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FINAL TECHNICAL REPORT

SIMULATION REQUIREMENTS FOR THE
LARGE DEPLOYABLE REFLECTOR (LDR)

by

Keto Soosaar

July 1984

The Charles Stark Draper Laboratory, Inc.

Cambridge, Massachusetts 02139

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Approved: _David G. Hoag_ 7/23/84
David G. Hoag

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SECTION 1

INTRODUCTION

The Large Deployable Reflector (LDR) is planned as an orbiting
astronomical telescope to explore the observable universe in the wave-
length region of 30 μm to 1 mm, a range that up to now is little known
due to the opacity of the atmosphere at these wavelengths. With both
spectroscopic and imaging capabilities, it is expected to provide major
contributions towards better understanding of topics of current interest
in cosmology, stellar evolution, galactic and extragalactic structures,
on the nature of interstellar media, and on evolutionary processes in
solar and planetary systems.

Preliminary studies by NASA/AMES, Jet Propulsion Laboratory[1],*
and by the scientific and technical community that gathered at Asilomar,
California for the LDR Science and Technology Workshop[2] have indica-
ted that a diffraction-limited system with an aperture ranging from 10 to
30 meters would provide the necessary resolution and sensitivity. Add-
itionally it was concluded that "light-bucket" type of operation would be
desirable for wavelengths lower than 30 μM.

From a technologies, space operational capability, and budgetary
planning points of view, the initial operational capability was aimed
for the late 1980's to early 1990's time frame. The individual technolo-
gies would, therefore, have to be maturing by the mid-eighties. It was
considered desirable to limit the system to single Space Shuttle load,

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* References at back of report.

and to use a relatively low operational orbit to permit future refurbishments and repairs. Some consideration has also been placed on the attachment of the LDR to the proposed Space Station, but observational constraints imposed by that orbit may not be in the best astronomical interest.

SECTION 2

SPACECRAFT SYSTEMS AND TECHNOLOGIES

It is not the intent here to describe in great detail all of the possible systems, subsystems and component technologies that will converge on the LDR, but in consideration of the type of simulations and analytical tools necessary, some reference needs to be made to some of the key options under consideration.

Figure 2-1 shows a representative LDR systems concept. It is clear that the reflector is indeed large, and therefore must also be lightweight and deployable to permit the use of the Space Shuttle. The consequence of all this is that the system will indeed be quite flexible, result in low dynamic resonant frequencies, and possibly experience considerable structure-control interaction phenomena affecting the optical behavior.

Since the operational wavelengths fell in the range between optical and radar, but tended towards the long-wave infrared at their shorter limits, it will be necessary to tolerance the system at these wavelengths. The net result will be that a figure of $\lambda/20$ will be required at 30 μ for diffraction-limited imaging operations, with some of the requirements more severe if the light-bucket mode at even shorter wavelengths is invoked.

The "optical" segments which comprise the main reflector must be of low weight and able to fit into the Shuttle bay in one piece, thus
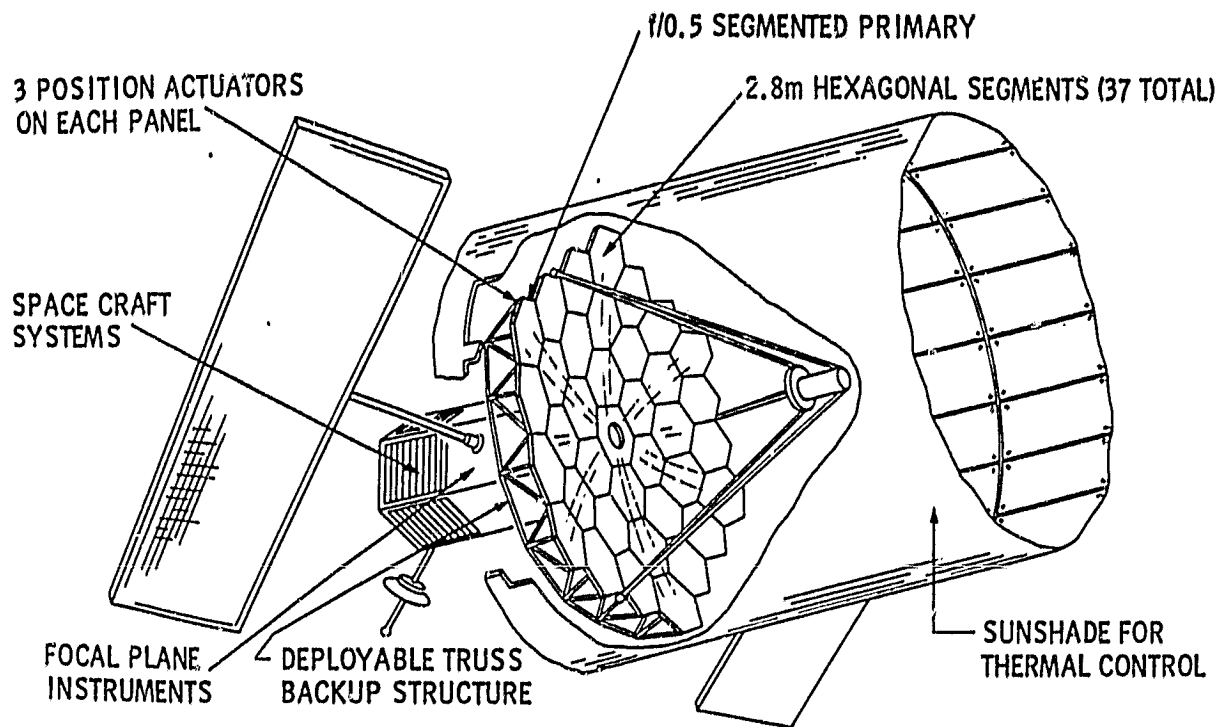
Figure 2-1. Concept for a 20-m large deployable reflector (LDR).[3]

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limiting their dimensions to about 4 meters. A considerable challenge exists in the manufacture of these segments, since the use of classical glass optics leads to excessive weight, cost and fabrication time. High-frequency radio-telescope segments of this size and low weight are available but have been manufactured only to about 300 μM operating wavelength. It is probable that a new concept incorporating active optics may be required to correct for manufacturing errors, thermal and dynamic disturbances.

The supporting mechanical substrate for these reflectors and for the optical train itself will be flexible and may respond to the various dynamic disturbances of the system. It is probable that active vibration control will need to be considered to maintain the pointing and optical train wavefront quality. A major source of disturbance comes from "chopping", the need to move major parts of the optical train for purposes of background cancellation by as much as an arc-minute at 2 to 10 Hz. Slewing at the rate of 20 degrees/minute is required to move from one observed source to the next. Due to the large amount of electrical power required, large panels with low natural frequencies will be encountered. Attitude control must deal then with these flexibilities while trying to maintain pointing accuracy of 0.5 arc-seconds and pointing stability of 0.05 arc-seconds.

It appears, therefore, that near optical tolerances must be maintained through the various control systems for figure, alignment, wavefront and pointing. These control systems must deal with structural flexibility and it is expected that overlaps in bandwidth will occur.

SECTION 3

TECHNOLOGY AND SYSTEMS VALIDATION

Since there exists very little precedent for a sensor of this size, complexity and precision, most of the key components, subsystems and the system itself must be validated prior to launch. Ground testing of such an integrated system will doubtless lead to complications. To avoid atmospheric testing errors in the optics, and spurious damping due to the air, the tests must be conducted in a vacuum tank. The flexibility of the reflector and optical train will be such that the effects of 1 g will be non-negligible. Finally it will be very difficult to assess the interaction of the rigid body dynamics and the structural flexibility except in a zero-g environment. It would be very risky, however, to assume that validation would be performed on the system once assembled in orbit. Individual components can be tested on "zero-'g" mounts but it is highly unlikely that the entire integrated and highly interactive system can be tested that way.

A partial answer to this dilemma lies in the development of highly sophisticated end to end simulations that account for all significant interactions and provide for a systems-level measure of performance.

SECTION 4

ANALYSIS AND SIMULATION TOOLS

Since there will be a large amount of new technologies, since there will be many major subsystems that can interact with each other nonlinearly, and since it 's unlikely that the LDR system can be adequately tested in 1 g prior to launch, it is crucial that reliable analysis and simulation tools be developed in parallel with the technologies.

Such tools must be able to characterize reliably the essential behavior of the LDR system, while taking into account the significant sources of uncertainty. Ideally it should begin with an expected radiometric model of the intended astronomical source, and a suitable expected model of the stellar background as inputs. An LDR model culminating with the point-spread-function and pointing time-histories is next. Finally if it is expected that significant post-detection image or signal processing will be needed, this should be modeled as well. Such an analysis-simulation tool will provide an end-to-end prediction of the performance of the LDR. The major emphasis of this tool should be, of course, on the actual LDR itself.

The "LDR Simulator" needs to include some of the following main features:

4.1   Satellite Thermal State

The Satellite Thermal State is the temperature distribution within the satellite itself. This is important to maintain the alignment of the optics to the instrument packages and the inertial reference sources, to determine thermal misalignments within the optical train and warpage of the mirror segments, and to establish the levels of the thermal self-emission of the optics.

4.2   Satellite Geometrical State

The Satellite Geometrical State represents displacements, both quasistatic and dynamic, beyond the expected tolerances. This will include geometrical misalignments from fabrication, assembly and deployment; thermal warpage must be determined through appropriate structural analysis codes; and the elastic response to dynamic on-board sources must be calculated and added to the previous two. Finally the spacecraft rigid-body deviation from its intended pointing direction must be determined.

4.3   Satellite Optical State

Given the static and dynamic misalignments with the optical train, the distorted point-spread function must be computed.

4.4   Scene-Sensor Interaction

The distorted point-spread function is convolved next with the "scene" consisting of the to be observed source superimposed on the expected background, and from that a photon stream to the focal plane instruments can be obtained.

4.5   Focal Plane Model

Photons impinging on the focal plane will be recorded directly by the means of "film"--for which a sensitivity model is needed, or turned by detectors into electron streams containing noise. Spectrometer optics models need to be included here as well, for those instruments. Scatter and thermal models may be needed in this segment as well.

4.6   On-Board Image/Signal Processing

If any on-board image/signal processing is done prior to transmission to the astronomers, models of this process and the additional noise sources that can be encountered here must be included.

SECTION 5

APPROACHES TO ANALYSIS AND SIMULATION TOOLS

At the beginning of any systems development venture, various ana-
lytical models will exist for the major features of the system behavior.
These might be simple physics-level tools to trade off parameters such as
resolution, collecting area, detection sensitivity, pointing stability,
etc., to eventually converge on a systems-level sensitivity of the
planned observatory. These tools which could be simple equations pro-
grammed on a hand calculator may or may not indicate some of the
technology problems still to be faced. These tools are useful in a
further sense, however, to help provide a zeroth order reference model
from which more sophisticated models and simulations can be developed.

A first order analysis tool will begin to incorporate some of the
technology features and provide some of the constraints. Such tools are
often of the "transfer-functions" variety and will go a long way towards
beginning to flesh out the system. Where the subsystems are simple and
non-interactive and very few if any nonlinear phenomena are encountered
then these may very well be quite adequate to characterize the behavior.
Such an analysis tool must be traceable to the physics-level tool in its
systems orientation and can incorporate some measured subsystem and com-
ponent characteristics. They tend however to only provide an instantan-
eous snapshot of the behavior, and usually a highly simplified one.

Where multiple control systems are encountered that have overlap-
ping bandwidths, and where these control systems are characterized by

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multi-input multi-output features, a transfer-functio. or frequency do-main approach becomes inadequate to represent time-varying systems. A similar condition applies also in the optical regime where high spatial variation and optics segmentation will tend to drive to enormous spatial frequency domain complications. System-level wavefront sensing and con-trol approaches moreover are most conveniently handled in the time and space domain, so that any evaluation of that kind of system is best han-dled through formal simulation approaches. The frequency domain approaches are most useful as engineering design tools, but for predic-ting the behavior of a system as complicated as the LDR a full-up simula-tion must eventually be developed.

SECTION 6

SIMULATION OF LDR

Once it is decided to develop a full-scale simulation further decisions are necessary: should it be real-time or not? The advantages of real-time simulations are obvious. Component models can be replaced at any time by the hardware itself and the simulation can evolve from a software based one into a breadboard representation. The real-time simulation, moreover, can be used as a reasonably precise analog which becomes the focus for any flight software development. Since the flight software development, its validation and verification, occupies an increasingly large part of the system development time, it is typical that access to any part of the flight hardware does not occur until relatively late stages in the system development. The real-time simulation and its evolution to a breadboard considerably relieve these pressures.

The disadvantages of a real-time simulation are considerable too. A dedicated or near-dedicated computer is nearly always called for and considerable computing throughput is necessary if high frequency multi-degree-of-freedom components (such as large reflectors) are encountered. The additional complexity of programming for real-time may raise the cost to twice that of non-real-time software.

Tremendous insight into the details of the technical problem, and a large amount of systems incompatabilities can be established with a non-real-time simulation. The discussion that follows for the LDR is applicable to both kinds of simulation, although the emphasis will be placed here on the non-real-time variety.

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Figure 6-1 indicates a typical architecture for the simulation of a system such as LDR. The major technologies of interest in the development of the models are heat transfer, structural mechanics and dynamics, spacecraft dynamics, control of figure, alignment and attitude, and optics.

The architecture demands that large numerical analysis software programs such as CINDA (thermal), NASTRAN (structural) and ACOSS V (optical) be kept out of the direct loop of the simulation. They are used but only to receive inputs from previous analyses and provide output to the next block. The blocks interface through data bases and this interface block may include interpolation routines to bring the various discretization approaches—finite difference, finite element and ray-trace to common nodal quantities.

Each block should be exercised by a specialist in that particular discipline—it is unwise to use "generalists" to run codes of this complexity. The specialist is responsible for the quality of the model that he has generated and for the correctness of his outputs into the common data base. Such simulations will contain few enduring models since the systems concept will evolve with time. Eventually the numerically-obtained data base may be replaced by experimentally derived data, but this need not be known by the next level of user.

6.1   Thermal Model

This block, which is contained outside the major flow of the simulation, is nothing more than a classical heat transfer program such as CINDA or the ADL Thermal Analysis Program. To be useful for space applications, it needs to have full radiative transfer capabilities along with view factors and other shading features. Inputs to this will consist of mechanical and thermal design parameters, orbital parameters and a numerical description of the internal heat sources. It will be clearly a non-steady state program but the dynamics are not sufficient to excite in the
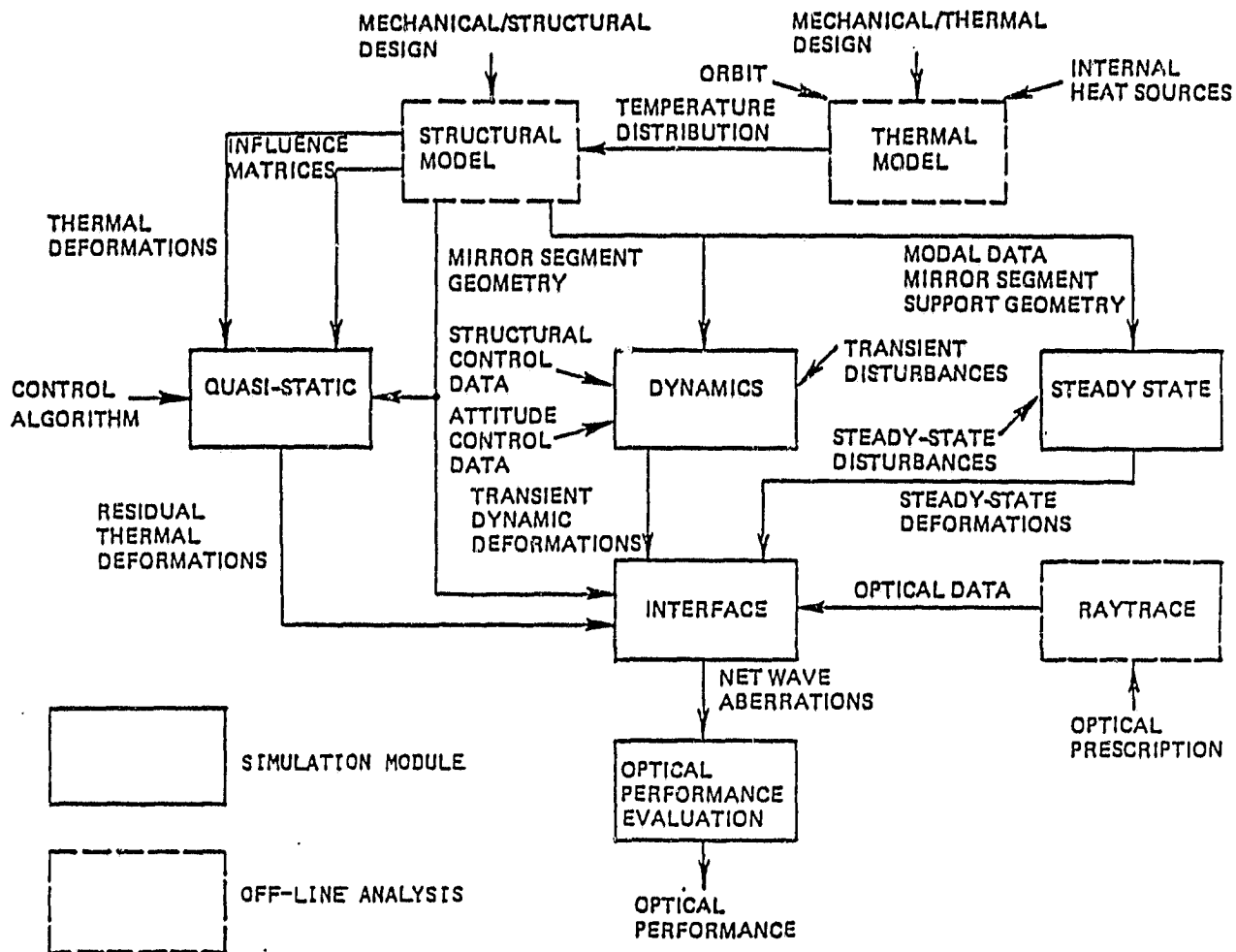
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Figure 6-1. LDR spacecraft and optics simulation.

general case spacecraft or elastic response. The output will be a
description (slowly time-varying) of temperature distributions in the
satellite. This data set then becomes one of the forcing functions for
the structural model as well as providing disturbances to the cryogenic
features of the LDR.

6.2   Structural Model

The structural analysis and modelling block also is contained out-
side the major flow of the simulation. This can include generally avail-
able programs such as NASTRAN, STARDYNE, ADINA, ANSYS, etc., or other
programs that are technically suitable for modeling the problem at hand.
For space applications, free-free modes must be available, however. In-
puts to the program will come from mechanical and structural design
parameters and the appropriate elastic properties. Outputs from this
block are many. The simplest is the net set of deformations of the
structure due to thermal and mechanical loads. For other parts of the
simulation, mode shapes and frequencies are extracted and placed in the
appropriate data bases.

6.3   Quasistatic

Since the LDR may be considered to have rigid body control of the
reflector segments, as well as possible figure control within the seg-
ments, the quasistatic block deals with these problems. A control law
input is required along with influence functions from the structural
model and gross initial displacements from the thermo-elastic response
augmented by initial fabrication and deployment errors. Further control-
related parameters can be input here as well such as actuator and sensor
quantization. The output is the net set of reflecting surface displace-
ments not subject to further controllability.

6.4   Steady State

The Steady State block is a useful design tool that allows a quick
response calculation to be made. The structural mode shape and frequency

data is assembled into individual equations of motion and peak responses
are calculated for each mode and for each disturbance. These can then be
summed in a non-phase-coherent manner or root-mean-squared to obtain
probable superposition. A frequency-domain representation in terms of a
structural dynamics transfer function may be obtained by further off-line
manipulation of the data.

6.5   Dynamics

The Dynamics block will contain probably the most computationally
complex part of such a simulation. Equations of motion for the coupled
rigid body and flexible representation for the simulation must be gener-
ated off-line, although it might be possible to connect an offline dynam-
ics program such as DISCOS to the block. Two control systems--attitude
and structural control will be encountered here and inputs from the
structural modeling block are necessary in terms of modeshape and fre-
quency data. A system-level equation of motion is assembled and inte-
grated with various clocks accounting for the bandwidths of the several
subsystems under consideration. Forcing functions--both environmental as
well as on-board will enter here, as well as detailed descriptions of the
control laws and any actuator and sensor characterizations. The output
of the dynamics module will be an instantaneous rigid body and elastical-
ly deformed state of the spacecraft.

6.6   Raytrace

The raytrace module is most appropriately off line since it is
usually part of a much larger optical design and analysis package such as
ACOSS V. The optical prescription for the LDR will be the input to the
module and two related calculations will be done. First a raytrace will
be performed to obtain the wave observations of the undeformed (refer-
ence) system. Then a "differential raytrace" will be obtained to estab-
lish an instantaneous change in the wave aberrations due to a motion of a
reflecting surface away from the reference positions. This data will
pass onto the following Interface module.

6.7 Interface

The purpose of the Interface module will be to merge the different spatial and temporal discretizations into a format suitable for the optical performance evaluations. With raytrace discretization as the standard, the outputs of the Quasistatic and Dynamics (or Steady State) are interpolated by means of bicubic splines to obtain total displacements at the incidence points of the raytrace on the various reflectors. This interpolation will be done as often as necessary as determined by the highest frequencies of interest in the Dynamics module. The displacements are then converted (via the differential raytrace) to net system wave aberrations and the information is placed in the output data set.

6.8 Optical Performance Evaluation

This final module takes the net wave aberrations and turns it first into a pupil function, then performs a two-dimensional (fast) Fourier transform on it, and finally performs a modulus squared operation. Thus the point-spread-function (PSF) and the power on the detector can be obtained. The deformed line of sight (LOS) is computed from the centroid of the PSF and is added to the rigid body LOS to obtain the system-level LOS.

SECTION 7

SIMULATION OF SCENE, FOCAL PLANE, AND PROCESSING

Once the optical point spread function and system LOS have been obtained, then some further steps will be necessary to establish the astronomical performance of the LDR. Figure 7-1 indicates how some of the next steps might be achieved.

7.1   Scene

The scene which the LDR will attempt to observe will consist of an astronomical source of interest superimposed on a suitable background. The nature of the source cannot readily be defined except as the radiant intensity of the limiting target of interest for the observatory at that particular waveband. The background will also provide some difficulties since there is little data to base it on, yet it may be a distinct limitation to the observations planned. Statistically based extrapolations from IRAS shifted to the proper wavelengths may provide some initial guidance. The scene has to be constructed in at least comparable spatial detail as the optical PSF, and should have several distinct regions so that chopping strategies can be tested.

7.2   Convolution

Since both the optical PSF and the scene are numerically obtained, it is necessary to perform the convolution numerically as well. This method has been found to be quite successful and can be made computationally efficient.
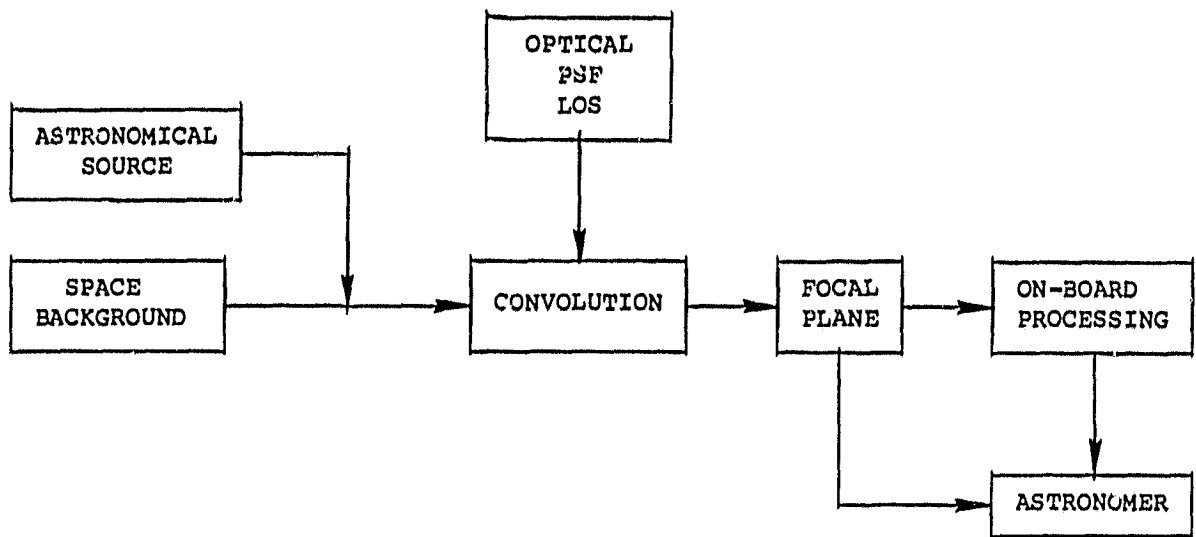
Figure 7-1. LDR Systems-Level Simulation.

7.3 Focal Plane

The photon intensity impinging on the focal plane is obtained in the convolution and the focal plane module converts this into electron streams for the detectors or into permanent records on film. The various conversion sensitivities and accompanying noise sources must be modeled here.

7.4 On-Board Processing

The electron stream from the focal plane may be passed through some on-board processing (e.g., background substraction in chopping) prior to transmission to ground. Each of such processes may change to signal to noise relationships of the data so that these must be quantified here.

SECTION 8

SUMMARY AND CONCLUSIONS

It has been the argument of this short report to try to make the case for the development of a detailed systems-level simulation in parallel with the development of the LDR systems concepts and the individual technologies needed. Doubtlessly such a simulation will not be inexpensive, particularly since a larger part of the investment must come at the beginning of the program when funds are scarce rather than later on when larger resources become available.

As has been discussed, physics-level and transfer-function types of representations may not provide a sufficiently detailed identification of the key technology issues in time to take steps to resolve them. Many of the models that are used as inputs to the simulation--in heat transfer, structures, dynamics, control and optics will be developed under any circumstances by the various subsystem groups. The purpose of the simulation is to merge the various existing data bases and allow a merging at the systems level. With careful prior planning a simulation as discussed above can be made to happen by the establishment early-on of a logical coherent architecture and then stringently enforcing various technology modeling activities to use the common data base approach for communicating their outputs. In this manner much duplicative effort is avoided, and the individual technology groups become more sensitive to their impact on other parts of the system. Clearly, configuration control on models must be enforced, and no one should be asked to simulate "glossy

cartoons"--i.e., spending more time on modeling and analysis of a concept than the systems designers spent on its genesis.

With any luck, a proper end-to-end simulation should be available prior to the commitment to a particular final configuration. It can thus be a tool for assessing competitive concepts, for identification of subsystem and technology cliffs, and in the avoidance of major systems performance "regrets." LDR will not be a simple satellite where each subsystem can operate independently of its neighbors, it requires a simulation tool commensurate with its hardware complexity.

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