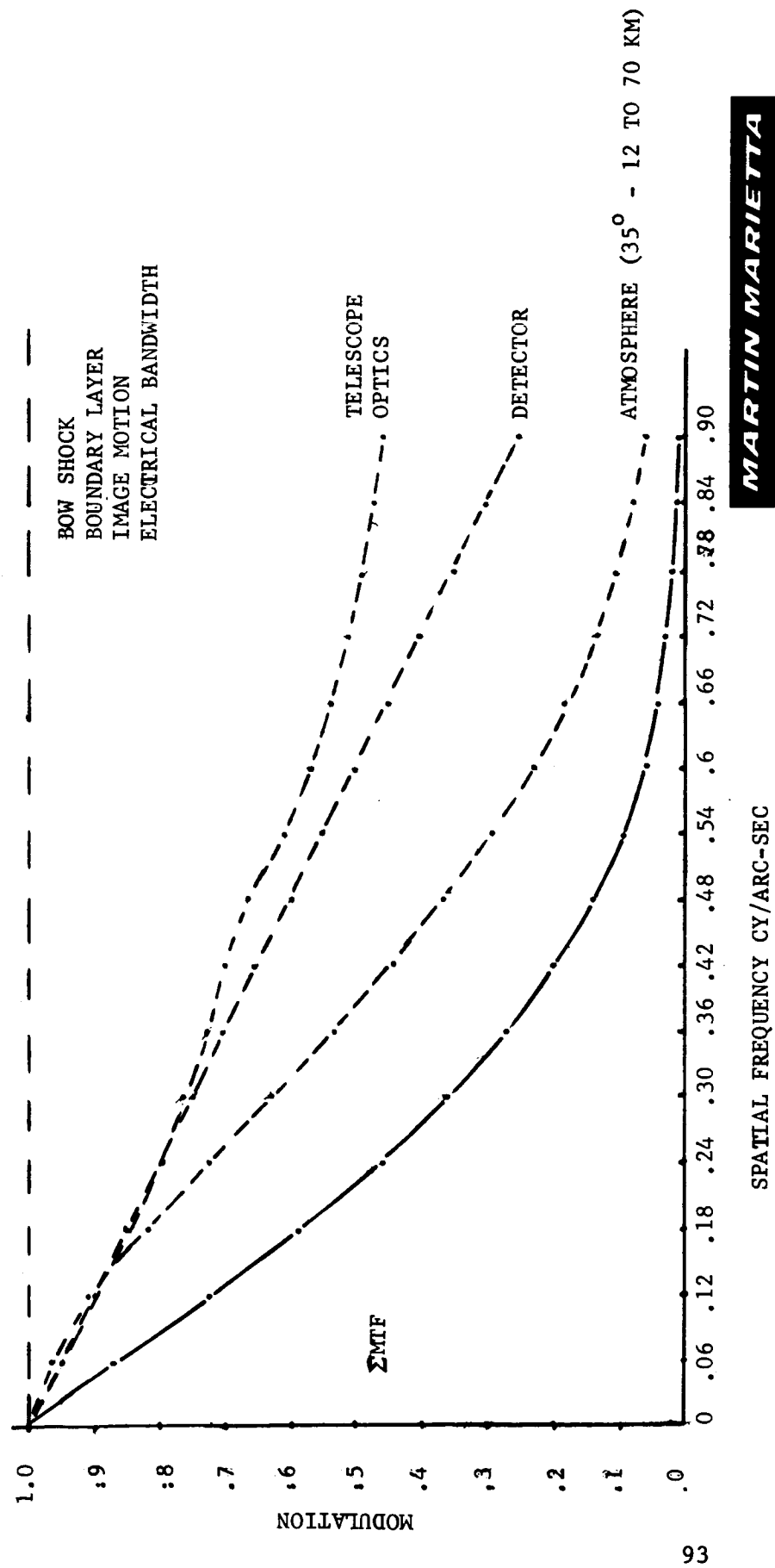
IMAGING SYSTEM PARAMETERS

FIG. 62

D_0 = 91.5 cm

F# = 13.5

FOCAL LENGTH = 1236.2 cm

DETECTOR (InSb)

Δf = 50x10³ Hz
λ_1 = 1.9 u

λ_2 = 2.7 u

C = 0.3*

*DERATING FACTOR

TEMP OF SOURCE(°K)	S/N	NEΔT (°K)	NEΔT (°K) DIGITAL 12 BIT
600	9	7	18
700	36	2	6
800	108	1	3
900	250	.5	1.3
1000	500	.3	.8
1100	900	.2	.6
1200	1400	.16	.4
1300	2100	.13	.3
1400	3000	.1	.25
1500	4100	.09	.22
1600	5400	.08	.19
1700	6800	.07	.17
1800	8400	.06	.15
1900	10,000	.05	.14

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MINIMUM RESOLVABLE TEMPERATURE

FIG. 63

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SPATIAL RESOLUTION

FIG. 64

SPATIAL RESOLUTION (METERS) vs **SPATIAL FREQUENCY CY/ARC-SEC**

282 SEC CASE
544 SEC CASE
791 SEC CASE
922 SEC CASE
YF-12 CASE

DESIGN GOAL 3 METERS
DESIGN GOAL 1 METER
DESIGN GOAL .3 METERS

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IMAGING SYSTEM PERFORMANCE (12 BIT DIGITAL CONVERSION)   FIG. 65

MAXIMUM RANGE = 75 KM

RESOLUTION = 1 METER

ΔT = 2.5%

SURFACE TEMPERATURE

800°K

1000°K

1500°K

SPATIAL RESOLUTION (M)

MINIMUM RESOLVABLE TEMPERATURE °K ΔT

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IMAGING SYSTEM PERFORMANCE (12 BIT CONVERSION)

FIG. 66

MINIMUM RANGE = 55 KM

SURFACE TEMPERATURE

RESOLUTION 1 METER

$\Delta T = 2.5\%$

700°K

800°K

1000°K

SPATIAL RESOLUTION (M)

2.0 1.8 1.6 1.4 1.2 1.0 .8 .6 .4 .2 0

0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36

MINIMUM RESOLVABLE TEMPERATURE °K ΔT

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C-2

After the data have been acquired and recorded, there will be
several levels of processing required to go from the flight
tape to an output tape containing calibrated and corrected data
suitable for further analysis by NASA Ames Research Center. This
processing will consist of five major steps; (1) unscrambling,
(2) intensity correction, (3) reconstruction, (4) geometric cor-
rection, and (5) calibration. Each of these steps is discussed
in detail in the following pages and processing flow diagrams
are included.

Unscrambling - The unscrambling algorithms will depend on the
final detector design and data acquisition logic and may change
significantly if there is a design change. The following algo-
rithms are based on the design as seen at this time. This in-
volves 600 detectors, organized so there is an initial vertical
array of 400 detectors followed by another centered vertical
array of 200 detectors.

```
  |
  |
  |        |
400 |      | 200
Array |    | Array
  |
  |
```
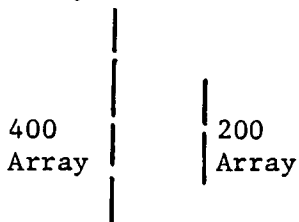
The system is designed to have a high probability for the Shuttle
passage to be in the center 200 detectors in both banks. The
extra 100 detectors on either side of this maximum probability
area increase the chances of getting some useable data.

These data will be recorded so that the detector values are
always in the order of 1 through 200 followed by 1 through 200.
This will yield data groups of 400 values. Each physical tape
record will be composed of an integral number of these data
groups. The flight tape will also contain a number of pre-
flight calibration data groups before the shuttle data-take and
postflight calibration data after the data-take. The calibration
data will be of the same basic format as the Shuttle image data
and must be recognizable as being different. These could be
flagged by a special code word in the data, by a different
record size for the calibration data, or even by a hand written
log of how many pre- and postflight calibration data groups
were taken.

The calibration data must be pulled from the tape and operated
on to yield a unique calibration value for each detector. These
data will be stored on permanent disk file for later use in
correcting the image data.

At this point the image data can be straightforwardly read from the data tape and separated into two image arrays, one of size 400xNG, where NG is the number of data groups, and the other of size 200xNG.

Intensity Correction – Since the correction algorithms are in some cases dependent on detector calibrations, they should be applied while each image data value can be related to a unique detector and before any spatial cropping or recombination is performed.

Figure 67 shows how the flow diagram separates each identifiable correction or conversion required. However, several of these operations can be performed together. For example, the detector and filter response corrections, as well as the radiant emittance to temperature conversion can be combined.

Watts/T	$\dfrac{Amps}{Watt}$	DN/Amp
Into Detector	Out of Detector	Electronics
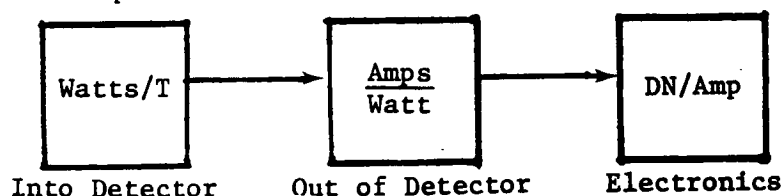
The above sequence occurs during the data-take. The inverse operation can be used during the correction procedure.

$$DN/T = \left(C_{1SE}\ \frac{W}{T}\right)\left(C_{2SE}\ \frac{A}{W}\right)\left(C_{3SE}\ DN/A\right)$$

$$T = DN/\left(C_{1SE}\right)\left(C_{2SE}\right)\left(C_{3SE}\right),$$

where DN is the recorded digital number.

The radiant emittance to temperature conversion is included in the first correction function C_{1SE}. The radiant emittance, $W = \varepsilon\sigma T^4$, where σ is the Shuttle surface emissivity.

The optical transmittance is a function of wavelength, but will be fairly constant over the chosen wavelength band.

$$T_{Corrected} = T*C_{Optics}$$

The filter wavelength band was chosen to avoid atmospheric absorption bands. At a Shuttle altitude of 75 km, an aircraft altitude of 14 km, and a tropical atmospheric model, the attenuation is approximately constant at 1.5%. This may vary with different altitudes and ranges, and can be calculated using the LOWTRAN3 (Ref. 12) atmospheric transmittance computer program.

IMAGE PROCESSING/UNSCRAMBLE AND INTENSITY CORRECTION

FIG. 67

FLIGHT TAPE

*
PULL PRE-AND POST-FLIGHT CALIBRATION DATA

STORE ON DISK

*
UNSCRAMBLE INTO REDUN- DANT IMAGES → 400 x NG IMAGE ARRAY
→ 200 x NG IMAGE ARRAY

*
RADIANT EMITTANCE TO TEMPERATURE CONVERSION

*
DETECTOR CORRECTION

*
FILTER RESPONSE CORRECTION

*
OPTICAL TRANSMITTANCE CORRECTION

**
ATMOSPHERIC ATTENUATION CORRECTION

*
SHOCK LAYER EFFECT CORRECTION → CORRECTED 400 x NG IMAGE ARRAY
→ CORRECTED 200 x NG IMAGE ARRAY

* NEW DEVELOPMENT
**EXISTING SOFTWARE

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$$T_{Corrected} = T*C_{atmo},$$

where $C_{atmo} = f(altitude, range)$.

As seen in the flow diagram, a correction for shock layer effect was identified as required, but investigation has shown this effect to be negligible.

Reconstruction – The above processing produces two arrays of corrected temperature values. These arrays may be recombined to produce a single temperature image of improved resolution or less random noise (see Fig. 68). However, recombination may or may not be desirable. If the Shuttle passage was within the high probability central area of both detector banks, the middle 200 values of the 400 array can be beneficially combined with the 200 array. This may also be the case if the larger portion of the image falls within the mid-200 area. The remaining portion of the Shuttle image would then be appended to the single combined image. This would produce a result in which a small portion of the image would be of lower resolution or higher noise content than the rest. This could be acceptable if the delineation was considered during the analysis phase to prevent false interpretation. If, however, the Shuttle image is largely outside the mid-200 area, recombination is probably not warranted and only the 400 element array would be processed, proceeding directly to the edge cropping step.

Some form of display is necessary to enable the above decision. This can be a low resolution, quick-look method and only the 400 element array must be considered. If the recombination technique is chosen, only the mid-200 elements of the 400-element array are used producing two redundant 200xNG image arrays.

a. Determine Optimum Recombination – At this point, the optimum recombination of the two redundant images must be determined. Two choices are available: (1) the two images can be registered, summed and averaged, producing a single image with random noise removed; and (2) the images would be meshed or interlaced to produce one image with improved resolution. The optimum of the two methods is dependent upon the angle at which the Shuttle passes across the detector array. If the angle-of-passage differs little from the alignment angle of the redundant sensor elements, the redundant images will have little offset and the averaging procedure will be more desirable. Conversely, if the angle-of-passage is different from the sensor element alignment angle, the resultant offset will allow the images to be meshed.

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IMAGE PROCESSING/RECONSTRUCTION AND GEOMETRIC CORRECTION   FIG. 68

PARTIALLY
CORRECTED
IMAGES

RECOMBINE
?

NO (USE 400 x NG IMAGE)

YES

ARE
IMAGE
ELEMENTS
OFFSET? *

NO

YES

SUM AND
AVERAGE
THE IMAGES *

MESH THE
IMAGES *

CONCATONATE
REMAINING
IMAGE PORTION *

CROP
IMAGE
BACKGROUND *

GEOMETRIC DISTORTION CORRECTION***
ITERATE

SHUTTLE
VIEW ANGLES
AND DISTANCE

3-D
LINE
DRAWING **

RUBBER
SHEET STRETCH
ALGORITHM *

SINGLE CORRECTED
TEMPERATURE
ARRAY

*   NEW DEVELOPMENT
**   MODIFY EXISTING SOFTWARE
***COULD BE PROCESSED AT JPL

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Because the angle-of-Shuttle passage may not be accurately known at processing time, another way to determine the optimum method is desirable. This can be done by computing the best registration position of the two images, i.e., whether it is a full pixel offset, thus indicating averaging, or a half pixel offset indicating meshing.

To do this, each image element is replaced by a 2x2 array of identical values.

X(2I - 1, 2J-1) = R(I,J)
X(2I-1, 2J) = A(I,J)
X(2I, 2J-1) - A(I,J)
X(2I, 2J) = A(I,J,), where I=1, NR (no. of rows)
                              J=1, NC (no. of columns)

If the above operation is done for both images, then X is the expanded version of image A and Y is the expanded version of image B.

By sliding image X over image Y one pixel at a time, the overall difference for each offset can be calculated. Start with a negative offset greater than the known possible maximum and do twice that number of overlays in both the horizontal and vertical directions offsetting one pixel at a time. Finally, the positioning that yields the lowest total difference is the best registration. If the final offset between X and Y is an even number of pixels, the averaging technique is indicated, and if odd, the mesh technique is better.

b. *Mesh Procedure* - The mesh procedure may be used on the expanded X and Y images immediately after registration. Using the expanded versions and summing and averaging them as registered produces a single image twice the number of rows and columns as the original image minus twice the offset and yields increased resolution.

P(I,J) = [X(I,J) + Y(I+VO, J+HO)]/2.

where I = 1, (2NR-2VO),

    J = 1, (2NC-2HO),

        VO is the vertical offset of X from Y
and HO is the horizontal offset of X from Y

The edge overlap of the above image should be removed. This operation may be best performed at the time of registration before the summing and averaging.

c. Average Procedure - The averaging technique is best performed
on the original images A and B, thus reducing the number of re-
quired operations. The proper registration of A and B is given
by one-half the final vertical and horizontal offsets determined
for the expanded images X and Y. The overlapping edges of A
and B as determined by the offsets can be removed before the
summing operation. If this is done, then the offsets need not
be used in the indexing of the newly defined A' and B' during
the summing.

A'(I,J) = A(I,J)

B'(I,J) = B(I + VO', J+HO'), where I = 1, NR-2VO'
$$J = 1, NC-2HO',$$
$$VO = VO/2,$$
$$\text{and} \quad HO = HO/2.$$

d. Concatenate Remaining Image Portion - If the recombination
procedure was used on the mid-200 element portion of the arrays
and a portion of the Shuttle image fell outside of this area,
it must now be concatenated to the recombined array. If the
averaging technique was used, there will be a one-to-one ele-
ment realignment relationship. However, if the meshing pro-
cedure was used, the outlying partial image array must be ex-
panded with each element replaced by a 2x2 array so that the two
arrays will match. The realignment in the horizontal direction
will be dependent on the horizontal offset determined during
recombination. The vertical alignment may require that the cor-
responding overlapping edge that was eliminated during recombi-
nation be restored to avoid a data discontinuity. A quick-look
display at this point to check the concatenation is desirable.

e. Crop Image Background - The above recombination and realign-
ment if required, will produce a rectangular array of picture
elements containing the Shuttle image and a surrounding back-
ground area. To reduce the number of picture elements, and
therefore, the number of operations needed for further proc-
essing, the background can be cropped leaving only a small
border.

Average the first and last 5 elements in both horizontal and
vertical directions to arrive at an average background level.

$$BKG = \frac{\Sigma A(I,J)}{N}$$

I-1,5 and I = NR-5, NR,
J=1,5 and J=NC-5, NC.

and N = total number of elements summed.

Move across the image array in a horizontal direction looking
for values greater than twice the average background. Note
the positions of these occurences and keep a running minimum and
maximum horizontal location check.

Do for each row of the image.

If (P(I,J) > 2 BKG),

then JMIN = Minimum of JMIN and J,

and JMAX = Maximum of JMAX and J.

Where J = 1, NC and I = 1, NR varying J first.

Repeat this operation in the vertical direction, finding the
vertical minimum and maximum locations.

If [P(I,J) > 2 BKG],

then IMIN = Minimum of IMIN and I,

and IMAX = Maximum of IMAX and I,

where I = 1, NR and J = 1, NC

varying I first.

The resultant horizontal and vertical max and mins should indicate
the outer most edges of the Shuttle image. These limits can be
expanded to produce a small outer border and the outlying image
elements eliminated.

Image display at this point is desirable because anomalous
values in the background area could produce false limits. If
this occurs the processing can be repeated on the new image and
more accurate results produced.

The result of the above processing is a single array contain-
ing corrected temperature values with extraneous background re-
moved. These data have not been adjusted to reflect the on-
board Shuttle centerline calibration measurements, nor have any
corrections been made to remove geometrical distortions or to
rotate the image to a plan view. A tape containing the tempera-
ture array data at this level of processing can be provided.

Geometric Distortion Correction - The temperature image data will
contain geometric distortions due to view angle, the motion of
the Shuttle across the sensor, and the relative motion between
the aircraft and the Shuttle. The nature of these distortions
cannot be predetermined nor accurately defined in a mathematical

sense, and therefore, cannot be corrected in a preprogrammed automatic processing procedure. An interactive procedure is required to perform these corrections, and an iterative method used wherein an adjustment is made and the resultant image displayed. This necessitates a complex interrelated software and hardware system. The development of this system would require hardware and labor beyond the scope of this contract. However, the existent image processing facility at JPL has the capability to perform the geometric distortion corrections. Preliminary discussions with JPL have confirmed the feasibility of this approach.

The geometric correction requires two separate steps. The first is to remove the distortions and produce a geometrically accurate image. The second is to rotate the image to present a plan view of the Shuttle underside as required for further thermal analysis by Ames Research Center.

The importance of first removing the distortions increases as the Shuttle view angles decrease (where 90° is normal to the underside) resulting in a canted view. To correct the distortions, a three-dimensional line drawing of the Shuttle, as seen from the corresponding flight view angles, is required. We currently have the capability to produce this plot as part of the large Thermal Radiation Analysis System computer code. A more optimum plot capability is inherent in the Computer Aided Design/Manufacturing System (CAD/CAM) currently being assessed. This system will be used if available.

The second step of the geometric correction requires the 3-D line plot to be rotated to a plan view. The above mentioned systems can also perform this function. Both the canted and plan view 3-D plots will be provided to JPL along with the partially corrected temperature image data tape. Using these inputs JPL can produce a tape containing the geometrically corrected and rectified image data.

Calibration - The geometrically corrected temperature data tape can be additionally processed to adjust for the on-board Shuttle temperature measurements (see Fig. 69). These measurements will be provided by Ames after each Shuttle flight, probably on magnetic tape, and will consist of 10 to 20 centerline measurements along with X and Y addresses corresponding to a predefined Shuttle coordinate system. These measurements must be registered and compared with the temperature array data.

If the temperature array datum has been rotated to a plan view, registration of the Shuttle data is fairly straightforward. The array elements corresponding to the centerline Shuttle calibration values can be identified and compared. Some manual interaction will be required in this procedure. This may simply mean

IMAGE PROCESSING/
CALIBRATION

FIG. 69

VIEW ANGLE & DISTANCE

CORRECTED IMAGE

SHUTTLE ON-BOARD TEMPERATURE MEASUREMENTS

** /***
3-D MAPPING FUNCTION

*
REGISTER SHUTTLE TEMPERA- TURES WITH IMAGE TEMPERATURES

*
CALCULATE DIFFERENCE ARRAY

DO DIFFERENCES VARY WITH X-Y POSITION
?

YES

NO

**
CALCULATE BEST FITTING PLANE TO DIFFERENCE ARRAY.

**
DETREND AND NORMALIZE IMAGE TEMPERATURE ARRAY

*
ADJUST IMAGE TEMPERATURES TO MATCH MEASURED TEMPERATURES

MAG TAPE OUTPUT

FINAL 2-D TEMPERATURE ARRAY

*NEW DEVELOPMENT
**MODIFY EXISTING SOFTWARE
***PURCHASE AND CONVERT

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looking at a printout of the Shuttle temperature array and noting the required values to be further processed. However, if the CAD/CAM system is available, the appropriate points can interactively be selected from a plan view Shuttle line plot. The image values at those points can be displayed or compared to the appropriate on-board measurements.

In fact, if the CAD/CAM system is used, the on-board calibration values can be related to the proper positions on the Shuttle image before it is rotated to the plan view. This can be done interactively by selecting the proper points on the canted 3-D Shuttle line drawing display. However, this operation cannot accurately compare the calibration values to the image unless all geometrical distortions have been corrected. Since the distortion correction and the rotation to a plan view are sequential operations, the plan view will normally be used for this registration procedure.

After the calibration values are registered with the temperature array values, a difference array should be calculated. This difference array will provide important information about the performance of both the temperature image array and on-board measurements. If both systems were performing well, the difference array should contain consistently small values. If there are anomalously high singular differences, a failure of the corresponding on-board measuring device may be indicated.

If the differences vary in an increasing or decreasing pattern with X-Y position, an erroneous trend is indicated. This might result if the Shuttle was tilted at an angle to the detectors so that the brightness varied measurably as the distance from sensor. Intensity variation of this nature would not be corrected in the rotation to a plan view operation, but can be corrected in the calibration procedure. The best fit straight line or plane, if these are also off-centerline values, can be computed and the entire image array normalized accordingly.

If the differences are of a random nature, the temperature array might be adjusted by an average difference or might be left unadjusted for further analysis by Ames.

The final calibrated temperature array data would be output on magnetic tape and sent to Ames. This is the final output as requested, and future processing for display purposes will not be pursued. The display diagrams (Figs. 70, 71 and 72) showing these potential displays are included here and may be considered as additional future options. A quick-look display method will be used at various points in the processing for decision making or to assure accuracy of the procedures.

IMAGE PROCESSING/
DISPLAY-GRAPHIC AND TABULAR

FIG. 70

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FINAL
TEMPERA-
TURE ARRAY

*
TABULAR PRINTOUT
OF ALL OR ONLY
SELECT TEMPERA-
TURES

/*
3-D
SHUTTLE
LINE PLOT

**
LINE GRID SUPER-
IMPOSED AND AVER-
AGE TEMPERATURES
PRINTED.

(SIZE LIMITED)

*
SELECT
TEMPERATURE
CONTOUR LEVELS

**
3-D
SHUTTLE LINE
PLOT

*/***
DRAW CONTOUR
MAP OVER
3-D PLOT

/*
3-D
SHUTTLE LINE
PLOT DISPLAYED
ON INTERACTIVE
GRAPHICS TERM.

**
CROSS HAIR
SELECTION OF
SURFACE POSITION

**
TERMINAL PRINT-
OUT OF CORRES-
PONDING TEMPERA-
TURE

*NEW DEVELOPMENT
**MODIFY EXISTING SOFTWARE
***PURCHASE AND CONVERT

IMAGE PROCESSING/
DISPLAY-GRAY SCALE AND COLOR IMAGES

FIG. 71

FINAL
TEMPERATURE
ARRAY

```
                    *                              *                          *
            ┌──────────────┐          ┌──────────────┐          ┌─────────────────────┐
            │ SELECT PORTION│          │ RESCALE      │          │ ALL VALUES   ABOVE  │
   ──────→  │ OF TEMPERATURE│ ──────→  │ INTO         │ ──────→  │ OR BELOW  SELEC-    │
            │ RANGE         │          │ GRAY LEVELS  │          │ TED PORTION ASSUME  │
            └──────────────┘          └──────────────┘          │ WHITE OR BLACK      │
                                                                  │ VALUE               │
                                                                  └─────────────────────┘
```

**   **   ***

┌────────────────┐   ┌──────────────────┐   ┌─────────────────────┐
│ GRAY SCALE-HALF│   │ GRAY SCALE IMAGE │   │ FALSE COLOR   │
│ TONE IMAGE WITH│   │ DISPLAY AND   │   │ IMAGE DISPLAY   │
│ 3-D LINE PLOT │   │ HARD COPY   │   │ AND PHOTO HARD   │
│ SUPERIMPOSED   │   └──────────────────┘   │ COPY   │
│ HARD COPY ONLY │   └─────────────────────┘
└────────────────┘

                                                          ┌─────────────────────┐
                                                          │ CROSS-HAIR   │
                                                          │ POSITION SELEC-   │
                                                          │ TION AND DVM   │
                                                          │ READOUT   │
                                                          └─────────────────────┘
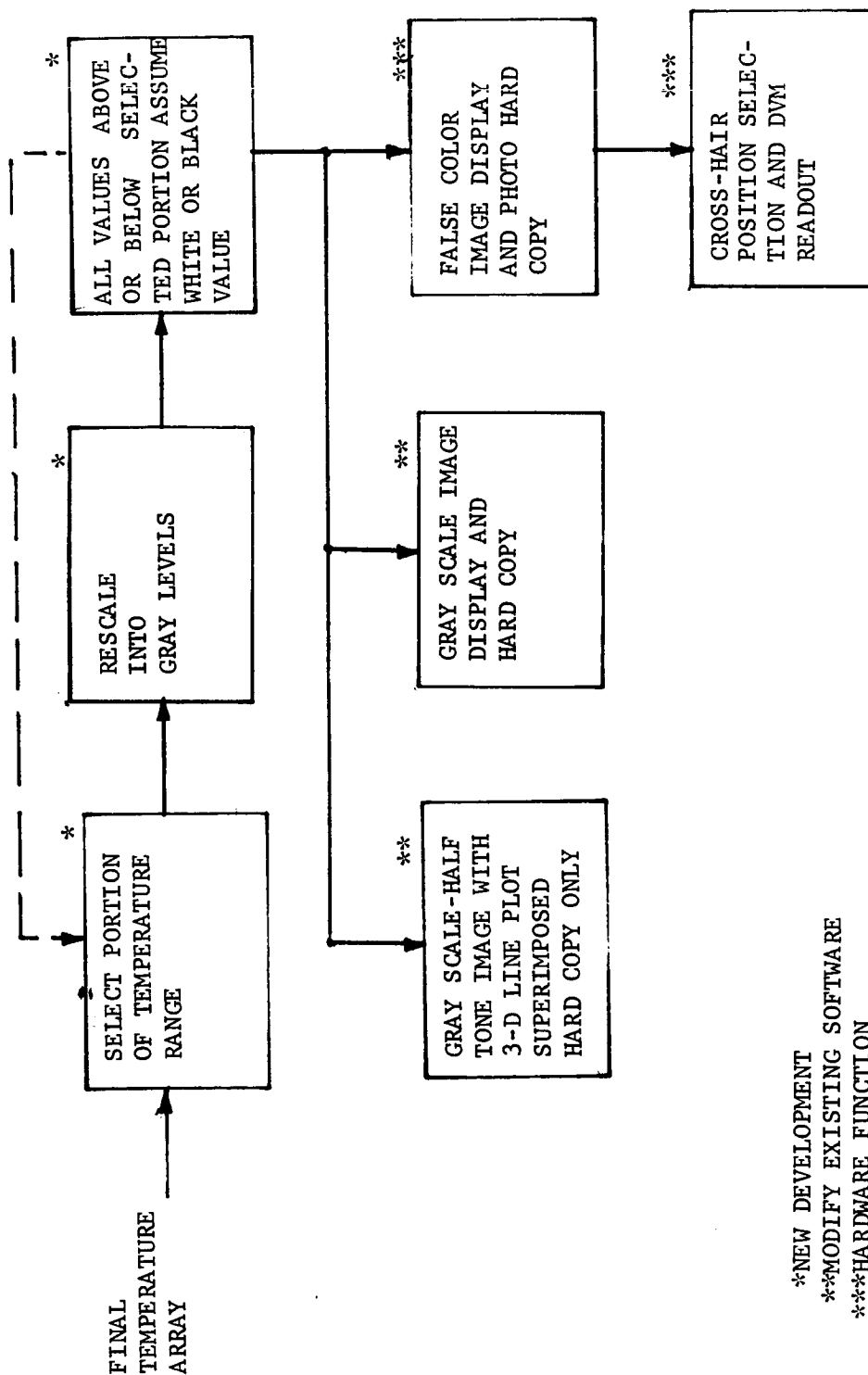
*NEW DEVELOPMENT
**MODIFY EXISTING SOFTWARE
***HARDWARE FUNCTION

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HARDWARE - PROCESSING AND DISPLAY CAPABILITY

FIG. 72

MAGNETIC TAPE -

*
```
CDC6500 WITH
FR80 PLOTTER &
INTERACTIVE
GRAPHICS TERMI-
NAL
```

o PROCESSING ALGORITHMS
o TABULAR OUTPUT
o CONTOUR MAPS
o GRAY SCALE IMAGE
  BY HALF-TONE EFFECT
o 3-D SHUTTLE PLOT
o IMAGE & 3-D PLOT
  SUPERIMPOSED
o MICROFILM OUTPUT

DISK
STORAGE

**
```
COMPUTER AIDED
DESIGN/MANUFAC-
TURING SYSTEM
(CAD/CAM)
```

o PROGRAMMABLE
o INTERACTIVE
  3-D PLOTTER
o 3-D MAPPING TO
  IMAGE ARRAY
o GRAY SCALE IMAGE
  BY HALF-TONE EFFECT
o 3-D PLOT & GRAY
  SCALE IMAGE INTER-
  ACTIVE GEOMETRICAL
  CORRECTION
o SELECTIVE TEMPERATURE
  READOUT
o TABULAR PRINTOUT OVER
  3-D SHUTTLE PLOT

***
```
VIDEO
IMAGE
PROCESSOR
```

o GRAY SCALE IMAGE
  DISPLAY AND PHOTO
  HARD COPY
o FALSE COLOR SELECTION,
  DISPLAY AND PHOTO HARD
  COPY
o CROSS-HAIR SELECTION
  OF X-Y POSITION AND
  DVM READOUT

*STANDARD COMPUTER FACILITY
**WILL BE AVAILABLE IN 1977
***SOME HARDWARE FOR MAGNETIC TAPE INPUT REQUIRED

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The preliminary cost breakdown is shown in Figure 73. Detailed
breakouts by work breakdown structure (WBS) task by month after
go-ahead are shown in Figures 74 through 78. The schedules de-
pict a start date in November 1977. However, if the program
start is delayed several months, the cost per fiscal year can
still be determined from the WBS breakouts. Final delivery of
hardware would slip month for month of start delay thereby pos-
sibly missing the first Shuttle Orbiter flight anticipated in
September 1979.

A WBS is included showing each subtask on which cost control will
be maintained. Each WBS item, having a separate number, will be
issued budget for that task. Reporting of charges against that
WBS number will ensure proper cost control.

The schedule shown has been predicated on the first observed
Shuttle flight occurring in September 1979, (see Figs. 79 to 89).
This may or may not be OFT-1. Long lead-time procurement dic-
tates a timely start in FY1978 to meet the September 1979 flight.

PRELIMINARY PROGRAM COST BREAKDOWN

FIG. 73

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	HOURS	PURCHASED PARTS	TRAVEL	COMPUTER
ENGINEERING DESIGN	7450		7K	
PROCUREMENT	1860	361.2K	6.3K	
ENGINEERING ASSEMBLY	2750		9K	
ENGINEERING TESTING	1800			
ENGINEERING SYSTEMS SUPPORT	2863		10K	
DENVER DATA SYSTEMS SUPPORT	2358		2K	7.5K
MFG/MODEL SHOP	1270			
QC SUPPORT	980			
PARTS ACCEPTANCE TESTS	450			
PROGRAM SUPPORT	2200			
	23981	361.2K	34.3K	7.5K

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FIG. 74

ACQUISITION SYSTEM

ESTIMATING INPUT SHEETS

Name IRIS
Dept _____ Ext ____
Section ____
Date ____

WBS 01100

PHASE I ____
II ____
III X

COMPUTER: CDC $1900 Units IBM ____ Units
Reason: Optical & Servo Analysis

TRAVEL: 2 Trips 1 Men 1 Days to East Coast
Reason Vendor Interface $1000
4 Trips 2 Men 2 Days to Santa Barbara
Reason Vendor Interface $2400
___ Trips ___ Men ___ Days to ____
Reason ____
___ Trips ___ Men ___ Days to ____
Reason ____

TOTAL TRAVEL - $3,400
TOTAL PROC. - $29,700
TOTAL COMP. - $1,900

LABOR RATIONALE:
Design, fabrication, assembly and testing including specific test equipment for the Acquisition System. Major procurements for this subsystem are also included.

Parts/Material - $25,000   Miscellaneous $1700
Test Equipment - $3000

MAN MONTHS BY LABOR GRADE:

41 ___	38 ___
43 ___	36 ___
45 ___	34 ___
47 ___	
49 ___	
50 ___	

FOLDOUT FRAME 2

MAN MONTHS BY MONTH

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	TOTAL
DESIGN	.1	.4	.4	.4	.4	.4	.3	.3																																										2.7
FABRICATION								.6	.6	.6	.6																																							2.4
ASSEMBLY											.5	.5	.5																																					1.5
TESTING						.2	.2	.2	.2	.2				.4	.1	.1	.5																																	3.9
TEST PROC.									.2	.2	.2	.1																																						.7
TEST EQUIPMENT					.4	.4	.4	.4	.3																																									1.9
Q.C.	.4		.3	.3	.4	.4	.2	.2																																										2.2
																																																		15.3
																																																		115

FOLDOUT FRAME

FIG. 75

IMAGE PLANE SYSTEM

ESTIMATING INPUT SHEETS

Name IRIS

Dept_____ Ext_____

Section_____

Date_____

WBS 01200

PHASE I _____
      II _____
      III __X__

TRAVEL: 6 Trips 2 Men 2 Days to Santa Barbara

Reason Subcontract $4,000

_____ Trips _____ Men _____ Days to_____

Reason_____

_____ Trips _____ Men _____ Days to_____

Reason_____

_____ Trips _____ Men _____ Days to_____

Reason_____

_____ Trips _____ Men _____ Days to_____

Reason_____

COMPUTER: CDC_____ Units IBM_____ Units

Reason:_____

TOTAL TRAVEL - $4,000

TOTAL PROC. - $218,700

TOTAL COMP. - 0

LABOR RATIONALE:

Design, fabrication, assembly and testing including specific test equipment and major procurements for the Image Plane System.

Parts/Material/Subcontract - $214,000

Test Equipment   - $3,000   Miscellaneous - $1,7000

MAN MONTHS BY LABOR GRADE:

41 _____	38 _____
43 _____	36 _____
45 _____	34 _____
47 _____	
49 _____	
50 _____	

MAN MONTHS BY MONTH

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	TOTAL
DESIGN	.1	.4	.6	.5	.4	.4																																													2.4
FABRICATION								.4	.4	.4	.4																																							1.6
ASSEMBLY													1	1	1																																			3
TESTING						.2	.2	.2	.2						.4		1	1	.5																															3.9
TEST PROC.									.2	.2	.1																																							.7
TEST EQUIPMENT							.4	.4	.4	.3																																								1.9
Q.C.							.3	.3	.3	.1	.1	.1																																						1.7
																																																			15.2

FOLDOUT FRAME

FOLDOUT FRAME

FIG. 76

ESTIMATING INPUT SHEETS

Name __IRIS__

Dept _____ Ext _____

Section _____

Date _____

WBS __01300__

PHASE I _____
II _____
III __X__

DATA SYSTEMS

COMPUTER: CDC _____ Units _____ IBM _____ Units _____

Reason: _____

TRAVEL: __2__ Trips __2__ Men __2__ Days to __East Coast__

Reason __Vendor Interface__ _____ $1,500

__4__ Trips __2__ Men __2__ Days to __West Coast__

Reason __Vendor Interface__ _____ $2,600

____ Trips ____ Men ____ Days to _____

Reason _____

____ Trips ____ Men ____ Days to _____

Reason _____

TOTAL TRAVEL - $4,100
TOTAL PROC. - $89,600
TOTAL COMP. - 0

LABOR RATIONALE:

Design, fabrication, assembly and testing including special test equipment
and major procurements for the Data System.

Parts/Materials - $84,000   Miscellaneous - $1,600

Test Equipment - $4,000

MAN MONTHS BY LABOR GRADE:

41 _____	38 _____
43 _____	36 _____
45 _____	34 _____
47 _____	
49 _____	
50 _____	

MAN MONTHS BY MONTH

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	TOTAL
DESIGN	5	5	5	5	5	5	5													35
FABRICATION									1	1	1									3
ASSEMBLY									2	2	2	2	2	2						12
TESTING							.1	.2	.2	.1					.4	1	1	1.5		3.7
TEST PROC.									.2	.2	.2	.2								.8
TEST EQUIPMENT							.4	.4	.4	.4	.2									1.8
Q.C.							.3	.4	.4	.3	.3	.2	.2							2.1
																				58.4
																				117

Columns 20–49 contain no entries.

FIG. 77

Name ___IRIS___

Dept _____ Ext _____

Section _____

Date _____

WBS ___01400___

PHASE I _____
II _____
III ___X___

SYSTEM SUPPORT

ESTIMATING INPUT SHEETS

COMPUTER: CDC $5,600 Units IBM _____ Units

Reason: Software Dev. and Data Reduction

TRAVEL:

5	Trips	4	Men	2	Days	to	NASA ARC

Reason ___Design Review___ $6,000

| 2 | Trips | 3 | Men | 10 | Days | to | NASA ARC |

Reason ___Installation___ $2,000

| 4 | Trips | 5 | Men | 5 | Days | to | NASA ARC |

Reason ___Calibration Flight___ $6,000

| 1 | Trips | 5 | Men | 3 | Days | to | NASA ARC |

Reason ___Flight Support___ $2,000

| 3 | Trips | 2 | Men | 3 | Days | to | WEST COAST |

Reason ___Data Reduction___ $2,000

TOTAL TRAVEL - $18,000

TOTAL PROC. - $21,200

TOTAL COMP. - $5,600

LABOR RATIONALE:

Conduct thermal study, provide interface with NASA, develope and test software,

provide flight support for installation, checkout, calibration and first OFT

flight. Also includes packing and shipping of system to NASA ARC.

Data Reduction Subcontract - $20,000

Consumables - $1,200

MAN MONTHS BY LABOR GRADE:

41 ___38___
43 ___36___
45 ___34___
47 _____
49 _____
50 _____

MAN MONTHS BY MONTH

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	TOTAL
THERMAL STUDY	.5	.5																																																1
NASA INTERFACE			.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1																																					1.2
SOFTWARE															1	1	2	2	2	1	1	1	1	1.4	2.8	1.4																								16.6
INSTALL/CHECKOUT																			3	3																														6
CAL FLIGHT																						3																												3
FLIGHT SUPPORT																						1.5	1.5																											3
																																																			30.8

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FOLDOUT FRAME

FIG. 78

ESTIMATING INPUT SHEETS

PROGRAM SUPPORT

COMPUTER: CDC _____ Units _____ IBM _____ Units

Reason: _____

Name __IRIS__
Dept _____ Ext _____
Section _____
Date _____

WBS __01500__

PHASE I _____
II _____
III __X__

TRAVEL: __5__ Trips __2__ Men __2__ Days to __West Coast__

Reason __Vendor Program Support__ $3,000

__3__ Trips __2__ Men __2__ Days to __East Coast__

Reason __Vendor Program Support__ $1,800

_____ Trips _____ Men _____ Days to _____

Reason _____

_____ Trips _____ Men _____ Days to _____

Reason _____

TOTAL TRAVEL - $4,800
TOTAL PROC. - $2,000
TOTAL COMP. - 0

LABOR RATIONALE:

Provide technical supervision, perform planning and cost conatrol. Provide

contract support, support procurement, reports, reproduction, and travel

support. Program Support Task

_____

Draft and Reproduction Supplies - $2,000

MAN MONTHS BY LABOR GRADE:

41 __38__
43 __36__
45 __34__
47 _____
49 _____
50 _____

MAN MONTHS BY MONTH

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	TOTAL
TECH SUP	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5	.5																												11
PROGRAM SUPPORT	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1																																						1.2
CONTRACTS	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03	.03																													.63
PROCUREMENT	1.2	1.2	1.2	1.2	1.2	1.2	1.2	.2	.3																																									11.1
REPORTS			.5				.5					.5				.5			.5																															3
																																																		26.93
																																																		119

FOLDOUT FRAME

FOLDOUT FRAME

SCHEDULE: INFRARED IMAGERY OF SHUTTLE

BLACK BOX #1 – ACQUISITION SYSTEM   FIG. 79
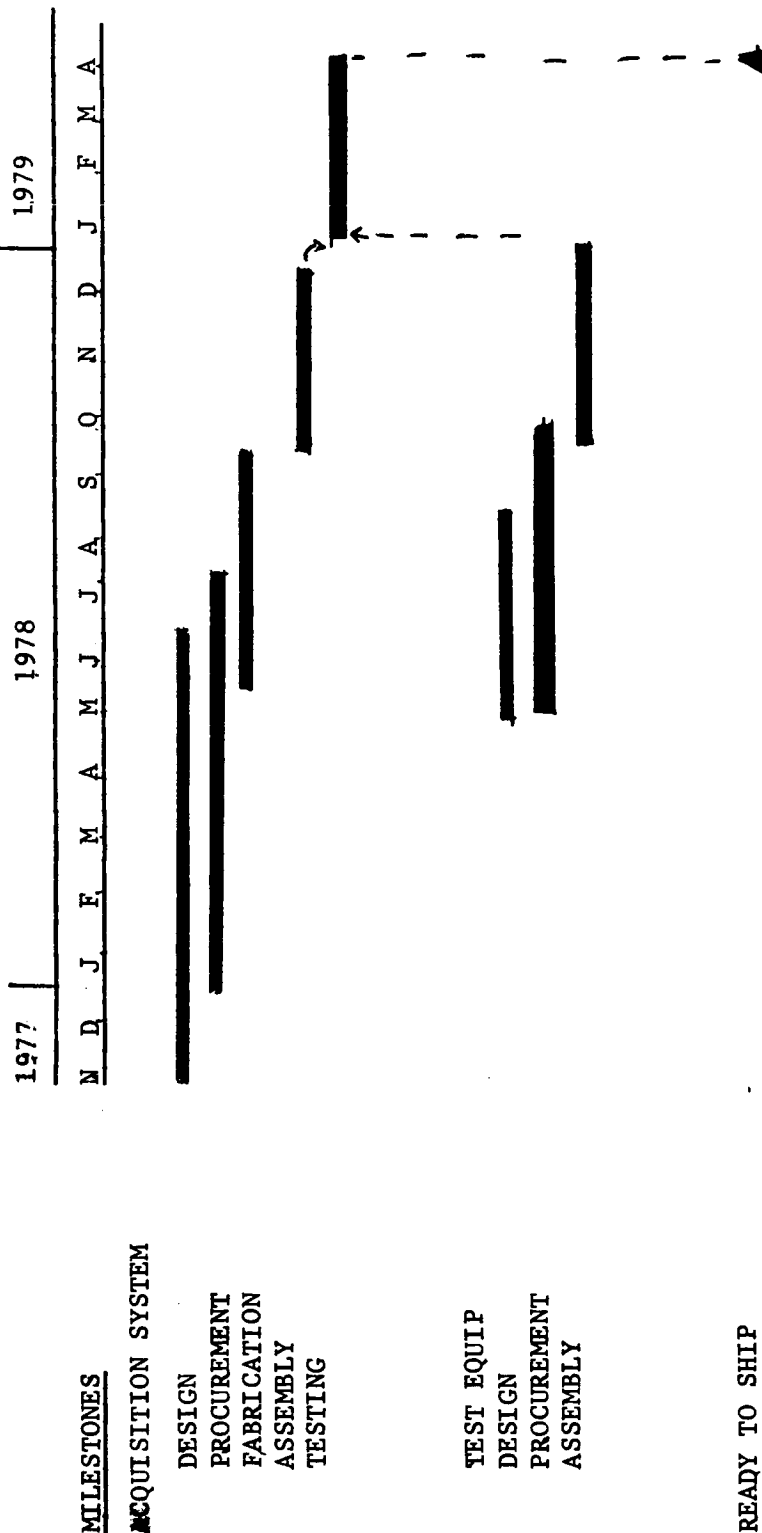
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SCHEDULE: INFRARED IMAGERY OF SHUTTLE

BLACK BOX #2 – IMAGE PLANE SYSTEM

FIG. 80
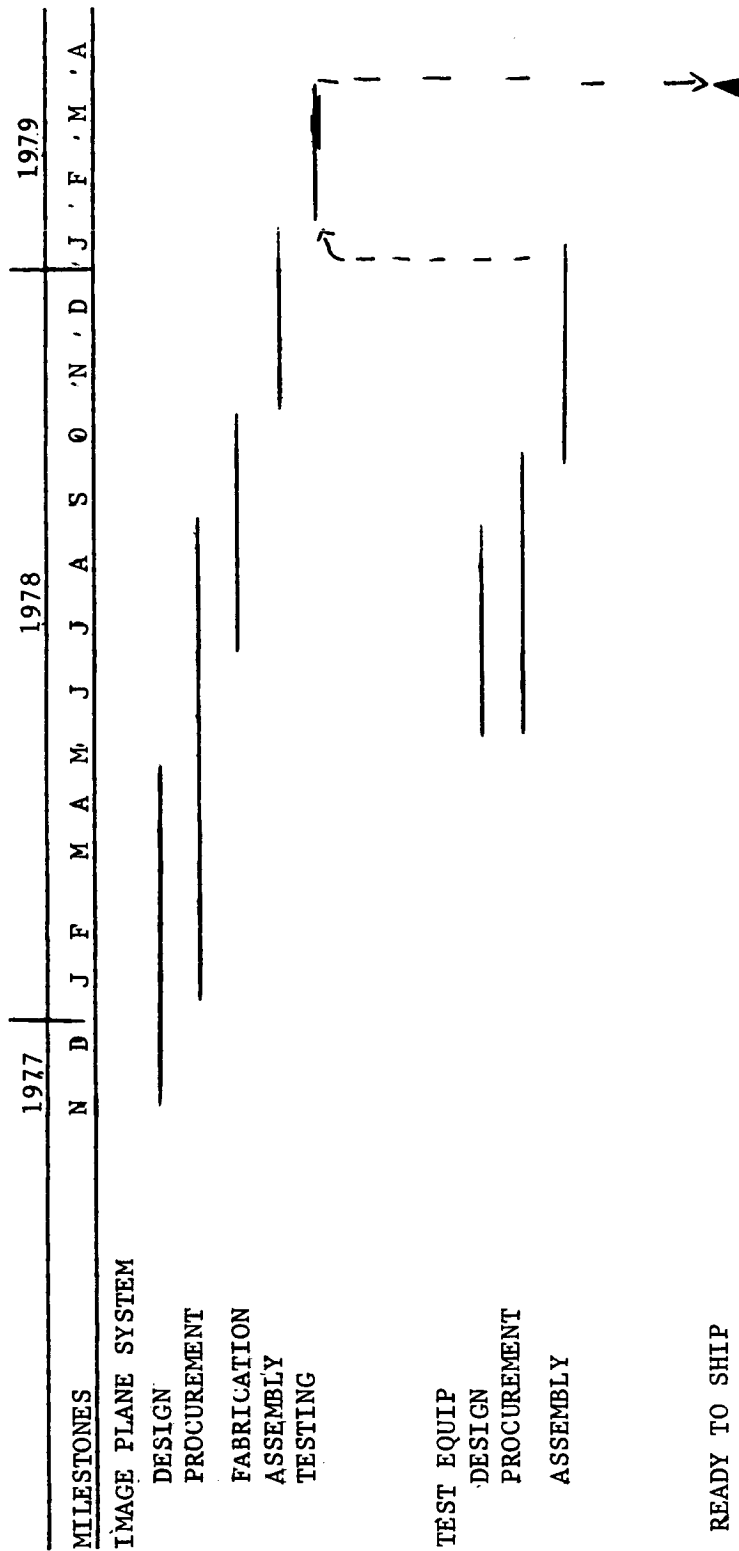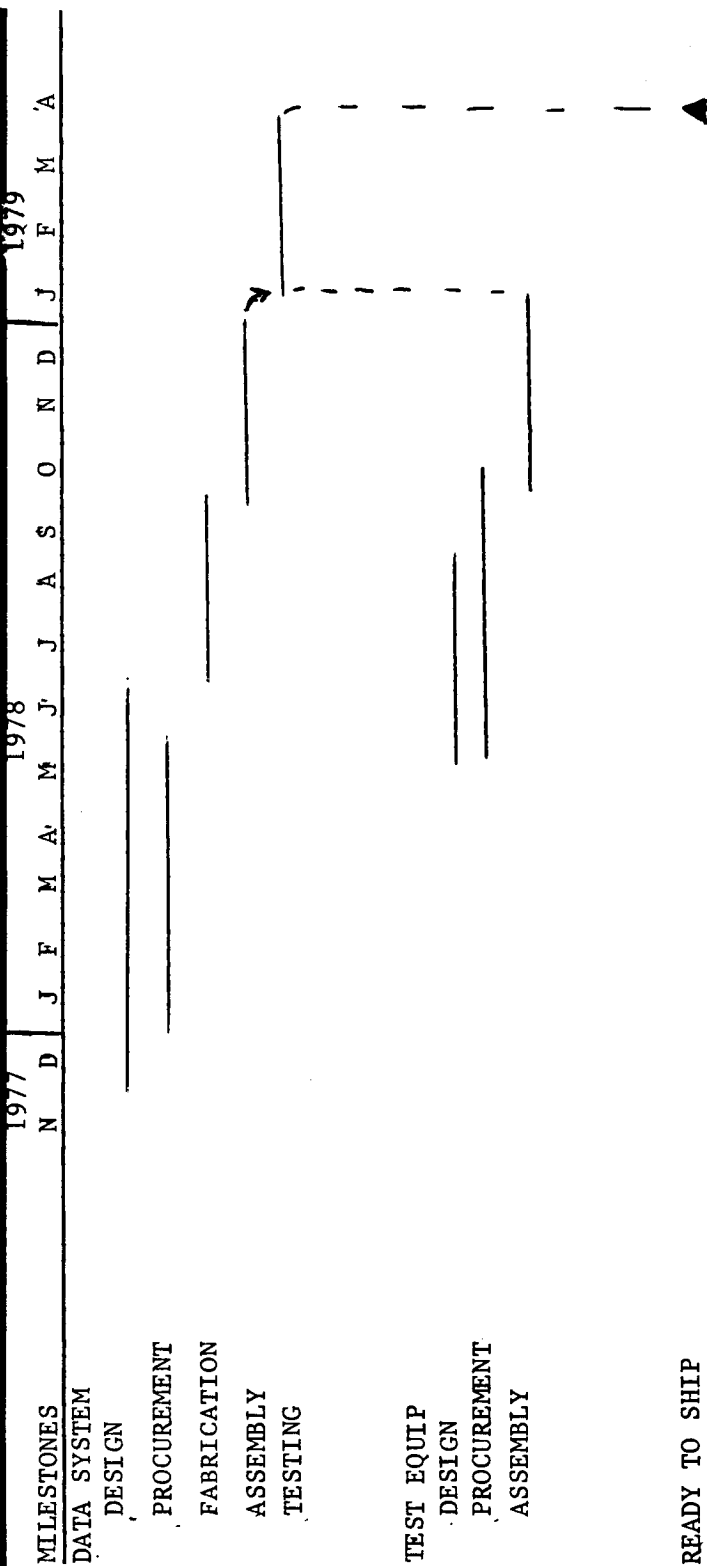
	1977		1978											1979			
MILESTONES	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A

IMAGE PLANE SYSTEM

DESIGN
PROCUREMENT
FABRICATION
ASSEMBLY
TESTING

TEST EQUIP
DESIGN
PROCUREMENT

ASSEMBLY

READY TO SHIP

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SCHEDULE: INFRARED IMAGERY OF SHUTTLE

BLACK BOX #3 - DATA SYSTEM

FIG. 81

MILESTONES	1977				1978										1979			
	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A

DATA SYSTEM
   DESIGN
   PROCUREMENT
   FABRICATION
   ASSEMBLY
   TESTING

TEST EQUIP
   DESIGN
   PROCUREMENT
   ASSEMBLY

READY TO SHIP

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SCHEDULE: INFRARED IMAGERY OF SHUTTLE

SYSTEM SUPPORT

FIG. 82

MILESTONES	1977		1978											1979									
	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O
CONTRACT GO-AHEAD	◄																							
SHIP IR SYSTEM																		◄						
INSTALLATION/CHECKOUT																								
CALIBRATION FLIGHT																				◄				
FIRST SHUTTLE FLIGHT																					◄			
DATA REDUCTION																					◄	◄		
STATUS REPORTS		◄			◄			◄		◄				◄		◄			◄				◄	

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SCHEDULE: INFRARED IMAGERY OF SHUTTLE

SOFTWARE

FIG. 83

	1977		1978											1979									
MILESTONES	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M.	J	J	A	S	O

SOFTWARE

DEVELOPMENT

OPERATION

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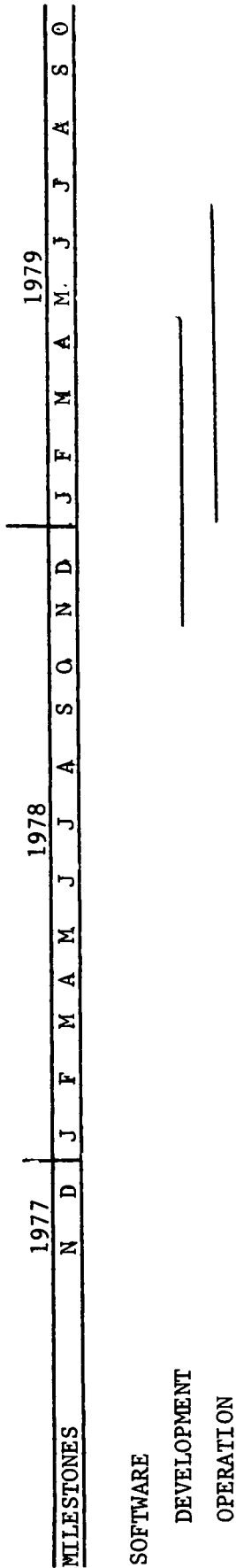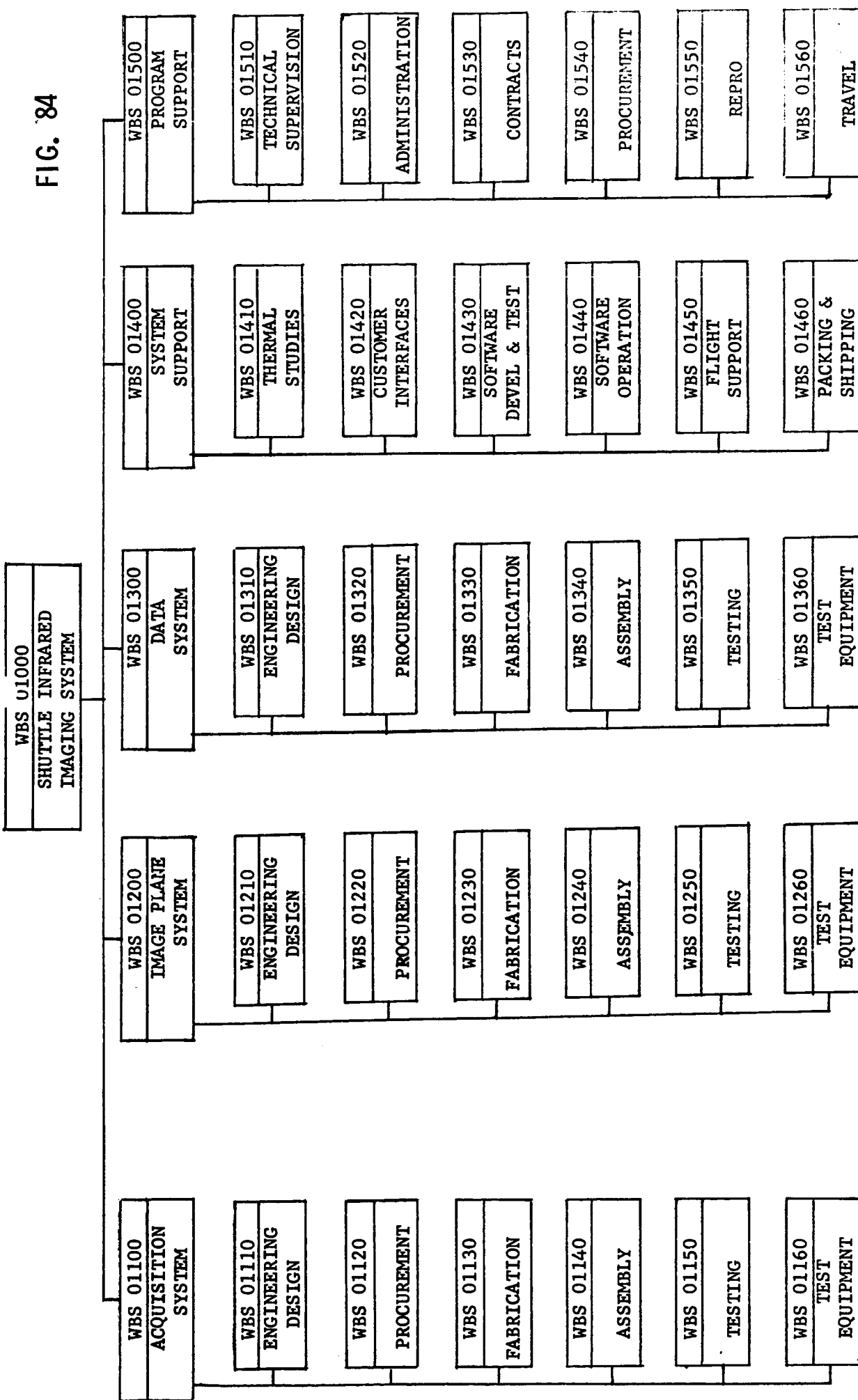
FIG. 84

WORK BREAKDOWN STRUCTURE FOR SHUTTLE INFRARED IMAGING SYSTEM

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2.0		01100
WBS LEVEL		**WBS NUMBER**

Acquisition System

WBS TITLE

DEFINITION

This effort shall design, procure parts/materials, fabricate, assemble, and test the acquisition system for infrared imaging measurements of the shuttle.

WORK CONTENT	**SOW NO.***
01110 - Design Acquisition System	
01120 - Procure parts/materials for acquisition system	
01130 - Fabricate piece parts for acquisition system	
01140 - Assemble acquisition system	
01150 - Test acquisition system	
01160 - Provide test equipment for acquisition system	

*01 = ENGINEERING; 02 = TOOLING; 03 = MANUFACTURING; 05 = QUALITY 06 = MFG TEST; 09 = OTHER TECHNICAL SERVICES.

2.0		01200
WBS LEVEL		**WBS NUMBER**

Image Plane System

WBS TITLE

DEFINITION

This effort shall design, procure parts/materials, fabricate, assemble, and test the Image Plane System for infrared imaging measurements of the shuttle.

WORK CONTENT	SOW NO.*
01210 - Design Image Plane System	
01220 - Procure parts/materials for Image Plane System	
01230 - Fabricate piece parts for Image Plane System	
01240 - Assemble Image Plan System	
01250 - Test Image Plane System	
01260 - Provide test equipment for Image Plane System	

***01 = ENGINEERING; 02 = TOOLING; 03 = MANUFACTURING; 05 = QUALITY
06 = MFG TEST; 09 = OTHER TECHNICAL SERVICES.**

2.0	01300
WBS LEVEL	**WBS NUMBER**

Data System
WBS TITLE

DEFINITION

This effort shall u.. 'gn, procure parts/materials, fabricate; assemble, and test the Data System for infrared imaging measurements of the shuttle.

WORK CONTENT	SOW NO.*
01310 - Design Data System	
01320 - Procure parts/materials for Data System	
01330 - Fabricate piece parts for the Data System	
01340 - Assemble Data System	
01350 - Test Data System	
01360 - Provide test equipment for Data System	

*01 = ENGINEERING; 02 = TOOLING; 03 = MANUFACTURING; 05 = QUALITY
06 = MFG TEST; 09 = OTHER TECHNICAL SERVICES.

2.0		01400
WBS LEVEL		**WBS NUMBER**

System Support	
	WBS TITLE

DEFINITION

This effort shall consist of those functions that are applicable, the complete Shuttle Infrared Imaging System.

WORK CONTENT	SOW NO.*
014 10 - Conduct Thermal Study	
01420 - Provide interface with NASA, Ames Research Center, Moffett Field, CA 94035	
01430 - Develop & Test Software	
01440 - Operate Software and Reduce Data	
01450 - Provide flight support consisting of installation, calibration, and checkout of system in C141 aircraft.	
01460 - Pack and Ship System	

*01 = ENGINEERING; 02 = TOOLING; 03 = MANUFACTURING; 05 = QUALITY
  06 = MFG TEST; 09 = OTHER TECHNICAL SERVICES.

2.0	01500
WBS LEVEL	**WBS NUMBER**

Program Support

WBS TITLE

DEFINITION

This effort shall consist of those functions that are necessary to support the contract.

WORK CONTENT	SOW NO.*
01510 - Provide Technical Supervision and Direction	
01520 - Perform Planning/Cost Control Support	
01530 - Provide Contract Support	
01540 - Procure supplies/materials that are not unique to system hardware.	
01550 - Provide reproduction, printing and presentations support	
01560 - Provide Travel Support	

*01 = ENGINEERING; 02 = TOOLING; 03 = MANUFACTURING; 05 = QUALITY 06 = MFG TEST; 09 = OTHER TECHNICAL SERVICES.

RECOMMENDATIONS FOR FUTURE WORK

Two items have been identified in the feasibility study for pos-
sible investigation to establish operating tolerances. The first
is the accuracy obtainable by the Reticle/Demodulation System
as part of the Acquisition System. Error sources for tracking
have been identified but some assumptions as to Shuttle image
size error and demodulation errors have been made. A breadboard
of the subsystem would prove valuable in ascertaining tracking
errors.

The second item is in the Data Handling System. The concept of
tying three detectors to a common amplifier and then multiplexing
10 amplifiers to the sample and hold/A to D is sound but needs to
be breadboarded to establish realizable data rates and amplifier
noise. In addition, the dynamic range can be checked for avail-
able detector/amplifiers and an estimate made of minimum ΔT.
These two tasks are recommended for follow-on work to the feasi-
bility study.

Figure 90 is an estimate of Engineering hours and purchased parts
to complete these tasks and Figure 91 is a preliminary schedule
for completion of the work.

FIG. 90

FOLLOW-ON TASK ESTIMATE

	HOURS	PURCHASE PARTS
TASK 1 - IMAGING SYSTEM		
BREADBOARD AMPLIFIER/DETECTOR SAMPLE & HOLD/AD	360	$12K
PERFORM DEVELOPMENT TESTS	290	
TASK 2 - ACQUISITION SYSTEM		
BUILD RETICLE/AMPLIFIER SYSTEM	240	$3.1K
PERFORM DEVELOPMENT TESTS	100	
SIMULATE SOFTWARE/SERVO ERRORS	220	$ .4K

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FIG. 91

INFRARED IMAGERY OF SHUTTLE – PRELIMINARY FOLLOW-ON CONTRACT SCHEDULE NAS2-9381

TASK	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.

FOLLOW-ON: GO-AHEAD

ENGINEERING

PROCUREMENT
DETECTOR
ELECTRONICS
RETICLE

FABRICATION/ASSY.

BREADBOARD TESTS

IMAGE PLANE SYS. { DETECTOR
AMP
MUX, A/D

{ RETICLE SYS.

ACQ SYS. { AMP
DEMOD
SERVO

REPORT
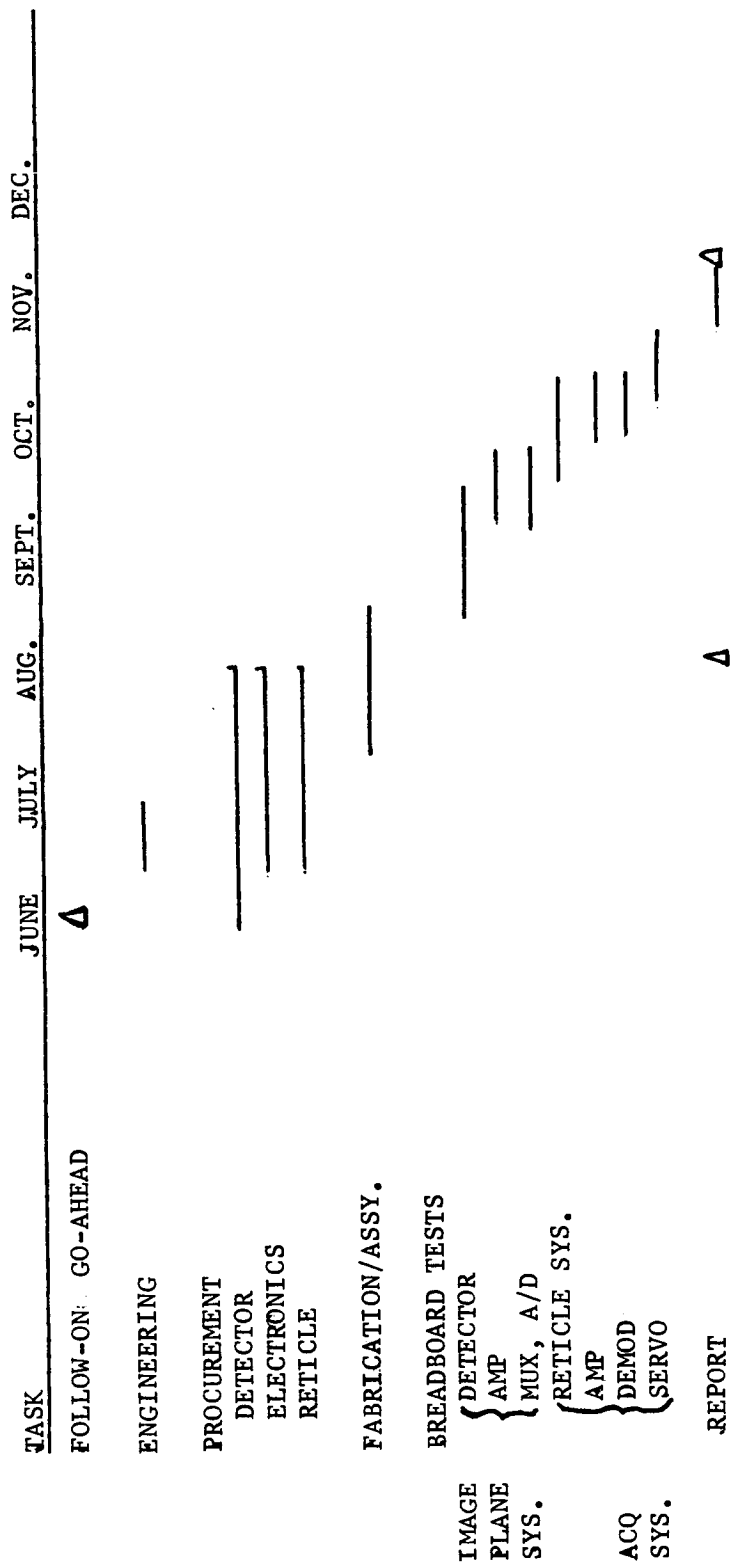
CONCLUSIONS

The feasibility of remote, high-resolution infrared imagery of the Shuttle Orbiter lower surface during entry to obtain accurate measurements of aerodynamic heat transfer has been demonstrated. In summary, the experiment is both feasible, within the current technology level, and requires minimum modification to the existing NASA C141 Airborne Infrared Observatory. The most important technical conclusions are as follows:

1) The four conditions of interest during the entry trajectory can be accommodated by an aircraft flying parallel to the Shuttle reentry ground track.

2) The temperature range that can be measured at an accuracy of 2.5% is from 700 to 1900 K depending on range. Temperatures below 700 K can be measured by relaxing the accuracy or re-scaling the Data System to limit the upper temperature to less than 1700 K.

3) The spatial resolution obtainable for the worst-case encounter with the Shuttle Orbiter (i.e., greatest range and maximum angle between LOS and Shuttle lower surface normal) is 1 meter at temperatures above 800 K. At higher temperatures and/or shorter ranges, this value can be as small as 0.4 meters.

4) An Acquisition System using a 6.25-cm aperture telescope and a single indium antimonide detector has been designed (preliminary) that will meet the acquisition requirements and will interface with the 91.5-cm telescope with minimum modification.

5) An Image Plane System using 600 indium antimonide detectors in two arrays has been designed (preliminary) that requires no modification to the existing telescope.

6) A Data Handling System built of components available currently has been designed (preliminary) that interfaces with the experimentors station and HP2100 computer (ADAMS) similar to any infrared experiment data system.

7) Thermal information from the sides of the Shuttle Orbiter can be obtained with degraded performance (i.e., temperatures below 800 K) by flying the C141 on the opposite side of the Shuttle ground track and in the direction opposite that which is optimun for lower surface viewing.

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----

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APPENDIX

The following set of tables (Figures 92 through 95) contain all
of the geometric data pertaining to the four specified aerothermo-
dynamic conditions for OFT-1. The 282-sec case represents peak
heating near the nose of the vehicle; the 544-sec case represents
peak heating further aft, the beginning of transition of boundary
layer from laminar to turbulent and body flap heating; the 791-sec
case represents the end of transition of the boundary layer and
fully developed turbulent flow; and the 922-sec case represents
lower surface turbulent boundary layer flow. The Shuttle alti-
tude, velocity, roll and pitch are given along with the aircraft
altitude for each case. The symbol definitions are as follows:

θ	Telescope elevation
R_p	Data range in kilometers - Distance from air-craft-to-Shuttle at the time prime data is taken.
A_Q	Acquisition angle in degrees - Azimuth angle ahead of or behind athwartships position when acquisition can first occur.
R_A	Acquisition range in kilometers - Distance from aircraft to Shuttle at first point of acquisition
α	Angle in degrees between 91.5-cm telescope line-of-sight and Shuttle underside normal when prime data are taken.
σ	Angle-in-degrees between acquisition telescope line-of-sight and Shuttle underside normal when acquisition first occurs.
Pix	Projected size of one pixel 50 x 50 micrometers on Shuttle surface given in meters.
MTF RES	Resolution based on MTF at a given modulation (%) in meters on the Shuttle surface.
$Image_D$	Shuttle image size wing tip to wing tip at prime data point given in minutes of arc.
$Image_A$	Shuttle image size nose to tail at first acquisi-tion given in minutes of arc.
Time to Cross	Time in milliseconds Shuttle image takes to cross one detector array.

Across Track   Number of detectors that the Shuttle image
Data Array   will intercept at prime data point.

Along Track Sample Sampling rate of each detector to match along
Rate   track resolution with cross track resolution.

C141 to Shuttle   The distance the C141 must fly displaced from
Ground Track   the Shuttle ground track for best observation.
Difference

Figure 96 depicts the streak camera configuration that has been
discussed in this report (see also Ref. 1).

FIG. 92

C141 DATA & ACQUISITION GEOMETRY - 282 SEC CASE

Shuttle Alt 74.3 KM
C141 Alt 12.5 KM
Shuttle Velocity 7.16 KM/Sec
Shuttle Roll 74°
Shuttle Pitch 40°

θ(o)	R_D(KM)	A_Q(o)	R_A(KM)	γ(b)	σ(o)	PIX(m)	MTF Res. @2% (m)	MTF Res. @5% (m)	Image$_D$ (min)	Image$_A$ (min)	Time To Cross (Milsec)	Across Track Data Array	Along Track Sample Rate
35	107.74	53.05	179.20	19.42	4.60	.46	.77	.92	.715	.626	4.57	51.48	15558
40	96.14	56.12	172.48	24.42	5.41	.42	.71	.85	.773	.650	4.57	55.70	16845
45	87.39	58.60	167.76	29.42	6.03	.40	.67	.81	.814	.667	4.57	58.61	17741
50	80.67	60.60	164.36	34.42	6.50	.39	.66	.79	.835	.681	4.57	60.14	18218
55	75.44	62.21	161.85	39.42	6.86	.39	.65	.78	.838	.691	4.57	60.22	18262
60	71.36	63.51	159.99	44.42	7.14	.40	.67	.80	.818	.698	4.57	58.06	17871
65	68.18	64.53	158.60	49.42	7.35	.42	.70	.84	.783	.704	4.57	56.37	17057
70	65.76	65.33	157.57	54.42	7.51	.45	.76	.91	.731	.708	4.57	52.41	15845

Optimum θ

282 sec case θ = 55°

C141 to shuttle ground track difference

43.27 KM

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CI4I DATA & ACQUISITION GEOMETRY - 544 SEC CASE

FIG. 93

Shuttle Alt.   63.7 KM
C141   12.5 KM
Shuttle Velocity   5.64 KM/SEC
Shuttle Roll   63°
Shuttle Pitch   40°

θ (o)	R_D(KM)	A_Q(o)	R_A(KM)	γ(o)	σ(o)	PIX(m)	MTF Res @2% (m)	MTF Res @5% (m)	Image$_D$ (min)	Image$_A$ (min)	Time to Cross (milsec)	Across Track Data Array	Along Track Sample Rate
35	89.26	51.64	143.84	9.89	2.68	.36	.61	.73	.907	.782	5.81	65.25	15496
40	79.65	54.77	138.08	14.89	1.77	.33	.55	.66	1.000	.815	5.81	71.95	17087
45	72.40	57.30	134.03	19.89	1.07	.31	.51	.62	1.07	.810	5.81	77.25	18347
50	66.83	59.35	131.11	24.89	.54	.29	.49	.59	1.12	.859	5.81	81.00	19238
55	62.50	61.00	128.95	29.89	.14	.29	.48	.58	1.15	.873	5.81	83.08	19733
60	59.12	62.34	127.35	34.89	.17	.29	.48	.58	1.16	.884	5.81	83.43	19816
65	56.49	63.39	126.15	39.89	.41	.29	.49	.59	1.14	.893	5.81	82.04	19485
70	54.48	64.21	125.56	44.89	.59	.31	.51	.62	1.09	.899	5.81	78.95	18750

Optimum θ

544 sec case θ = 50°

C141 to shuttle ground track difference

52.96 KM

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CI4I DATA & ACQUISITION GEOMETRY -79I SEC CASE

FIG. 94

Shuttle Alt   54.2 KM
C141 Alt   12.5 KM
Shuttle Velocity   3.49 KM/SEC
Shuttle Roll   50°
Shuttle Pitch   39°

θ°	R_D(KM)	A_A(o)	R_A(KM)	γ(o)	σ(o)	PIX(m)	MTF Res. @2% (m)	MTF Res. @5% (m)	Image$_D$ (min)	Image$_A$ (min)	Time To Cross (milsec)	Across Track Data Array	Along Track Sample Rate
35	72.70	43.83	100.78	.23	10.32	.29	.48	.58	1.12	1.099	9.38	80.59	11835
40	64.87	47.09	95.29	5.23	8.81	.26	.43	.48	1.26	1.168	9.38	90.66	13314
45	58.97	49.80	91.37	10.23	7.23	.24	.40	.48	1.38	1.222	9.38	99.35	14591
50	54.43	52.05	88.51	15.23	6.65	.22	.37	.45	1.47	1.264	9.38	106.41	15626
55	50.90	53.89	86.39	20.23	5.90	.21	.36	.43	1.55	1.297	9.38	111.60	16389
60	48.15	55.40	84.79	25.23	5.30	.21	.35	.43	1.59	1.322	9.38	114.78	16856
65	46.01	56.60	83.60	30.23	4.84	.21	.35	.43	1.61	1.342	9.38	115.85	17014
70	44.37	57.55	82.71	35.23	4.48	.21	.36	.43	1.59	1.357	9.38	114.78	16856

Optimum θ

791 sec case θ = 45°

C141 to shuttle ground track difference

41.70 KM

C141 DATA & ACQUISITION GEOMETRY - 922 SEC CASE FIG. 95

Shuttle Alt   43.9 KM
C141 Alt   12.9 KM
Shuttle Velocity   2.37 KM/SEC
Shuttle Roll   45°
Shuttle Pitch   28°

θ_o	R_D(KM)	A_Q(o)	R_A(KM)	γ(o)	$\sigma_{(o)}$	Pix(m)	MTF Res. @2% (m)	MTF Res. @5% (m)	Image$_D$ (min)	Image$_A$ (min)	Time To Cross (milsec)	Across Track Data Array	Along Track Sample Rate
35	54.74	40.88	72.41	6.44	15.74	.22	.37	.44	1.47	1.497	13.82	105.81	10546
40	48.84	44.13	68.06	1.44	13.97	.19	.32	.39	1.66	1.606	13.82	119.94	11955
45	44.40	46.85	64.95	3.55	12.53	.17	.29	.35	1.84	1.693	13.82	132.45	13202
50	40.99	49.14	62.66	8.55	11.37	.16	.27	.33	1.98	1.762	13.82	142.95	14240
55	38.33	51.03	60.96	13.55	10.43	.15	.26	.31	2.10	1.817	13.82	151.11	15061
60	36.25	52.58	59.67	18.55	9.69	.15	.25	.30	2.17	1.861	13.82	156.69	15618
65	34.64	53.83	58.71	23.55	9.11	.15	.25	.30	2.21	1.894	13.82	159.53	15901
70	33.41	54.81	57.99	28.55	8.66	.15	.25	.30	2.21	1.920	13.82	159.53	15901

Optimum θ

922 sec case θ = 35°

C141 to shuttle ground track difference

44.84 KM

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STREAK CAMERA CONFIGURATION

FIG. 96

PROTECTION OF IMAGE PLANE DATA SYSTEM

DATA RANGE

SHUTTLE ALTITUDE

TELESCOPE ELEVATION

ACQUISITION ANGLE

ACQUISITION RANGE

AIRCRAFT ALTITUDE

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